Journal of Marine Systems 156 (2016) 16–29

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Water age, exposure time, and local flushing time in semi-enclosed, tidal basins with negligible freshwater inflow

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ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form 20 November 2015
Accepted 25 November 2015
Available online 4 December 2015

Keywords:
Water renewal
Water age
Local flushing time
Exposure time
Semi-enclosed basin
Lagoon of Venice

ABSTRACT

Within the framework of tidally flushed, semi-enclosed basins with negligible freshwater inflow, and under steady periodic flow conditions, three frequently used local transport time scales to quantify the efficiency of water renewal, namely water age, exposure time, and local flushing time are studied and compared to each other. In these environments, water renewal is strongly controlled by diffusion, and it is significantly affected by the return flow (i.e., the fraction of effluent water that returns into the basin on each flood tide). The definition of water age is here modified to account for the return flow, in analogy with exposure time and local flushing time. We consider approximate time scales, whose accuracy is analyzed, in order to overcome problems related to the size of the computational domain and to reduce the computational effort. A new approximate procedure is introduced to estimate water age, which is based on the water aging rate. Also, the concept of local flushing time as a relevant time scale is introduced. Under steady periodic conditions, we demonstrate that the local flushing time quantitatively corresponds to water age, and well approximates exposure time when the flow is dominated by diffusion. Since the effort required to compute water age and exposure time is greater than that required to compute the local flushing time, the present results can also have a practical interest in the assessment of water renewal efficiency of semi-enclosed water basins. The results of a modeling study, in which the lagoon of Venice is used as a benchmark, confirm the substantial quantitative equivalence between these three transport time scales in highly diffusive environments.

1. Introduction

Knowledge of the rate at which estuaries and semi-enclosed basins flush nutrients and pollutants seaward is important for management since it partially determines their trophic state and health (e.g. Miller and McPherson, 1991; Lucas et al., 2009; Lucas, 2010; Brodie et al., 2012). Transport time scales are key parameters for the quantitative assessment of water renewal of estuaries and tidal basins and they have long been used to this purpose (e.g. Bolin and Rodhe, 1973; Vollenweider, 1976; Zimmerman, 1976; Takeoka, 1984; Wolanski, 2007). A variety of terms such as residence time, flushing time, transit time, turnover time, and age identifies different time scales that are widely used to describe transport and removal of materials from water bodies. Most of these time scales can be averaged over the whole basin or they can be defined locally, at every position in the basin, to provide a more detailed, spatially distributed information on the water renewal capacity of a basin.

Among the many transport time scales to quantify the local rate of water renewal, the most frequently used are residence time and water age. Residence time is the time required for a particle of water to move from its present location out of the basin (Zimmerman, 1976; Takeoka, 1984; Prandtle, 1984); water age is the time a water particle has spent since entering the basin through one of the boundaries, i.e., it is the time required for a water particle to travel from the basin inlet to its present location (Bolin and Rodhe, 1973; Monsen et al., 2002; Delhez et al., 1999). These definitions are unambiguous in the case of steady, convective flow with distinct inlet (source) and outlet (sink), as in Fig. 1a.

For a tidally flushed basin with negligible residual currents and freshwater inflow, water renewal is strongly controlled by diffusion. In addition, the inlet of a tidal basin acts alternatively as a source, during the flood phase of the tide, and as a sink during the ebb phase; that is, the sink and the source are located at the same position (the "short circuit case", Fig. 1b). Also, a significant fraction of effluent water can return to the basin on each flood tide (Sanford et al., 1992; Delhez et al., 2004); accordingly, to correctly assess water renewal of a basin, a region larger than the basin itself has to be considered (de Brauwere et al., 2011). All these conditions add complexity to the problem, which may lead to increased ambiguity and complications in the definition of time scales (Bolin and Rodhe, 1973; Delhez, 2013).

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http://dx.doi.org/10.1016/j.jmarsys.2015.11.006
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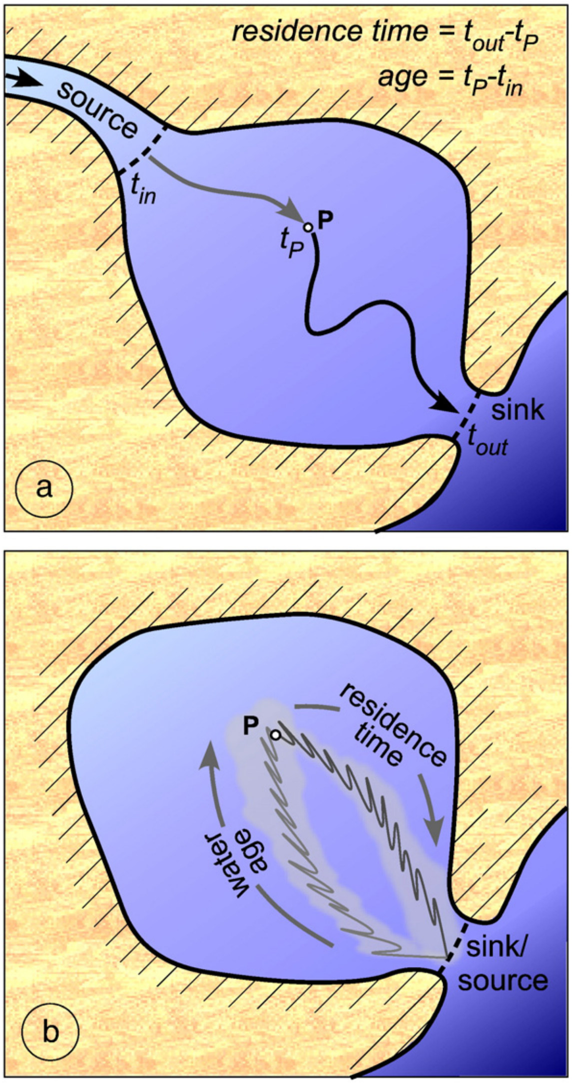

Fig. 1. Schematic illustration of residence time and water age for the case of convective flow (a), and diffusion-dominated, tidal flow (b).

The increased use of numerical models to assess transport time scales has yielded deeper insights on renewal dynamics in semi-enclosed water bodies. Primarily, numerical applications moved the focus from global, or bulk time scales, such as flushing time, turnover time, average residence time, to more informative local time scales and their spatial distribution (e.g. Oliveira and Baptista, 1997). The computational effort required to estimate local time scales is however different for the different time scales: the computational effort required to assess, e.g., exposure time using a standard approach is by far much greater than that required to compute water age (Delhez et al., 2004). In order to reduce computational costs, it is therefore of interest to study the relationships, if any, between different time scales.

Renewal time scales, such as water age or residence time, are commonly used to measure the typical water renewal efficiency in a given domain. In this view, their spatial distribution, or their bulk or spatially averaged value under typical or averaged hydrodynamic and climatic conditions, is of interest. The study of the fate of, e.g., a pulse injection of a tracer under actual hydrodynamic and climatic conditions is a rather different issue which is not addressed here. In this work we consider steady periodic flow conditions and tidally flushed, semi-enclosed basins with negligible residual currents and freshwater inflow.

Within this framework, we study and compare three different transport time scales, namely water age, exposure time, and local flushing time, and demonstrate their substantial equivalence.

We then use the lagoon of Venice as a case study and estimate the spatial distribution of water age, exposure time, and local flushing time. We assess the reliability of commonly used approximations, and compare these time scales one with another.

2. Materials and methods

To avoid misunderstandings and even erroneous conclusions, as stated by (Bolin and Rodhe, 1973), it is important to introduce precise definitions and to use them with care. For that reason, we begin with some definitions before presenting and discussing our results.

2.1. Relevant definitions

Let's first look at the definition of water parcel. From the Lagrangian point of view, a water parcel is a system of elementary water particles. The water parcel travels and deforms in time, but it keeps containing all and only the same particles. This concept of water parcel makes little sense in the presence of diffusion because the particles of a parcel experience very different fates.

From the Eulerian point of view, a water parcel is a small, control volume of water, with a fixed boundary. It is the latter definition that we use in this paper. Indeed, the property of a water parcel is defined as the average of the properties of all water particles forming the water parcel (e.g. Zamora et al., 2012).

In the light of using mathematical modeling to assess time scales, hereinafter, we denote with ω the domain of interest, i.e. the basin, and with Ω an extended domain, which include ω and a portion of the sea connected to the basin through one or more inlets.

2.2. Residence and exposure time

(Zimmerman, 1976) defines the residence time as the time a particle takes to reach the outlet. Takeoka (1984) extends the definition to apply to a water parcel as follows.

Consider a pulse injection of a tracer at $t = 0$ so that the tracer concentration distribution within the domain ω is $c_0(\mathbf{x}, \mathbf{x}_0) = c(\mathbf{x}, \mathbf{x}_0, t = 0) = \delta(\mathbf{x} - \mathbf{x}_0)$, with $\mathbf{x}$ the position, $\mathbf{x}_0$ the injection point, and δ the Dirac generalized function. The average concentration in the basin is then

$$\bar{c}(\mathbf{x}_0, t) = \frac{1}{\omega}\int_{\omega} c(\mathbf{x}, \mathbf{x}_0, t)d\omega. \quad (1)$$

Takeoka (1984) defines the *remnant function*, $r(\mathbf{x}_0, t)$, as

$$r(\mathbf{x}_0, t) = \bar{c}(\mathbf{x}_0, t)/\bar{c}_0(\mathbf{x}_0) \quad (2)$$

with $\bar{c}_0(\mathbf{x}_0) = \bar{c}(\mathbf{x}_0, t = 0)$, and shows that the average residence time of the injected tracer is given by

$$T_r(\mathbf{x}_0) = \int_0^{\infty} r(\mathbf{x}_0, t)dt. \quad (3)$$

The residence time defined in this way, sometimes referred to as pulse residence time (e.g. (Miller and McPherson, 1991; Huang and Liu, 2009), is quite common in the recent literature (Sheldon and Alber, 2002; Orfila et al., 2005; Gourgue et al., 2007; Yuan et al., 2007; Camacho and Martin, 2013; Etemad-Shahidi et al., 2013).

From the operational point of view, Eq. (3) implies that, to evaluate the mean residence time of a water particle, we need to estimate the time behavior of the tracer concentration in the basin until the concentration itself becomes negligible. The procedure is rigorous and effective