Journal of Marine Systems 153 (2016) 25–41

Contents lists available at ScienceDirect

Journal of Marine Systems

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

Probabilistic approach of water residence time and connectivity using Markov chains with application to tidal embayments

C. Bacher [a],*, R. Filgueira [b], T. Guyondet [b]

[a] French Institute for Sea Research (IFREMER), BP70, 29280 Plouzané, France
[b] Department of Fisheries and Oceans, Gulf Fisheries Centre, Science Branch, P.O. Box 5030, Moncton, NB E1C 9B6, Canada

ARTICLE INFO

Article history:
Received 19 June 2015
Received in revised form 4 September 2015
Accepted 8 September 2015
Available online 18 September 2015

Keywords:
Transfer time
Transfer rate
Residual flow
Indicators
Aquaculture
Hydrodynamics

ABSTRACT

Markov chain analysis was recently proposed to assess the time scales and preferential pathways into biological or physical networks by computing residence time, first passage time, rates of transfer between nodes and number of passages in a node. We propose to adapt an algorithm already published for simple systems to physical systems described with a high resolution hydrodynamic model. The method is applied to bays and estuaries on the Eastern Coast of Canada for their interest in shellfish aquaculture. Current velocities have been computed by using a 2 dimensional grid of elements and circulation patterns were summarized by averaging Eulerian flows between adjacent elements. Flows and volumes allow computing probabilities of transition between elements and to assess the average time needed by virtual particles to move from one element to another, the rate of transfer between two elements, and the average residence time of each system. We also combined transfer rates and times to assess the main pathways of virtual particles released in farmed areas and the potential influence of farmed areas on other areas. We suggest that Markov chain is complementary to other sets of ecological indicators proposed to analyse the interactions between farmed areas — e.g., depletion index, carrying capacity assessment. Markov chain has several advantages with respect to the estimation of connectivity between pair of sites. It makes possible to estimate transfer rates and times at once in a very quick and efficient way, without the need to perform long term simulations of particle or tracer concentration.

1. Introduction

Physical exchanges play a key role in marine ecosystems. In many cases, the transport and the mixing of particulate and dissolved matters control the dynamics and the main characteristics of marine abiotic and biotic components. Monsen et al. (2002) stress the importance of assessing the time scale related to physical processes, and quote a number of studies dealing with biogeochemical processing, thermal stratification in lakes, mineralization of organic matter, primary production, harmful algae blooms, structure and functioning of microbial loop where physical time scales play a major role. Looking at possible control of eutrophication by benthic communities, Officer et al. (1982), Cloern (1982), and Hily (1991) clearly identified residence time as a key parameter to the interactions between biological processes. They were followed by Dame and Prins (1998) who established that carrying capacity for suspension feeding bivalves is a function of primary production turnover rate, bivalve filtration rate and water residence time. The assessment of carrying capacity gave birth to a number of modelling studies where the water renewal time of bays and estuaries were precisely quantified (Guyondet et al., 2005; Koutitonsky et al., 2004). Along with physical time scales, pathways of substances transported by water movement were also investigated in a number of recent studies. Ghezzo et al. (2015) defines connectivity as the physical dispersion of particles which are passive or which interact with their environment (e.g., larvae corresponding to the pelagic phase during the life cycle of organisms). Such studies are motivated by the need to identify the potential effect of living (e.g., pathogens) or non-living (e.g., pollutant) substances on the growth, survival and production of species of interest (e.g., keystone species, cultivated species) as well as the spatial interactions between distant populations having a pelagic life stage. This is no surprise that many authors argue that quantities like water renewal times and connectivity contribute to the assessment of health of aquatic systems and are a prerequisite to the development of indicators for management (Abdelrhman, 2005; Adams et al., 2012; Cucco and Umgiesser, 2006; Dumas et al., 2012; Filgueira et al., 2015; Guyondet et al., 2013; Huang, 2007; Miller and McPherson, 1991; Mudge et al., 2008; Ribbe et al., 2008; Thomas et al., 2012; Treml et al., 2008).

The main concepts of mixing time scales can be found in Bolin and Rodhe (1973), Zimmerman (1976), Takeoka (1984) and Monsen et al. (2002), but the vocabulary remains very diverse — e.g., retention time, flushing time, e-flushing time, residence time, local residence time, average residence time, integral residence time, age, turnover time,

---

* Corresponding author.
E-mail address: cedric.bacher@ifremer.fr (C. Bacher).

http://dx.doi.org/10.1016/j.jmarsys.2015.09.002
0924-7963/

exposure time, transit time, and local effect time. All these terms refer to the time that a single or an amount of particles stay within a domain or, alternatively, the time needed to leave the domain. Definitions and methods used to measure the time scale also account for spatial scale and size. Some authors consider the time for a particle to cross a spatial domain (e.g., bay, estuary), others measure the time that a particle in one region of a domain will take to reach another region or to exit the whole domain. In other cases, a global indicator of the water renewal time for the whole domain is sufficient. For instance, residence time (RT) is the time until a water parcel at a specified location leaves a given domain, which can be an estuary, a bay or a portion of the open ocean. Local residence time (LRT) is the time period for concentration of a uniformly distributed tracer to drop below a threshold value at a specific location within the embayment. It is sometimes called the e-flushing time when the concentration follows an exponential law and the threshold is equal to 1/e, e = 2.718 (Dumas et al., 2012). The average of local residence time over an embayment is the integral residence time (IRT, Koutitonsky et al., 2004). The IRT is useful to compare coastal ecosystem studies, while the LRT allows to analyse the structure of water mixing within an ecosystem and the potential response of that ecosystem to perturbations — e.g., human activities (Koutitonsky et al., 2004).

Though there are a few examples of the estimation of mixing time scales on the basis of data (e.g., salinity) and simple equations (Abdelrhman, 2007; Miller and McPherson, 1991; Mudge et al., 2008; Zimmerman, 1976), pathways of particles are usually not observable and models are therefore needed when the spatial patterns of local time characteristics are investigated (Ribbe et al., 2008). On the basis of three-dimensional, depth or laterally-averaged two-dimensional circulation models, Lagrangian (Adams et al., 2012; Basterretxea et al., 2012; Braunschweig et al., 2003; Brooks et al., 1999; Ghezzo et al., 2015; Monsen et al., 2002; Orfila et al., 2005; Safak et al., 2015; Tartinville et al., 1997; Thomas et al., 2012; Thompson et al., 2002; Wijeratne and Rydberg, 2007) or Eulerian (Abdelrhman, 2005; Cucco and Umgiesser, 2006; De Brye et al., 2012; Delhez and Deleersnijder, 2002; Döös and Engqvist, 2007; Dumas et al., 2012; Gourgue et al., 2007; Gustafsson and Bendtsen, 2007; Guyondet et al., 2013; Huang, 2007; Koutitonsky et al., 2004; Plus et al., 2009; Ribbe et al., 2008; Shen and Wang, 2007; Treml et al., 2008; Yuan et al., 2007) methods allow to track the passage of passive tracers or single particles.

As mentioned above, different time scales have been assessed in these case studies using one definition or another. In addition, some authors moved a step forward by computing the connectivity between areas within the domain of interest (Basterretxea et al., 2012; Ghezzo et al., 2015; Thomas et al., 2012; Treml et al., 2008). To evaluate the optimal size and locations of marine protected areas (MPA) near SW Mallorca Island, Basterretxea et al. (2012) assessed the connectivity among near-shore habitats and showed that the drifting distance of fish larvae was consistent with the MPA design. For this purpose the domain of interest is divided into a number of spatial boxes and simulations of particles drift are run with a series of initial conditions and during a period corresponding to the larval duration. Connectivity is defined as the number of particles arriving into box i from box j by the end of period divided by the number of particles initially released in box j. Thompson et al. (2002) built transition probabilities in a similar way. Using a 3D tidal circulation model of a macrotidal area (Passamaquoddy bay), they divided the bay into 15 boxes and estimated transition using stochastic particle tracking. They also introduced Markov chain theory and assessed some properties of the system — e.g., first passage time, probability to stay in a box or move to another box after a given time. Leguerrier et al. (2006) developed an algorithm based on Markov chain theory and computed residence time, first passage time, rates of transfer between boxes and number of passages in a box using transition matrix. As an illustration, they applied this algorithm to a simple food web and the same physical system as Thompson et al. (2002) and showed how to analyse preferential pathways of matter into simple systems. We propose to adapt the algorithm from Leguerrier et al. (2006) to physical systems described with a high resolution hydrodynamic model. Current velocities have been computed by using a 2 dimensional grid of elements and circulation patterns were summarized by averaging Eulerian flows between adjacent elements. Flows and element volumes allow to compute probabilities of transition between elements. Instead of running simulations of particles movement, we applied Leguerrier's algorithm to the resulting transition matrix and we were able to easily compute some characteristics of the system — e.g., average time needed by virtual particles to move from one element to another, rate of transfer between 2 elements, residence time.

This study relies upon previous works on hydrodynamic modelling on 3 bays and estuaries in Eastern Canada. The objectives were the following:

1) Extend the Markov chain to 2D systems to compute residence time, transfer rate, transfer time
2) Compute connectivity in relation with aquaculture issues
3) Compare ecosystem properties.

2. Material and methods

2.1. Study sites

Three sites have been recently investigated on the Eastern Coast of Canada for their interest in shellfish aquaculture, a sector which plays an important economic role in this region.

Tracadie Bay is a bar-built embayment located on the north shore of PEI (46°23′N 62°59′W, Fig. 1). It is the smallest (19.4 km^2, 44×10^6 m^3, Table 1) and shallowest (maximum depth 7 m, Fig. 1) bay considered in this study, and is open to the Gulf of St. Lawrence through two channels, a main one located on the West side of the bay and a breach in the central part of the sand barrier which formed in December 2009 after several storms touched ground on PEI. Winter Harbour is a sub-basin located at the southwest side of Tracadie Bay where a small river drains ($\approx$1 m^3 s^{-1}). The complexity of the embayment morphology, expressed as the ratio between the coastline length and the root square of the area, indicates that Tracadie Bay is the least complex of the three systems (Table 1). The tidal range is 0.3–1.0 m and the instantaneous exchange of bay with the offshore is up to 868 m^3 s^{-1}, which results in a renewal time of 8.4 days (Table 1).

The Richibucto Estuary is a bar-built river estuary located in southeastern New Brunswick along the Northumberland Strait (46°41′N 64°50′W, Fig. 1). It is the intermediate-sized embayment of this study (33.2 km^2, 58×10^6 m^3, Table 1), with maximum depths of 10 m in the central channel (Fig. 1). The estuary is open to the Northumberland Strait through two permanent channels and a narrow breach (width 25–30 m and depth 1.2 m) in the centre of the sand dunes located east of the main channel. The system can be divided into three areas: North Arm, Central Harbour and Baie du Village. Two rivers discharge into the estuary. The Richibucto River ($\approx$24 m^3 s^{-1}) runs into the Central Harbour and St. Charles River ($\approx$5 m^3 s^{-1}) into the North Arm. These three areas result in a more complex morphology compared to Tracadie Bay (Table 1). The tidal range is 0.3–1.3 m and the instantaneous exchange of bay with the offshore is up to 2040 m^3 s^{-1}, resulting in an average renewal time of 6.6 days (Table 1). This renewal time is the shortest of the three studied systems. It should be noted that this value differs significantly among the three main areas of the system, with the North Arm and Baie du Village areas having larger renewal times than the Central Harbour.

The Malpeque Bay system is a bar-built embayment located on the north shore of PEI (46°32′N 63°48′W, Fig. 1). It is the largest system of this study, covering a surface area of 223.6 km^2 and a total volume of 629.5×10^6 m^3 (Table 1), with maximum depth of 12 m (Fig. 1). The bay is open to the Gulf of St. Lawrence through three permanent channels, the main one located in the northeastern part of the system and