Some basic hydrodynamic concepts to be considered for coastal aquaculture

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Valle-Levinson, A. 2013. Some basic hydrodynamic concepts to be considered for coastal aquaculture. *In* L.G. Ross, T.C. Telfer, L. Falconer, D. Soto & J. Aguilar-Manjarrez, eds. *Site selection and carrying capacities for inland and coastal aquaculture,* pp. 147–158. FAO/Institute of Aquaculture, University of Stirling, Expert Workshop, 6–8 December 2010. Stirling, the United Kingdom of Great Britain and Northern Ireland. FAO Fisheries and Aquaculture Proceedings No. 21. Rome, FAO. 282 pp.

Abstract

Some basic hydrodynamic concepts that may influence coastal aquaculture activities are presented. Moreover, a pair of simple criteria for deciding whether it makes a difference to locate a cage or cluster on one side of a basin or the other is presented. These criteria are based on the non-dimensional Ekman and Kelvin numbers. Finally, a simple criterion based on tidal excursion at an aquaculture site is proposed for optimal cage or cluster separation. This criterion allows determination of "ellipses of influence" for a given cluster or cage, which indicates the potential area in the body of water that may be influenced by suspended and dissolved materials associated with aquaculture activities.

Introduction

The concepts described herein may apply to mariculture and to aquaculture activities in brackish waters, i.e. coastal aquaculture. According to FAO (2007), coastal aquaculture accounts for 50 percent of the worldwide production of fish, crustacean and molluscs in terms of the fishery value. As far as quantity is concerned, coastal aquaculture (brackish water culture and mariculture) accounts for 43 percent of the world's production. Clearly, coastal aquaculture in the world provides a sizable source of food and economic prosperity. A basic question that arises is: how sustainable is coastal aquaculture? This is an easy question with a very difficult answer. An attempt to begin an answer is presented here. In particular, a simple criterion based on tidal excursion at an aquaculture site is proposed for optimal cage or cluster separation.

Many coastal aquaculture farms are located in estuaries, where the interaction between riverine and oceanic waters determines the capacity of the estuary to flush. This capacity to flush a semi-enclosed coastal body of water is what motivates the need to understand its circulation features. Aquaculture activities in a well-flushed system will certainly have a lesser impact on the environment, and in turn the environment will have lesser effects on the organisms being cultured, than aquaculture activities in a poorly flushed system. Well-flushed basins should make aquaculture more sustainable, or have a larger carrying capacity (ability of a system to sustain the activity), than poorly flushed basins. In the latter, water and sediment quality deterioration from aquaculture-related activities would limit the productive period of the basin and drastically limit its carrying capacity. Even within a given basin, flushing will be more efficient at some locations than at others because of the way the water circulates. Therefore, in order to make the best decision on the appropriate site for aquaculture activities, and to increase the carrying capacity of a basin, it is imperative to understand the temporal and spatial variability of its circulation and its mass field (temperature, salinity and density).

This presentation seeks to synthesize the most salient aspects of temporal and spatial variability of water circulation, with special emphasis on estuaries, in order to help optimize size selection decisions at those environments. Examples of aquaculture activities in estuaries abound all over the world, e.g. Canada, Scotland, the Kingdom of Norway, the Republic of Chile, the Socialist Republic of Viet Nam, People's Republic of China, Central America. The concepts presented here apply, in one way or another, to all or most estuarine systems. This paper presents a section on circulation in estuaries, followed by a section that links the circulation to flushing times and carrying capacity. A section that describes a potential tool for determining carrying capacity, to be implemented in 3 phases, follows the presentation. The paper closes by proposing a criterion for siting contiguous aquaculture clusters, before presenting a brief paragraph with summary and recommendations.

Circulation in estuaries

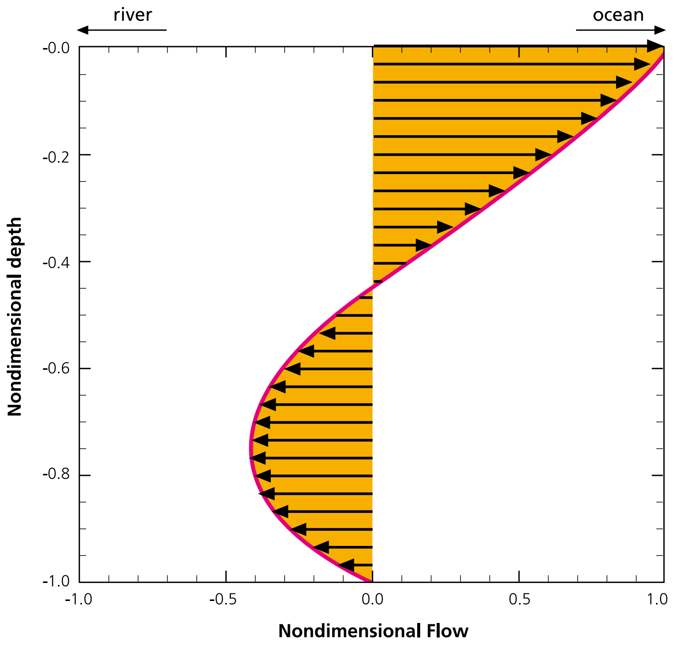
Circulation in estuaries, and in any basin, determines its capacity to flush or self-clean. In this section the basic structure of estuarine circulation is presented. A discussion on how tides, earth's rotation, bathymetry, winds and water balance affect the basic circulation structure is also presented.

Basic Circulation Structure

An estuary is characterized by the mixture of salty oceanic water and fresh water, from rivers or glaciers, in a semi-enclosed basin. This definition, however, does not apply to estuaries in arid regions where the physical process controlling the long-term circulation, namely water density gradients, is essentially the same as that in temperate and high latitude estuaries. That is why it is not crucial to get distracted by definitions of estuaries. Instead, it is practical to follow the arguments of US Supreme Court Justice Potter Stewart, who in 1964 said that pornography is hard to define but that you know it when you see it. The same can be said about estuaries, it is hard to provide an all-inclusive definition but they are identifiable upon sight. Fjords are also estuaries, found in high latitudes where they were carved by glaciers, and represent basins with typical intense aquaculture activities. Rias, found in tectonic areas in the Iberian Peninsula, are estuaries with intense aquaculture activities, too.

The interaction between riverine and oceanic waters causes a long-term circulation that appears from averaging the water motion over one or several tidal cycles. Riverine waters are less dense because they have less salt relative to ocean waters and will move along the surface of the estuary toward the ocean. Heavy ocean waters will exhibit a net landward motion along the bottom layers of the estuary (Figure 1). This two-layered, vertically sheared or vertically varying, circulation is typically known as *gravitational circulation* or *density-driven circulation*. It has traditionally been called *estuarine circulation*, but the name is not necessarily accurate because the circulation in estuaries, the true estuarine circulation, is driven by additional processes; not only by density gradients. For a thorough review on these definitions, see e.g. Valle-Levinson (2010). Independently of how it is called, this net circulation, caused by freshwater forcing, is modified by tidal forcing to establish the ability of the estuary to flush and its carrying capacity.

FIGURE 1
Gravitational circulation showing net surface outflow and net bottom inflow



Tidal variability

The net circulation in estuaries or density-driven circulation, as mentioned above, consists of net surface outflow and net bottom inflow resulting after averaging out the tidal influence. However, the tide itself may modulate the strength of the density-driven circulation by causing more vigorous mixing during spring tides (tides with largest range in the month – highest tides and lowest tides) than during neap tides (tides with the smallest range). Enhanced vertical mixing between relatively fresher and saltier waters during spring tides will dampen the density-driven circulation in an estuary and its ability to flush. In neap tides, the density-driven circulation is expected to be more robust than during spring tides because of reduced mixing.

Tides not only modify the mass field in an estuary by modulating vertical mixing, they also produce a net or average circulation. This tidally driven net circulation is produced by the distortion of tidal waves as they enter and propagate into an estuary. The net circulation produced by tides in semi-enclosed basins can counteract the effects of the density-driven circulation. In its simplest form, the net circulation caused by tides consists of surface inflow and bottom outflow. In most cases, this circulation is rather weak, compared to the gravitational circulation. But in some cases, where the tidal range is greater than one tenth of the estuary's depth or where the tide is distorted by reflection on the basin's walls, tidal net flows need to be taken into account. In the case when flow produced by tidal distortions is important, it may dominate the long term circulation and flushing of the estuary, i.e. ultimately will dictate its carrying capacity.

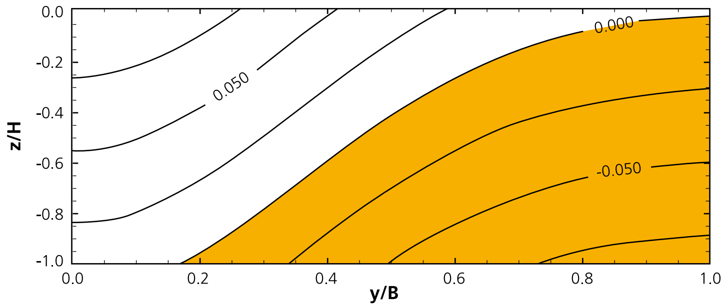
Influence of earth's rotation

In addition to being modified by tides, the gravitational circulation in estuaries can be influenced by earth's rotation through the Coriolis effect or Coriolis accelerations. In essence, Coriolis accelerations deflect flows to the right in the northern hemisphere and to the left in the southern hemisphere. This effect is only appreciable to an observer on a reference frame that is fixed in space, a non-inertial reference frame. When modified by earth's rotation, the gravitational circulation in northern hemisphere estuaries will therefore tend to exhibit stronger outflows on the left side of the estuary (looking landward) than on the right. Similarly, inflows will be stronger on the right side of the estuary than on the left. The gravitational circulation thus will exhibit a lateral structure and a vertical structure (Figure 2). The consequence of earth's rotation effects is that one side of an estuary will flush buoyant fluids and particles more efficiently than the other. This segregation of flushing efficiency should be considered for selecting the site of aquaculture facilities.

As can be seen, it is essential to determine whether an estuary is influenced by Coriolis effects or not. The typical criterion used to determine the importance of earth's

FIGURE 2

Gravitational circulation (in m/s) affected by earth's rotation in a rectangular channel (looking into the channel)



Note: White shaded contours represent seaward along-channel flow.Dark-shaded contours denote flow into the channel (away from the observer)

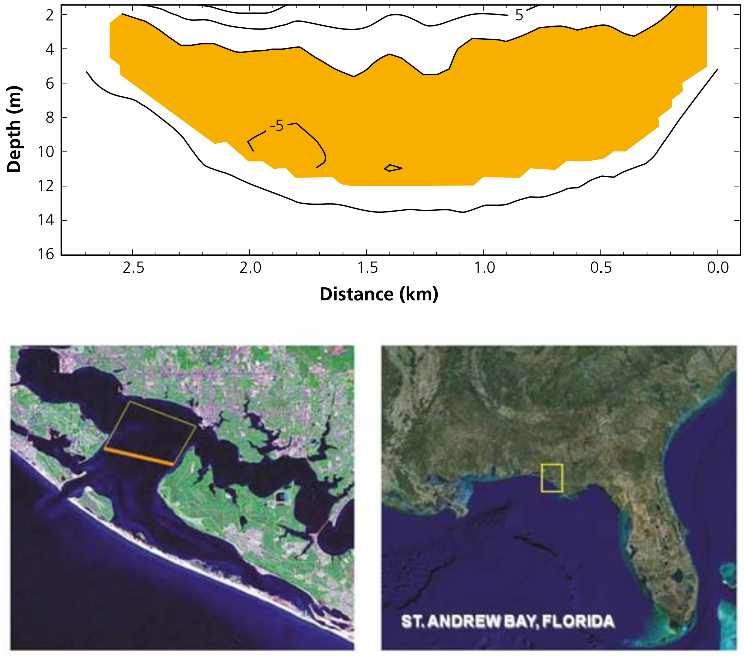
rotation in a fluid motion requires that the basin is wider than the internal radius of deformation, or internal Rossby Radius, R_i:

$$R_i = \frac{\sqrt{g\frac{\Delta\rho}{\rho_0}H_1}}{f}$$

where $\Delta\rho$ is the density contrast between outflowing and inflowing waters in the basin, g is the acceleration due to gravity, ρ_0 is a reference water density, f is the Coriolis parameter $(O\ 10^{-4}\ s^{-1})$ and H_1 is the layer of the outflowing (or inflowing) water. Thus, the internal Rossby Radius has units of length. However, not only the width of the basin dictates whether earth's rotation will affect the motion or not. The dynamical depth of the basin may also determine whether Coriolis effects are influential or not. The dynamical depth is characterized by the fraction of the water column H occupied by the depth of frictional influence, sometimes referred to as Ekman layer depth d (e.g. Kasai *et al.*, 2000). Such non-dimensional dynamical depth is analogous to the inverse of the Ekman number, which will be defined in the following paragraph. In basins where H/d >~ 4, a dynamically deep basin like a fjord, Coriolis effects become most evident. But even in narrow basins (narrower than the internal Rossby radius), lateral flows produced by Coriolis accelerations may re-distribute mass and momentum across the basin. Therefore, these accelerations may be quite important in modifying the basin's flushing efficiency.

FIGURE 3

Mean flows in St Andrew Bay estuary, Florida, on the Gulf of Mexico. Upper panel shows contours of mean flow (in centimeters per second) with the same convention as on Figure 2. Lower left panel shows the location of the transect shown in the upper panel

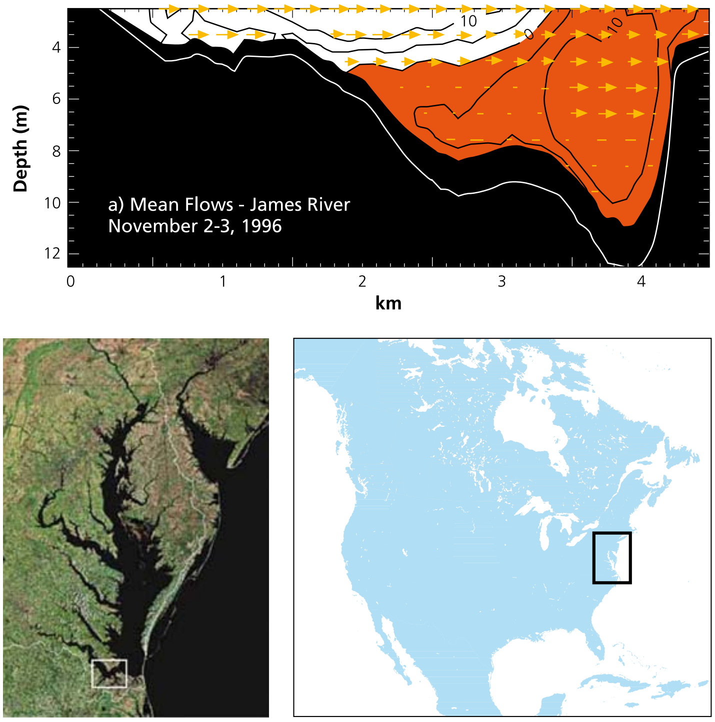


Note: Upper panel shows contours of mean flow (in centimeters per second) with the same convention as on Figure 2. Lower left panel shows the location of the transect shown in the upper panel.

Earth's rotation effects may be further understood in terms of the competition between Coriolis accelerations and frictional influence. This competition between friction and Coriolis accelerations is characterized by the nondimensional Ekman number Ek. When friction is weak, even negligible, Ek is << 1 and the density-driven flow will exclusively be modified by Coriolis acceleration. An example of this situation may be illustrated with measurements of net exchange flows, averaged after one tidal cycle, in a subtropical estuary of the Gulf of Mexico (Figure 3). The flow structure in St Andrews Bay on the western Florida coast exhibit vertical variability in the exchange flow, with outflow toward the ocean at the surface and inflow underneath. The outflow is strongest on the left hand side of the cross-section, looking landward, because of the earth's rotation effects.

On the other hand, when *Ek* is close to 1, friction overwhelms Coriolis and earth's rotation effects are unimportant. In this situation, the exchange flow associated with gravitational circulation might be more laterally variable than vertically variable. This is illustrated with measurements of net exchange flow in a temperate estuary, tributary to the Chesapeake Bay in the eastern coast of the United States (Figure 4). The cross-section at the James River shows net inflows in the deepest part of the cross-section, extending from the bottom to the surface. Net outflows are found segregated to the shallowest portions of the section, also occupying the entire water column. It is evident from the two examples shown in Figures 3 and 4, that the location of an aquaculture facility near the left of the estuary (looking landward) would cause different environmental impacts at each of the two estuaries. Therefore, it is essential to determine the structure of net exchange flows and its variability through time in order to help select an appropriate site for aquaculture activities.

FIGURE 4
Mean flows for a transect in the James River, Virginia, in the Chesapeake Bay.
Arrows represent transverse flows (not discussed)



Influence of Bathymetry

In addition to the competition between earth's rotation and friction, the shape of the bottom, or bathymetry, can play a determinant role in shaping the net exchange flow structure in a basin. Theoretical results of density-driven flows, supported by observations in several estuaries, show that different bathymetric shapes yield vertically or horizontally sheared flows (Figure 5). When a channel has steep bathymetry, as in a triangular or V-shape, the exchange is laterally varying. But as the channel becomes flatter and flatter, as in a U-shape, the exchange becomes vertically varying. These results underscore the statement that the location of aquaculture activities may produce different environmental effects whether they are established on one side of the estuary or the other.

Influence of Wind

Wind forcing may also alter the gravitational circulation in estuaries. When the wind blows in a semi-enclosed basin, it drags the surface waters in approximately the same

FIGURE 5

Gravitational circulation (normalized by maximum inflow) modified by bathymetry. Same contour convention as in Figures 2, 3 and 4

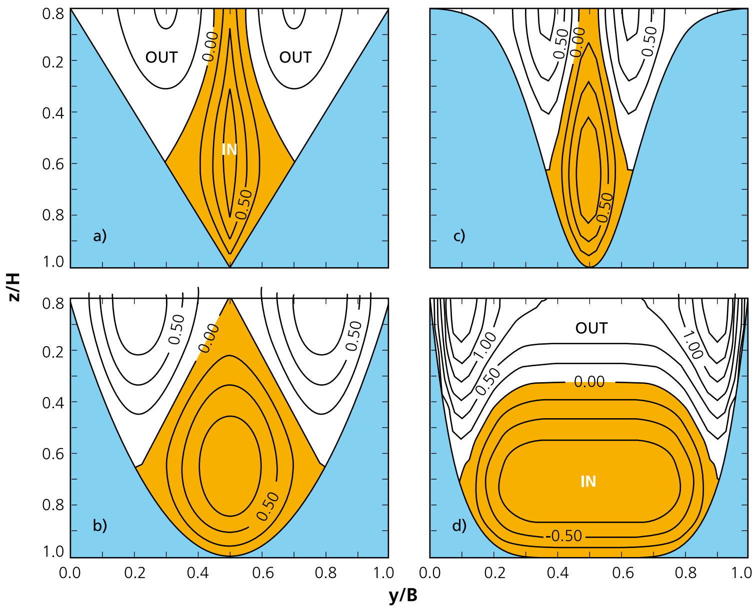
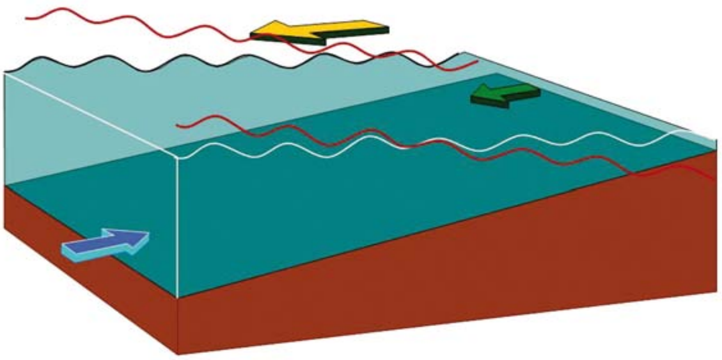


FIGURE 6

Diagram of wind-driven flow in a channel



Note: Yellow arrow represents wind. Green arrow is downwind flow at surface and blue arrow is upwind flow. The water surface is distorted by wind from the white lines to the red lines.

direction in which it blows. This wind-driven transport piles water up in the downwind direction, causing a water level slope inside the basin (Figure 6). In turn, the water level slope drives a near-bottom circulation that moves in the opposite direction to that of the wind blowing at the surface. In essence, the response of a semi-enclosed basin to wind forcing is downwind flow at the surface and upwind flow at depth. Thus, a seaward wind should reinforce the gravitational circulation and a landward wind will oppose it. In any estuary, it should not be uncommon to have seaward or landward winds that reinforce or retard the density-driven flow. It is essential to recognize these interactions in order to understand the flushing efficiency of the basin.

In the same way that bathymetry modifies the density-driven flow, bathymetry can also shape the structure of wind-driven flows. In a similar way (Figure 5) for density-driven flows, a V-shaped bottom configuration produces laterally varying wind-driven exchange flows (Figure 7). Analogously, a U-shaped bathymetry favors the vertically varying exchange pattern. Therefore, depending of the shape of a basin's bathymetry, some portions of the coastline will be more favourable for aquaculture activities in terms of their potential impact on the environment, and ultimately on their own sustainability.

Influence of water balance

In tropical and subtropical latitudes, the influence of riverine waters may be sporadic or completely absent. At those latitudes, the balance between water losses caused by evaporation and water gains from pluvial precipitation can modify the water balance in the estuary and produce reverse circulations. In the case that evaporation exceeds precipitation, the water density inside the basin will become greater than the density of the adjacent ocean. This will favour the development of near-bottom waters flowing toward the ocean and near-surface waters flowing from the ocean toward the basin. This is called inverse gravitational circulation. Because there is a net water loss from evaporation in the basin, the ability of an inverse estuary to flush will be drastically reduced as compared to a normal estuary. Similarly, there are basins that exhibit inverse circulation conditions part of the year, during a dry season, and typical gravitational circulation during the wet season (Figure 8). Water quality conditions in these systems are clearly worsened during the dry season. Therefore, inverse estuaries or seasonally inverse estuaries are prone to exhibit more serious water quality problems because of their reduced flushing efficiency. These natural variations may have deleterious effects for aquaculture activities and in turn, these activities could be more damaging to these susceptible environments.

FIGURE 7

Wind-driven circulation (in m/s) modified by bathymetry (analytical expression for each bathymetry is shown). Same contour convention as in Figures 2, 3 and 4

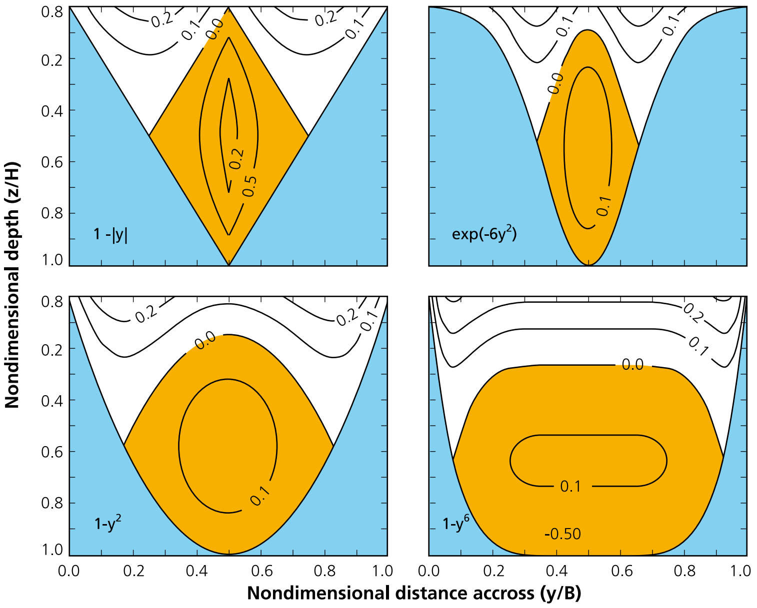
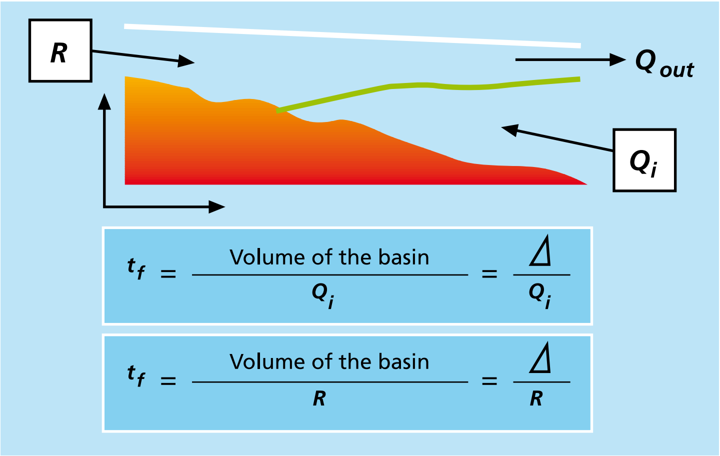


FIGURE 8

An illustration of the concept of flushing time

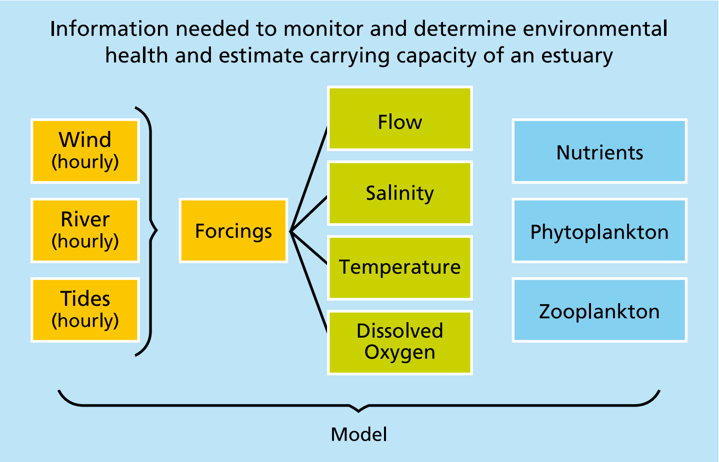


Flushing times and carrying capacity

The circulation in estuarine systems results from the complex interplay among river discharge, tides, winds, earth's rotation and bathymetry. Elucidation of such complex interplay is necessary to accurately determine the capacity of estuarine systems to flush and ultimately to assess the carrying capacity of a basin. There are different ways to estimate and define the time required to renew the waters of an estuary as outlined by Sheldon and Alber (2002; 2006) and Lucas (2010). There are actually concepts related to *turnover* or *flushing time*, *residence time*, water *age*, and *transit time*. Each of these concepts describes distinct processes that effect water or material (dissolved or suspended) renewal in an estuary.

Flushing time or turnover time t_f is the time required to replace the volume of a basin Δ typically by the volume inflow Q_i associated with the gravitational circulation, i.e. $t_f = \Delta / Q_i$ (Figure 9). This approach requires reliable quantification of net volume inflow into the basin. For dissolved or suspended matter, the flushing time will be given

FIGURE 9
An illustration of the concept of flushing time



by the ratio of the total mass of dissolved or suspended matter M throughout the basin to the flux F of mass M through the basin, i.e. $t_f = M / F$. An alternative definition of flushing time takes into account the river volume discharge R, instead of the volume inflow from the ocean Q_i, i.e. $t_f = \Delta / R$. Yet another definition calculates flushing time from the volume of fresh water in the basin Δ_f, where $\Delta_f = \Delta(S_o - S_m)/S_o$ and S_o and S_m are the ocean salinity and the basin's average salinity, respectively. Thus, the alternative form of this turnover time estimate is $t_f = \Delta_f / R$. Any of the preceding definitions involve processes that will vary greatly for different tidal, wind and river discharge forcing conditions. Therefore, one value of flushing time does not appropriately represent actual conditions.

Additional definitions of flushing time explicitly include the effects of tides through the volume of the tidal prism Δ_p and the tidal period T_p. The tidal prism volume is the volume of water that enters a basin with every tidal cycle and equals the surface area of the basin times the tidal range. The turnover time then is given by $t_f = \Delta\, T_p / \Delta_p$. Note that the ratio Δ / Δ_p is the volumetric portion related to the tidal prism. In essence, this definition documents the number of tidal cycles required to flush the basin. Because Δ_p will also change from spring to neap tides, this approach will yield a range of values for flushing time.

Residence time is the time required for water or material elements found initially at certain locations of a basin to exit the basin. This concept is different from flushing time in the sense that flushing time represents one value, or a range of possible values, for the entire system. Residence time implies a space-dependent distribution for the same system. It is typically represented with contour maps obtained from numerical model results. These contour maps indicate the time it would take for a fluid or material element to leave the basin at all locations in the basin. Contour maps should be generated for different tidal phase releases of the fluid element and for various forcing conditions related to freshwater discharge and wind.

The age of an element of fluid is the time it has remained within a basin since the time it entered. Similarly to residence time, age depends on the location of the basin. Contour maps of age are typically generated with numerical models to yield a comprehensive representation of areas most prone to pollution. Combining maps of residence time and age yields *transit times* for particles or fluid elements throughout the basin.

It appears, from the descriptions of flushing, residence and transit times, that the best way to characterize regions with most sensitivity to water quality issues, e.g, regions of low oxygen or high nutrients, might be to use maps of residence and transit times. These maps will only be reliable if they are produced with a well-tested and carefully calibrated numerical model. Such a model can help in guiding the locations of aquaculture centres to take maximum advantage of the carrying capacity of the system. For instance, the model could predict threshold values for transit times, nutrients and dissolved oxygen that cannot be exceeded in order to maintain aquaculture activities sustainable, thus optimizing the system's carrying capacity.

Numerical model – basic information required

Another suggestion of this paper is that in order to optimize the carrying capacity of a basin, a bullet-proof numerical model is required to help in the decision-making. The development of such a bullet-proof model is titanic, given the natural variability of a coastal basin. Model development and implementation shall involve three basic stages. 1) Carry out studies to determine the spatial structure and temporal variability of circulation and mass distributions in the basin. This stage will allow better understanding of the system. 2) Develop, calibrate and validate a numerical model that reliably represents actual environmental conditions. This stage will allow emulation of the system. 3) Use the model to determine different scenarios related to aquaculture sites and size of production, and find the optimal number and location for those sites. This stage will allow making decisions about the system. Each one of these stages involves an extremely challenging set of activities. Thus, each one of the 3 proposed stages should be developed sequentially because of the strong dependence of stage 2 on stage 1 and of stage 3 on stage 2. Maybe stages 2 and 3 can be started before stage 1 is completed, but reliable results will only be obtained with the successful completion of the previous stage.

The first stage, carry out studies to determine the spatial structure and temporal variability of circulation and mass distributions in the basin, shall entail field studies and numerical model simulations. Field studies shall involve measurement of the main forcings that drive and shape the system, namely wind velocity, river discharge, tidal forcing and bathymetry (Figure 9). These are essential variables needed to understand and model the system. Other essential variables that need to be measured to understand and model the system are hydrographic: currents, temperature, salinity and dissolved oxygen. These variables can be measured routinely and should be sampled at high spatial and temporal resolutions. High spatial resolutions can be achieved with surveys that collect underway data, while high temporal resolutions can be attained with mooring deployments. Other challenging variables to measure are biochemical: phytoplankton, zooplankton, nutrients, oxygen demand in the water column and in the sediments. These biochemical variables are quite important but cannot yet be measured reliably with the same temporal and spatial resolution as hydrographic variables; the technology is almost there, however. Part of the first stage should also be the development of a numerical model of the system to carry out process-oriented studies to better understand the information provided by the field surveys. This model will be the first step toward the second stage.

The second stage of developing a model to determine carrying capacity and siting of aquaculture activities consists of development, calibration and validation a numerical model that reliably represents actual environmental conditions. This three-dimensional model should use the main forcings assessed from stage 1 to try to represent the flow and hydrographic conditions observed. There are a good number of numerical models, already developed, that simulate the hydrodynamics and some water quality aspects in coastal environments. It will be a matter of personal option and/or expertize with a particular model the deciding factor of which one to choose for implementation at the basin. This stage can be arduous because of the multiple parameters that need to be tuned for the model to produce acceptable results. A quantitative measure of the quality of the numerical model results should be implemented to decide when the next stage can be started.

The third stage will consist of using the model to determine different scenarios related to aquaculture sites and size of production, and find the optimal number and location for those sites. This stage is the bottom line of the activities and could be developed in operational mode in such a way that the addition of new sites can be evaluated effectively. This stage will simulate, at the very least, the impact of number and location of aquaculture sites on the concentration of dissolved oxygen. This will be one way of determining the carrying capacity of the study basin. Additional variables to simulate could include nutrients, phytoplankton and zooplankton, involving a marked increase effort to achieve it.

The 3 stages proposed above are quite elaborate. In many cases, the development of the three-stage approach might be unfeasible or unrealistic. For rapid and simple diagnostics a few other tools could be used. For instance, on the basis of the physical concepts discussed throughout this document one can use criteria to determine whether one side of the basin is more prone to flush water seaward or not. These criteria are presented next, as well as a simple criterion to determine an area of influence of a cage or cluster of cages.

Simple criteria to determine whether flow is different across the basin

In essence, two simultaneous criteria can be used to determine whether lateral variations in hydrography and flow are expected to be relevant in a semi enclosed system, i.e. whether it would make a difference to locate a cage on one side of the basin or the other. The first criterion can be given by the ratio of internal Rossby radius to width of the system *W*. If this ratio, which is also known as the Kelvin number K_e is greater than 0.25, it is likely that lateral variations will appear because the earth's rotation will cause a long-term lateral segregation of inflows and outflows (Valle-Levinson, 2008).

The second criterion is the Ekman number E_k, which equals A_z, the eddy viscosity (m^2/s), over the product of Coriolis parameter f and H^2 where H is the maximum depth of the cross-section:

$$E_k = \frac{A_z}{fH^2}$$

Taking A_z of 0.001 m^2/s as a typical value and f as 0.0001 s^{-1}, E_k could be simplified to $10H^{-2}$. If $E_k > 0.001$ it is likely that some lateral variations will appear because of bathymetric and frictional effects (Valle-Levinson, 2008). It is then proposed here that when both **$K_e < 0.25$ and $E_k < 0.001$**, then it would likely make very little difference across the basin to locate aquaculture activities on one side of the basin, relative to the other.

Simple criterion for separation of clusters of aquaculture facilities or cages

For cases when an elaborate approach to determine siting and carrying capacity (as that outlined in the Numerical Model section) is unfeasible, a simple approach centred on the tidal excursion at the site can be used to optimize the distance between contiguous facilities. The tidal excursion is the distance a suspended or dissolved material would travel throughout one half tidal cycle (throughout flood tidal flow or throughout ebb tidal flow). For this approach, two tidal excursion length scales need to be determined: the along-basin tidal excursion D_x and the across-basin tidal excursion D_y:

$$D_x = \frac{U_0 T}{\pi}; \quad D_y = \frac{V_0 T}{\pi}$$

where T is the dominant tidal period in seconds and U_0 and V_0 are the maximum along-basin current and across-basin current, respectively. These expressions are obtained from the integration of a sinusoid motion over half its cycle. The expressions can also be used for elucidating the area of influence of wind-driven currents for winds with period T. Note that for a semidiurnal tide (T = 44712 s or 12.42 hrs), a tidal current of 1 m/s yields an excursion D_x of ~14 km, which should be the minimum distance between clusters or cages in a basin with those characteristics. This distance would ensure that the interaction between dissolved and suspended material from different sites is minimized.

The values of D_x and D_y can be used to draw "ellipses of influence," or areas of influence, of each site or cluster (Figure 10). The ellipse of influence coordinates e_x, e_y are given by:

$$e_x = D_x \cos\Phi \cos\omega t - D_y \sin\Phi \sin\omega t$$

$$e_y = D_x \sin\Phi \cos\omega t + D_y \cos\Phi \sin\omega t$$

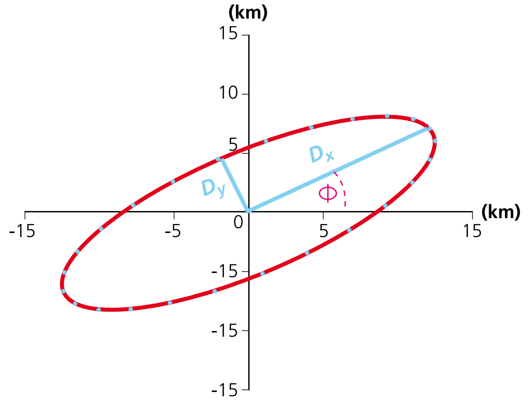
where Φ is the preferred or predominant direction of the current (degrees from East; could be zero if there is no preferred direction), ω is the frequency of the tide ($2\pi/T$) and t is time at appropriate intervals between 0 and T. These ellipses of influence may be used to represent areas of potential deleterious effects of a site on a neighbouring cluster. The information needed to generate the ellipses is: a) main direction of tidal currents (principal-axis direction) Φ; b) tidal current amplitude (maximum strength) in the main direction U_0; c) tidal current amplitude in the direction perpendicular to Φ, i.e. V_0; predominant period of the tide T; and the maximum displacements in the along-basin and across basin directions, i.e. D_x and D_y.

Summary and recommendations

In order to allow coastal aquaculture activities to be sustainable in a given basin, a three-stage process is proposed. This process should eventually allow determination of carrying capacity of the basin and optimal location of facilities. All stages of the process that leads to sustainability of aquaculture in a basin would involve the study of the basin through a combination of field measurements and numerical model implementation, calibration and validation. Basic forcing agents that need to be considered in the study are freshwater discharge (and its seasonal variability), atmospheric forcing (with its synoptic and seasonal variability), tidal forcing (with semidiurnal, fortnightly and seasonal variability), bathymetric effects and earth's rotation effects. These forcing agents would determine temporal and spatial variations of relevant parameters, such as hydrography, dissolved oxygen, and nutrients. Each of the stages proposed would allow understanding of, emulation of, and decision-making in the basin.

FIGURE 10

Ellipse of influence showing the main parameters that define it. In this case, Dx is 14 km, Dy is 5 km and is 30 degrees. The center of a cage would be located at (0, 0)



More easily applicable recommendations have to do with the location of neighbouring cage clusters on the basis of the "ellipse of influence." Also, two criteria based on non-dimensional numbers are proposed to be applied simultaneously in order to determine whether it would make any difference to locate clusters on either side of a channel-like basin.

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