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Current variability in a wide and open lacustrine embayment in Lake Geneva (Switzerland)

A.M. Razmi [a,*], D.A. Barry [a], R. Bakhtyar [a,1,2], N. Le Dantec [a,3], A. Dastgheib [b], U. Lemmin [a], A. Wüest [c,d]

[a] Laboratoire de technologie écologique, Institut d'ingénierie de l'environnement, Faculté de l'environnement naturel, architectural et construit (ENAC), Ecole polytechnique fédérale de Lausanne (EPFL), Station 2, 1015 Lausanne, Switzerland
[b] UNESCO-IHE, PO Box 3015, 2601 DA, Delft, Netherlands
[c] Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, Faculté de l'environnement naturel, architectural et construit (ENAC), Ecole polytechnique fédérale de Lausanne (EPFL), Station 2, CH-1015 Lausanne, Switzerland
[d] Eawag, Surface Waters, Research and Management, CH-6047 Kastanienbaum, Switzerland

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A B S T R A C T

Field measurements and numerical simulations were used to determine the effects of dominant meteorological conditions on the hydrodynamics of a wide (aspect ratio ~2), relatively deep (seasonally stratified) and open lake embayment (Vidy Bay, Lake Geneva). A three-dimensional hydrodynamic model (Delft3D-FLOW) was employed to simulate flow in the lake. High-resolution maps of wind, temperature and humidity (over the lake) were applied as input to drive the model. Because wind was the main force driving flow in the lake, currents in the embayment were investigated systematically for different wind conditions and seasonal stratification. Satisfactory model validation was achieved using drifter and moored measurements within the embayment. Markedly different circulation patterns were measured within the embayment, with the transition from one pattern to another occurring abruptly for small changes in wind direction. These distinct patterns resulted from relatively small changes in the large gyre of Lake Geneva's main basin, especially the angle between the current in front of the embayment and the embayment shoreline. The boundary between the embayment and the pelagic zone was defined by the largest gyre within the embayment. This study shows that, (i) in a large lake, complex current patterns can occur even within a minor embayment, and (ii) that these patterns can transition rapidly over a small range of wind directions. Near-shore gyre can occur for lengthy periods, which has implications for flushing of discharges within the embayment.

Introduction

Flow at the lateral boundary of a lake is affected by shoreline morphology. More generally, near-shore processes within a given embayment are responsible for cross-shore variability of water constituents and affect the distribution and dispersal of released effluents (Bedford and Abdelrahman, 1987; George, 1981; Scavia and Bennett, 1980). Entrapment, where pollutants are confined to the embayment for some period, is of particular interest (Ge et al., 2010; Okubo, 1973; Palmarsson and Schladow, 2008) as it may allow undesirable near-shore accumulation of pollutants (George and Edwards, 1976). The interaction of circulation in the embayment with pelagic waters determines exchanges of mass, momentum and energy between them (Glorioso and Davies, 1995; Palmarsson and Schladow, 2008; Signell et al., 1990). Because different hydrodynamic processes (e.g., wind-induced currents, waves, Coriolis force, and thermal stratification) are involved, the flow field in a lake embayment can be complex (Wells and Sealock, 2009). Assessing the importance of these processes for circulation patterns is essential for understanding the hydrodynamics in the lake's near-shore zones (Falconer et al., 1991; Schladow and Hamilton, 1997; Sheng and Rao, 2006).

Embayments can be broadly classified based on geomorphic characteristics, viz., general configuration, water depth and aspect ratio, as follows:

- *General configuration*. We consider if the embayment shoreline shape is semi-enclosed or open. For example, if an embayment shoreline can be approximated by an arc of a circle, then the embayment is open if its boundary forms part of the inner sector of that circle. Otherwise, the embayment boundary forms part of the circle's outer sector, and

* Corresponding author. Tel.: +41 21 693 5793; fax: +41 21 693 8035.
E-mail addresses: amir.razmi@epfl.ch (A.M. Razmi), andrew.barry@epfl.ch (D.A. Barry), roham.bakhtyar@unc.edu (R. Bakhtyar), nicolas.ledantec@epfl.ch (N. Le Dantec), a.dastgheib@unesco-ihe.org (A. Dastgheib), ulrich.lemmin@epfl.ch (U. Lemmin), alfred.wueest@epfl.ch (A. Wüest).
[1] Now at: Department of Environmental Sciences and Engineering, The University of North Carolina, Chapel Hill, North Carolina 27599-7431, USA.
[2] Now at: Coastal and Hydraulics Laboratory, US Army Engineer Research and Development Center, Vicksburg, Mississippi 39180-6133, USA.
[3] Now at: Centre de Etudes Techniques Maritimes et Fluviales (CETMEF), Laboratoire de Génie Côtier et Environnement (LGCE), 155 rue Pierre Bouguer, Technopôle Brest Iroise–BP 5–29280, Plouzané, France.

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the embayment is semi-enclosed. More generally, if the embayment's largest interior horizontal dimension is greater than the dimension of its mouth, then the embayment is semi-enclosed, otherwise it is open.

- *Water depth*. We class embayments as shallow or deep depending on the (potential) presence of a well-defined thermocline in summer months.
- *Aspect ratio*. A narrow/wide (in plan) embayment has an aspect ratio less than/greater than unity (taking the major axis along the shoreline). Generally, the interior parts of narrow embayments are progressively less exposed to the influences of currents in the pelagic zone. On the other hand, currents in embayments with large aspect ratios are likely to be part of larger pelagic circulations, more so for aspect ratios much greater than unity.
  - o Limiting large aspect ratios: There is an additional question concerning the limiting case of open embayments with very large aspect ratios. As the aspect ratio increases, the embayment becomes less and less pronounced. Put another way, when does a small indent on a coastline become an embayment? Following Albert et al. (2005), we suggest that an indent becomes an embayment if its geometry induces a nearshore circulation under wind forcing.

Based on these morphometric criteria, we identify eight embayment types. In Table 1, a summary of nearshore circulation under wind forcing studies on embayment hydrodynamics is given. For ease of reference, Table 1 separates semi-enclosed and open embayments into two categories, with the other two criteria yielding four embayment types for each category. As Table 1 reports, most studies have been either on semi-enclosed embayments or narrow open embayments (e.g., Rueda and Cowen, 2005; Wells and Sealock, 2009).

The hydrodynamics of an embayment are determined by the combined effect of the barotropic and baroclinic forces (Apel, 1987). For the former, studies have been carried out mainly on either wave and tidal forcing (e.g., Harris et al., 2009), or on the combination of wave-driven and wind-induced circulations (Grifoll et al., 2013). These investigations are mostly concerned with embayments adjacent to very large water bodies (e.g. ocean). For instance, several studies on temperature gradients due to solar heating, evaporation and freshwater inflows in such embayments have been reported (Lawrence et al., 2004; Palmarsson and Schladow, 2008; Rueda and Cowen, 2005). In addition, there are numerous oceanographic investigations (Cosoli et al., 2012; Drake et al., 2005; Gutierrez et al., 2006; Paduan and Rosenfeld, 1996; Murray, 1975; Wang et al., 1994) focusing on current variability in embayments, most of which combine wind forcing with waves and tides in semi-enclosed embayments. For these oceanic embayments, significant factors controlling the current variability are the spatial variability of the wind stress, water column stratification and the coastline configuration (e.g., Drinkwater, 1989). These studies inspired the present investigation, which considers a small open lacustrine embayment in a natural lake, although with the expectation that differences will occur due to the relatively low energy environment characterizing lakes vis-à-vis oceans, such as the insignificant role of tides and waves as well as the limited wind fetch.

Flow within semi-enclosed embayments is separated by topographic constrictions from that in the adjoining pelagic zones (Little Sodus Bay in Lake Ontario) whereas they are much more strongly linked for open embayments (McCormick and Schwab, 2008). Littoral zones in shallow embayments are subjected to accentuated rates of heating or cooling compared with pelagic zones, leading to the generation of convectively driven currents (Fer et al., 2002). Depending on the season, surface water can flow either offshore or onshore with reverse flows in the bottom layer, generating a circulation (Lawrence et al., 2004; Palmarsson and Schladow, 2008). In open shallow types (1 and 2, Table 1), such convectively driven currents can play a key role in embayment flow patterns.

In open narrow types (2 and 4, Table 1), generally circulations are caused by the wave-current interactions and bottom slope (Signell et al., 1990). For open, wide types (1 and 3, Table 1), studies have focused mainly on the effect of tides and interaction of tides and currents within the embayment in very large water bodies (Jouona et al., 2006). No studies investigated wind-induced circulations in the open, wide and deep embayments (Type 3, Table 1).

Lake Geneva is the largest lake in Western Europe, with a surface area of about 580 km^2. Vidy Bay, near Lausanne (Fig. 1a) is open, wide and deep, and was the focus of this study. Unlike many other embayment studies, tides and waves are not factors in Vidy Bay's currents. Circulation within Vidy Bay is of interest from the water quality perspective because it hosts a wastewater treatment plant effluent outfall (Bonvin et al., 2011; Czekalski et al., 2012), while there is a major drinking water intake located about 3 km away towards the west (Fig. 1a).

The purpose of the present paper is to investigate current variability within this wide and deep embayment as part of a large lake. Wind is the main driver of current variability in Lake Geneva, and thus we focus on its role in forming currents in Vidy Bay. As part of the investigation, we provide a precise definition of the embayment's offshore boundary, so as to quantify exchange between the embayment and the pelagic zone. We proceed by making use of field measurements and 3D numerical simulations.

Background and Methods

The major elements in our analysis are field experiments and numerical modeling:

(i) field experiments were carried out on near-surface water motion in the embayment via drifters (these data are in addition to existing data sets, described below). (ii) a numerical model was validated with field data (comparison of the numerical predictions and field observations of currents, vertical temperature profiles, and drifter studies) in the embayment. After validation, the model was used to study currents in the embayment due to factors such as the basin-scale pelagic gyre, Coriolis force, wind, thermal stratification, shoreline orientation, and bottom slope. The model was applied to test the interaction between wind forcing and other possible processes in order to understand near-shore gyre formation in the embayment.

Study site

Fig. 1 shows Lake Geneva and Vidy Bay. Lake Geneva is an intermontane lake with, in the eastern part, sheltering surrounding topography that disturbs the wind field over the lake (Lemmin et al., 2005). Tides and surface waves do not greatly influence the lake's currents (e.g., Graf et al., 1979). The lake is large enough to be affected by Coriolis forcing (Lemmin et al., 2005). Wind is thus the main force driving the currents in the lake (Apel, 1987; Wüest and Lorke, 2003), with wind variability contributing the current variability in the lake (Lemmin and D'Adamo, 1996).

Vidy Bay is characterized as a wide (aspect ratio ~2) and deep (up to ~70 m) embayment. Within it, there is a wastewater treatment plant (WTP) outfall located ~500 m offshore, at ~30 m depth. Vidy Bay also receives discharges from a river and an overflow drain. The typical WTP discharge rate is 1–3 m^3 s^{-1}, reaching ~7 m^3 s^{-1} during rain events. The corresponding values for the river are ~0.2 m^3 s^{-1} and ~4.8 m^3 s^{-1}, while the overflow discharge varies between 0.04 and 0.4 m^3 s^{-1}, for dry and rainy weather, respectively.

Dominant Wind Regimes

Statistical analysis of meteorological data showed that wind directions over the lake are variable, with some dominant directions