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New analytical equation for dispersion in estuaries with a distinct ebb-flood channel system

Anh Duc Nguyen[a,b,d,*], Hubert H.G. Savenije[a,b], Mick van der Wegen[c], Dano Roelvink[c]

[a] Department of Management and Institutions, UNESCO-IHE Institute for Water Education, 7 Westvest, P.O. Box 3015, 2611 AX Delft, The Netherlands
[b] Department of Water Management, Faculty of Civil Engineering and Applied Geosciences, Delft University of Technology, Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
[c] Department of Water Engineering, UNESCO-IHE Institute for Water Education, 7 Westvest, P.O. Box 3015, 2611 AX Delft, The Netherlands
[d] Center of Hydroinformatics, Southern Institute for Water Resources Research, 2A Nguyen Bieu, Ho Chi Minh City, Vietnam

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ABSTRACT

Tidal pumping caused by residual horizontal circulation is an important but ill-understood mechanism producing longitudinal salt dispersion in well-mixed estuaries. There are two types of residual circulation that cause tidal pumping: (1) interaction of the tidal flow with a pronounced flood-ebb channel system; and (2) interaction of the tidal flow with an irregular bathymetry. Residual ebb-flood channel circulation is an important large-scale mixing mechanism for salinity intrusion, as shown in the Western Scheldt in the Netherlands, which is a well-mixed estuary with a distinct ebb-flood channel system. This paper provides a new simplified conceptual model and a new analytical equation for this type of mixing. Firstly, using a fully three-dimensional hydrodynamic model as a "virtual laboratory" and employing a decomposition method, the characteristics of the residual ebb-flood channel circulation in the Western Scheldt are analysed. Secondly, a conceptual model and an analytical equation determining the dispersion coefficient are developed, which take into account relevant parameters for tidal pumping, such as the tidal pumping efficiency, the tidal excursion and the length of the branches. Subsequently, the newly developed equation is compared to the results of the "virtual laboratory". The comparison confirms an agreement between the newly developed equation and the "virtual laboratory" in determining the residual transport and the tidal pumping dispersion coefficient. Finally, the equation is applied to observations in the Western Scheldt. The application yields good results in determining the longitudinal dispersion compared to dispersion values obtained from the salt budget.

1. Introduction

The tidal pumping mechanism, which is caused by residual horizontal circulation, is an important but ill-understood part of tidal circulation producing longitudinal dispersion. Fischer et al. (1979) defined "tidal pumping" as the energy available in the tide that drives steady circulations similar to what would happen if pumps and pipes were installed to move water about in circuits. There are two types of residual circulation that cause tidal pumping: (1) interaction of the tidal flow with a pronounced flood-ebb channel system; and (2) interaction of the tidal flow with an irregular bathymetry. Residual ebb-flood channel circulation is an important large-scale mixing mechanism for moving pollutants and transporting salinity upstream against a mean outflow of freshwater as shown in the Western Scheldt (Savenije, 2005, pp. 116–117). The Western Scheldt (see Fig. 1), the Netherlands, is an estuary with a distinct ebb-flood channel system. Similar types of estuaries are found in the Chesapeake Bay, Maryland, USA (Ahnert, 1960); the Columbia river estuary in USA; the Pungue estuary in Mozambique as well as several small estuaries in the U.K. van Veen et al. (2005) described the Western Scheldt as an estuary with a regular system of ebb and flood channels. Jeuken (2000, p. 24) identified two basic channel types in the Western Scheldt estuary: (1) main channels and (2) connecting channels. The main channels transport most of the tidal discharge, sediments and salinity. They are the largest channels in the system and they appear in two forms: a curved main ebb channel and a straight main flood channel. The connecting channels are the smaller channels that either link two large main channels or a large main channel with a small main channel. The transport function of the connecting channels is limited.

* Corresponding author. Department of Management and Institutions, UNESCO-IHE Institute for Water Education, 7 Westvest, P.O. Box 3015, 2611 AX Delft, The Netherlands.

E-mail address: d.nguyen@unesco-ihe.org (A.D. Nguyen).

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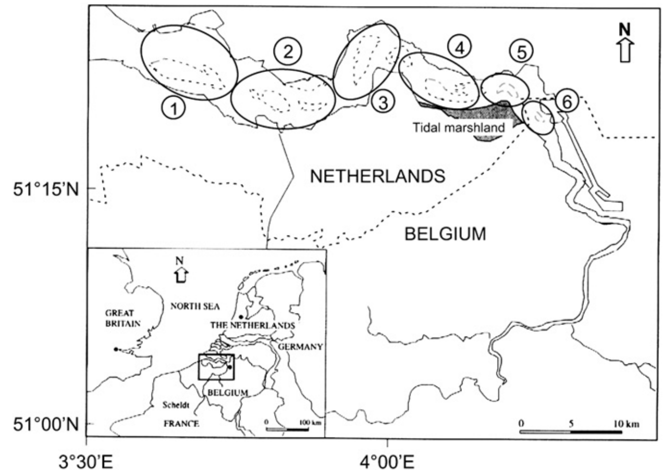

Fig. 1. The Western Scheldt estuary in the Netherlands, showing six ebb-flood channel loops in ovals.

Savenije (1993a) found that gravitational (density-driven) circulation is the main mixing mechanism if salinity gradients are large (as occurs in the central part of estuaries). The river flow plays an important role to drive the gravitational circulation, which is accompanied by both vertical and lateral salinity gradients. In wide estuaries, lateral stratification generally makes the largest contribution to density-driven mixing (Fischer et al., 1979). However, in the seaward part of estuaries, where the density difference is small, the interaction between tide and geometry, which generates residual (horizontal) circulation, is the main mixing mechanism. McCarthy (1993) presented an analysis on residual circulation generated by the combined effect of tide and gravitational circulation in an estuary with exponentially varying width. Although his study did not consider the important transport mechanism by ebb-flood channel interaction, it clearly demonstrated that tide-driven mixing is dominant in the downstream part of estuaries, while density-driven mixing is dominant in the upstream part of estuaries. Density-driven mixing is a function of the salinity gradient, whereas tide-driven mixing is a function of the salinity and the width.

Based on comprehensive reviews of Fischer et al. (1979), Zimmerman (1986) and Geyer and Signell (1992), it can be seen that many authors have tried different methods to quantify tidal-driven dispersion. Several authors used a decomposition method (e.g. Fischer, 1976; Lewis, 1979; Uncles and Jordan, 1979; Uncles et al., 1985; Pino et al., 1994; Dyer, 1997; or Sylaios and Boxall, 1998). A number of authors proposed to determine the effective longitudinal tidal-driven dispersion as a function of mixing length and velocity. Examples of this approach can be found in Arons and Stommel (1951) and Zimmerman (1976). Arons and Stommel proposed $D = kU_0l_0$ (where D, k, U_0, l_0 are the dispersion coefficient, a constant, velocity scale and mixing length scale, respectively). k is understood to be a constant for one estuary. However, because the values of k widely varied, it resulted in a very large range of computed values. Zimmerman (1976) developed the "tidal random walk" theory and model, which considers the Lagrangian motions in estuaries resulting from the purely advective effects of tidal and residual currents and takes into account pronounced horizontal residual circulations generated by tide-topography interactions. Due to the presence of residual eddies, the velocity field cannot be considered uniform and in fact it varies considerably over distances of the order of the tidal excursion. Zimmerman (1976, 1981) derived an equation for the longitudinal dispersion coefficient, which is formally the same as the equation of Arons and Stommel. The main innovation in the equation of Zimmerman is that k has a well-defined physical meaning, being a function of λ and ν (i.e. the dimensionless parameters reflecting mixing length and tidal velocity). However, to obtain reasonable values for k, good quality and detailed observations are needed. Zimmerman applied his theory to a lagoon system (i.e. Dutch Wadden Sea), which does not have well-defined channels such as occur in alluvial estuaries studied herein. The fact that the topography of alluvial estuaries obeys geometrical laws creates an opportunity to expand this theory and make it more predictive.

Later, de Swart et al. (1997) applied the "tidal random walk" model to the Ems estuary and obtained good results, at least qualitatively, in estimation of the dispersion coefficients. However, they recommended that although the simple random walk model can be used to get upper bounds for the dispersion coefficients, simulations using a detailed 3D-numerical model are necessary in order to obtain lower bounds for the values of dispersion coefficients. This agrees with assessments in Geyer and Signell (1992), which stated that numerical models provide a means of isolating the influence of tidal advection from these other processes and they can simulate the nonlinear effects that produce residual circulations.

The aims of this paper are to investigate the residual circulation caused by the interaction of the tidal flow with the flood-ebb channel system in the Western Scheldt and to study the effect of tidal pumping caused by the flood-ebb channel residual circulation on the salinity distribution. This paper provides a new conceptual model and a new analytical equation for this type of tidal-driven mixing. Firstly, we use a fully three-dimensional hydrodynamic model as a "virtual laboratory" and employ a decomposition method to characterise the residual ebb-flood channel circulation in the Western Scheldt. Secondly, a conceptual model and an analytical equation determining the dispersion coefficient are developed, which take into account several important parameters of the tidal pumping mechanism, such as the tidal pumping efficiency, the tidal excursion and the length of the branches. Subsequently, the newly developed equation is compared to the results of the "virtual laboratory". Finally, the equation is applied to observations in the Western Scheldt. The application yields good results in determination of the longitudinal dispersion compared to dispersion values obtained from the salt budget and hence it is demonstrated that the newly developed equation can be applied to a real estuary.

2. Methodology

2.1. "Virtual laboratory" residual salt transport

In order to analyze the characteristics of the residual ebb-flood channel circulation, a considerable set of data on residual flow components is required. The collection of such information would require a major operation, consisting of a dense network of monitoring points over a considerable period of time. Moreover, substantial errors on measurements may result (Lane et al., 1997). In practice, it is not feasible to obtain these data from the field. Therefore, in this paper, a fully three-dimensional hydrodynamic model (DELFT3D) has been used as a "virtual laboratory" of the Western Scheldt estuary to provide the data on hydrodynamics and salinity. For details on the operation of the hydrodynamic model and the key features of the formulations used, reference is made to Lesser et al. (2004).

Some relevant information on the schematisation of the hydrodynamic model is summarized as follows:

(1) Configuration. In total the grid includes approximately 12,500 active points, grid cells sizes vary from 800 m × 800 m at the