Continental Shelf Research 116 (2016) 122–135

Contents lists available at ScienceDirect

Continental Shelf Research

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

Research papers

Sediment transport in a surface-advected estuarine plume

H.Y. Yao [a,b,*], N. Leonardi [b,c], J.F. Li [a], S. Fagherazzi [b]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[b] Department of Earth and Environment, Boston University, 675 Commonwealth Avenue, Office STO 141G, Boston, MA 02215, USA
[c] Department of Geography and Planning, University of Liverpool, Liverpool L69 7ZT, UK

ARTICLE INFO

Article history:
Received 13 February 2015
Received in revised form
17 January 2016
Accepted 23 January 2016
Available online 26 January 2016

Keywords:
Estuarine plume
Sediment transport
Coastal current
Freshwater transport
Flood

ABSTRACT

The interplay between suspended-sediment transport and plume hydrodynamics in a surface-advected estuarine plume is studied using a three-dimensional numerical model. Our analysis focuses on the formation of a sediment-rich alongshore current and on the effect of sediments on the structure of the recirculating freshwater bulge. We introduce the ratio Y between the traveling time of sediment along the bulge edge and the settling timescale. When $Y < 1$, suspended sediments enter the alongshore coastal current. When $Y > 1$ the sediments are deposited within the bulge. We find that a critical range of settling velocities exist above which no transport in the costal current is allowed. Critical settling-velocity values increase with river discharge. Therefore, low magnitude and long-lasting floods promote sediment sorting in the continental shelf. We further find that, for a given flood duration, intermediate flood magnitudes at the limit between subcritical and supercritical flow maximize the alongshore sediment transport. Similarly, for a fixed input of water and sediments, intermediate discharge durations maximize alongshore sediment transport.

1. Introduction

Buoyant fresh water discharges are one of the main drivers for coastal and shelf currents and their hydrodynamics determine the fate and transport of sediments, nutrients and pollutants entering the ocean (Geyer et al., 2004a; Liu et al., 2007; Lohrenz et al., 1999; Warne et al., 2002; Wright, 1977). Sediment plumes are thus crucial for the morphodynamic evolution of coastal areas, and understanding their complex dynamics would promote a more effective management of these environments.

Many buoyant inflows remain trapped at the surface of shelf water, forming a thin plume on top of ambient water and maintaining little or no contact with the shelf bottom while spreading offshore (Geyer et al., 2004b; Yankovsky and Chapman, 1997). A well-documented feature of surface-trapped river flows is their deflection by the Coriolis force which triggers a flow circulation within the plume (Geyer et al., 2004b; Yu, 2006). Near the river mouth, flow inertia can be considered the main hydrodynamic driver. Farther from it, earth rotation causes the river outflow to evolve into a coastal current flowing in the direction of a propagating Kelvin wave (i.e. with the shore on the right in the Northern hemisphere, see (Geyer et al., 2004b; Nof and Pichevin, 2001). Numerical results using a semi-analytical 2.5D model indicate that in marine environments where the depth of water exceeds the Ekman scale (typically 10–30 m), the direction of suspended sediment transport in the lower water column is different from the depth integrated water flow direction because of velocity veering induced by the Coriolis effect (Shapiro, 2004).

Numerical (e.g. Chao and Boicourt, 1986; Marsaleix et al.,1998), and empirical (e.g. Masse and Murthy, 1992) investigations confirm that the river plume can be divided into two main regions: a baroclinic eddy that forms near the river mouth (the recirculating bulge) and an alongshore coastal current (Fig. 1). Among others, noticeable examples of anti-cyclonic rotating bulges are those discharged from Chesapeake Bay and Delaware Bay in the USA and the Yangtze River in China (Geyer et al., 2004b; Yu, 2006). Freshwater bulge grows in time and as long as its radius is relatively low it remains attached to the coast with a large freshwater fraction delivered to the coastal current. When the bulge size exceeds a critical limit, it separates from the coast and cyclically regrows, causing the flow in the coastal current to be intermittent (Horner-Devine et al., 2006). The higher is the discharge the bigger is the freshwater bulge and the faster the bulge becomes unstable. For supercritical flow (densimetric Froude number higher than one) the bulge becomes unstable after 5 rotations (e.g. after around 5 days, Horner-Devine et al., 2006). Fig. 2 shows example of freshwater bulge at the end of the 5th numerical day and for different discharge conditions; in panel D we show an example of unstable bulge starting to detach from the coast: the location

* Corresponding author at: State Key Laboratory of Estuarine and Coastal Research East China Normal University, Shanghai 200062, China
E-mail address: jason.a.yao@hotmail.com (H.Y. Yao).

http://dx.doi.org/10.1016/j.csr.2016.01.014
0278-4343/

List of parameters

Parameters	Meaning, Units
B	River mouth width, M
C	Suspended sediment concentration in the plume, kg/m^3
C_r	Concentration of suspended sediment, kg/m^3
$C(x, y)$	Surface suspended sediment concentration at (x, y), kg/m^3
f	Coriolis parameter, s^{-1}
G'	Reduced gravitational acceleration with sediment, m^2/s
g	Gravitational acceleration, m^2/s
g'	Reduced gravitational acceleration without sediment, m^2/s
H	River mouth depth, M
h	Plume depth, M
h_o	Plume depth at the coast, M
$\bar{h}$	Average plume depth, M
L	Plume width, M
L_i	Inertial radius, M
m	Constant coefficient
Q	River discharge, m^3/s
Q_{fcc}	Freshwater transport in the coastal current with sediment, m^3/s
Q_{fcc0}	Freshwater transport in the coastal current without sediment, m^3/s
ΔQ_{fcc}	Decrease of freshwater transport in the coastal current, m^3/s
Q_{ssc}	Sediment transport in the coastal current, kg/s
R_f	Distance from freshwater center to mouth, M
R_c	Distance from sediment distributional center to mouth, M
r_s	Bulge radius, M
S	Salinity at calculated point, Psu
$S(x, y)$	Surface salinity at (x, y), Psu
S_o	Salinity of ambient sea water, Psu
S_r	River salinity, Psu
ΔS	Salinity anomaly between river discharge and ambient sea water, psu
T_{st}	Sediment transport time scale, s
$T_{\omega s}$	Sediment settling time scale, s
v	Flow velocity, m/s
v_r	River flow velocity, m/s
x_f	Horizontal distance from freshwater center to shoreline, m
Y	Sediment time scale ratio
y_f	Longitudinal distance from freshwater center to extension cord of mouth, m
x_i	Horizontal distance from calculated point to shoreline, m
y_i	Longitudinal distance from calculated point to extension cord of mouth, m
α	Constant coefficient
β	Constant coefficient
γ	Constant coefficient
ρ_o	Density of ambient sea water, kg/m^3
ρ_r	River discharge density without sediment, kg/m^3
ρ_s	Density of suspended sediment, kg/m^3
$\Delta\rho$	Density anomaly between river fluid and ambient sea water without sediment, kg/m^3
$\Delta\rho'$	Density anomaly between plume and ambient sea water with sediment, kg/m^3
θ_f	Angle between freshwater center-mouth and shoreline, °
θ_c	Angle between sediment distributional center-mouth and shoreline, °
ω_s	Settling velocity of suspended sediment, mm/s
ω_{cs}	Critical settling velocity, mm/s

where the outer bulge current impinges on the wall has moved toward the inlet, cutting off the flow of the alongshore current.

Numerous studies have been carried out to gain physical insight into the dynamics of surface trapped river plumes using either laboratory experiments (Avicola and Huq, 2003a, b; Horner-Devine et al., 2006), field measurements (Hickey et al., 1998; Masse and Murthy, 1992), and analytical and numerical models (Beardsley and Hart, 1978; Chao and Boicourt, 1986; Fong and Geyer, 2002; Nof and Pichevin, 2001). However, these studies mainly focused on the structure and dynamics of the freshwater bulge and of the coastal current. Less attention has been paid to the effect of Coriolis forces on sediment dispersal and transport (see Hetland and Hsu, 2013).

The aim of this study is to extend previous work on the hydrodynamic of surface trapped river plumes to systems where fine sediments are also present. Specifically, we use numerical experiments to analyze the reciprocal interactions between sediment transport and plume hydrodynamics. We focus on the effect of sediments on the structure of the recirculating freshwater bulge and coastal current and on the effect of centrifugal forces on sediment delivery to the ocean. Special attention is given to the study of the alongshore sediment transport in the coastal current. We further focus on fine cohesive sediments that do not deposit in proximity of the river mouth and are more likely transported within the freshwater bulge and in the alongshore current.

For fine cohesive sediments, the settling velocity also depends on flocculation at high sediment concentrations (Van Leussen, 1988). The relationship between suspended sediment concentration and settling velocity has been explored by many researchers (Gibbs, 1985; Krone, 1962; Winterwerp, 2002; You, 2004) and it was found that settling velocity is independent of suspended sediment concentration C when $C < 0.3$ kg/m^3, while it increases as a function of concentration for $0.3 < C < 4.3$ kg/m^3 due to flocculation (You, 2004). However, flocculation likely affects only a part of the sediment load, and a fraction of very fine sediments can be still transported far from the river mouth. For example, suspended sediment concentrations in the turbidity maximum zone of the Yangtze Estuary varies from 2 to 10 kg/m^3, with flocculation trapping large amounts of sediment inside the river mouth (Li and Zhang, 1998). Based on calculations performed by Milliman (1985) and Liu (2007), it is believed that about 30% of total sediment flux discharged from the Yangtze River is transported several hundred kilometers southward and deposits along the Zhejiang–Fujian coastal zone. Our results are mainly relevant for the sediment fraction that is transported far from the river mouth and contributes to the along-shelf sediment diffusion (Driscoll and Karner, 1999). The manuscript is organized as follow: after describing the numerical model and numerical-model setup, we define a series of variables and parameters used in the investigation. The results section is divided into two main parts: in the first part we focus on the effect of sediments on the structure and geometry of the freshwater bulge and freshwater transport in the alongshore coastal currents. This section explores the effect of changes in water density caused by sediments, in analogy with salinity