THE INFLUENCE OF RIVER DISCHARGES, TIDES, AND WINDS ON ESTUARINE PLUME IN NORTHWEST PENINSULAR MALAYSIA

by

MUHAMMAD SYUKRI

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To very special people in my life:
my late mother Djuairiah Sabi,
my wife Rini Safitri
and
my son Raushan al Kasyfie Muhammad

The origins of oceanography lie in voyaging...

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List of Abbreviations

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ADCP	Acoustic Doppler current profiler	29
APHA	American Public Health Association	98
AVHRR	Advanced very high resolution radiometer	34
CDOM	Coloured dissolved organic matter	38
DID	Department of Irrigation and Drainage, Malaysia	54
DNPS	Daya Bay nuclear power station	34
DOC	dissolved organic carbon	18
E	East	41
ENE	East Northeast	82
ESE	East Southeast	82
GF	Glasfaser Rundfilter	98
GIS	Geographic Information System	34
GPS	Global Positioning System	66
ICAM	Integrating cavity absorption meter	39
IPTS-68	The International Practical Temperature Scale of 1968	101
IUPAC	International Union of Pure and Applied Chemistry	103
Landsat TM	Landsat Thematic Mapper	38
LiDAR	Light Detection and Ranging	38
MMS	Malaysian Meteorological Services	58
MMSD	Malaysian Mapping and Survey Department	54
mg	Milligram	99
mg/l	Milligram per liter	99
MSL	Mean Sea Level	53
MST	Malaysia Standard Time	53
N	North	41
NE	Northeast	79
NASA	National Aeronautics and Space Administration	39
OBS	Optical backscatterance sensor	15

p	Pressure	100
POC	Particulate organic matter	18
ppt	Parts per thousand	101
PSS-78	The Practical Salinity Scale 1978	36
psu	Practical salinity units	29
ROFI	Region of Freshwater Influence	65
S	Salinity	79
S	South	28
SBS	Southern Brazilian Shelf	65
SCT	Salinity, conductivity and temperature	65
SLFMR	Scanning low frequency microwave radiometer	35
SPOT	Satellite Pour l'Observation de la Terre, is a commercial earth observation satellite	28
SW	Southwest	79
SPM	Suspended particulate matter	365
SSW	South Southwest	82
T	Temperature	65
TSS	Total suspended solids	34
W	West	79
WNW	West Northwest	82
YSI	Yellow Spring Instrument	65

List of Symbols

Name	Definition	Page
A^*	Absorption coefficient for sediment	38
a_x	Absorption coefficient for nonsediment constituents	38
B^*	Specific backscatter coefficient	38
A	Weigh of filter + residue	99
B	Weigh of filter	99
B	Buoyancy anomaly	20
C	Volume of water sample filtered	99
C'	Sediment volume concentration	19
C_D	Non-dimensional bottom drag coefficient	19
D	Depth of typical plume	11
f	Coriolis parameter	11
G	Acceleration of gravity	11
H	Depth	12
K	Kelvin number	24
K	Secant bulk modulus	100
L	Along shore length	12
γL	Across shore length	12
R_i	Richardson number	19
R_g	Richardson gradient number	106
R_L	Layer Richardson Number	107
R'_d	Reflectance	37
R_{bias}	Residual reflectance	37
r_i	Baroclinic Rossby radius	11
ρ	Average density of plume water	11
ρ_a	Density of ambient coastal water	11
ρ_s	Density of siliceous sediment	20
U	Current velocity	12
U_{max}	Total current velocity	19

U_w	RMS wave orbital velocity	20
u_g	Average current velocity in x direction	20
V	Specific volume	100
v_c	Magnitude of along shelf current	20
‰	Part per thousand (unit of salinity)	111
Φ	Diameter	98
σ_t	Density	105
$t_0(\lambda)$	Ozone and water vapor absorption optical depth for channel λ,	37
$t_r(\lambda)$	Rayleigh optical depth for channel λ	37

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PENGARUH LUAHAN SUNGAI, PASANG SURUT DAN ANGIN TERHADAP PLUM ESTUARI DI BARATLAUT SEMENANJUNG MALAYSIA

ABSTRAK

Tujuan thesis ini adalah untuk mengkaji struktur daripada plum estuari dan perairan pantai secara spasial dan temporal di baratlaut Semenanjung Malaysia. Pengukuran saliniti, suhu dan sedimen terampai (TSS) dijalankan bagi kawasan plum Muda, plum Prai dan dibahagian bawah Estuari Merbok. Di samping itu imej digital (imej udara) dan pengukuran arus juga diperolehi di beberapa tempat kajian yang terpilih. Luahan daripada sungai Muda adalah satu orde kali ganda lebih tinggi daripada Sungai Prai dan Sungai Merbok.

Keputusan yang diperolehi menunjukkan ciri-ciri permukaan plum bagi estuari dan perairan laut yang dipengaruhi oleh luahan air sungai, tenaga pasang surut dan juga oleh kekuatan angin. Semasa luahan tinggi, pergerakan bagi plum estuari Muda dan plum Prai ke perairan laut adalah masing-masingnya sekitar 4 km dan 2 km dari garis pantai. Keluasan permukaan yang dilitupi oleh estuari plum tersebut adalah bagi masing-masingnya sekitar 30 km^2 dan 13.5 km^2. Semasa luahan rendah, jarak plum akan berkurangan makin berdekatan sekitar 1-2 km dari garis pantai.

Pasang surut adalah penyebab kepada campuran dan penstrataan daripada plum. Plum Muda dan bahagian bawah Estuari Merbok, semasa perubahan daripada pasang surut perbani (*spring tides*) kepada pasang surut anak (*neap tides*), struktur plum bertukar daripada penstrataan separa atau homogen (pasang surut perbani) kepada penstrataan tinggi (pasang surut anak). Kepekatan TSS yang tinggi adalah konsisten bagi plum Muda dan plum Prai dan bahagian bawah Estuari Merbok semasa pasang surut perbani dibandingkan dengan semasa pasang surut anak disebabkan oleh tenaga pasang surut perbani yang lebih tinggi. Sebaliknya semasa pasang surut anak perlakuan yang sama bagi kepekatan TSS tidak diperolehi. Tiada korelasi yang jelas diperolehi diantara ciri-ciri plum dan kekuatan angin, kecuali

semasa kekuatan angin yang kencang yang menunjukkan terdapat bukti bahawa pergerakan plum adalah mengikuti arah angin.

Penderiaan jauh memberikan maklumat secara dua dimensi bagi struktur permukaan plum estuari. Imej digital jelas menunjukkan bahawa plum Prai akan terherot ke arah selatan/utara semasa luahan air sungai yang rendah/tinggi. Perlakuan ini dipengaruhi oleh pasang surut.

PENGARUH LUAHAN SUNGAI, PASANG SURUT DAN ANGIN TERHADAP PLUM ESTUARI DI BARATLAUT SEMENANJUNG MALAYSIA

ABSTRAK

Tujuan thesis ini adalah untuk mengkaji struktur daripada plum estuari dan perairan pantai secara spasial dan temporal di baratlaut Semenanjung Malaysia. Pengukuran saliniti, suhu dan sedimen terampai (TSS) dijalankan bagi kawasan plum Muda, plum Prai dan dibahagian bawah Estuari Merbok. Di samping itu imej digital (imej udara) dan pengukuran arus juga diperolehi di beberapa tempat kajian yang terpilih. Luahan daripada sungai Muda adalah satu orde kali ganda lebih tinggi daripada Sungai Prai dan Sungai Merbok. Keputusan yang diperolehi menunjukkan ciri-ciri permukaan plum bagi estuari dan perairan laut yang dipengaruhi oleh luahan air sungai, tenaga pasang surut dan juga oleh kekuatan angin. Semasa luahan tinggi, pergerakan bagi plum estuari Muda dan plum Prai ke perairan laut adalah masing-masingnya sekitar 4 km dan 2 km dari garis pantai. Keluasan permukaan yang dilitupi oleh estuari plum tersebut adalah bagi masing-masingnya sekitar 30 km^2 dan 13.5 km^2. Semasa luahan rendah, jarak plum akan berkurangan makin berdekatan sekitar 1-2 km dari garis pantai. Pasang surut adalah penyebab kepada campuran dan penstrataan daripada plum. Plum Muda dan bahagian bawah Estuari Merbok, semasa perubahan daripada pasang surut perbani (*spring tides*) kepada pasang surut anak (*neap tides*), struktur plum bertukar daripada penstrataan separa atau homogen (pasang surut perbani) kepada penstrataan tinggi (pasang surut anak). Kepekatan TSS yang tinggi adalah konsisten bagi plum Muda dan plum Prai dan bahagian bawah Estuari Merbok semasa pasang surut perbani dibandingkan dengan semasa pasang surut anak disebabkan oleh tenaga pasang surut perbani yang lebih tinggi. Sebaliknya semasa pasang surut anak perlakuan yang sama bagi kepekatan TSS tidak diperolehi. Tiada korelasi yang jelas diperolehi diantara ciri-ciri plum dan kekuatan angin, kecuali semasa kekuatan angin yang kencang yang menunjukkan terdapat bukti bahawa pergerakan plum adalah mengikuti arah angin. Penderiaan jauh memberikan

maklumat secara dua dimensi bagi struktur permukaan plum estuari. Imej digital jelas menunjukkan bahawa plum Prai akan terherot ke arah selatan/utara semasa luahan air sungai yang rendah/tinggi. Perlakuan ini dipengaruhi oleh pasang surut.

THE INFLUENCE OF RIVER DISCHARGES, TIDES, AND WINDS ON ESTUARINE PLUME IN NORTHWEST PENINSULAR MALAYSIA

ABSTRACT

The aim of the thesis was to investigate the spatial and temporal structure of estuarine plume and coastal waters in northwest Peninsular Malaysia. Measurements of salinity, temperature, and TSS were carried out at the Muda plume, Prai plume and the lower Merbok estuary. In addition, aerial images and current measurements were also obtained through several selected field surveys. The discharge of the Muda River was an order of magnitude more than Prai and Merbok Rivers. The results suggest that the surface plume characteristics of the estuaries and coastal waters are influenced by freshwater discharge, spring-neap tidal energy, and to some extent by wind forcing. During high discharge, the offshore extent of the Muda and Prai estuary plumes were approximately 4 km and 2 km respectively. The surface horizontal areas covered by these plumes were 30.0 km^2 and 13.5 km^2, respectively. During low discharge, the extent of plumes were closer to the coastline at about 1-2 km offshore. Tides were responsible for the mixing and the stratification of the plumes. The Muda plume and the lower Merbok Estuary, during the transition of spring-to-neap periods that change the plume structure from partially-mixed or homogeneous (spring tide) to highly stratified (neap tide). There were consistently higher TSS concentrations of Muda and Prai plume waters and Merbok Estuary during spring tides than at neap tides due to stronger spring tide energy. On the contrary, during neap tide a similar behavior of TSS concentration was not found. No obvious correlation was found between the plume characteristics and wind forcing, except during strong winds when there were some evidence of plume movement according to wind direction. Remote sensing provided information on the two-dimensional surface structures of the estuary plumes. For example, the aerial images clearly showed snapshots of the Prai plume being deflected to the south/north during low/high discharge. These behaviors were influenced by tides.

Chapter One
Introduction

1.0 Introduction

In studying and observing the coastal and estuary, the very first it is important to understand the basic concepts and their characteristics. The coastal area is significantly affected by various forcing mechanisms occurring over a broad range of spatial and temporal scales. The coastal ocean response to these various forcing mechanisms depends critically on the geometry and topography of the region, as well as the scale of the forcing. These relevant forcing mechanisms influencing the coastal characteristics are: river discharge, tidal range, atmospheric events (wind, waves, atmospheric temperature, rainfall, and density gradients (buoyant plumes)).

The estuary is a dynamic mixing areas for fresh and salt water, is particularly important because their high productivity. The term estuary means the lower tidal reaches of a river. Elliott and McLusky (2002) concluded that as existing definitions would never be suitable for all needs, a different approach is required. According to a contemporary definition and most scientist accept the definition of Pritchard (1967), based on physical characteristics: "an estuary is a semi-enclosed body of water having a free connection with the open sea and within which the seawater is measurably diluted with freshwater draining from the land". The estuary functions as a buffer between the ocean and the land. It can filter sediment and pollutants from the water before it flows into the oceans. Basically, all estuaries will interact physically with the open coast. This interaction is expressed in terms of both the influence of the estuary on the coast, and the influence of the coast on the estuary. It is important to understand the dynamics of estuarine systems, especially their water and sediment movement.

The movement of river waters into estuary and coastal region is part of an interconnected environmental system. Freshwater discharge is one of the most influential landscape processes affecting physical structure and function in estuaries, deltas and coastal. As a natural process, rivers drain freshwater discharge from rainfall events over land. The runoff and the downstream movement of materials is one of the primary controls over the productivity of estuarine systems and coastal waters. The river discharge collects a variety of materials as it moves through the river's catchment, lands and waterways including nutrients, sediments and contaminants depending on the catchment characteristics. Upon reaching the sea at the estuary mouth, the discharge drives a buoyant plume into coastal and shelf waters. It is an interesting phenomena that can be observed, a distinct color difference between the river and seawater. The area that appears to be extension of more brown color river water than seawater into the coastal zone is called a plume.

1.1 Motivation

The study areas are the estuaries and coastal waters of the Northwest of Peninsular Malaysia, are well known for their productive and diverse marine ecosystem, but little is known about the physical oceanography of the region. The Muda, Merbok and Prai Rivers, as a representative of tropical estuaries and coastal waters, drain into the Malacca Straits. There are some other factors deciding upon the complexity of the hydrodynamic phenomena such as: river discharges, tides, winds, atmospheric temperatures changes and sediment transport that appears in the estuaries and coastal waters.

Understanding the interactions between estuaries or coastal waters and global changes cannot be achieved through estimation or laboratory studies alone. Observational studies of key environmental processes is a significant and vital method that must be used to achieve its overall objectives, particularly in view of the fact that many of the uncertainties and real natural problems and processes occurring within the estuaries and coastal waters. This thesis is intended as a guide for those wishing to contribute to the objective of elucidating plume dynamics, suspended sediment concentration, turbidity (Secchi depth), density, salinity and temperature distribution in estuaries and coastal waters. Characteristics behavior of all these parameters directly correlated with the plume, that also as a representative of tropical plume. Figure 1.1a shows a schematics plan view of an estuary plume while Figure 1.1b illustrates a cross shore section of the plume, with the less dense river water overlying the more dense seawater. The vertical section shows how the plume floats out into the seawater, creating strong turbulence along its boundary as the fresh river water is absorbed into the seawater surroundings. The plume eventually spreads and mixes with ambient coastal waters.

This study has historically been motivated by the desire to both exploit and preserve resources in estuaries and coastal waters. It was done by the need to understand the distribution and fate of these estuarine waters, after their release into the coastal zone. The study will focus on the characteristics of the estuary plume in the study areas. The study is designed as a 1-year research for Muda coastal zone, starting in July 2001 and ending in August 2002, 6-months in Merbok River estuary, and 4-months in Prai coastal zone.

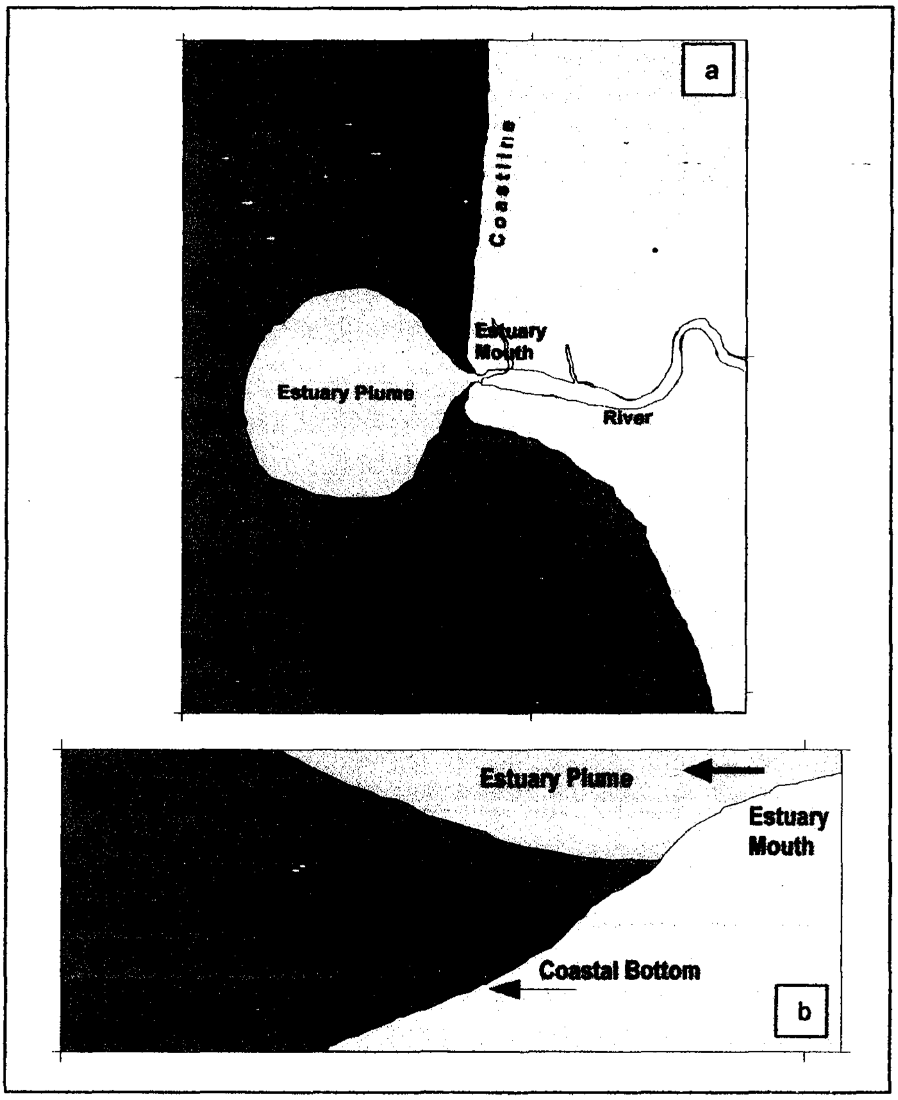

Figure 1.1 (a) A schematic plan view of an estuary plume in the coastal water, and (b). A vertical section of an estuary plume as the fresher water discharge from the estuary to coastal water.

1.2 Hypothesis

Studies on the temporal and spatial structures of the estuary plume are of considerable interest not only because of its influence on the physical processes of the shelf circulation but also because of its close relationship to environmental problems. In particular, the vast amount of land-drained materials, suspended materials, and sewage brought onto the continental shelf through the river discharge may significantly affect the formation of the estuary plume in the coastal zone. It is, therefore, important to have a general understanding of the coastal circulation as well as trace and predict the pathways and distributions of estuary plume in coastal waters.

This study demonstrates the movement of estuary plumes from the estuary mouth to inshore systems. Measurements taken near the mouth of the estuary systems are more representative of the processes that are occur in rivers that are dependent on the characteristics of that river system. Samples taken at close proximity to the mouth may generally be high in suspended matter that are related to the river source and also bottom sediment of coastal water.

The hypotheses or assumption made in this study are:

- ❑ High/low river discharge that related to the wet/dry season is one of the most influential factors affecting the physical structure of the estuary plume. As a natural process, freshwater discharge forcing and the downstream movement of sediments is one of the primary control of the characteristic of coastal sea. During high discharges (wet season) are expected well develop of estuary plume. On the other hand, from low discharges (dry season) are expected would result less or no plume.
- ❑ Tidal forces would produces cross shelf plume water movements. A mixing of sea and river water by tidal energy would determine the movement of plume water from the coastal water. During neap tides, it is expected that the plume waters would pushed landward on flood phase. While, during spring tides it is expected that the plume water would push further seaward on ebb phase. The magnitude of plume movement in spring tides would be higher than in neap tides.
- ❑ Wind force will induce a shear stress on the surface water causing the plume water to move in the general direction of the wind, and transfer energy to the

water column. During periods of strong winds, it is expected that the movement of plume water would follow the direction of the wind. In periods of weak wind, there is no significant influence on plume water movement.

1.3 Objectives and scope

The general objective of this study is to elucidate the basic physical processes associated with the characteristics of estuary plume. In particular, the study will focus on understanding river discharge, tidal, and wind forcing in determining the structure, patterns and fate of the plume. One of the key contributions of this work is quantification of both the along and cross shore motions of plume waters, and their distribution around the lower estuary.

The study have the following major objectives:

- To investigation the spatial and temporal structure of the Muda, Merbok and Prai Rivers estuary plume under a range of river discharge, tide and wind regimes.
- To carry out aerial surveys and observe their significant relationships with field measurements.
- To determine the physical mechanisms governing plume near the estuary mouth and coastal zone.

To carry out the objectives of the study, the area of observation will be established and will include: (1) the observations of salinity, temperature, density, total suspended solids (TSS), and Secchi depths near the mouths of three rivers of many tributaries flowing into coastal of Northwest Peninsular Malaysia, (2) the collection and measurement of tidal phase, rainfall, river discharge, water level, atmospheric temperature, current velocity, and wind speed and direction at specific locations inside the coast, estuary and in land.

In order to achieve the above objectives, it is need to limit the scope of study and provide some coherence. This study will focus on the theme of coastal and lower estuary processes and exchange i.e., identifying and understanding processes that are important in flowing plume water and associated seasonal, dynamical and physical oceanography across and along the shore and lower estuary. Even this is not a new problems in physical oceanography, however the objective of this study emphasis on this problem in motivated by several factors:

- ❑ To obtain a more thorough understanding of the hydrographic characteristics and dynamics of the Muda and Prai coastal waters, lower Merbok Estuary and the adjacent estuary mouth region.
- ❑ To delineate the extent and distribution (spatial and temporal distribution) of the Muda, Merbok and Prai Estuary plume in relation to the local hydrology characteristics and assesses the potential processes that might control (or have affected) the distribution of plume water in the coastal area and lower estuary.
- ❑ To use recent developments of instrumentation and techniques to gain new insights into estuary and coastal processes, wind driven over coastal and buoyant plumes associated with river discharge onto coastal waters.

1.4 Thesis outline

The study is done base on the need to understand processes occurring in estuary and coastal region arises from a variety of historic and contemporary topics in physical oceanography. It includes observation of the estuary and coastal dynamics in the Northwest Coastal of Peninsular Malaysia. In particular, the study focuses on the interactions of estuary (brackish estuarine) discharge in coastal after it leaves the estuary mouth, and also in lower estuary. It is very interesting and important role in coastal ocean and estuary dynamics because of it acts as a repository of organic matter in marine sediments, and source of nutrients and contaminants. This phenomenon is one of the interesting features to understand from this study.

The thesis is organized as follows. In Chapter 2, a brief review of the relevant theoretical and experimental investigations are presented in order to place the present work its appropriate context. In chapter 3, study sites characteristic, meteorological and hydrography data, field and laboratory works, and the methods are explained briefly. In Chapters 4, 5 and 6 present results and analysis from all observation conducted in the Muda, Merbok and Prai Rivers. Finally, Chapter 7 provides conclusions and significant findings of the results and suggests directions for future research.

Chapter Two

Literature Review

Studies of the characteristics and structures of estuary plume are very interesting not only because of its influence on the physical processes of the coastal circulation but also because of its close relationship to environmental and ecosystem problems. In particular, it is important to have a general understanding of the coastal circulation as well as to trace and to predict the trajectories and distributions of estuary plume in the coastal ocean.

2.0 Estuary plume structures

Several research and observations show that estuary plumes have different structures in different regions. In general, the plume structure is principally determined by the local conditions like the total volume of freshwater outflow, winds, tides, coastal currents and bathymetry. A review is given by Wiseman and Garvine (1995). Estuary plumes can be characterized by a Kelvin number, the ratio of the width of the river mouth to the baroclinic Rossby radius (Garvine, 1987):

$$K = w / r_i \qquad 2.1$$

and

$$r_i = \frac{\{gd(\rho_a - \rho)/\rho_a\}^{1/2}}{f} \qquad 2.2$$

where ρ is the average density of plume water, ρ_a is the density of ambient coastal water, g is the acceleration of gravity, d is the typical plume depth, and f is the Coriolis parameter. Physically for a plume with small K, the deflection of the plume alongshore tends to be dominated by motion of ambient coastal water, not by the anticyclonic turning action of Coriolis force, while for of order unity or larger effects of the earth rotation or the Coriolis force becomes important. Garvine (1995) offered a method to classify buoyancy flows in coastal waters. He considered the balance of the following forces: horizontal advection, Coriolis, pressure gradient, wind stress and bottom stress. Figure 2.1 shows an idealized buoyant plume.

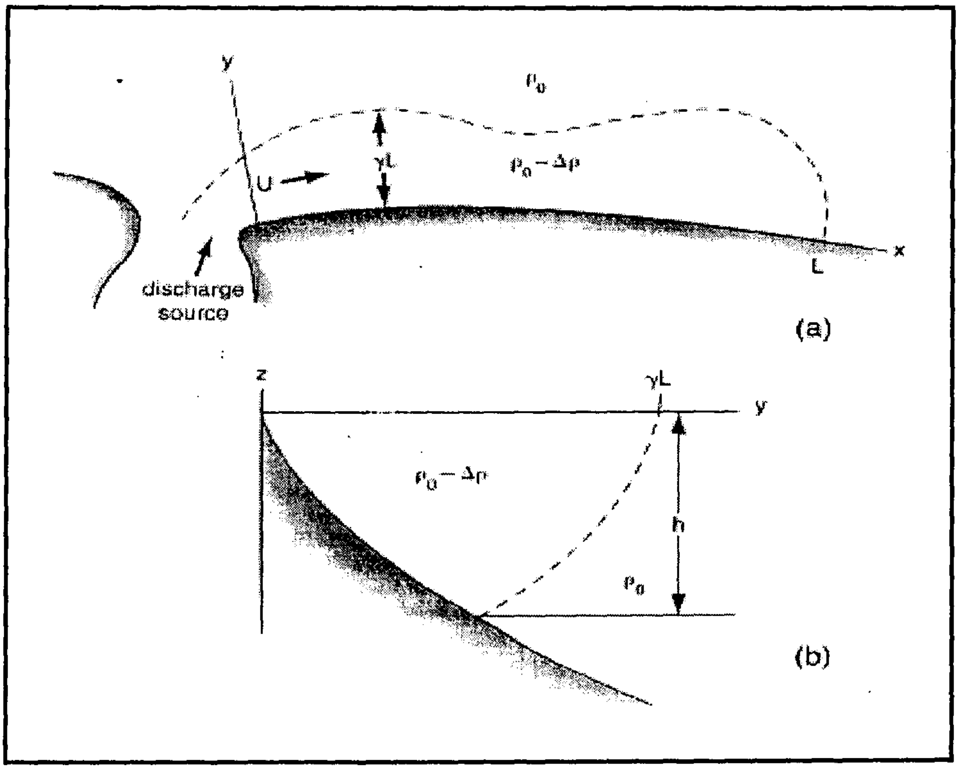

Figure 2.1 Sketch of buoyant layer scales. (a) x and y are alongshore and across-shore coordinates. Dashed line denotes a bounding isopycnal contour for the buoyant layer. U is typical alongshore buoyant water velocity. L and γL are the alongshore and the across-shore length scale, respectively. (b) A typical across-shore vertical section with vertical coordinate z. Dashed line shows typical bounding isopycnal for the buoyant of typical depth h. (from Garvine, 1995).

This kind of estuary plume is described by theoretical model to obtain approximate solutions to several problems which are interpreted to yield new insights of these phenomena (O'Donnell, 1990). However, James (1997) dealing with regions of the sea where the dynamical effect of the coastal discharge of relatively freshwater is significant by developed the anticyclonic circulation model that can change the expected direction of the discharge plume. For the mathematical description of plume structure, Poulos and Collins (1994) predicted the spread of freshwater outflow for a small river based upon a combination of frictionally-controlled and buoyant plume dispersal models. Here, the estuary plume decelerates rapidly for the first 400 m to seaward of the estuary mouth, and at the transitional zone, the plume has lost then its initial momentum and it is controlled now by buoyant forces and entrainment processes.

Fennel and Mutzke (1997) studied the initial evolution of a buoyant plume. They stated that estuary plumes are forced by two mechanisms: (i) momentum added to the ocean at the estuary mouth and (ii) intrusion of buoyancy at the estuary mouth. Several researchers such as, Ingram (1981), O'Donnell (1990), Ruddick *et al.* (1995), James (1997) and Broche *et al.* (1998) implied that the study of estuary plume is a subject related to river discharge. Since the river discharge is fairly small, mixing between river water and seawater to be extremely small, thus the estuary plume might be disturbed by turbulence advected from beyond the location. When the amount of river discharge becomes much larger, the salt water is pushed out from the estuary mouth so that the estuary plume becomes supercritical (Murota and Nakatsuji, 1988; Chao, 1998).

The freshwater inflow provides a direct input of momentum as well as a large buoyancy source, both of which contribute to the motion over the shelf. The surface salinity distribution and the suspended sediment distribution from the Eel River plume exiting the mouth of the Bay are shown in Figure 2.2 and Figure 2.3. These observations indicate that the suspended sediment was behaving nearly conservatively within the plume during the high-flow, down welling conditions, and that sediment was being lost to settling during the falling-flow, upwelling conditions. Beside that, because of high rates of particulate and river discharge, the estuarine processes usually take place on the adjacent continental shelf instead of in a physically confined estuary (Dagg *et al.*, 2004). The other results suggest that Fouha Bay (at southwest coast of Guam) is flushed annually by waves generated from typhoons passing to the

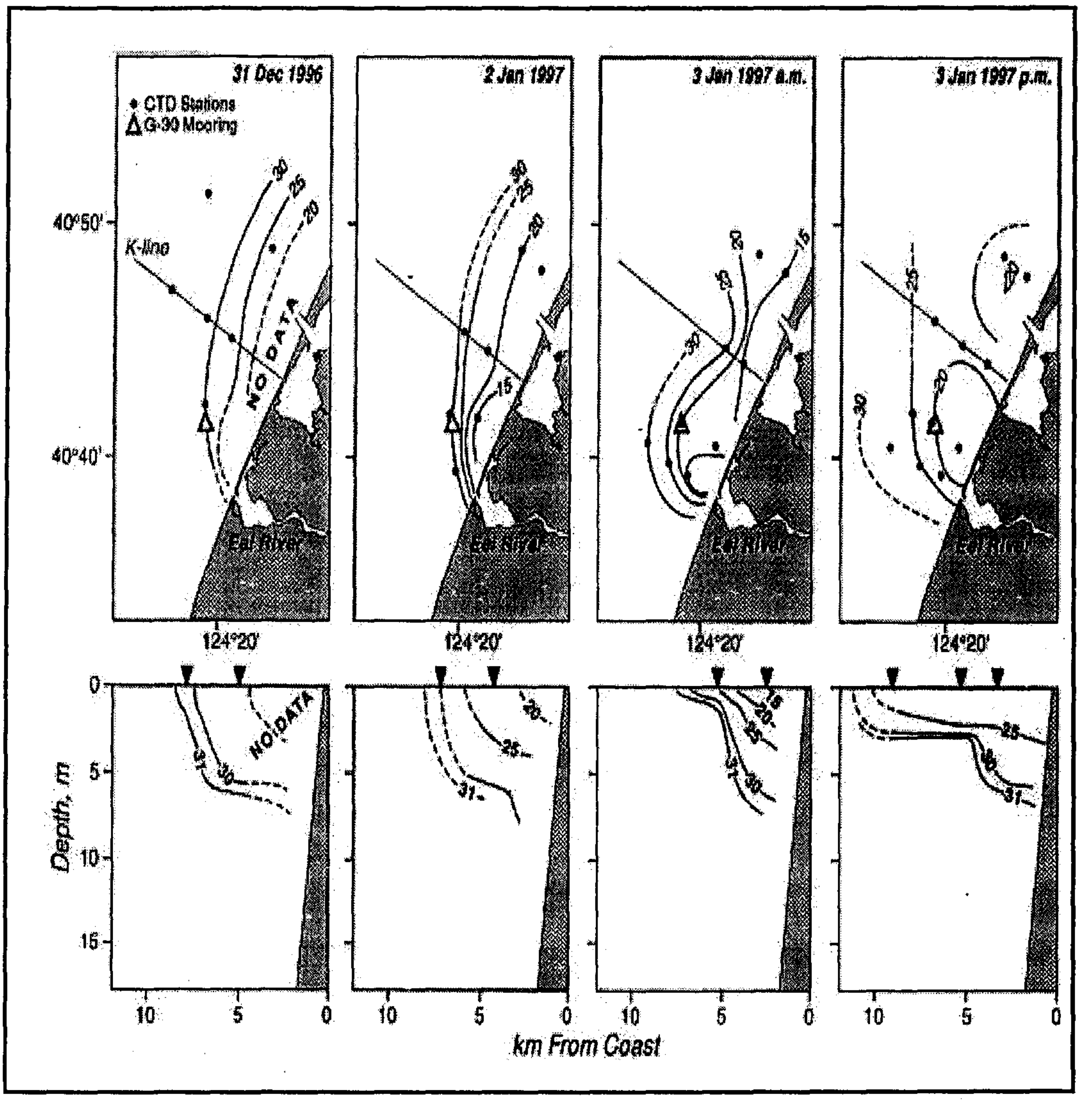

Figure 2.2 Salinity distributions during the January 1997 flood. Upper panels: near-surface (1.5m) salinity distributions; lower panel: cross-sections at river mouth (from Geyer *et al.*, 2000).

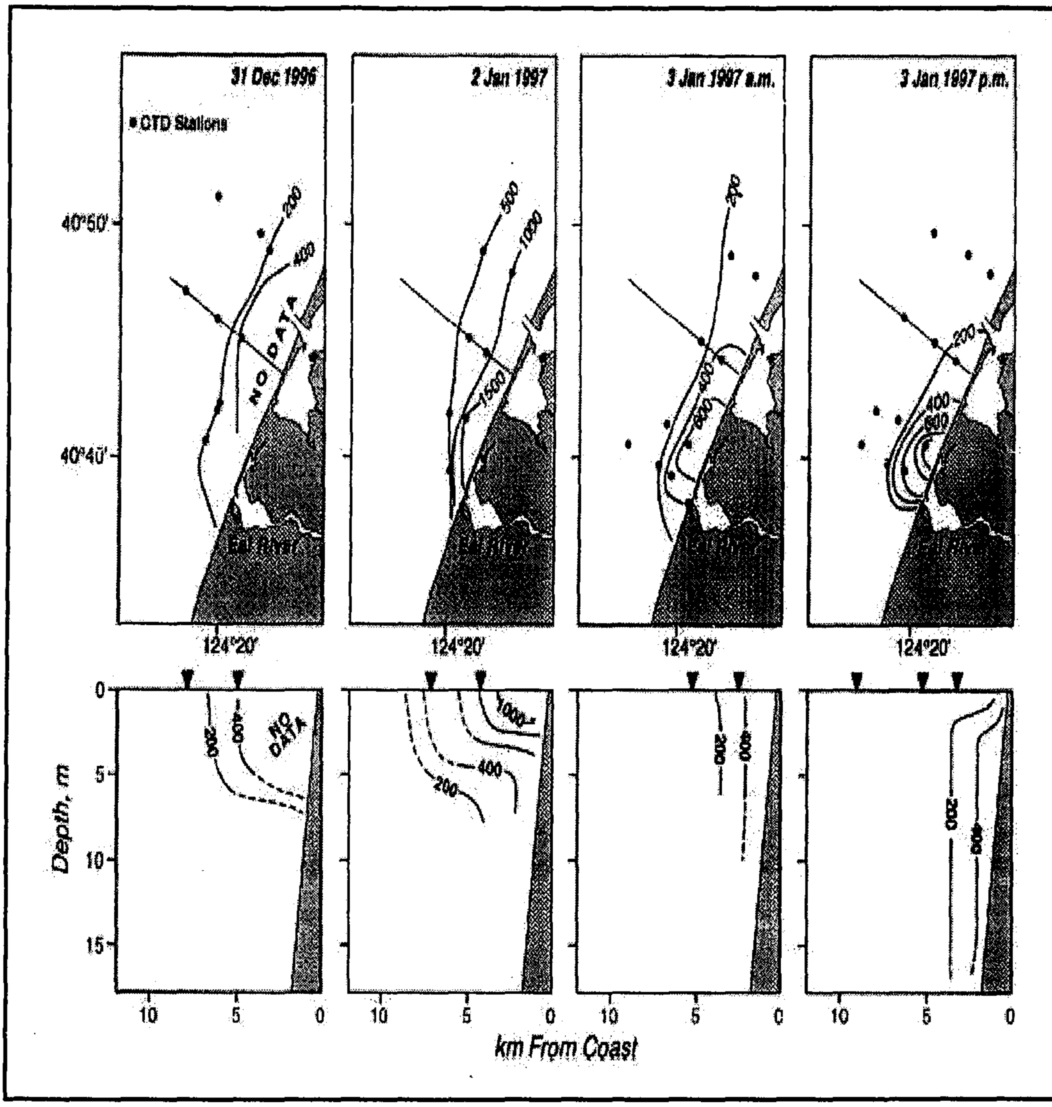

Figure 2.3 Total suspended sediment distributions during the 1997 flood. Upper panels: near-surface (1.5 m) suspended solids, based on water samples; lower panel: cross-sections at river mouth, based on water samples and optical backscatterance sensor (OBS) profiles (from Geyer *et al.*, 2000).

south of Guam. If sediment input can be substantially reduced through improved land-use practices, water and substratum quality should improve and provide the conditions for reef regeneration to occur (Wolanski *et al.*, 2005).

2.1 Sediment transport

Coastal areas and estuaries are an important element in cycle processes, because much of the sediment found on the ocean floor is derived from land and reaches the ocean through rivers and their estuaries. There are a variety of interesting and important dynamical processes that occur within the coastal regions after the modified river water leaves the estuary. A plume typically forms as the buoyant water spreads away from the mouth of the estuary.

In coastal area, sediment transport in estuary plumes is controlled not only by the trajectory of the freshwater plume, but also by rate of settling, the plume thickness and plume velocity (Geyer *et al.*, 2000). The dynamics and structure of plumes of small rivers differ considerably from those of large rivers, due to differences in the physical scales of the processes near the estuary mouth (Garvine, 1995) and relatively short duration from small (e.g., Eel and Waipaoa River), and large sediment input compared to large river (e.g., Columbia, Mississippi, and Amazon River) (Wheatcroft, 2000). The transport processes of sediment from the small river to the coastal ocean occurs in freshwater plume, whose trajectories may strongly depend on discharge magnitude and sediment load, the rate of flocculation of particles within the plume, and the ambient oceanic conditions (currents and density structure) (Morehead and Syvitsky, 1999) and a region's climate and local drainage-basin characteristics (e.g., headwater elevation) (Syvitsky and Morehead, 1999).

On the contrary, transport processes of estuary plume for large rivers cannot be understood by simply scaling up the magnitudes and impacts of dominant processes in smaller rivers. Time and space scales over which these transport and transformation processes occur vary greatly, depending on factors such as scales of discharge, suspended sediment loads, latitude of discharge, and winds and tides, which affect plume behavior, and also affected by meteorology and climatology, bottom topography of the receiving site and orientation of plume (Dagg *et al.*, 2001) and planetary rotation (Simpson and Sharples, 1994; O'Donnell, 1990). For examples, these effects (river discharge and the amount of sediment loads) for the world's largest river are summarized in Table 2.1.

Buoyancy is a key mediating factor in the transports and transformations of estuary plume in the coastal margin. The expansion, contraction, and alongshore orientation of surface plumes are often influenced by tide and wind conditions (Davies and Xing, 2001; Schallenberg and Krebsbach, 2001; Joordens *et al.*, 2001), besides river discharge and wave conditions (Scully *et al.*, 2004; Wright *et al.*, 2002; Aubertot and Echevin, 2002; Durand *et al.*, 2002; Wheatcroft, 2000; Mullenbach and Nittrouer, 2000).

Table 2.1 Discharge data for the world's largest rivers (from Dagg *et al.*, 2001).

River (Country)	Water discharge $10^9\ m^3y^{-1}$	Sediment discharge $10^9\ m^3y^{-1}$	Drainage basin $10^6\ km^2$	POC $10^6\ ty^{-1}$	DOC $10^6\ ty^{-1}$
Amazon (Brazil)	6300	1150	6.15	13.0	19.1
Zaire (Zaire)	1250	43	3.82	2.8	10.15
Orinoco (Venezuela)	1200	150	0.99	2.0	4.5
Ganges-Brahmapura (Bangladesh)	970	1050	1.48	nd	nd
Yangtze (China)	900	480	1.94	4.4	11.8
Yenisey (Russia)	630	5	2.58	0.17	4.86
Mississippi (USA)	530	210	3.27	0.8	3.5
Lena (Russia)	510	11	2.49	0.46	3.38
Mekong (Vietnam)	470	160	0.79	nd	nd
Parana/Uruguay (Brazil)	470	100	2.83	1.3	5.9
St. Lawrence (Canada)	450	3	1.03	0.31	1.55
Irrawaddy (Burma)	430	260	0.43	nd	nd
Ob (Russia)	400	16	2.99	nd	3.69
Amur (Russia)	325	52	1.86	nd	nd
Mackenzie (Canada)	310	100	1.81	1.8	1.3
Xi Jiang (China)	300	80	0.44	nd	nd
Salween (Burma)	300	100	0.28	nd	nd
Columbia (USA)	250	8	0.67	nd	0.5
Indus (Pakistan)	240	50	0.97	nd	0.75
Magdalena (Columbia)	240	220	0.24	nd	nd
Zambezi (Mozambique)	220	20	1.2	nd	nd
Danube (Romania)	210	40	0.81	nd	nd
Yukon (USA)	195	60	0.84	nd	nd
Niger (Africa)	190	40	1.21	0.66	0.53
Purani/Fly (New Guinea)	150	110	0.09	nd	nd

Notes: POC: particulate organic matter; DOC: dissolved organic carbon, nd: no data.

In addition to the surface plume, in some instances the freshwater also produces coastal current locally and the fate of these coastal currents far downstream and over long time scales as they move downstream due to the effects of turbulent mixing, friction and other processes. The offshore penetration of buoyant water depends on three dimensionless parameters: scaled inlet volume transport, scaled breadth and scaled "diffusivity" (Narayanan and Garvine, 2002; James, 2002). A model of radial, time dependent spreading of shallow buoyant layer over a motionless, deep ambient layer is developed by Garvine (1984). Wright *et al.* (2001) develop a simple model that incorporates the influence of ambient shelf current on gravity-driven transport of suspended sediment, shows in Figure 2.4 and Scully *et al.* (2002) applied this model in the Eel River, to examine the formation of the mid shelf flood deposit on the continental margin. The governing equation for total current velocity U_{max} is (Wright *et al.*, 2001):

$$U_{\max} \cong \left(U_w^2 + u_g^2 + v_c^2\right)^{1/2} \qquad 2.3$$

where U_w is rms wave orbital velocity, u_g is average velocity in x direction, and v_c is the magnitude of along shelf current. Richardson number is given:

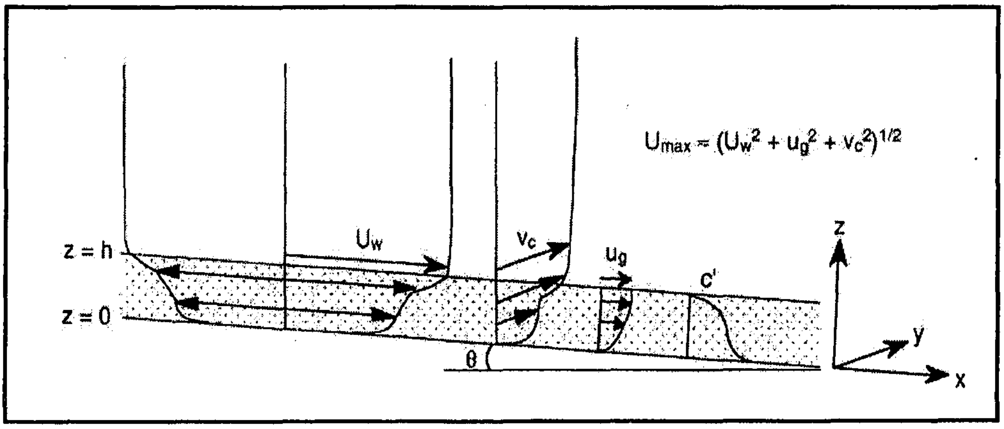

Figure 2.4 Schematic diagram illustrating estuary plume push by gravity driven flow (from Wright *et al.*, 2001).

$$R_i \cong gs\frac{\left(\partial c'/\partial z\right)}{\left(\partial u/\partial z\right)^2} \cong \frac{\left(B/h^2\right)}{\left(U_{\max}/h\right)^2} \cong \frac{B}{U_{\max}^2} \qquad 2.4$$

where *g* is acceleration of gravity, *s* is the submerged weight of siliceous sediment relative to sea water, *c'* is sediment volume concentration, and *B* is buoyancy anomaly integrated over the thickness of turbid layer.

For case of stratified gravity flows in which $U_{max}=U_g$, and combined with the classical Chezy equation $B\sin\theta = C_D u_g^2$ to yield:

$$R_i \cong \frac{C_D}{\sin\theta} \qquad 2.5$$

C_D is a non-dimensional bottom drag coefficient, and the maximum sustainable flux associated with the gravity driven flow is:

$$Q_{cr} \cong \frac{u_{cr}\rho_s B_{cr}}{gs} \cong \frac{\rho_s(\sin\theta)Ri_{cr}^2 U_{\max}^3}{gsC_D} \qquad 2.6$$

where $\rho_s \approx 2.65$ is the density of siliceous sediment.

Many investigators have described the importance of physical characteristics of estuary plumes and sediment transport phenomena from different perspectives, on the basis of mathematical models (Poulos and Collins, 1994; Khondaker, 2000), numerical model (Syvitski and Bahr, 2001; Wu and Falconer, 2000; Scully *et al.*, 2002; Davies and Xing, 2001), remote sensing (Bowers *et al.*, 1998), laboratory experiments (Gustafsson *et al.*, 2000; Savory and Toy, 2000; Thill *et al.*, 2001; Davies and Ahmed, 1996), field observations (Hill *et al.*, 2000; Liu *et al.*, 2000; Wright *et al.*, 2001; Emeis *et al.*, 2002; Christiansen *et al.*, 2002).

Besides that, the settling behavior of sediment transport of a river flow, has been studied elsewhere, for examples in the southern Brazilian shelf (Soares and Moller Jr, 2001), the Kara Sea Rivers in Arctic Ocean (Harms *et al.*, 2000), the Tseng-wen River in southern Taiwan (Liu *et al.*, 2002; Liu *et al.*, 2002a), the Eel River in northern California continental shelf (Ogston *et al.*, 2000; Wright *et al.*, 2002; Geyer *et al.*, 2000; Syvitski and Morehead, 1999), and the Satilla River Estuary, Georgia (Zheng *et al.*, 2003).

In estuaries, the movement of a salt wedge into the estuary not only retards the movements of bed load, it also has an effect on the suspended sediment transport. Beside, freshwater runoff from river into the estuary is an important element of the dynamics over many estuaries. There are a variety of interesting and important dynamical processes that occur within the estuary. Since estuary outflows tend to be less saline and hence lighter that the ambient shelf water, a plume typically forms as the buoyant water spreads away from the mouth of the estuary.

The vertical and horizontal structure of buoyant plumes also varies. Most previous studies have focused on the plumes distribution that influence by the direction and strength of wind and discharge volume of the river. Some plumes, such as the Pomeranian Bight River plume (Mohrholz *et al.*, 1999) was mainly control by the local wind forcing as well as the baroclinic pressure gradients. This condition is contrast with the situation in the ocean water estuary plumes that are mainly controlled by tidal currents and the Coriolis force. However, under relatively different condition, in dry seasons during the winter, Wong *et al.* (2004) modeled the small scale circulation associated with the plume front in the Pearl River Estuary. Generally, the plume front is formed by salinity gradient between the estuarine water and the higher salinity shelf waters.

The relative importance of stratification-destratification processes in the Mobile Bay is described by Schroeder *et al.* (1990) and in the Merbok Estuary is described by Uncles *et al.* (1990). However, Garvine (1995) has provide a simple classification system for buoyant discharge based on the Kelvin number (*K*), the ratio of the buoyant plume width to the baroclinic Rossby radius. Then, Wiseman and Garvine (1995) stressed the importance of the Kelvin number in characterizing anticipated plume behavior. They showed that without strong external forcing, a northern hemisphere plume will turn anticyclonically and attach to the coast, where it then merges into a coastal current.

2.2 Factors affecting estuary plume

A variety of different factors can influence estuary plume in the coastal, including tides, winds, variations in the river discharge, and ambient shelf circulation (Hill *et al.*, 2000; Geyer *et al.*, 2000; Tillis, 2000; Gelfenbaum and Stumpf, 1993).

2.2.1 River discharges

The discharge of freshwater from river onto coastal region typically results in the formation of a buoyant plume. Fennel and Mutzke (1997) stated that estuary plumes forced by two mechanisms: (i) momentum added to ocean at the estuary mouth and (ii) intrusion of buoyancy at the estuary mouth. It is occurs in river or estuary or out on the continental shelf depends to a large part on the strength of the river discharge (Gelfenbaum and Stumpf, 1993; Bowden and El Din, 1966). Table 2.1 shows several the word's largest river that have large enough discharge to produce a buoyant plume each year. While small scale estuary plume such as the Koombana Bay plume, Western Australia (Luketina and Imberger, 1987) the plume in the Tees River, northeast coast of England (Lewis, 1984), the Eel River plume, northern California

(Mullenbach and Nittrouer, 2000; Wheatcroft, 2000; Curran *et al.*, 2002; Ogston and Sternberg, 1999), the Satilla River plume, Georgia (Blanton *et al.*, 2001), the Ebro River plume, Spain (Durand *et al.*, 2002), and the plume some rivers along the Greek shoreline (Poulos and Collins, 1994) had lengths of a few to a few tens of kilometers and remained well defined for short time periods (several hours).

At large scales, the estuary plume show a common feature regardless of the size of the plume or the amount of the freshwater introduced on the shelf (Gelfenbaum and Stumpf, 1993). Estuary plume regions, the area in which influenced of freshwater and the dynamical effect of coastal discharge occur. Garvine (1999) and then Narayan and Garvine (2002) developed a three dimensional nonlinear model to define the fate of plumes that produced by freshwater discharge from rivers and estuaries. Beside, Ye and Garvine (1998) developed for barotropic tidal flows, then the anticyclonic circulation can deflected the estuary plume from its expected turning direction as it leaves the estuary mouth (James, 1997). This is shown in Figure 2.5, which is a coastal current flowing out of the river and a front cross the river between the stratified zone and offshore water.

2.2.2 Tides

It is significant that the tides affected by bathymetry of the oceans, seas, bays, and river estuaries as the tidal forces are transmitted and modified by fluid dynamic forces. Several field studies were conducted to examine the spreading of surface plume formed by buoyant water flowing from river into ocean. Marmorino *et al.* (2000) reported strong pulses of estuary plume from large estuaries, such as Chesapeake Bay, and tends to bulge outward over the continental shelf. The tidal modulation near the estuary mouth typically produces along the seaward edge of the discharge a strong salinity front, which delineates the buoyant outflow from well-mixed, denser

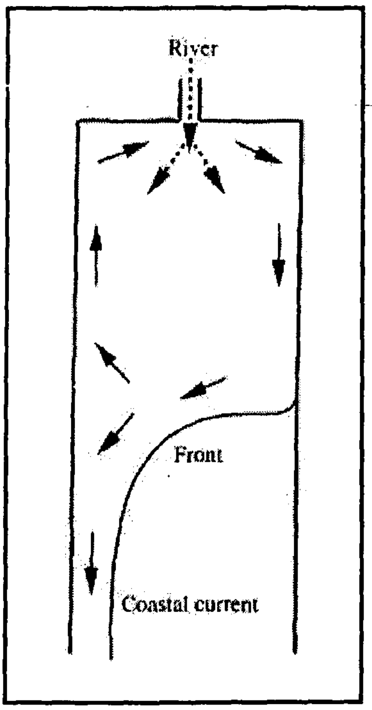

Figure 2.5 Conceptual diagram of river flow, according to the strength of outflow, the plume may turn to left or right (from James, 1997).

shelf water and which moves outward with the ebbing tidal current. Another example, the largest delta environment on the Pacific coast of South America, the San Juan River delta is dominated by tide. The interacting processes that influence the hydrodynamics of the distributary channels in the delta are either fluvial and tidal processes (Restrepo and Kjefve, 2002; Blanton *et al.*, 2002; Zheng *et al.*, 2004).

In addition, Liu *et al.* (2002) stated that the basic influence of plume behavior is coastal tide. Since the river runoff and sediment discharges are constant, the basic plume dispersal pattern is determined by the interaction of the sediment-laden buoyant effluent and the flow field (tidal currents). In the Chesapeake Bay estuary, the tidal variability of the flows was dominated by semidiurnal constituents that displayed greatest amplitudes and phase lags near surface and in the channel (Levinson *et al.*, 1998). Schallenberg and Krebsbach (2001) describe the horizontal tidal movements and salinity gradients in the Taieri Estuary during a flood tide period. They shown the tidal movement covered 8.3 km downstream, which corresponded to a mean tidal velocity of 1.18 kmh^{-1}. De Ruijter *et al.* (1997) investigated and illustrated the phenomena of a pulsed estuary plume within the Rhine discharge along the Netherlands coast effect as the tide advects river water along the coast, and the spreading of the plume approximately 5 km offshore.

A much larger scale plume is found in the Gulf of Mexico at the mouth of the Mississippi River (Dagg *et al.*, 2001) and at the Connecticut River (Garvine, 1986), which is deflect the plume eastward with the ebbing tidal currents and westward with the flood tidal current. Figure 2.6 show contrast structure of surface density a long centerline of plume during flood and ebb phase in the Mississippi River, in which the reduction of on plume density results from the reduced salinity of discharge.

2.2.3 Winds and waves

The ocean surface usually is a complex of many different kinds of waves, that generated by wind. The faster the wind, the longer the wave blows, and the bigger the area over which the wind blows, the bigger the waves. The association of hydrographic structure of the outflow plumes at the estuary mouth has been studied in several studies. Geyer *et al.* (2000) have shown that a significant Eel Estuary plume forms during early stages of floods, and generally moves northward along the coast under influence of strong southerly winds that commonly occur at the leading edge of storm systems. At the same sites, Hill *et al.* (2000) described the effective settling velocities as important mechanism for speeding the removal of sediment from the estuary mouth. Ogston *et al.* (2000) proposed an additional transport mechanism of estuary plume seaward, that observed at wind and wave condition over the winter flood period, with maximum wind speeds and wave heights were approximately 23 m/s and 11.5 m.

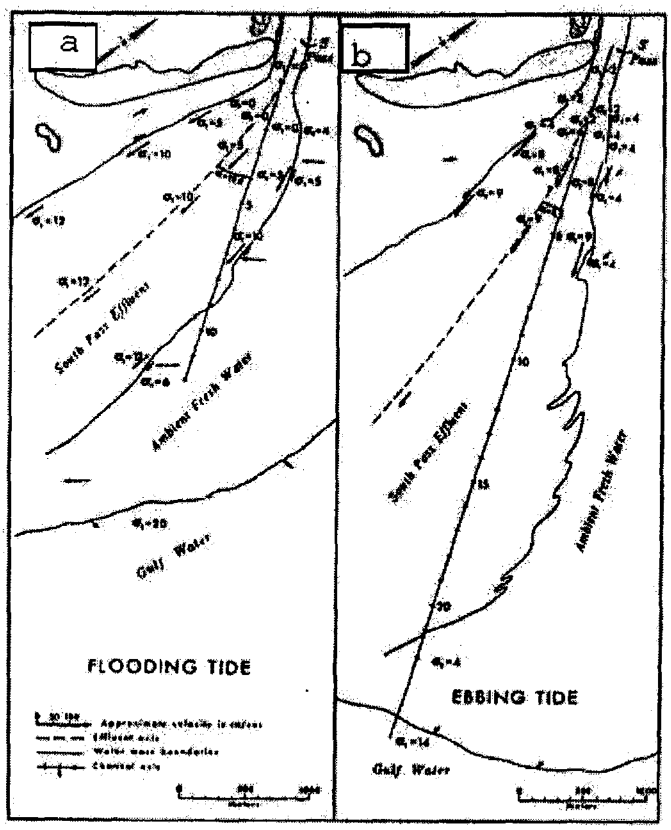

Figure 2.6 A schematic diagram of the structure of surface density in the Gulf of Mexico at the mouth of the Mississippi River during (a) the flood tide and (b) ebb tide (from Dagg *et al.*, 2001).

Beside, Kourafalou (2001) addressed circulation due to buoyancy and wind stress in development and evolution of estuary plumes. Again, Soares and Moller Jr. (2001) described the structure of the La Plata River plume, although located many kilometers south of the Southern Brazilian Shelf (SBS), has its plume advected toward the SBS by coastal currents where it interacts with Patos Lagoon runoff.

The importance of wind and wave to affecting the estuary plume were studied theoretically by Thain *et al.* (2001) using a numerical model to solve the free surface flow induced by linear water waves propagating with collinear vertically sheared turbulent current, to estimate the wave amplitude decay rate in combined wave current flows. The other model described by Savory and Toy (2000) for determination of variation of total circulation within plume with distance from the source that influenced by a crosswind. Ruddick *et al.* (1995) found in their simulations the stratification and alongshore salinity structure in Rhine-Meuse plume, with wind speed of 8.5 m/s the stratification is reduced by wind-mixing and the plume is confined to coastal band 10 km wide. Then, Chiavassa *et al.* (1995) used the same method in the same region and compared with SPOT data, and found the accurate and same results.

Furthermore, Haren (2001) estimated the wave height and wind stress magnitude and direction in central North Sea, using acoustic Doppler current profiler (ADCP). Liu *et al.* (2002) recently addressed a study of biogeochemical response to climate change in the South China Sea and the western Philippines, where the surface circulation changes drastically with season in response to the alternating monsoons. They found a sharp contrast between both regions, and show strong seasonal changes of phytoplankton distribution in this region. At the other site, the Tseng-wen River, southern Taiwan, Liu *et al.* (1999) examined the three mechanisms that control nears bed suspended sediment concentration near the estuary mouth, those are: horizontal advection, downward settling, and the resuspension, and stated the important factors of tidal phase and wind field in controlling the expansion and contraction of the estuary plume.

De Ruijter *et al.* (1997) stated that low frequency variations of stratification and circulation in Rhine ROFI (Region of Freshwater Influence) are driven primarily by the buoyant river input and varying wind stress at the surface, and Estournel *et al.*, (2001) determined the sensitivity for turbulence kinetic energy. They illustrated the spreading of the plume as it turns towards the north with highest stratification condition lying 3 to 5 km offshore and lower stratification conditions shoreward are due to tidal, wind and waves mixing show in Figure 2.7.