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COASTAL SEDIMENTARY TRAPS AS POTENTIAL BORROW SOURCES
FOR NOURISHMENT OF NEIGHBOURING EROSIONAL BEACHES

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1 INTRODUCTION ........................................................................................................1
2 NEARSHORE SAND DEPOSITS ................................................................................4
  2.1 Introduction ...........................................................................................................4
  2.2 Sedimentary processes at tidal inlets .................................................................4
  2.2.1 Ebb-tidal deltas ...............................................................................................12
  2.2.2 Ebb-tidal delta evolution at jettied inlets .......................................................17
  2.2.3 Sediment bypassing at tidal inlets .................................................................20
  2.3 Small river deltas .................................................................................................23
  2.4 Management strategies .......................................................................................25
3 STUDY AREA .............................................................................................................30
  3.1 Introduction ..........................................................................................................30
  3.2 Northern Adriatic inlets .......................................................................................32
    3.2.1 A-P relationship for northern Adriatic inlets ..............................................35
  3.3 Hydrological regime of rivers in the Veneto plain ..............................................37
4 MATERIAL AND METHODS ........................................................................................45
  4.1 Introduction ..........................................................................................................45
  4.2 Data collection and analysis .................................................................................45
    4.2.1 Bathymetric surveys and sediment sampling ............................................48
    4.2.2 Laboratory analysis .......................................................................................50
  4.3 Spatial analysis ......................................................................................................50
    4.3.1 Digital mapping .............................................................................................50
    4.3.2 Ebb-tidal delta volume calculation ..............................................................51
  4.4 Analysis of small river deltas deposits ...............................................................56
5 RESULTS .....................................................................................................................57
  5.1 Introduction ..........................................................................................................57
  5.2 Ebb-tidal deltas ......................................................................................................57
    5.2.1 Lido ebb-tidal delta .......................................................................................57
      5.2.1.1 Ebb-tidal delta volume calculation .......................................................57
      5.2.1.2 Sedimentology ......................................................................................63
      5.2.1.3 Management options ...........................................................................69
    5.2.2 Malamocco ebb-tidal delta .........................................................................72
    5.2.3 Chioggia ebb-tidal delta ..............................................................................74
    5.2.4 Caleri ebb-tidal delta ....................................................................................77
      5.2.4.1 Ebb-tidal delta volume calculation .......................................................77
      5.2.4.2 Sedimentology ......................................................................................79
      5.2.4.3 Management options ...........................................................................84
    5.2.5 Porto Buso ebb-tidal delta ..........................................................................85
  5.3 Tidal prism – ebb-tidal delta volume relationship .............................................88
5.4 River delta deposits.................................................................................................................. 91
5.4.1 Piave river mouth ................................................................................................................. 91
5.4.2 Adige river mouth .................................................................................................................. 97
5.4.3 Sile river mouth .................................................................................................................... 103
5.5 Sand resources geodatabase .................................................................................................. 106
5.5.1 Personal geodatabases .......................................................................................................... 106
5.5.2 Ebb-delta geodatabase .......................................................................................................... 107
6 CONCLUSIONS ......................................................................................................................... 110
REFERENCES .............................................................................................................................. 113

Index of Figures

Figure 2.1 – Morphological features at tidal inlets (after: USACE, 2002) ......................................... 5
Figure 2.2 – Relationship between mean tidal range and wave height (after: Davis and Hayes, 1984, modified) ............................................................... 6
Figure 2.3 – Tidal inlets morphologies (after: Hubbard et al., 1979, modified) ................................. 7
Figure 2.4 – Offset typologies at tidal inlets ................................................................................ 8
Figure 2.5 – Tidal inlet stability curve (after: Escoffier, 1940, modified) ........................................ 10
Figure 2.6 – Time-velocity asymmetry at tidal inlets (after: Hayes and Kana, 1976) .................... 13
Figure 2.7 – Sketch maps of an idealized inlet showing: A. near and far fields of ebb-jet flow; B. convergent flood flow field; and C. composite ebb/flood flow field (after: Oertel, 1988, modified) .................................................................................................................. 14
Figure 2.8 – General ebb-tidal delta morphology (after: Hayes, 1980). .......................................... 15
Figure 2.9 – Different ebb-tidal typologies (after: Oertel, 1975) .................................................... 16
Figure 2.10 – Conceptual model of a stabilized ebb-dominated tidal inlet (after: Pope, 1991, modified). A: collapse of ebb-tidal delta lobe. B: erosion of ebb-tidal delta platform. ............. 18
Figure 2.11 – Ebb-tidal delta development at untrained (A) and trained (B) inlets (after: Marino and Mehta, 1988) .................................................................................................................. 19
Figure 2.12 – Definition sketch for inlet morphology and associated features, with simplified sediment pathways (after: Kraus, 2002) .............................................................. 22
Figure 2.13 – Concept sketch for reservoir inlet morphology model (after: Kraus, 2002) .......... 22
Figure 2.14 – Section view of a delta slope (after: Reading, 1996) ............................................... 24
Figure 2.15 – Coastal sand bars at river mouths (after: Reading, 1996) ........................................... 25
Figure 2.16 – Isolines of the overfill factor $R_A$ (from CUR, 1987) ............................................. 29
Figure 3.1 – Study area and aerial photographs of investigated sites .......................................... 31
Figure 3.2 – Ebb-tidal delta evolution during jetties construction at Lido inlet, 1882-1898 (after: Lippe, 1984, modified) .......................................................... 33
Figure 3.3 – Beach accretion at Punta Sabbioni beach after jetties .............................................. 34
Figure 3.4 – Experimental A-P relationship for northern Adriatic inlets ........................................ 36
Figure 4.1 – Residual Method (after: Dean and Walton, 1973) .......................................................... 51
Figure 4.2 – Stages of development of the Semi-Automatic De-trending Procedure: Chioggia inlet example .......................................................... 53
Figure 4.3 – Ebb-tidal delta volume calculation at Lido inlet. (A) First order polynomial trends surface and associated residual map; (B) second order polynomial trend surface and associated residual map; (C) third order polynomial trend surface and associated residual map. All negative values are below -0.25m; negative anomalies inside the main ebb-channel are not shown. ..................................................................................................................................55

Figure 5.1 – Lido ebb-tidal delta, 1987 ..........................................................................................58
Figure 5.2 – Lido bathymetric map, 2006 ...................................................................................59
Figure 5.3 – Lido ebb-tidal delta, 2006 ..........................................................................................60
Figure 5.4 – Isopach map of the Lido ebb-tidal delta (after Donda at al., 2008).........................62
Figure 5.5 – Lido sand-percentage distribution ...........................................................................64
Figure 5.6 – Lido mean grain size distribution ..........................................................................66
Figure 5.7 – Lido sorting distribution ...........................................................................................66
Figure 5.8 – Cluster analysis – dendrogram ...............................................................................67
Figure 5.9 – Lido cluster distribution ...........................................................................................68
Figure 5.10 – Lido potential borrow area .................................................................................70
Figure 5.11 – Lido bathymetry after hypothetical dredging ...........................................................70
Figure 5.12 – Malamocco inlet bathymetric map, 1987 ................................................................72
Figure 5.13 – Malamocco inlet ebb-tidal delta, 1987 ..................................................................73
Figure 5.14 – Chioggia bathymetric map, 1987 ..........................................................................75
Figure 5.15 – Chioggia ebb-tidal delta .......................................................................................76
Figure 5.16 – Caleri bathymetric map ..........................................................................................77
Figure 5.17- Caleri ebb-tidal delta ...............................................................................................78
Figure 5.18 – Caleri sand-percentage distribution ......................................................................79
Figure 5.19 – Caleri mean grain size distribution ......................................................................81
Figure 5.20 – Caleri sorting distribution .....................................................................................81
Figure 5.21 – Cluster analysis - dendrogram .............................................................................82
Figure 5.22 – Caleri cluster distribution ......................................................................................83
Figure 5.23 – Buso inlet bathymetric map ....................................................................................86
Figure 5.24 – Buso ebb-tidal delta ...............................................................................................87
Figure 5.25 – Tidal prism – ebb tidal delta volume relationship for northern Adriatic inlets
(after: Fontolan at al., 2007, modified) .........................................................................................88
Figure 5.26 – Piave river delta bathymetric map, november 1972 ................................................92
Figure 5.27 – Piave river delta bathymetric map, may 1973 .........................................................92
Figure 5.28 – Piave river mouth, differences nov72-may73 ..........................................................93
Figure 5.29 – Piave river delta bathymetric map, april 2002 ........................................................94
Figure 5.30 – Piave river delta bathymetric map, may 2005 ........................................................94
Figure 5.31 – Piave river mouth, difference 2002-1972 ...............................................................95
Figure 5.32 – Piave river mouth, difference 2005-1973 ...............................................................95
Figure 5.33 – Piave river mouth, difference 2005-2002 ...............................................................96
Figure 5.34 – Adige river mouth bathymetric map, november 1973 ............................................98
Figure 5.35 – Adige river mouth bathymetric map, may 1975 .....................................................98
Figure 5.36 – Adige river mouth bathymetric map, june 2001 ....................................................99
Figure 5.37 – Adige river mouth bathymetric map, december 2003 ..........................................100
Figure 5.38 – Adige river mouth bathymetric map, may 2005 ....................................................100
Figure 5.39 – Adige river mouth bathymetric map, may 2006 ....................................................101
Figure 5.40 – Adige river mouth, difference 2005-1975 ............................................................102
1 INTRODUCTION

Beach erosion has strongly affected a large number of beaches along the northern Adriatic coastal area over the past 20 years. Among the different engineering solutions available to contrast coastal erosion, the soft-engineering practice of beach nourishment is widely recognized as a good compromise between desired outcomes and negative environmental impacts.

One of the major issues concerning beach nourishment activities is the necessity to find suitable sources of sand, with the purpose of both reducing costs and minimizing environmental impacts. As stated by Finkl (1994), strategies for sand management are becoming increasingly more important as a coastal management tool. Also, the same author suggests that new sand management strategies, based on sound geological principles, must reflect sensitivity to environmental concerns. Rising sea levels, increased shore erosion, decreasing supplies of suitable fill materials (both on-and off-shore) and increasing concerns over environmental impacts associated with coastal protection measures (Finkl, 1994) are some of the reasons for a significant interest in these coastal problems.

Along the Venice lagoon barrier island system and adjacent beaches (i.e. Jesolo, Sottomarina, Pellestrina, Isola Verde), $8 \times 10^6$ m$^3$ of sand have been placed after nourishment projects carried out in the 1990s. Nowadays the Venice Water Authority (Magistrato alle Acque through its concessionary Consorzio Venezia Nuova, 2006) plans the placement of a total volume of $3 \times 10^6$ m$^3$ of sand for beach maintenance, suggesting that critical beach erosion can be mitigated by smaller but more frequent nourishments. Previous nourishment projects were carried out through the utilization of sand borrow areas located offshore, at a distance of approximately 20km from the coast, a solution that present high operational costs.

An alternative solution may be represented by the use of nearshore sand deposits, located in the proximity of tidal inlets or within the delta front area outside river mouths. Since inlets are the only access pathways between a lagoon and the sea, one of the major problems in terms of navigability is their intrinsic incapacity to maintain a predetermined configuration. Due to the longshore drift, the channel can shift and cause continuous filling of abandoned routes. Moreover, during storms landward pushes can increase the natural rise of the terminal lobe of the ebb-tidal delta, enhancing the phenomenon of shoaling at the channel entrance. During
the last decades, the practice of “ebb shoal mining” (Cialone and Stauble, 1998) has been progressively increasing, with the rising demand for suitable beach fill material along barrier islands. Ebb-tidal delta mining gives a new outlook on beach re-equilibrium projects since a large amount of sand, well compatible to native adjacent beaches, is stored by the ebb-tidal delta and easily mined at low cost. Dredging of an inlet opening and channel may also represent a good compromise between navigational needs and the rational use of dredged material.

Several potential borrow areas were analysed in the present study, focussing on the evaluation of sand features deposited outside tidal inlets and river mouths, as a consequence of existing local hydrodynamic conditions. The coastal area object of the investigation is the northern Adriatic coastal area between the Isonzo and Po rivers, consisting of lagoon-river delta systems fronted by barrier islands and sandbars fed by tidal inlets. New data were collected through bathymetric surveys and sediment sampling and integrated with data from older surveys, thus obtaining a rather complete and uniform catalogue of sand resources. The development of a specific geostatistical procedure was also a main objective of the research, aimed at obtaining reliable results concerning ebb-tidal delta volumes. Considerable changes on the northern Adriatic barrier island systems and associated inlets have occurred over the last century as a result of intense human activity, including construction of permanent structures on both the barriers and the inlets. Those structures are mainly seawalls and groins designed to fix the shoreline and jetties to keep inlets from migrating and to maintain a given channel depth. Both natural and stabilized inlets were investigated, leading to a specific analysis concerning the morphodynamics of stabilized inlets.

Summarizing, the present research has been developed through several phases. A detailed analysis of the overall morphology of different nearshore features such as natural and stabilized inlets and small river deltas has been conducted, mainly using ESRI ArcGIS™ software, followed by the elaboration of predictive numerical relationships concerning inlet parameters (i.e. tidal prism, cross-sectional area and ebb-tidal delta volume). The results obtained were then discussed and compared with analogue relationships elaborated for other environmental settings (i.e. the U.S.A and New Zealand coasts), highlighting the influence of local morphodynamic factors in determining ebb-tidal delta growth along the northern Adriatic coastal area.
Methodological analyses concerned a large number of geostatistical tests through ESRI ArcGIS™ Geostatistical Analyst extension, that allowed to obtain a specific procedure for calculating ebb-tidal delta volumes. Finally, with the aim to provide a useful and agile tool for sand resources management, all results were integrated into a GIS geodatabase, named Ebb-delta Geodatabase, which includes the individuated potential sand borrow areas with associated grain size characteristics.
2. NEARSHORE SAND DEPOSITS

2.1 Introduction

In the present study, a detailed investigation has been carried out on different nearshore morphologies, in order to evaluate sand storage potential of shallow areas located in the proximity of the coast. The interaction of waves and tides along barrier islands coastlines causes the deposition of typical morphologies outside the inlet throat at tidal inlets, known as ebb-tidal-deltas, while at river mouths sediments are deposited mainly by fluvial discharge, forming river deltas. The genesis and morphodynamic evolution of these typologies of nearshore morphologies is different and it will be examined in detail in the following paragraphs.

2.2 Sedimentary processes at tidal inlets

Tidal inlets are natural openings along barrier coastlines where sea water penetrates land and their main function is to provide a connection between the ocean and bays, lagoons, marshes or tidal creek systems. The flow pattern at tidal inlets may be very complex due to the interaction of the tidal-generated current and currents approaching the inlet due to waves breaking on shallow areas, wind stress currents, and currents approaching the inlet due to wave breaking on adjacent beaches (USACE, 2002).

Inlet hydraulic efficiency is naturally maintained by tidal currents (Davis and Fitzgerald, 2004) while in general channel morphology varies depending on: (Hayes, 1980):

1) the interaction between tidal prism and wave energy;
2) tidal prism\(^1\) amplitude;
3) backbarrier area and morphology;
4) time-velocity asymmetry\(^2\) of tidal currents (Postma, 1967; Hayes, 1969).

All these factors contribute to specific inlet configurations, thus generating different sedimentary patterns. Tidal inlets, particularly when not fixed by jetties, have very high sand

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\(^1\) Tidal prism: the volume of water that enters through the inlet channel during flood flow and then exits during ebb flow (USACE, 2002).

\(^2\) Time asymmetry means that the maximum flow velocities do not occur at midtide but at some other stage of the tidal cycle, while velocity asymmetry of tidal currents means that the maximum flow velocity or duration above a given velocity is greater for either the flood or the ebb state.
trapping capabilities as a consequence of the strong interference generated by tidal currents on the littoral drift. The main morphological features characterizing tidal inlets are the inlet channel and tidal deltas, fan-shaped sand bodies that develop after the reduction in current velocity outside the inlet throat. Two delta typologies were individuated and described (Hayes, 1969), in relation to dominant flux direction:

- **Flood-tidal deltas**: sand bodies located along the landward side of the inlet channel, formed after the predominant action of flood tidal currents;
- **Ebb-tidal deltas**: sand bodies deposited at the seaward end of the inlet, their accretion is mainly imputable to the action of ebb-tidal currents;

![Figure 2.1 – Morphological features at tidal inlets (after: USACE, 2002)](image)

The importance of the interaction between wave and tide energy in determining inlet configuration was first recognized by Hayes et al., (1979). Davies (1964) first illustrated the importance of tidal range in shaping the world coastlines and classified them as either:
2. NEARSHORE SAND DEPOSITS

1) **Microtidal**: tidal range = 0-2m
2) **Mesotidal**: tidal range = 2-4m
3) **Macrotidal**: tidal range > 4m

Hayes et al (1973) and Hayes (1975) described shoreline configurations associated with each type and related the occurrence of various geomorphic features to tidal range. Hubbard (1977) and Nummedal et al. (1977) applied these concepts directly to tidal inlets. They concluded that within the microtidal and mesotidal ranges, a spectrum of inlet configurations exists, primarily as a response to the dominance of either tidal or wave forces.

![Figure 2.2 – Relationship between mean tidal range and wave height (after: Davis and Hayes, 1984, modified)](image)

On the basis of their general morphology and of sedimentary structures distribution in the proximity of the channel, Hubbard et al. (1979) described inlets from North Carolina, South Carolina and Georgia which are exposed to different wave energy regimes and tidal currents. The description can be generalized to different contexts and bring to the following classification:

- **tide-dominated inlets**: their formation is exclusively imputable to the action of tidal currents. They present a well-established and deep main channel, stable and symmetric, (Davis and Gibeaut, 1990), flood oriented, flanked by linear channel margin linear bars and among them the upfdrift one results more developed. While the ebb-tidal delta is generally well-developed, due to sand deposition after ebb current decreasing velocity and the interaction with wave energy, flood-tidal delta is poorly developed or nonexistent.
Sand bodies landward of the inlet throat are confined to tidal point bars in the backbarrier area.

- **wave-dominated inlets**: inlet features are mainly built by wave action. Tidal channels are less developed and shallower in comparison with the tide-dominated type, often presenting bifurcations at the landward or seaward side of the channel. Sediment enters the inlet due to wave action and to a lesser extent to flood tide (which flows through the channels), developing large, lobate flood-tidal deltas into wide, open lagoons. Ebb-tidal delta, due to stronger wave energy compared to ebb-tidal current, is poorly developed and it is located in the proximity of the beach. Inlet channels, often symmetrical and shallow, are not stable and subject to migration or closure processes, if not artificially stabilized. (Davis and Gibeaut, 1990).

- **transitional inlets**: inlets subject to the same extent to the action of wave and tide, they present a wide range of intermediate morphological features (Davis and Gibeaut, 1990) and are more complex to describe. In general, sand bodies are found in the vicinity of the ebb-dominated tidal channel.

Figure 2.3 - Tidal inlets morphologies (after: Hubbard et al., 1979, modified)
At wave-dominated and transitional inlets, although wave energy dictates the amount of sediment supplied to the inlet, it is the relative importance of waves vs. tidal currents that determines where the majority of the sand will ultimately be deposited and the form those deposits will take (Hubbard et al., 1979).

Based on the morphology of the barrier coastlines flanking the inlet channel, Lynch-Blosse and Kumar (1976), recognized different types of inlet configuration:

1) **Straight**: the updrift and downdrift shorelines are aligned and wave induced erosion is counterbalanced by the longshore sediment transport.

2) **Updrift offset**: the updrift shoreline extends more seaward, due to a high rate of sediment accumulation by longshore transport.

3) **Downdrift offset**: in this configuration, the downdrift shoreline extends more seaward. The interaction between tidal currents and longshore currents leads to the formation of a channel margin linear bar on the updrift side of the inlet channel. This feature,
which is a specific portion of the ebb-tidal delta morphology and that will be described more in detail in the following paragraph, protects the downdrift area from wave action. During flood tide a laminar flux of water enters the tidal channel, while during ebb tide, the water flux is more constrained in the ebb-tidal channel leading to the formation of a pressure gradient between the channel axis and the flanks. The hydrostatic gradient is then balanced by a water (and sediment) flux from the downdrift portion towards the tidal channel, and along the downdrift coast there exist a circulation reversal with respect to the dominant circulation along the coast (Nordstrom, 1987).

When longshore currents are strong the sediment transport inside the inlet channel may cause inlet closure or alternatively the channel is forced to migrate in a downdrift direction in order to maintain equilibrium (Johnson, 1919; Oertel, 1975). Due to the importance of inlets for navigability and access to bay areas, hydrodynamic and sedimentary processes occurring at tidal inlets have been intensively investigated since last century.

In general, inlet stability is imputable to the existing balance between sedimentary processes that tend to close the channel and scouring processes that maintain the channel open. Escoffier (1940) presented a theory concerning the stability of an inlet under the influence of erosional-depositional conditions which tend to enlarge or reduce the size of the inlet cross-sectional area. Inlet stability is represented by a curve named “closure curve”, where inlet cross-sectional area is plotted against maximum current velocity. The maximum of the curve corresponds to the critical area $A_c$, the value of cross-sectional area indicating maximum stability of the inlet channel. Values of cross-sectional area lower than $A_c$ indicate instable conditions of the inlet channel, while higher values are indicative of stable condition, as shown in Figure 2.5.
Figure 2.5 – Tidal inlet stability curve (after: Escoffier, 1940, modified)

Several Authors tried to define the value of $A_c$; among them O’Brien (1931, 1969) showed that the size of a tidal inlet is closely related to its tidal discharge and he demonstrated that a strong correlation exists between an inlet’s tidal prism ($P$) and its throat cross-sectional area ($A$):

$$A = cP^n \quad (1)$$

where $c$ and $n$ are empirical constants.

Many other Authors have used this type of analysis to define the equilibrium state of a tidal inlet (Jarrett, 1976; Gao and Collins, 1994; Hughes, 2002; Nishi et al., 2006). Jarrett’s empirical expression (equation 2), which is the most widely used, was derived from data of inlets located in coastal environments that present different energetic conditions, i.e. the United Stated Atlantic, Pacific and Gulf Coast. Moreover, it includes both natural and jettied inlets. As a consequence, the variability in the morphology of the different sites is large leading to a general formula which does not take into account other factors influencing channel equilibrium conditions.
As suggested by many Authors (Bruun and Gerritsen, 1960; Bruun, 1978; Gao and Collins, 1994; Kraus, 1998; 2005), within tidal inlet equilibrium processes, attention should be focused on the dynamic balance between the transport capacity, provided by ebb currents flowing through the inlet, and longshore sand transport that is caused by wave action on the sides of the entrance. According to Kraus (1998), reduced littoral transport leads to a larger equilibrium cross-sectional area for the same tidal prism. As a consequence, in cases of higher littoral drift, the equilibrium cross-sectional area is smaller than under conditions of weak littoral drift because less sediment is removed from the inlet throat during each tidal cycle. This could be explained by taking into account the flow efficiency of the inlet throat in moving sediment through the inlet. In order to increase current speed through the entrance, and to maintain an equilibrium state according to Escoffier’s (1940) closure curve, the inlet is subjected to a reduction in its cross-sectional area.

Kraus (1998) derived a theoretical form for the coefficient \(c\) in the \(A-P\) relationship in which the effect of longshore sediment transport has been included.

\[
C = \left( \frac{\alpha \pi^3 m^2 W_e^{4/3}}{Q g T^3} \right)
\]  

(3)

in which \(\alpha\) = empirical sediment transport coefficient of order unity, \(m^2\) = Mannings coefficient squared (units of sec\(^2\)/m\(^{2/3}\)), \(W_e\) = equilibrium or minimum width of inlet and \(T\) is the main tidal period as diurnal or semidiurnal.

According to the author (Kraus, 2005), values of \(c\) obtained with his formula are in the order of magnitude as those empirically determined. Assuming qualitative validity of the equation, the cross-sectional area depends weakly, but inversely on the gross longshore transport rate, such that for all other factors being equal, the inlet channel cross-sectional area would tend to be larger for areas with smaller transport rates (Kraus, 2005).

Bruun (1978) also noted that dual-jettied inlets tend to have smaller equilibrium cross-sections for two reasons:

a) the jetties “organize” the flow so it is more efficient for removing sediment,
b) the jetties help decrease the amount of littoral material that enters the inlet throat.
The calculation of tidal prism can be done using different methods. Mason and Sorensen (1971) described two methods, the first by basin volume calculation and the second from current meter data:

\[ P = A \cdot h \]  \hspace{1cm} (4)
\[ P = V \cdot S \cdot T \]  \hspace{1cm} (5)

Where:
- \( P \) = spring tidal prism \((m^3)\)
- \( A \) = bay area \((m^3)\)
- \( h \) = tidal amplitude inside the bay \((m)\)
- \( V \) = mean current velocity inside the channel \((m/s)\)
- \( S \) = tidal channel section \((m^2)\)
- \( T \) = tidal wave period \((s)\)

Jarrett (1976) calculated tidal prism through the application of the “cubature method”, which takes into account the time required for a tide to propagate through a bay and segments the bay into subareas rather than assuming a uniform rise and fall of the bay tide. An analysis of the results determined from the application of the different methods, showed that volumetric calculations determined from current meter data varied by 100% compared to calculations based on the other two methods (Oertel, 1988). Therefore, the calculation of the tidal prism needs to be standardized in order to compare statistics of inlet parameters such as cross-sectional area or ebb-tidal delta volume.

2.2.1 Ebb-tidal deltas

In tide-dominated environments sand is largely stored in the jet spreading area, which is named far field (Oertel, 1988), and this sand deposit forms the ebb-tidal delta. This morphology can have a significant impact on the local coastal sedimentary budget, acting as a valve on the coastal sedimentary supply, regulating the sand exchange between estuaries or lagoons and the open coast, and also trapping the longshore sediment transport (Hicks and Hume, 1997). Ebb-tidal deltas are important morphological features also because: (1) they represent huge sand reservoirs, (2) sand shoals associated with ebb-tidal deltas reduce wave
energy on landward beaches, and (3) they affect the bypass process towards downdrift shorelines.

Many studies have been carried out on ebb-tidal deltas in different coastal areas (Mason and Sorensen, 1971; Boothroyd, 1978; Hayes, 1979, 1980; Hubbard et al, 1979; FitzGerald, 1988; Imperato et al, 1988; Marino and Metha, 1987, 1988; Oertel, 1988; Sha, 1990; Stauble, 1993; Smith and FitzGerald, 1994; Davis and FitzGerald, 2004; Elias and van der Spek, 2006).

The genesis and morphology of ebb-tidal deltas are related to the phenomenon described by Postma (1967) as time-velocity asymmetry. Maximum ebb currents are stronger near low tide instead of reaching maximum velocity at half of the tidal cycle. When water begins to flood into the tidal channel with a relatively low velocity, the ebb flow is still flushing. This hydrodynamic condition determines a net flux separation between ebbing and flooding currents and the segregation of flood currents at the flanks of the ebb currents. Thus a wide and deep channel is formed (main ebb channel) while at the sides of the inlet the flooding tide occurs at two smaller channels (marginal flood channels).

Figure 2.6 – Time-velocity asymmetry at tidal inlets (after: Hayes and Kana, 1976)
Following Hayes and Kana (1976), the main morphological features characterizing the ebb-tidal delta morphology are:

- **main ebb channel**: mainly scoured by ebb-tidal currents. When spreading seaward, the ebb-jet in the main ebb channel intercepts longshore currents (Sha, 1989), thus channel depth decreases with increasing distance from the inlet mouth due to sediment deposition,

- **swash platform**: depositional feature located outside the inlet channel where sediments are reworked by wave action (Oertel, 1972),

- **swash bars**: features shaped by wave action (King, 1972), formed by sediments deposited in the terminal section of the swash platform,

- **terminal lobe**: terminal section of the ebb-tidal delta, it exhibits a steep concave profile directly connected to the sea floor,

- **channel margin linear bar**: elongated sand deposit which occurs on one or both sides of the main ebb channel. It develops after the interaction of water fluxes characterized by opposite directions: the tidal flux (either flooding or ebbing) and the longshore current which runs perpendicularly to the channel. Thus a downdrift feature, similar to a levee, originates (Lynch-Blosse and Kumar, 1976),

- **marginal flood channels**: located at the sides of the inlet, characterized by flooding currents.

Figure 2.7 – Sketch maps of an idealized inlet showing: A. near and far fields of ebb-jet flow; B. convergent flood flow field; and C. composite ebb/flood flow field (after: Oertel, 1988, modified)
More specifically, different ebb-tidal delta configurations are determined by the relative influence of wave action with respect to the energy associated with tidal currents and the dominant direction of longshore transport (Oertel, 1975). As shown in Figure 2.9, different ebb-tidal delta morphologies may form either by the prevalence of tidal currents on longshore currents or by the opposite condition, with the general shape being influenced by longshore currents direction.
As recognized by several Authors, ebb-tidal delta morphology and extension is a function of tidal prism and inlet exposure to wave energy (Walton and Adams, 1976; Nummedal et al., 1977; Hayes, 1994). According to Carr and Kraus (2001) the offshore extent and dimension of the ebb-tidal delta is in great part determined by the magnitude of the tidal prism, the slope of the nearshore shelf, and the ebb-jet confinement caused by jetties in case of stabilized inlets. Similarly to the relationship that was found linking cross-sectional area and tidal prism, a direct proportionality has been showed between ebb-tidal delta volume and tidal prism (Walton and Adams, 1976). On the basis of the studies conducted by Dean and Walton (1973), Walton and Adams (1976), Marino and Metha (1987) and Hicks and Hume (1996), the empirical relationships describing the amount of sand stored in the ebb-tidal delta as a function of the tidal prism are the following:

\[ V_{WA} = 6.6 \times 10^{-3} P^{1.23} \]  
\[ V_{MM} = 5.6 \times 10^{-4} P^{1.39} \]  
\[ V_{HH} = 1.88 \times 10^{-4} P^{1.41} \]

WA = Walton and Adams (1976)  
MM = Marino and Mehta (1987)  
HH = Hicks and Hume (1996)
where: $V = \text{ebb-tidal delta volume in m}^3$, $P = \text{spring tidal prism in m}^3$.

These relationship were elaborated based on ebb-tidal deltas exposed to different degrees of wave action. Walton and Adams (1976) proposed three different possible equations, among which equation (6) represent a general expression, relative to mildly, moderately and highly exposed coasts, the latter featuring the lowest delta volumes. In this case, the large scatter in the dataset may reduce or remove any difference, thus great attention must be placed in comparing ebb-tidal delta volumes from areas exposed to significantly different energetic conditions.

According to Hicks and Hume (1996), ebb-tidal delta volume increases with decreasing wave energy, decreasing sand grain size, and increasing sine of the jet angle.

Moreover, ebb-tidal delta volume can be greatly influenced by the “maturity state” of the ebb-tidal delta structure. As it will be described more in detail in the following section, after inlet stabilization through the construction of jetties the ebb-tidal delta morphology tends to shift seaward, and several years may be needed to reach equilibrium conditions. In general, following the formation of a new inlet or the stabilization of a natural inlet, the rate of growth of the ebb-tidal delta is mainly dependent upon the rate of sediment supply from the longshore transport. The larger the littoral drift, the faster the rate at which the ebb-tidal delta will reach a new equilibrium size (Dean and Walton, 1973). That means that the availability of sediment is an important factor influencing variations in the ebb-tidal delta size as well as the volume of material trapped. The same Authors reported that when a new inlet is dredged or a natural inlet trained, sediment trapping usually occurs rapidly initially, followed by a much slower rate of entrapment.

### 2.2.2 Ebb-tidal delta evolution at jettied inlets

To contrast the natural tendency towards migration and closure, a widely applied engineering solution in many coastal areas is to stabilize inlets trough jetty construction. The process is nowadays assuming an increasing importance since a large amount of inlet structures in different countries were stabilized with jetties, mainly to improve navigability. The effects of inlet stabilization, however, may be relevant and may modify the shape and seaward extent of the ebb-tidal delta, and also the nearshore sedimentary budget.
At natural entrances, sand transport processes and the associated effects on adjacent shorelines depend substantially on the magnitude of longshore sediment transport (Dean, 1989). Modified inlet entrances may cause additional impact to the adjacent shorelines and sediment losses to adjacent beaches can be the result of (Dean, 1989):

- Blocking of the net longshore sediment transport by the updrift jetty,
- Jetting of sand farther seaward to the ebb-tidal delta,
- Removal of sand to maintain channel depth with disposal in deep water.

Relatively few studies, among the many addressing tidal inlet and ebb-tidal delta morphodynamics, investigated the evolution of ebb-tidal morphology after jetty construction. Studies conducted on the southeastern coast of the United States (Pope, 1991) illustrated the response of inlet systems to jetty construction. As described by the author, inlet evolution in response to stabilization include initial scouring of the main channel, a fairly rapid collapse of the natural ebb-tidal delta lobe as waves scour the ebb-tidal delta structure and transport the sediment toward the beach. Eventually, the ebb-tidal delta platform may steepen as waves release materials to the downdrift shoreline (Figure 2.10).

Modifications in the distribution of sediments are also due to the greater depth of water in which the deposition takes place. Tomlinson (1991) analysed in detail the development of the ebb-tidal delta at the Tweed River Entrance (tidal river inlet) in Northern New South Wales, Australia following the extension of jetties at the tidal entrance.

---

**Figure 2.10 – Conceptual model of a stabilized ebb-dominated tidal inlet (after: Pope, 1991, modified). A: collapse of ebb-tidal delta lobe. B: erosion of ebb-tidal delta platform.**
As discussed by the author (Tomlinson, 1991) at this location, the ebb-tidal delta morphology and natural sand bypassing mechanism change extensively since the extension of the jetties, which had occurred during the period 1962-1964. A new delta formed further offshore under the influence of the constriction of the ebb discharge by the jetties. The examination of inlet associated morphologies at four sites before and after stabilization (Pope, 1991) showed that the effects of an inlet ebb-tidal delta structure may extend over a broad area and changes to that feature, either natural or man-induced, may take many years to fully evolve. Moreover, there appears to be a direct correlation between inlet size and response time.

FitzGerald and Hayes (1980) have observed that wave refraction around the ebb-tidal delta may cause a longshore transport reversal along the downdrift barrier. At St. Marys Entrance, after the construction of massive rock jetties in 1904, the ebb-tidal delta shifted approximately 3km seaward since 1855/75. Deposition occurred at the northern 3km of Amelia Island, which is located at the downdrift side of the inlet, due to a reversal in sand transport caused by localized wave refraction across the historical ebb-tidal delta (Byrnes and Hiland, 1995).
2. NEARSHORE SAND DEPOSITS

2.2.3 Sediment bypassing at tidal inlets

Inlet sediment bypassing is the process by which sediments moves from the updrift to the downdrift side of the inlet, involving the inlet channel and the ebb-tidal delta (FitzGerald et al., 2000). Processes of sediment bypassing between the ebb-tidal delta and adjacent coastlines develop frequently in natural conditions and are essential in maintaining a balanced sediment budget along a barrier island coastline (Sexton and Hayes, 1982); hence any modification on the shape and volume of the ebb-tidal delta may significantly affect adjacent shorelines. However, not all inlets bypass sand, as bypassing occurs according to the state of maturity of the ebb-tidal delta, wave conditions, magnitude of the tidal prism and other factors (Kraus, 2002).

Mechanisms of natural sediment bypassing were first described by Bruun and Gerritsen (1959); they observed that bypassing can take place mainly by three methods:

1. wave action along the terminal lobe of the ebb-tidal delta,
2. tidal currents being deflected,
3. by the relocation of tidal channels and migration of bar complexes.

Bruun and Gerritsen (1959) expressed the different bypassing processes using a stability criterion:

\[ r = \frac{M_{\text{mean}}}{Q_{\text{max}}} \]  \hspace{1cm} (9)

Where \( r \) represents the ratio between the mean, net longshore sediment transport rate \( (M_{\text{mean}}) \) to the inlet \( (\text{m}^3/\text{year}) \) and the maximum fluid discharge \( (Q_{\text{max}}) \) during spring tidal conditions \( (\text{m}^3/\text{sec}) \), that corresponds to the tidal prism. The Authors concluded that inlet with small ratios \( (r = 10-20) \) will bypass sediment through methods 2 and 3, while large ratios \( (r = 200-300) \) indicate wave driven bypassing around the ebb-tidal delta (method 1).

Dean (1988) described natural bypassing with the ebb tidal delta as a continuous process. Similar to method 1 (Bruun and Gerritsen, 1959), the littoral drift is taken into account, as waves and tidal currents drive the longshore transport around the terminal lobe of the ebb-tidal delta, thus assuring the supply of sediment to downdrift shorelines. Method 2, described by Bruun and Gerritsen (1959), may also be viewed as a continuous mechanism. FitzGerald (1988, 2000) classified discontinuous methods for inlet sediment bypassing along mixed energy shorelines. These processes are fundamentally related to method 3 (Bruun and
Two of these mechanisms, stable inlet processes and ebb-tidal delta breaching, are based upon the migration of large bar complexes formed on the downdrift side of the ebb-tidal delta. Unlike the continuous bypassing mechanism described by Dean (1988) and Bruun and Gerritsen (1959, method 1), both stable inlet processes and ebb-tidal delta breaching, result in the bypassing of discrete packets of sediment.

Bypassing mechanisms occurring at jettied inlet were also individuated (FitzGerald et al., 2000); in most cases the sand accumulates along the updrift beach causing progradation or it is deposited in the channel and has to be dredged. In general, the amount of sand that bypasses jettied inlets depends on various factors such as inlet size and jetty length, channel depth, tidal current strength and ebb-tidal delta morphology. Moreover, the deeper depth at which the ebb-tidal delta is displaced after stabilization reduces the effect of waves and delays the formation of bar complexes.

With regard to the timescale associated with sediment bypassing, examination of South Carolina inlets has shown that this parameter is variable and related to inlet size (Gaudiano and Kana, 2001). Neglecting wave climate, the Authors found a positive relationship between bypassing cycle and tidal prism, whereby larger systems required longer cycles than smaller systems.

Kraus (2002) developed a mathematical model, the Tidal Inlet Reservoir Model (TIRM), to calculate sand bypassing and change in volume of ebb-tidal delta, that is represented by analogy to a series of reservoirs or beakers (Figure 2.13). Bypassing is assumed to occur continuously and the equation governing change of the volume $V_e$ of the ebb-tidal delta is:

$$\frac{dV_e}{dt} = Q_{in} - (Q_{e out})$$

(10)

Where $t = \text{time}$ and $(Q_{e out})$ = rate of sand going out of the ebb-tidal delta.

The input transport rate is assumed known (and be represented by the longshore transport rate), while the remaining unknown is the output transport rate. The “reservoir model assumption” is to assume that the output rate is proportional to the input rate times the volume of sand in the beaker as a proportion to the equilibrium volume (Kraus, 2002).
The rate of sand leaving or bypassing the ebb-tidal delta is expressed as:

\[
(Q_E)_{out} = \frac{V_E}{V_{Ee}} Q_{in}
\]

(11)
In which $Q_{in}$ is taken to be constant. Equations (10) and (11) give:

$$\frac{dV_E}{dt} = Q_{in} \left( 1 - \frac{V_E}{V_{Ee}} \right)$$  \hspace{1cm} (12)

with the initial condition $V_E(0) = 0$ the solution of equation (12) is:

$$V_E = V_{Ee} \left( 1 - e^{-\alpha t} \right)$$  \hspace{1cm} (13)

in which the parameter $\alpha$ gives a characteristic time scale for the ebb-tidal delta.

$$\alpha = \frac{Q_{in}}{V_{Ee}}$$  \hspace{1cm} (14)

This analytical expressions have proved to be very useful in the analysis of the evolution of ebb-tidal delta features, providing quantitative predictions of the time required for the ebb-tidal delta to reach equilibrium volume. Hence, the model can be applied to calculate the recovery time of the ebb-tidal delta after sand mining, which is an essential information for the evaluation of sand management strategies.

### 2.3 Small river deltas

The genesis of sand bodies at the seaward end of river mouths is substantially different from the development of tidal inlet morphologies. In the present study, the development of sand bars associated with small river deltas have been investigated, thus a general overview of deltaic processes is illustrated.

When river sediment is delivered to the coast more rapidly than it can be removed by marine processes, a delta can form. According to Wright (1978), “deltas are defined more broadly as coastal accumulations, both subaqueous and subaerial, of river derived sediments adjacent to, or in close proximity to, the source stream, including the deposits that have been secondarily modeled by waves, currents or tides”.

Fluvial processes govern mechanisms and rate of occurrence of sediment discharge, while oceanographic processes such as wave and tidal regime influence the distribution of sediment outside the river mouth. Sediment grain size, water depth at the depositional site, climate and rate of subsidence of the delta are parameters that also influence deltaic deposition patterns.
Delta models as the one developed by Galloway (1975) attributes primary control on delta morphology to variations in the rate of wave, tide and river influence. Deltaic sediments are both subaerial and submarine deposits, which can range in thickness from a few meters to more than 50 meters (Mississippi River Holocene delta). Wright (1978) subdivided deltas into several basic physiographic zones including the prodelta and delta-front deposits, which are directly connected to the river mouth systems, the distributary network, interdistributary and distributary margin deposits and a delta shoreline.

More precisely:

a) **Delta front:** results from the deposition of the coarsest material at a short distance from the river mouth. A significant fraction of this deposition is from bed load and depositional features include distal bar silts, distributary mouth bar sands, and redistributed marine deposits such as tidal ridges and shoreface deposits.

b) **Prodelta:** component of delta systems unaffected by waves or tides, where fine grained sediment (mud and silt) accumulates from suspension and forms laminated beds.

Mouth bars form at the upper edge of the delta front, at the mouth of distributaries; they are mostly sandy and tend to coarsen upwards. The action of the river-water flow and the sediments discharge builds up a background upon which the effect of other factors, deforming and shaping an already formed bar, is displayed. The balance of the sediment deposit at the bar area is of great importance. If the energy of longshore currents exceeds the volume of sediment discharged by the river, the bar is dismantled. Otherwise, it may grow.

![Figure 2.14 – Section view of a delta slope (after: Reading, 1996)](image-url)
It is evident, therefore, that the rate of river discharge may be viewed as a primary control of sediment deposition at bar areas. The dependence on river discharge and the seasonality of this parameter lead to an episodic nature of depositional events, which are mainly related to major river discharge (i.e. flood events). Wave action can play an important role in winnowing and reworking of mouth-bar deposits; this may lead to merging with prograding beach ridges and if wave action is very important mouth bars are entirely transformed.

### 2.4 Management strategies

Sand management along sandy coastlines affected by erosion requires a detailed knowledge of the morphodynamics of the different features interacting within the coastal system. Hence, data collection and monitoring of tidal inlets, associated features and surrounding beaches is required, as well as reliable tools for predicting morphology changes (Zarillo and Brehin, 2007).

Inlets are the only access pathways between a lagoon and the sea and one of the major problems in terms of navigability is their intrinsic incapacity to maintain a predetermined configuration. Due to the longshore drift, the channel can shift and cause continuous filling of abandoned routes. Moreover, during storms landward pushes can increase the natural rise of
the terminal lobe of the ebb delta, enhancing the phenomenon of shoaling at the channel entrance. During the last decades, the practice of “ebb shoal mining” (Cialone and Stauble, 1998) has been progressively increasing, with the rising demand for suitable beach fill material along barrier islands. Ebb shoal mining gives a new outlook on beach re-equilibrium projects since a large amount of sand, well compatible to native adjacent beaches, is stored by the ebb-tidal delta and easily mined at low cost. Dredging of an inlet opening and channel may also represent a good compromise between navigational needs and the rational use of dredged material.

In general, the use of ebb-tidal delta material is most readily justified in cases where sediments are being removed in conjunction with channel maintenance or deepening and when the sediment is to be placed on the immediate downdrift beach thereby expediting the natural bypassing processes, or where the sand is to be removed from an ebb-tidal delta that extends a substantial distance seaward (Dean, 2002).

Moreover, detailed investigations must address the following issues (Marino and Mehta, 1988):
- the necessity to furnish an estimation of ebb-tidal delta volume, in order to evaluate the potential source of sediment for beach nourishment;
- the need to assess the role of inlets in influencing the rate of erosion of downdrift shorelines, as a result of interruption or deflection of the littoral drift (Bruun et al., 1978);
- the evaluation of inlet sediment accumulation, as an essential tool to account for the long term sedimentary budget of shorelines interrupted by inlets.

As an example from the United States, Dean (1989), reported that in 1986 the Florida State Legislature enacted the so-called “Beaches Bill” of Florida which included important provisions related to sand management at inlets. Specifically, the provision 161.142 “Declaration of public policy respecting improved navigation inlets” states that “all construction and maintenance dredgings of beach-quality sand should be placed on the downdrift beaches […]

At Ocean City Inlet, Maryland, a dual-jetty inlet with a ebb-tidal delta complex experienced seaward radial migration of the outer ridge of the ebb-tidal delta in response to jetty rehabilitation in 2002 (the south jetty was raised and sand tightened). Although in the area, natural sand bypassing occurs by transport from north to south, the ebb-tidal delta contains a
sand bank on its northern extent that is maintained primarily by the ebb jet as it sweeps from south to north. Thus, transport that maintains the sand tongue is in the opposite direction from the natural bypassing, and growth of the sand tongue on its northwestern tip impinges on the navigation channel. This sand feature was identified as a potential beach fill borrow site for mechanical bypassing to Assateague Island, as removal of sand there would not directly interrupt the natural bypassing pathway, and the material is not a source for Ocean City beaches to the north.

Different issues concern the mining of sand deposits located in the proximity of river mouths. In fact, due to the episodic nature of fluvial discharge processes, major impacts could derive from sand extraction at these sites. Therefore, the following necessary conditions must be stated in order to correctly define and evaluate the utilization of sand deposits located outside river mouths:

- the necessity of periodical dredging at the river mouth, where real impediments for navigability occur;
- the evaluation of an existing equilibrium state of the submerged delta morphology, in which no significant erosional processes affect the sea floor.

When these conditions are not verified, sand mining could lead to a destabilization of the sedimentary processes at the river mouth, and also affect sediment supply to adjacent beaches.

Finally, an analysis is required to assess the compatibility of the borrow area material with the native beach material, from a functional perspective (USACE, 2002). In general, to be considered a suitable sand source for beach nourishment, the borrow area must present the following characteristics:

- the thickness of the sand deposit should be at least one or two meters, if to be removed by a cutter-head dredge,
- it must be free of rocks and contains a minimal silt and clay contents (i.e. < 95%) for beaches that are being nourished for recreational purposes,
- the grain size distribution must be similar to that of the native sand, according to existent models (James, 1975).

It is assumed that a theoretical sand source must be very similar to the native sand of the beach targeted for nourishment. This assumption is the basic principle of the classical
formulas reported in literature for beach nourishment practices (CUR, 1987), and these are based on the comparison between mean grain size (Mz) and sorting (φ) of native and borrow sediment (James, 1975). More in detail, James (1975) developed a method to calculate:

- $R_A$: overfill factor
- $R_J$: renourishment factor

Conceptually, the overfill factor is the volume of borrow material required to produce a stable unit of usable fill material with the same grain size characteristics as the native beach sands. The renourishment factor provides an estimate of the frequency of renourishment if the selected borrow source is texturally different from the native beach sand. The overfill factor is computed using the following relationships between the borrow and native beach material:

$$\frac{\sigma_{\phi b}}{\sigma_{\phi n}} \quad (15)$$

and

$$\frac{M_{\phi b} - M_{\phi n}}{\sigma_{\phi n}} \quad (16)$$

Where

$\sigma_{\phi b} =$ standard deviation or measure of sorting for borrow material,

$\sigma_{\phi n} =$ standard deviation or measure of sorting for native material,

$M_{\phi n} =$ mean sediment diameter for native material,

$M_{\phi b} =$ mean sediment diameter for borrow material.

Values obtained using these relationships are then plotted in the graph presented in Figure 2.16. The value of $R_A$ can be obtained by interpolating between the values represented by the isolines. Values of the overfill factor greater than 1.0 indicate that more than one unit of borrow material will be needed to produce one unit of fill material.
Figure 2.16 – Isolines of the overfill factor $R_A$ (from CUR, 1987)

$R_j$ is calculated through the following equation:

$$R_j = e^{\left[ \Delta \left( \frac{M_\phi - M_{\phi n}}{\sigma_{\phi n}} \right) - \frac{\Delta}{2} \left( \frac{\sigma_{\phi b}^2}{\sigma_{\phi b}^2} - 1 \right) \right]}$$  \hspace{1cm} (17)

Where $\Delta$ is a number between 0.5 and 1.5, depending on the selective capacity of the environment. James (1975) recommends $\Delta=1$ for practical use; for this value equation (17) has been plotted providing $R_j$ values indicating stability or instability of the beach-fill. Values of $R_j > 7$ generally indicate unstable projects.
3 STUDY AREA

3.1 Introduction

The northern Adriatic coastal area, between the Isonzo and Po rivers, mainly consists of lagoon-river delta systems fronted by barrier islands and sandbars fed by tidal inlets (Figure 3.1). Sediment supply from the northern Adriatic rivers (Isonzo, Tagliamento, Piave, Adige, Brenta) has been the main responsible for the formation of the barrier island system. The coastline can be divided in two distinct portions: the first, which extends from Adige River mouth to Porto di Piave Vecchia (the former Piave river mouth, from 1682 Sile River mouth), is characterized by several barrier islands fronting the Venice Lagoon, elongated in a SSE-NNW to WSW-ENE direction. This sector has been severely modified in the past by human interventions aimed at protecting the Venice lagoon, and alterations to the natural setting continue nowadays. The northern sector extends from Porto di Piave Vecchia to Isonzo river mouth and it is characterized by beaches elongated mainly in a WSW-ENE direction. In the past the mainland was totally occupied by lagoons and marshes, while during last century land reclamation for agricultural purposes reduced the wetland surface, now present only in the northern area (Baseleghe and Grado-Marano lagoons).

In regards to frequency and intensity, the wind climate in the area is characterized by a prevalence of winds blowing from the I quadrant, mainly from the ENE (the Bora) (Carrera, et al., 1995). South-easterly winds (the Scirocco) that have a longer geographical fetch (over 800km) are also important. Tides are semi-diurnal and their range is one of the widest in the Mediterranean, with mean spring-tide values of 86cm in Trieste and 100cm in Venice, and mean neap-tide values of 22 and 20cm respectively (Dorigo, 1965; Polli, 1970).

The concomitance of spring-tides, seiches, south-easterly winds and low atmospheric pressure can cause a sea-level rise of 160cm (locally called “acqua alta”). Mean significant wave height during the year is lower than 0.5m (Dal Cin and Simeoni, 1994), while the highest offshore wave height, both for Bora and Scirocco storms, is about 5m (Cavaleri et al., 1996). An estimate of wave energy for the northern Adriatic area in the form of $H^2T^2$ (H and T corresponding to the significant wave height and period) can be obtained using the complete series of 2000-2003 three-hourly measurements available from the RON-APAT wave gauge located offshore Ancona (Lat. 43°37’46”, Long. 13°30’13”).
The annual value is 15.61 m$^2$s$^{-2}$. Longshore drift in the area occurs westward from the Isonzo River to Lignano, eastward and westward along the cuspatie Tagliamento river delta, and
southwestward from Baseleghe to Chioggia; along the southern coastline, from the Po delta to Chioggia, the longshore drift is directed northward (Bondesan et al., 1995).

3.2 Northern Adriatic inlets

Within the above described climatic, wave and tidal regime, a variety of inlets exist and exhibit different configurations. In regard to tidal inlets morphology, despite the microtidal regime, limited wave influence tends to produce tidal inlets of the tide-dominated type (Hubbard et al., 1979). Unjettied or embanked inlets, as well as inlets where short jetties have limited influence on ebb-tidal delta growth, such as Lignano, S.Andrea, Grado, Primero, Baseleghe and Caleri inlets, are referred to as natural or “almost natural” inlets (Fontolan et al., 2007(a);(b)).

Venice and Grado-Marano lagoons are two large basins, the first 55,000ha and the second 16,000ha. They are the only remnants of the formerly huge Adriatic estuary that once extended over 200km, from the southern Po delta to the Isonzo river mouth (Dorigo, 1965). Six inlets are located along the Grado-Marano lagoon-barrier island system, which extends over 20km. From W to E we find Lignano (embanked), S.Andrea (natural), Buso (jettied), Morgo (partially occluded), Grado (embanked-small jetties), Primero (embanked), connected to five main sub-basins. Lignano and Buso are the largest inlets, with tidal prism values of 40 ×10^6 m^3 and 26 ×10^6 m^3 respectively. Buso inlet was stabilized by the construction of jetties between 1964-1969.

Baseleghe is a natural inlet located along the Veneto coast, where water exchange between the Caorle lagoon and the sea occurs. The tidal prism of this basin has strongly been reduced, from ca. 15.5 ×10^6 m^3 in 1891 to ca. 3.3 ×10^6 m^3 in 1983 (Fontolan, 2004). This is a consequence of the reclamation of most of the surface occupied by tidal marshes for agricultural purposes. All three inlets, Lido, Malamocco and Chioggia, connecting the Venice lagoon with the Adriatic sea, are fixed by large jetties which extend far offshore. During the period 1808-1840 the jetties at Malamocco inlet were built to avoid shoaling inside the channel and to improve navigability; for the same reason long jetties were also built at the inlets of Lido (1890-1910) and Chioggia (1911-1933). The mean water volume of the Venice lagoon is approximately 700×10^6 m^3, the semi-diurnal volume exchange with the sea is about 350 ×10^6 m^3 during spring tides and 175×10^6 m^3 during neap tides (Silvestri et al., 2000). The tidal prism at
Lido inlet is about $145 \times 10^6 \text{m}^3$, at Malamocco inlet $136 \times 10^6 \text{m}^3$ and at Chioggia inlet $82 \times 10^6 \text{m}^3$ (Consorzio Venezia Nuova, 1989).

Until 1882, three different inlets (Tre Porti, S.Erasmo, S.Nicolò) occupied the area of the present Lido inlet. However, after the construction of two long jetties between 1882 and 1910, the three channels were united to form the Lido inlet (Muraca, 1982).

The northern jetty is 3635m long and the southern jetty 3155m. A large ebb-tidal delta and a strongly asymmetric swash platform once existed outside the Lido inlet before jetty construction; when examining the shape and orientation of these sandbars in older data, there is strong evidence of a southward net littoral drift. Due to the great difficulty in navigation and the strong dynamic behaviour of this channel, local authorities decided to fix the lagoon entrance with jetties. As a result, after construction, the ebb-tidal delta quickly eroded (Figure 3.2) and the main ebb flow was strongly diverted seaward.

Figure 3.2 – Ebb-tidal delta evolution during jetties construction at Lido inlet, 1882-1898 (after: Lippe, 1984, modified).
Beach accretion close to the updrift jetty (Figure 3.3) also reveals the existence of a southward net littoral drift. Punta Sabbioni beach has accreted at a rate of more than 10 my\(^{-1}\) since 1886, but more precisely the rate of growth has been 15.8\,my\(^{-1}\) between 1908 and 1933 and 10.7\,my\(^{-1}\) between 1933 and 1968. Since 1968, the rate of beach accretion has decreased, to 8.7\,my\(^{-1}\) in the period 1968-1980, to 8.5\,my\(^{-1}\) in the period 1980-1987 (Consorzio Venezia Nuova, 1989). The littoral drift has been estimated to be between 350\,000 and 400\,000\,m\(^3\)y\(^{-1}\) as an average for the whole period (Muraca, 1982) whereas the current longshore input can be estimated to be in the order of 150\,000\,m\(^3\)y\(^{-1}\) (Consorzio Venezia Nuova, 1989).

Caliari lagoon, which is connected to the sea through Caleri inlet natural entrance, is located in the northern portion of the area once occupied by the wide Po river delta; its basin surface extends approximately over 1150ha with a tidal prism of 9.50 × 10\(^6\)m\(^3\).

Dorigo (1965) calculated tidal prism values for all inlets along Grado-Marano lagoon by using different methods (through current meter data and cubature), while for Baseleghe and Caleri inlets the tidal prism value were calculated more recently through the application of the basin method (Furlani, 1999; Fontolan et al., 2007(c)). Tidal prism values for the Venice lagoon inlets are reported by Consorzio Venezia Nuova (1989); they have been calculated through the application of the cubature method (Jarrett, 1976) and by the application of a mathematical model. In Table 3.1 all values and references are summarised.
3. STUDY AREA

Table 3.1 – Tidal prism values for northern Adriatic inlets and associated references

<table>
<thead>
<tr>
<th>Basin</th>
<th>Spring tidal prism $10^6\text{ m}^3$</th>
<th>Dorigo (1965)</th>
<th>CVN (1989) Cubature method</th>
<th>CVN(1989) Unidimensional model</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>Morgo</td>
<td>1.429</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buso</td>
<td>26.296</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S.Andrea</td>
<td>9.700</td>
<td></td>
<td></td>
<td>3.12</td>
<td>(Segala, 1999)</td>
</tr>
<tr>
<td>Lignano</td>
<td>40.00</td>
<td></td>
<td></td>
<td>5.200</td>
<td>(Furlani, 1999)</td>
</tr>
<tr>
<td>Caleri</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2.1 A-P relationship for northern Adriatic inlets

A regression analysis of the A-P values for the northern Adriatic inlets dataset is shown in Figure 3.4. This regression presents some small differences with the calculations carried out following Jarrett’s (1976) formula. The smaller northern Adriatic inlets were found to have wider hydraulic sections than those calculated by Jarrett’s (1976) general formula. Only the jettied inlets (the largest three along the curve) tend to be well represented by the classical O’Brien (1931, 1969) relationship for dual jetties. Although limited to eleven sites, the A-P relationship displayed in Figure 3.4 for the northern Adriatic shows very little scattering, and this is confirmed by its high correlation coefficient. The northern Adriatic A-P relationship does not appear to exhibit different behaviour at natural, almost natural, and jettied inlets. As a general rule, northern Adriatic tidal inlets with P smaller than $5\times10^7\text{ m}^3$ tend to develop wider cross sectional areas than corresponding inlets with the same tidal prism found in the United States. Conversely, only the three largest inlets (Lido, Malamocco and Chioggia) fell precisely inside O’Brien’s (1931; 1969) proposed relationship for dual jetties.
Due to the limited influence of longshore transport along the northern Adriatic coastline, in almost all cases the orientation of the main ebb channel is symmetrical, being slightly asymmetrical and rotated downdrift at the terminal end of the channel margin linear bar and the terminal lobe. The inlet showed a typical updrift or downdrift offset configuration only in a few cases. Since a morphological response of the mutual interaction between tidal forces and sediment longshore drift is an inlets tendency to change orientation or migrate, the overall symmetrical or slightly asymmetrical configuration is evidence of the effectiveness of the tidal current in intercepting the longshore sedimentary load directed toward the main ebb channel. Sediment trapping leads to growth of channel margin linear bars located updrift, which tends to curve towards the distal end, thus enhancing the morphological contrast of the terminal lobe shoal. The examined jettied inlets appear to have reached hydrodynamic equilibrium as their A-P relationship was not significantly different from other cases. This could be due to the fact that these jetties were constructed approximately 100 years ago along the Venice littoral shore, and 40 years prior at Buso, a sufficient length of time for adaptation of the cross-sectional area to the newly restricted conditions.
At Caleri inlet, as illustrated in Figure 3.4 ed in Table 3.2, for the same tidal prism the value of cross-sectional area calculated through the empirical formula (Fontolan at al., 2007(a);(b)) resulted twice as much than the measured value. In presence of high sediment input to the inlet caused either by wave action during storm events or by longshore transport, the channel velocity increases in order to scour sediments and maintain equilibrium conditions, thus reducing channel cross-sectional area. Since Caleri inlet is not only directly exposed to E-NE storm but also located at the confluence of opposite longshore transport paths, the resultant inlet configuration may be a consequence of its necessity to maintain strong channel velocities, thus leading to a reduced cross-section.

Table 3.2 – A-P values for northern Adriatic inlets

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Tidal Prism</th>
<th>Area</th>
<th>Northern Adriatic relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primero</td>
<td>6.00E+06</td>
<td>696</td>
<td>750</td>
</tr>
<tr>
<td>Grado</td>
<td>2.34E+07</td>
<td>2045</td>
<td>2063</td>
</tr>
<tr>
<td>Morgo</td>
<td>1.40E+06</td>
<td>215</td>
<td>254</td>
</tr>
<tr>
<td>Buso</td>
<td>2.63E+07</td>
<td>2216</td>
<td>2250</td>
</tr>
<tr>
<td>S.Andrea (1960)</td>
<td>9.70E+06</td>
<td>1232</td>
<td>1071</td>
</tr>
<tr>
<td>Lignano</td>
<td>4.00E+07</td>
<td>3438</td>
<td>3074</td>
</tr>
<tr>
<td>S.Andrea (1999)</td>
<td>3.12E+06</td>
<td>559</td>
<td>461</td>
</tr>
<tr>
<td>Lido 1984</td>
<td>1.45E+08</td>
<td>7916</td>
<td>8012</td>
</tr>
<tr>
<td>Alberoni 1984</td>
<td>1.36E+08</td>
<td>7320</td>
<td>7639</td>
</tr>
<tr>
<td>Chioggia 1984</td>
<td>8.20E+07</td>
<td>4840</td>
<td>5243</td>
</tr>
<tr>
<td>Baseleghe</td>
<td>3.04E+06</td>
<td>435</td>
<td>452</td>
</tr>
<tr>
<td>Caleri</td>
<td>9.50E+06</td>
<td>532</td>
<td>1055</td>
</tr>
</tbody>
</table>

3.3 Hydrological regime of rivers in the Veneto plain

In the Veneto plain, the major Alpine rivers are characterized by a fluvial regime that presents significant seasonal differences (nivo-glacial hydrological regime): flow and sediment discharge values are in fact highly dependent on flood events occurring periodically during the year. Other rivers, such as the Sile river, present a different fluvial regime due to their particular
genesis of groundwater-fed rivers. The Sile river is one of the main rivers originating within the spring-belt; in these rivers, hydrology is dominated by interaction with the underlying regional aquifer. Aquifer storage exerts a strong temporal control on flow regimes by buffering variability in recharge timing and intensity to produce a stable flow regime with a well-defined annual pattern. Data concerning Sile river discharge are taken at the Casier measurement station, which is located approximately 55km far from the river mouth. Mean annual discharge values\(^3\) at Casier is 55 m\(^3\)/s, with minimum values reaching 33 m\(^3\)/s and maximum values reaching 76 m\(^3\)/s (Bondesan and Sauro, 1998).

At present, the river mouths have no subaerial deltaic accretions and the salt wedge is developed in the open sea (Zunica, 1971; Dal Cin, 1983). Few rivers are in a natural or semi-natural condition as water diversions for hydro-electric power production, agriculture and industry caused, especially in the last 50 years, decreased flows through the basins. Within this context, an exception is represented by the Tagliamento river, that can be considered the last large river in the Alps essentially maintaining more natural morphological and ecological characters (Ward et al., 1999; Gurnell et al., 2001). The Tagliamento river did not exerted a strong influence on the hydrodynamics and sedimentation of the Venice lagoon, thus was not as strongly modified as other rivers located in the Veneto plain (Zunica, 1971).

On the other hand, Piave, Sile, Brenta and Adige rivers have been hugely impacted by human activities during the last centuries, starting from 1600 to the present time (Surian and Rinaldi, 2003). The first engineering activities were aimed at the protection of the Venice lagoon from impoundment, thus river mouths that originally discharged directly into the lagoon were diverted seaward and rivers experienced considerable channel adjustment. In the last decades other human interventions such as sediment extraction (gravel and sand mining), dams and channelisation exerted a major impact on rivers, with heavy consequences on sediment supply to the littoral area. The major dams, that within the Piave basin started to function between 1959 and 1965, have subtracted large quantities of water and solids. The practice of sediment mining which was very intense in the period between 1959 and the 1970s and it is still going on nowadays (although with a lower intensity) is also one of the main responsible for lower sediment supply.

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\(^3\) Ufficio Idrografico del Magistrato alle Acque, mean values 1966-1985.
In the following sections a detailed investigation concerning the recent morphological evolution of the Piave and Adige river mouths will be presented, hence more specific information on the hydrological regime of these rivers are now provided.

The lower course of the Piave River extends from Ponte di Piave to the river mouth, which is located about 30km northeast of Venice. This lower course has been artificially straightened in places (Surian, 1999) and in the coastal plain the river is embanked. Flow in the Piave River has been substantially modified during the last 70 years and particularly during the last 40 years (Surian, 1999), mainly regulated for irrigation and hydroelectric power generation. It has been estimated that dams trap the sediment yield from more than 50% of the drainage basin (Surian, 1999). Barrages disrupting sediment transport through the middle course are located in the localities of Soverzene, Busche, Fener and Nervesa (Surian, 1999).

For the purpose of this study, bedload sediment transport measures would have provided fundamental information on river sediment supply to the coast, especially for the coarsest fraction which is the most relevant for nourishment of the littoral areas. Unfortunately, data collection in recent years is absent, and the more exhaustive data set was collected by the Venice Water Authority (Ufficio Idrografico del Magistrato alle Acque) during the period 1929-1938 at Segusino.

In the absence of bedload measures, streamflow measurements registered at Nervesa della Battaglia (streamflow measurement station) from 1961 to 1998 were examined. The data did not show any particular trend, and no significant variations seemed to occur between the period 1972-1998 and the previous decade (1961-1971), as major variations in flow regime had occurred after the 1950s following human interventions. Overall, as reported by the “Autorità di Bacino dei fiumi Isonzo, Tagliamento, Livenza, Piave, Brenta-Bacchiglione” within the “Progetto di Piano Stralcio per la sicurezza idraulica del medio e basso corso del Piave” (2001), the mean flow, that at Soverzene exceeds 50 m$^3$/sec, is reduced by several diversions to a few m$^3$/s, if not completely interrupted. Moreover, it is reported being difficult to artificially maintain a 5 m$^3$/s discharge during summer season.
More recent daily discharge measurements are available for the period January 2002-January 2003 at Nervesa della Battaglia. As shown in Graph 3.3, major flood events occurred in November 2002, and high flow values are recorded also in May and June (as is to be expected from a nivo-glacial regime). These flood events could be responsible of periodic recharges of the submerged delta and the associated mouth bars.
The Adige River is the second largest sediment supplier to the Adriatic Sea. CNR (1976) reported an average estimated solid annual transport of \(886 \times 10^3\text{ty}^{-1}\) and a mean water discharge of \(207 \text{m}^3/\text{s}\). Rectification of both the river mouth and the terminal part of the river channel was actuated with the aim to protect surrounding areas against floods. Similarly to the Piave river, a reduction in sediment transport capacity has occurred starting from the second half of the last century, caused by water diversions for agricultural uses and hydro-electrical power production.

Streamflow measurement station for the lower course of the Adige river is located at Boara Pisani, at a distance of 51km from the river mouth. Discharge measurements started in 1923 and continue nowadays, while suspended solids transport measurements were not collected between 1941 and 1957 and were eventually interrupted at the end of the 1970s. Mean annual values and daily discharge values\(^4\) at Boara Pisani are reported, relative to the period 1923-2000.

\(^4\)Data relative to the period 1923-1983 were provided by the “Adige Basin Authority”, data relative to the period 1983-2000 were collected by the “Ufficio Idrografico e Mareografico di Venezia”
Flow measurement values are representative, in analogy with the Piave river, of a nivo-glacial regime. Differences in the measured values at Boara Pisani within the overall time frame, as for example the increase in flow registered during the autumn-winter period (Zunica, 1971), is imputable to the opening of reservoirs located in the upper course of the river.
Heavy utilization of river waters for human activities started during the decade 1941-1951. Until 1941, the river basin could be considered as characterized by a “natural” state, while after the construction of several dams for hydro-electrical power production and following the numerous diversions actuated for agricultural uses, the hydrological regime has been strongly modified. For this reason, data collected before and after the 1950s were not compared, as they are considered representative of different fluvial regimes. In general, Adige daily discharge values varies between 140 and 380 m$^3$/s, with maximum values reach 1800 m$^3$/s.

The overall tendency for the entire 80 years period shows a decreasing trend in flow discharge, mainly due to the already mentioned human impacts. Until the 1950s, a great variability in the values were registered, while in the following years this variability progressively diminished. An increasing tendency, however, has been registered starting from 1995, and the analysis of the data series filtered with a power 5 moving average, shows a cyclic trend in mean discharge values, characterized by a 10-12 years time period. Opposite to the constant trend registered in the previous 20 years, the filtered values calculated for the more recent years show an increase in discharge values, leading to a new cycle characterized by stronger discharges. The same trend is evident if examining daily maximum discharge values: a high variability of values has occurred until the 1970s, followed by a strong decrease in peak values and a variability lower than 250 m$^3$/s. Filtering of the daily values with a power 5 moving average shows the same cyclic trend with a period of 10-12 years.

Taking into account the total solids transport (bedload transport + transport in suspension), registered values seem to show a trend analogue to the one relative to discharge values. As illustrated in Table 3.3, the suspended solid fraction has decreased during the period 1958-1975, if compared to the previous period (1929-1942).

Table 3.3 – Adige river total solids transport, 1922-1975

<table>
<thead>
<tr>
<th>Period</th>
<th>Mean annual discharge (10$^6$ m$^3$)</th>
<th>Transport in suspension (10$^3$ t/year)</th>
<th>Bedload Transport (10$^3$ t/year$^1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1922 – 1950</td>
<td>7760</td>
<td>1110 (2)</td>
<td>46</td>
</tr>
<tr>
<td>1958 – 1975</td>
<td>6530</td>
<td>851</td>
<td>35</td>
</tr>
</tbody>
</table>

1 Values obtained by the application of the Einstein-Brown formula.
2 Value obtained from measures collected during the period 1929 – 1942, corrected by the rate between fluxes in 1922 – 1950 and 1929 – 1942.
As previously stated, major flood events are responsible for significant sediment discharge at river mouths. In the case of the Adige river, major floods basically occurred during winter periods before the year 1951, while in the following years they have been distributed more uniformly throughout the year. This trend of decreasing winter flood events and consequent increasing summer flood events may be imputable to the opening of the reservoirs, more frequent in the summer months (CNR, 1976).
4 MATERIAL AND METHODS

4.1 Introduction

One of the main purposes of the research has been the development of a reliable methodology in order to evaluate sand volumes trapped at ebb-tidal deltas. A GIS system is an optimal way to homogenize and perform analyses of data coming from different sources, as it does allow for vector and raster data capture, integration and data conversion, interpolation, powerful surface and volumetric modelling, and spatial and statistical analysis of observational data (Allen at al., 2007). Using both newly collected data and data from previous studies of tidal inlet morphodynamics along the northern Adriatic coastal area (Fontolan et alii., 2007; Cirilli, 2004; Furlani, 1999; Segala, 1999), ebb-tidal delta volumes were calculated by a newly developed semi-automatic geostatistical procedure (ADP). Similarly to bathymetric data, grain size data were processed using GIS to produce different maps illustrating sediment properties; mean grain size and sorting (or standard deviation) are in fact fundamental parameters for the evaluation of ebb-tidal deltas as potential borrow sites.

Finally, comparisons of bathymetric maps relative to different time periods allowed for a quantitative evaluation of erosional-depositional processes occurring within submerged delta morphologies at river mouths.

4.2 Data collection and analysis

In the initial phase of the study, data from different bathymetric surveys and information on grain size characteristics have been acquired from several data sources. The main sources of information for the present research have been:

1. an exhaustive dataset provided by the Venice Water Authority (Magistrato alle Acque through its concessionary Consorzio Venezia Nuova);
2. the Coastal Group inlet database;
3. several historical maps;

The dataset provided by the Magistrato alle Acque through its concessionary Consorzio Venezia Nuova consists of a series of bathymetric measurements collected along the entire
littoral area from the Adige river mouth to the Piave river mouth, during the period 2001-2006 and it is summarised in Table 4.1. Unfortunately, the surveyed bathymetric lines at the Brenta river mouth were not sufficiently extended seaward to allow a characterization of the submerged delta; hence, this study area was not taken into account in the research. All data were collected by Te.Ma. snc by using a single beam echo-sounder (Odom Echotrak MKII) coupled with a GPS RTK positioning system.

Table 4.1 – Data provided by the Magistrato alle Acque through its concessionary Consorzio Venezia Nuova

<table>
<thead>
<tr>
<th>Surveyed area</th>
<th>Period</th>
<th>N. profiles</th>
<th>Depth end of the profiles</th>
<th>Sediment samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adige river mouth</td>
<td>June 2001</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2001</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2002</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2003</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2004</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2005</td>
<td>11</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2006</td>
<td>11</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td>Brenta River mouth</td>
<td>June 2001</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2001</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2002</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2003</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2004</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2005</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2006</td>
<td>13</td>
<td>-9</td>
<td></td>
</tr>
<tr>
<td>Sile river mouth</td>
<td>December 2002</td>
<td>12</td>
<td>-4/-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>November 2003</td>
<td>14</td>
<td>-4/-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2005</td>
<td>13</td>
<td>-4/-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Multibeam</td>
</tr>
<tr>
<td>Piave river mouth</td>
<td>April 2002</td>
<td>9</td>
<td>-5.50</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>May 2002</td>
<td>11</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>December 2002</td>
<td>13</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2003</td>
<td>53</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>October 2003</td>
<td>53</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2005</td>
<td>57</td>
<td>-5.50</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Multibeam</td>
</tr>
<tr>
<td>Lido inlet</td>
<td>2000</td>
<td></td>
<td>Dredged channel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>April 2004</td>
<td></td>
<td>Dredged channel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2005</td>
<td></td>
<td>multibeam</td>
<td></td>
</tr>
<tr>
<td></td>
<td>May 2006</td>
<td></td>
<td>Dredged channel</td>
<td></td>
</tr>
</tbody>
</table>
Another data source for this research is represented by the Coastal Group inlet database. Six inlets have been studied since 1994 within the projects carried out by the Coastal Group of the Trieste University-DISGAM, and investigations included bathymetric surveys and sediment sample collection. Collected data were not homogeneous, because of the different survey techniques and instruments used. In older surveys, an analogue echo-sounder along with a topographic total station were employed, whereas the more recent surveys have benefited from modern technology such as DGPS positioning coupled to a digital echo-sounder. Owing to the time-consuming older survey techniques first used at Primero, S. Andrea and Baseleghe, the bathymetric data are sparse, and consist of some channel cross sections, some shoreline normal profiles, and a relatively small number of scattered measurements in intertidal areas, though these were expertly selected to capture the most significant morphologies. Only the more recent surveys at Grado and Lignano, have been uniformly covered by a regular sounding grid. The sounding grids were specifically designed, after analysis of the existing bathymetric data, to capture the most important morphologies of the ebb-tidal delta. A dataset for sediment grain size is available for every inlet. Samples were collected by scuba diving or by Van Veen grab, depending on water depth.

Table 4.2 – Data collected by the DISGAM-Coastal Group

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Lagoon</th>
<th>Date of survey</th>
<th>No. of sediment samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primero</td>
<td>Grado</td>
<td>1997</td>
<td>62</td>
</tr>
<tr>
<td>Grado</td>
<td>Grado</td>
<td>2002</td>
<td>53</td>
</tr>
<tr>
<td>Lignano</td>
<td>Marano</td>
<td>2003</td>
<td>101</td>
</tr>
<tr>
<td>Baseleghe</td>
<td>Caorle</td>
<td>1999</td>
<td>46</td>
</tr>
</tbody>
</table>

Data collected were elaborated through ESRI ArcGIS™ software to obtain Digital Elevation Models (DEM) of the seafloor morphology and also thematical maps; ebb-tidal delta volumes and characteristics were evaluated through the application of the methodology described in detail in section 4.3.

Finally, several historical maps were gathered. The majority of these data were not available in digital version, thus in the initial phase of the study they were all converted into digital format.
4. MATERIAL AND METHODS

and subsequently geographically referenced through ArcGIS™ Georeferencing Tool. Summarizing, the information selected and used in the research to perform the analyses are the following:

a) Bathymetric map of the Venice Lagoon barrier island coastline, comprising Lido, Chioggia and Malamocco inlets (Brambati, 1987);

b) Bathymetric maps representing data collected at Piave river mouth (Di Silvio and Lippe, 1976) in:
   - November 1972
   - March and may 1973

c) Bathymetric maps collected at the Adige river mouth by CNR (1976; 1980) in:
   - November 1973
   - May and august 1974
   - May and august 1975
   - August 1976
   - August 1977

4.2.1 Bathymetric surveys and sediment sampling

After the examination of all collected data, seafloor elevation measurements outside Lido and Caleri inlets were acquired in may 2006 and july 2006, respectively. Moreover, recently collected data at Buso inlet were acquired thanks to OGS (2006) within the VECTOR project. Lido and Buso surveys are considered particularly significant owing to the fact that these inlets are representative of jettied inlets strongly influenced by human activity. Twenty-three bathymetric profiles were acquired at Lido inlet the 25th and 26th of may 2006; fifteen shore perpendicular profiles 7200m long and eight shore parallel profiles 3800m long were collected by using a digital single beam echo-sunder (Lowrance LcX 16) coupled with a 12 channel GPS Lowrance receiver, mounted on a 11m long vessel. Position was determined through a GPS Trimble positioning system.

At Caleri inlet, a rectangular grid of 180m×180m was used to collect bathymetric profiles for a total length of 48km. Data acquisition was performed by the following equipment:
   - Benthos PSA916 sounding equipment,
4. MATERIAL AND METHODS

- DGPS Thales Navigation (Magellan Professional®) Promark™3,
- Tablet pc Itronix® Duo-Touch + software NavPro 6 (Communication Technology)

A rectangular grid of 100m×100m was used at Buso inlet to collect bathymetric profiles for a total length of 250km; data were gathered using a single beam echo-sounder in October and November 2006. On the 5m long vessel property of the OGS, the following equipment was mounted:
- Garmin sounding equipment + 12 channel Garmin GPS 76 receiver,
- Ashtech G12 Lite receiver + DGPS LandStar MkIV Thales Tracs Ltd,

In all cases, a notebook was used to manage simultaneously the acquisition of position and bathymetry data, and eventually the post-processing phase was performed through the following steps:
- Calibration of physical and chemical characteristics of the water column,
- Adjustment of transducer variations originated by vessel’s pitch and roll,
- Tide observations were used to correct soundings to chart datum. At Lido inlet 24-hourly tide observations were recorded at 10-minute intervals by the A.P.A.T. Lido S. Nicolò tide gauge. At Caleri inlet 24-hourly observations were recorded at 10-minute intervals by the A.P.A.T Caleri tide gauge. At Buso inlet a tide gauge was positioned on a benchmark located within the inlet channel, observations there were recorded at 5-minute intervals.
- Data filtering through moving average has been applied singularly to each profile, in order to detect and eliminate the influence of wave motion,
- Accidental variations “spikes” (i.e. objects on the seafloor; seaweeds, etc) were detected and eliminated manually, by singularly examining each profile.

Bathymetric values were eventually obtained and errors associated with the measurements were estimated to be between ±2cm and ±7cm.

Sediment sampling was conducted offshore Lido and Caleri inlets: 71 sediment samples were collected at Lido inlet and 62 at Caleri inlet by Van Veen grab. In both cases, sediment samples were taken at points coincident with the nodes of the rectangular grids set for the bathymetric profiles.
4. MATERIAL AND METHODS

4.2.2 Laboratory analysis

After being washed, samples were sieved with a 63 µm sieve to separate the sand fraction from the pelitic fraction; shell fragments were separated by sieving with a 1 mm sieve. Samples were washed and treated with H$_2$O$_2$ to eliminate organic fraction and salt, then dried at 80°C for 24 hours. In both cases grain size analyses were carried out using a Macrogranometer© settling tube and classical grain size statistical parameters ($\phi$ notation) are represented following Folk and Ward (1957).

4.3 Spatial analysis

4.3.1 Digital mapping

ESRI ArcGIS™ software was used to store and analyse all bathymetric and grain size data. Digital Elevation Models (DEMs) of the seafloor bathymetry were produced for every study site mainly through Triangulated Irregular Networks (TIN) and simple kriging techniques. In general, triangulation methods is reliable when the available data is not regularly spaced but the shortcoming is that it creates a very angular surface. Moreover, especially when generating DEMs by triangulation from contour inputs (i.e. contour lines extracted from historical maps), the triangulation method do not preserve the form of minor ridges and valleys. However, it has been possible to improve the resulting model by introducing data from different surveys and adding vector elements, inferred from collected data. The resulting bathymetries were converted to raster format, a grid of regularly spaced cells. Cell spacing was chosen according to survey data resolution. In cases were data collected were regularly spaced and with a sufficient resolution, kriging techniques were directly used to produce DEMs. Finally, multivariate geostatistics have been used to obtain detailed maps concerning grain size characteristics of the potential borrow sites. Depending on data coverage, either Inverse Distance Weighting (IDW) or kriging procedures have been applied to produce sand-percentage, mean grain size and sorting distribution maps.
4. MATERIAL AND METHODS

4.3.2 Ebb-tidal delta volume calculation

A simple estimate of ebb-tidal delta volume can be obtained using formulas available in literature (Walton and Adams, 1976; Marino and Mehta, 1988; Hicks and Hume, 1996). Nonetheless, even when using the same tidal prism value, estimated volumes sometimes double depending on the formula adopted. Moreover, these mathematical relations were constructed on data coming from Atlantic inlets, which may be different from those of the Adriatic. Thus, applicability is not guaranteed and other methods must be applied to give more reliable estimates of the sand volume stored in ebb-tidal delta structures.

A methodology was developed to quantify the ebb-tidal delta area and volume of various northern Adriatic inlets. Different techniques exist to evaluate the evolution of inlet ebb-tidal delta structures and calculate ebb-tidal delta volume and area (Stauble, 1998): among these the Residual Method calculates volume in ebb-tidal deltas by reference to idealized no-inlet contour lines. The Residual Method fits a Digital Elevation Model to a no-delta hypothetical bathymetry.

In the manually developed original method, the parallel updrift and downdrift bathymetric lines of an inlet far from the influence of the channel were assumed as the natural topography of the coast without the inlet (Walton and Adams, 1976). Hicks and Hume (1996, 1997) presented data collected from tidal inlets of New Zealand and developed a procedure for ebb-tidal delta volume calculation using SURFER™ software. One of the major challenges of this research was the construction of a reliable virtual no-delta bathymetric configuration.

Figure 4.1 – Residual Method (after: Dean and Walton, 1973)

This graphical method in fact leads to variable results since different operators may draw
different curves for the same regional trend. Following Mehta et al. (1996) possible human error in these calculations can be in the order of 30 percent, but typically range from 5 to 15 percent. Hence, as the procedure is somewhat subjective, an attempt was made to develop an automatic procedure based on the methodology first presented by Dean and Walton (1973). To minimize operator intervention in the building of the “no-delta” bathymetry, a GIS geostatistical procedure based on the original depth data, was applied and herein referred to as the Semi-Automatic Detrending Procedure (ADP). The first step involved the manual procedure, followed by an automatic interpolation procedure which was tested through the following steps:

\textit{a. Construction of a Digital Terrain Model (DEM) of the real bathymetry.}

As previously exposed, the DEMs were produced with the triangulation method (TIN) and kriging interpolation techniques. Efforts were made to improve the models of those inlets lacking complete survey data and the resulting DEMs were considered sufficiently accurate to perform the required calculation.

\textit{b. Construction of the no-delta bathymetry.}

This is the most crucial stage in the procedure, as stated in previous studies (Hicks and Hume, 1996;1997; Stauble, 1998), because of the large source of error in the calculation process. One of the main aims of this project was to minimize operator intervention when defining the no-delta bathymetry. Several tests were carried out to compare the results of methods adopted in previous studies and to find an improved, less subjective, methodology. Following Hicks and Hume (1996), representative equilibrium shape profiles from areas outside the ebb-shoal area were used to create an idealized no-inlet bathymetry. As a first attempt, 2 to 4 lateral profiles located in the littoral area not affected by the ebb-tidal delta structure, were used to develop different polynomial trend surfaces. Afterwards, the entire dataset was used to create different polynomial trend surfaces. The use of the entire dataset resulted in a less subjective and more precise procedure, because it avoided operator error when selecting lateral profiles. In cases of contour data extracted from historical maps, a grid of points with z attribute, regularly spaced, was extracted from the DEMs, and these points
were used to create the polynomial surfaces. An example of the procedure is shown in Figure 4.2.

Figure 4.2 – Stages of development of the Semi-Automatic De-trending Procedure: Chioggia inlet example
First, second, and third order polynomial trend surfaces were created and evaluated, both for statistical relevance (Davis, 2002; Grohmann, 2005) and for correspondence with the overall morphology of the coastal area. Higher degree trend surfaces were not considered in the analysis due to the fact that these surfaces are more representative of the true configuration than the idealized no-delta bathymetry. All trend surfaces provided a significant fit to the observations (values of $r^2$ were between 0.83 and 0.90).

It is extremely important to emphasize that in this type of application, as reported by Davis (2002), statistical tests of significance are not a suitable guide when selecting degree of trend surface because the problem is not one of statistical estimation. Rather, the objective is to closely simulate the regional trend of the sub-surface. The application of different polynomial trends can lead to relevant differences in the following steps of ebb-tidal delta volume calculation (up to 40-50%), and at this final step of the procedure, expert judgement is necessary to evaluate which degree of trend surface is the most adequate in the representation of no-delta bathymetry.

c. **Subtraction of the different no-delta surfaces from the real bathymetry and creation of different Residual Maps.**

In order to obtain accurate residual maps, cell by cell calculations between the bathymetric rasters were carried out.

d. **Ebb-tidal delta volume calculation.**

Volume was calculated for the different configurations using cells with positive values in the residual surface. The Residual Method (Walton and Adams, 1976; Hicks and Hume, 1996) consists of the calculation of the positive anomalies while negative anomalies identify mainly channel morphologies. At Lido inlet (Figure 4.3) the differences in volume calculation by subtraction of first, second and third order polynomial trend surfaces were estimated to be 40% between first and second order, and around 50% between first and third order. As previously stated, the choice of the third order trend-surface was driven by the strong bathymetric offset. As a result, a more precise ebb-tidal delta residual morphology, as well as a reduced extension of the significant negative values outside the delta domain can be observed (Fig. 5c).
Figure 4.3 – Ebb-tidal delta volume calculation at Lido inlet. (A) First order polynomial trends surface and associated residual map; (B) second order polynomial trend surface and associated residual map; (C) third order polynomial trend surface and associated residual map. All negative values are below -0.25m; negative anomalies inside the main ebb-channel are not shown.
4. MATERIAL AND METHODS

4.4 Analysis of small river deltas deposits

Morphologic changes in the nearshore area adjacent to river mouths were determined by comparison of DEMs relative to different time periods. Similarly to the analysis conducted at ebb-tidal deltas, DEMs of the seafloor surface were produced directly from digital bathymetric data or through the digitalization of historical maps, following the methodology described in section 4.3.1. The comparison of digital bathymetric data for the same region but different time periods provides a method for calculating net movements of sediment into (accretion) and out of (erosion) the area of study (Byrnes and Hiland, 1995).

The application of the ADP method have been taken into account also in this cases, owing to the fact that submerged river delta morphologies are characterized by a seaward deflection of bathymetric lines. However, the application of the method was subordinate to the evaluation of equilibrium conditions at river deltas, in terms of no net erosional processes. Anticipating the results that will be reported in section 5.4, it is to highlight that the ADP procedure was not applied at river deltas. In fact, the investigated submerged morphologies were found to have lost a large quantity of sediments during the last thirty years.
5 RESULTS

5.1 Introduction

The overall results of the analysis are illustrated in the following sections. Elaborations concerning ebb-tidal delta volume calculation are presented first, followed by a discussion concerning the relationship found for the northern Adriatic inlets between tidal prism and ebb-tidal delta volume.

Analyses of the recent and present morphological evolution of submerged delta morphologies at river mouths are then shown, and eventually follows a description of the GIS geodatabase which has been developed to organize information concerning the characteristics of the investigated sand borrow areas. This management tool represents the final outcome of the research and it could be implemented and integrated in the future, following the updating of existent data or the acquisition of new information at different sites.

5.2 Ebb-tidal deltas

Following the procedures described in section 4.3, both newly collected data and data from older surveys were analysed. At Lido and Caleri inlet the acquisition of bottom-surface sediment samples allowed the investigation of sedimentary patterns at ebb-tidal delta morphologies, while at Chioggia and Malamocco inlets, due to the scarcity of updated data, only a preliminary analysis on sand volumes was conducted. After the acquisition of recently collected bathymetric data (OGS, 2006), the results of ebb-tidal delta volume calculation at Buso inlet are also presented. Finally, results concerning ebb-tidal delta volumes were plotted against tidal prism values to obtain a P-V relationship for the northern Adriatic inlets.

5.2.1 Lido ebb-tidal delta

5.2.1.1 Ebb-tidal delta volume calculation

The application of ADP to the 1987 data, following the procedure described in section 4.3.2 and illustrated in Figure 4.2, allowed the identification of the ebb-tidal morphology and
5. RESULTS

provided a preliminary estimation of sand volume, which was calculated to be around $7 \times 10^6 \text{m}^3$. Due to the strong asymmetry between the updrift and downdrift coasts, a third-order polynomial trend surface was chosen. The resulting map (Figure 5.1) shows the potential deposit, which develops in front of the inlet throat and in the downdrift area, starting from the 5/6m water depth. The terminal lobe appears to be situated in correspondence of the 11m water depth, and the delta feature reaches maximum thickness values (between 2m and 2.50m) in its distal portion.

![Figure 5.1 – Lido ebb-tidal delta, 1987](image)

As original data have been subjected to digitalization and to rather complex processing phases through GIS, these preliminary results were considered only an initial estimation of ebb-tidal delta volume, that needed to be validated by more updated surveys.

The results of the 2006 bathymetric survey carried out at Lido inlet are shown in Figure 5.2. Bathymetric contour lines south of the southern jetty give evidence of an ebb-tidal delta structure, a cuspate-shaped sand body developing in the southern-downdrift direction. Due to the confinement of flow by the jetty construction, sand is being deposited at greater water
depths and new ebb-tidal delta growth has occurred seaward of the jetties. The modern terminal lobe of the ebb-tidal delta at Lido inlet is delineated by the -13m contour line. Dredging operations are required almost yearly to maintain suitable channel depth for navigation; the shipway is evident on the eastern side of the area, where a portion of the ebb-tidal delta is scoured. On a yearly basis, dredging operations extract 150,000m$^3$ of sediment to maintain the channel depth at 11m. (Libardo, 2008 personal communication). The ADP has been applied in the case of Lido inlet and the no-delta bathymetry has been created through interpolation of all bathymetric data points.

The volume calculation based on the data collected in 2006, gave an estimate of 5.81 × 10$^6$m$^3$ of sand deposited in the ebb-tidal delta, a lower value than the one calculated on the basis of the 1987 data, although characterized by the same order of magnitude. The sand accumulation evidenced in Figure 5.3 appears very similar to the feature obtained through the previous elaboration; the morphology exhibits the same arcuate shape and location with maximum thickness values reaching 3m in front of the inlet jett-spooling area, at a distance of 2.5km.

![Lido bathymetric map, 2006](image-url)
5. RESULTS

from the inlet throat. The well-defined terminal lobe reaches the 12m water depth, at a
distance of approximately 3.100km from the inlet throat.

Figure 5.3 – Lido ebb-tidal delta, 2006

In order to compare ebb-tidal volumes obtained through ADP with empirical relationships
(see section 2.2.1), theoretical equilibrium volume has been calculated. Previous investigations
(Furlani, 1999; Segala, 1999; Fontolan et al., 2007) had showed that the empirical relationship
obtained by Hicks and Hume (1996) applied to five northern Adriatic ebb-tidal deltas provides
values comparable with those calculated by the geostatistical procedure, differently to what
found for values calculated through equation (6) or (7).

Considering the tidal prism value of 145 ×10⁶ m³, the application of equation (8) gives an
estimate of the equilibrium volume of sand stored in the Lido ebb-tidal delta as 7.18 × 10⁷ m³,
one order of magnitude greater than the value calculated using the geostatistical procedure.
In order to explain the large difference, possibly related to the fact that the ebb-tidal delta has
not reached equilibrium volume, a conceptual model was applied. The model, in which the
morphodynamic evolution of the area after jetty construction (accretion of updrift beach; decrease on longshore transport) was examined, is based on a simplified application of the Tidal Inlet Reservoir Model (TIRM) by Kraus (2002). As described in section 2.2.3, this is a mathematical model developed for calculating long-term sand bypassing and change in volume of inlet morphological features. One of the assumptions of the TIRM, is the existence of an ebb-tidal delta equilibrium volume, depending on hydrodynamic conditions. Ebb-tidal deltas store sand and serve as a conduit for sand bypassing in the vicinity of the inlet. Bypassing towards the downdrift beach occurs according to the maturity state of the tidal delta, wave conditions, magnitude of the tidal prism, and other factors (Kraus, 2002). As far as a newly formed ebb-tidal delta is concerned, after jetty construction, sand is expected to be completely stored in the ebb-tidal delta, because this structure is still too immature for by-passing sand to the downdrift area. This difficulty is due to the lower wave effectiveness to winnow the newly formed ebb-tidal delta, which is located far offshore, in an area of greater depth than the natural one. The original TIRM was used in a simplified form, which ignores the output associated with the by-pass. As described in section, the model predicts time delays in growth of morphological features, such as ebb-tidal deltas, through the formula:

\[ V_E = V_{Ee} \left(1 - e^{-\alpha t}\right) \]

where \( V_E \) = volume of ebb-tidal delta, \( V_{Ee} \) = equilibrium volume of ebb-tidal delta, \( t \) = time, and \( \alpha = Q_{in}/V_{Ee} \).

In the case of Lido inlet, the parameters entering the formula are \( Q_{in} = 150,000 \text{ m}^3\text{y}^{-1} \) (CVN, 1989) and \( V_{Ee} = 7.18 \times 10^7 \text{ m}^3 \), calculated by equation (8). The value of \( \alpha \) calculated for these parameters is 0.00209, thus giving an R value of 479. Since R values over the conventional limit of 150 indicate poor “by-pass” inlets from the updrift to the downdrift area, mainly stable with deep channel (Bruun and Gerritsen, 1959), this confirms the assumption that sediment losses due to the by-pass towards the downdrift beach can be neglected. Giving a time period of 100 years (after the construction of the two jetties), the application of the model gives a value of \( V_E = 13.5 \times 10^6 \text{ m}^3 \), while the estimate found through the Residual Method gives a value of \( 5.81 \times 10^6 \text{ m}^3 \).

A consideration has to be made at this point, with regard to the interruption of the southward net littoral drift by the northern jetty, and the consequential accretion of Punta Sabbioni beach. From the beginning of 1900 to 1968, the rate of accretion has been high, more than 10 my\(^{-1}\), thus the entrapment of sand by the seaward extension of the north jetty may have subtracted
sediment from the development of the ebb-tidal delta. Since 1968, the rate of growth has been decreasing. Moreover, the beach has nearly reached the end of the jetty (300 m further), once approaching this point the process of sediment bypassing inside the inlet and transport by tidal currents could have begun. This consideration leads to the conclusion that for the application of the above formula a timeline of 40 years should be considered. The result of the application of the Reservoir Model with \( t = 40 \) years gives a value of \( V_E = 5.76 \times 10^6 \) m\(^3\), very close to the volume calculated through ADP. Following the opening of a new inlet or the training of a natural inlet, the rate of growth of the ebb-tidal delta is mainly contingent upon the rate of supply of sediment from the littoral drift. The larger the drift, the faster the rate at which the ebb-tidal delta will develop to its new equilibrium size. (Dean and Walton, 1973).

Donda at al. (2008), reported the results of another recent survey conducted in the area offshore Lido inlet. Three seismic profiles were collected and processed, leading to the individuation of an ebb-tidal delta feature, which is reported to have developed after jetties stabilization, in accordance to our findings.

Figure 5.4 – Isopach map of the Lido ebb-tidal delta (after Donda at al., 2008)
Also, a comparison between the isopach map showed in Figure 5.4. and the map of Figure 5.3 indicates a correspondence between the identified depositional features, with area of maximum thickness located outside the inlet throat at a distance of approximately 2.5km from the jet-spread area. Nevertheless, possibly due to the different survey methodologies applied, some differences in the shape and extent of the deposit arise from the comparison. The well-defined arcuate-shaped feature obtained from this last study’s survey appears to be wider, as it is reported being 6km long and 4km wide and reaching a maximum thickness of 6m. Since ebb-tidal deltas are identified as depositional anomalies superimposed on the present bathymetrical configuration, the application of the Residual Method leads to the identification of these anomalies, whereas seismic profiles may detect a broad overlying sedimentary structure. However, a correspondence between the two surveys has been found concerning the area of maximum deposition and the overall downdrift oriented shape of the deposit, thus providing an important validation of the applied methodology. Finally, the application of the TIRM in its simplified version would certainly need to be validated by other surveys conducted at jetted inlets, whereas the conceptual model here presented well explained the morphological evolution occurred at Lido inlet during the last century and the morphodynamics processes responsible for ebb-tidal delta development.

5.2.1.2 Sedimentology

Grain size variations are important factors in sedimentary environments as they can be related to differences in tidal and wave energy (Smith and FitzGerald, 1994). In order to investigate sedimentary patterns at Lido ebb-tidal delta, grain size parameters were analysed and the results of the laboratory analysis were processed through GIS interpolation techniques. Following Nota (1959), 35 samples corresponding to the 49.3 % of the overall sample consist of sand (pelitic fraction less than 5%); 21 samples corresponding to the 29.6 % of the total sample consist of pelitic sand (pelitic fraction between 5% and 30%) and 15 samples corresponding to the remaining 21.2% consist of very sandy pelite (pelitic fraction between 30% and 70%). Sand distribution within the ebb-tidal delta exhibit a decreasing trend: sand constitutes the majority of sediments deposited at shallower depths while from the 8m water depth the percentage of the finer fraction starts to increase. Very sandy pelite characterizes both the bottom surface at water depths greater than 10/11m and the dredged channel.
Due to the strong asymmetry of the inlet adjacent shorelines, seafloor facing the Cavallino Peninsula is characterized by a steeper gradient, hence shallow morphologies connected to the ebb-tidal delta are not present. This configuration leads to a higher percentage of fine sediments deposited in this area, as shown in Figure 5.5. Mean grain size values are comprises in the range 2.0-4.5φ, resulting in 5 different classes equally distanced at distances of 0.5φ. The trend in the mean grain size parameter (Figure 5.6) also highlights a pattern of deposition characterized by coarser sediments (2.0-2.5φ) concentrated in the area outside the inlet throat, where high current velocities decrease abruptly to enhance settling of the coarsest fraction. The trend is characterized by a progressive fining seaward, with finer sediments found in the seafloor adjacent to the Cavallino Peninsula, eastward of the tidal channel. The asymmetric spreading pattern of mean grain size could be related to the local sedimentary drift, southwestward directed. On the northern side of the ebb-tidal delta the presence of fine sediment seems to be related to the classical grading of the shoreface, where the abrupt change from sand to mud occurs around the local closure depth. Thus wave effectiveness and winnowing are the main forcing for sediment distribution on the southern side of the delta.
and the occurrence of sand deposits at depths greater than the closure depth testifies the effectiveness of tidal current in generating sediment patterns typical of a far field. Sorting distribution is illustrated in Figure 5.7; with the exception of a small area of very well sorted sediments facing Lido shoreline, the distribution follows a rather regular pattern characterized by progressively seaward increasing values. Only at shallow water depths waves may affectively act to rework bottom sediments and may exert a selection on the deposited material by removing the finer fractions.
5. RESULTS

Figure 5.6 – Lido mean grain size distribution

Figure 5.7 – Lido sorting distribution
5. RESULTS

Additionally, cluster analysis has been applied to the samples. This methodology allows to represent data through a hierarchical classification, which is graphically illustrated by a dendrogram. Frequencies distribution data, at 0.5φ intervals, were processed through a statistical software (STATISTICA) by the application of the linkage Ward grouping method – squared Euclidean distances. Ward’s linkage method uses the analysis of variance to evaluate the distances between clusters, attempting to minimize the Sum of Squares of any two hypothetical clusters that can be formed at each step. The dendrogram, as shown in Figure 5.8, was then cut at a distance of 20 (Dleg/Dmax)*100 and this led to the subdivision of the overall sample in 4 groups.

Figure 5.8 – Cluster analysis – dendrogram

- **Cluster 1**: groups the 19 finest samples, characterized by mean grain size values between 3.5φ and 4.0φ, moderately sorted;
- **Cluster 2**: groups the 15 coarsest samples, 2.5φ, very well sorted;
- **Cluster 3**: group 18 samples, characterized by mean grain size values of 3.0φ, well sorted;
- **Cluster 4**: group 19 samples, characterized by mean grain size values of 3.0φ, moderately well sorted.
Graph 5.1 – Clusters frequency distribution

Figure 5.9 – Lido cluster distribution
A map representing cluster distribution within the area is illustrated in Figure 5.9, in which the predominance of samples pertaining to cluster 2 in the area outside the inlet throat is clearly shown. As previously stated, in this area the ebb-jet velocity diminishes abruptly owing to the ebb-flow spreading seaward, leading to deposition of the coarsest fractions to form the ebb-tidal delta morphology.

Finer and lesser sorted sediments are distributed in the deepest seafloor portions, located beyond the terminal part of the ebb-tidal delta and in the entrance channel. Sediments characterized by intermediate grain size values are located within the ebb-tidal delta morphology, with better sorted sediments at lower water depths where wave energy can easily act to rework the seafloor. At greater water depths, in correspondence to the ebb-tidal delta terminal lobe, sediments are not easily reworked by wave action thus lesser sorted.

5.2.1.3 Management options

The final step of the evaluation procedure consisted in the identification of a potential sand borrow site within the ebb-tidal delta, given specific queries to the GIS database. The conditions set for the queries are the following:

- Deposit thickness > 0.5m;
- % sand > 95%;
- $M_z < 2.75\phi$;
- Sorting < 0.5$\phi$

Mean grain size values were selected as being representative of the majority of beach sediments deposited along the northern Adriatic coastal area. The setting of greater values would in fact identify sand sources characterized by borrow sediments finer than the native sediments, thus leading to an inefficient beach-fill (see section 2.4). The result of the query process is illustrated in Figure 5.10: the potential borrow site was estimated to extend over an area of 2.228.940m$^2$, located in the part of the ebb-tidal delta morphology more adjacent to the coast. The site is located at water depths between 6m and 8m, with a sand percentage >95%, and mean grain size values between 2.15$\phi$ and 2.75$\phi$. The potential deposit reaches a maximum thickness of 1.95m. Given the hypothesis of dredging a uniform layer of 80cm, the sand volume that could be extracted is estimated to be around 1.830.000m$^3$. 
Figure 5.10 – Lido potential borrow area

Figure 5.11 – Lido bathymetry after hypothetical dredging
The resulting seafloor bathymetric configuration was elaborated though digital mapping and it is shown in Figure 5.11. In this case, the dredging of a 80cm thick layer would preserve the ebb-tidal delta morphology thus avoiding strong modifications of the nearshore bathymetry. The application of the TIRM was found to be useful also in order to calculate the hypothetical recovery time of the submerged delta feature. In fact, given a new ebb-tidal delta volume of $3.98 \times 10^6 \text{m}^3$ obtained after dredging, it is estimated that a period of 14-15 years is needed to reach initial volume, being constant both tidal prism and longshore transport rate.

Graph 5.2 – Hypothetical recovery time for the Lido ebb-tidal delta after dredging on the basis of the Tidal Inlet Reservoir Model
5. RESULTS

5.2.2 Malamocco ebb-tidal delta

Malamocco inlet serves as a conduit for waters flushing inside and outside the central portion of the Venice lagoon. Through the examination of the 1987 bathymetric map (Figure 5.12) it is possible to observe inlet configuration, which is only slightly asymmetrical due to beach accretion on the updrift barrier island. The inlet channel, the first to be stabilized through jetties in 1808-1840, reaches a maximum water depth of 20m, and extends far seaward due to the long jetties reaching the 10m seafloor water depth, the northern jetty being 300m longer than the southern one.

![Figure 5.12 – Malamocco inlet bathymetric map, 1987](image)

Owing to its central location within the Venice Lagoon barrier island system and its use as main shipway to the Porto Marghera industrial area, the evolution of Malamocco inlet and offshore area in the last century have been particularly complex. Dredging operations have been carried out frequently since the channel stabilization, to maintain a navigable pass. Outside the inlet throat, the influence of the ebb-jet spreading seaward extends far offshore, generating a strong interference to longshore currents on both sides; bathymetric lines are
5. RESULTS

deflected quite symmetrically towards the water depth of 14m. Littoral drift is mainly intercepted by Lido inlet and Chioggia inlet and the longshore transport rate after jetties construction was estimated around 30,000 m$^3$ y$^{-1}$ (CVN, 1989).

ADP have been applied to Malamocco inlet bathymetric data through the use of a third order polynomial surface in order to obtain the hypothetical no-delta bathymetry. The depositional feature represented in Figure 5.13 was estimated to store around 4,380,000 m$^3$ of sediments, reaching a maximum thickness of 2.50 m. The ebb-tidal delta morphology, although also in this case downdrift located, significantly differs from the lobate-shaped feature individuated at Lido inlet. The overall deposit exhibits a more elongated shape and maximum thickness values are reached at shallower depths.

Equilibrium volume was calculated through the application of the Hicks and Hume (1996) formula, giving a value of 65,430,164 m$^3$. Also in this case a great difference was found between the ADP calculated value and the result of the formula, giving value to the hypothesis that Malamocco ebb-tidal delta have experienced a morphological evolution similar to the one
5. RESULTS

occurred at Lido inlet, leading to the formation of a new ebb-tidal delta after jetty construction. However, the analysis of Malamocco ebb-tidal delta appears rather controversial, due to the complex hydrodynamics processes occurring in the area, and these preliminary results must be carefully evaluated. A comparison with more recent surveys would be useful in order to detect more precisely the submerged morphologies; unfortunately at present there is a lack of updated data. The TIRM was applied to analyse the long-term changes in volume of the ebb-tidal delta after jetty construction; in this case the input parameters are: \( Q_{in} = 30000 \text{m}^3\text{y}^{-1} \) (CVN, 1989) and \( V_{e} = 6.54 \times 10^7 \text{m}^3 \), calculated by equation (8). The value of \( \alpha \) calculated for these parameters is 0.000459. The model gives a value of 4.348.742 \text{m}^3 of material stored after a time period of 150 years; if considering 1840 as the initial time of development of the ebb-tidal delta structure this results indicates that the volume calculated through ADP could be comparable with the 1990-predicted value. Although this result well agree with our estimation, collected data were not considered sufficiently reliable to provide an exact volume, but only a preliminary estimation concerning the location and extent of the ebb-tidal delta.

5.2.3 Chioggia ebb-tidal delta

Chioggia inlet is situated at the southern end of Venice lagoon. During the 1930s it was stabilized through the construction of jetties, and since that time the inlet’s natural equilibrium has continued to be effected by periodical maintenance dredging, and more recently the construction of a detached breakwater 520m long in front of the inlet (Villatoro, 2007). The available data (Brambati, 1987) were digitized in order to analyse the bathymetric configuration outside the inlet and to apply the ADP procedure. Figure 5.14 illustrates the seafloor morphology: as for Lido and Malamocco inlets, the construction of jetties led to a seaward shifting of the entire ebb-tidal delta system. Bathymetric lines configuration reveals the existence of a submerged morphology located between the 6m and the 12m water depth. Although the overall inlet configuration is not as asymmetrical as at Lido inlet (the adjacent shorelines are more parallel), a third order polynomial surface was selected to represent the no-delta bathymetry.
Moreover, in this case the differences in ebb-tidal delta volume calculation arising from the subtraction of a third or a first order polynomial trend are in the order of ±200,000 m$^3$, thus very small. The potential sand deposit was estimated to be around 1,845,000 m$^3$ for a thickness>0m; 1,106,000 m$^3$ for a thickness>0.5m; 587,000 m$^3$ for a thickness>1m.

Figure 5.15 illustrates the isopach map elaborated after ADP procedure; the ebb-tidal delta deposit appears to be quite asymmetrical and located in the southern area outside the inlet throat. No channel margin linear bars or any specific features are evident, although a poor precision in the representation could be due to scarce original data quality. Therefore, a more detailed bathymetric survey and sediment sampling would be useful to provide a more detailed characterisation of the ebb-tidal delta morphology. Villatoro (2007) presented the results of a recent (2005-2006) bathymetric survey and sediment sampling outside Chioggia inlet. The author also recognized the asymmetrical ebb-tidal delta being situated south-east of Chioggia inlet mouth and not being characterized by any specific feature such as a channel margin linear bar.
Volumetric growth is not easily calculated in this case; Villatoro (2007) estimated the rate of growth between 1990 and 2006 to be around 50,000 m$^3$y$^{-1}$, while CVN (1989) reports the longshore transport rate after jetties construction being around 40,000 m$^3$y$^{-1}$. According to Hicks and Hume (1996), the equilibrium volume would be 27,079,172 m$^3$, which is significantly greater than the volume obtained through the application of the Residual Method. Also in this case, collected data are to be considered not sufficiently reliable to calculate an exact value, thus the simplified version of the TIRM was applied to Chioggia ebb-tidal delta only to provide a preliminary analysis concerning the rate of growth of the delta feature. Input parameters in this case are: $Q_m = 40,000$ m$^3$y$^{-1}$ (CVN, 1989) and $V_{eq} = 2.71 \times 10^7$ m$^3$, calculated by equation (8). The value of $\alpha$ is 0.0059. The value obtained for a period of 55 years after jetties construction, corresponding to the year 1988, is 2,113,004 m$^3$, which is slightly greater than 1,845,000 m$^3$. Therefore, given the actual longshore transport rate, the ebb-tidal delta would need a great amount of time to reach theoretical equilibrium volume.
5. RESULTS

5.2.4 Caleri ebb-tidal delta

5.2.4.1 Ebb-tidal delta volume calculation

Caleri tidal inlet, as shown in Figure 5.16, exhibits a quite symmetrical configuration. The main ebb channel is initially diverted southward flanking Albarella island shoreline, and when spreading seaward it assumes an orientation perpendicular to the coast. A marginal flood channel is developed adjacent to the downdrift coast. As a consequence of the symmetrical configuration, characterized by lateral swash bars adjacent to the ebb-jet spreading area, the channel margin linear bar is not present. Bathymetric lines are deflected to the same extent on both the updrift and downdrift sides of the inlet, and they become straighter in correspondence to the 4m water depth.

![Figure 5.16 – Caleri bathymetric map](image-url)
In order to evaluate the potential volume of sand stored in the ebb-tidal delta, the ADP has been applied. In the case of Caleri inlet, due to the symmetrical configuration of the inlet/ebb-tidal delta system, a first order polynomial trend was applied to create the no-delta bathymetry. The result of the procedure is shown in Figure 5.17; as for Lido, Chioggia and Malamocco inlets only positive anomalies are displayed to evidence the ebb-tidal delta morphology. The estimated positive values is $1.400.000\,\text{m}^3$, with a volume of $363.000\,\text{m}^3$ for a thickness $>0.5\text{m}$ and a volume of $56.000\,\text{m}^3$ for a thickness $>1\text{m}$. In this case, the calculation well agrees with the estimation provided by the application of the Hicks and Hume (1996) formula, which gives a value of $1.330.843\,\text{m}^3$.

The ebb-tidal delta morphology is symmetrical or slightly asymmetrical in the downdrift direction. The terminal lobe is located at the $3\text{m}$ water depth and swash bars are present on the downdrift side of the inlet channel, possibly fed by an active sand bypass process to the downdrift coast. Given the shallower depth at which the sand features are located, wave induced currents can be effective in reworking sediments thus moving them landward.

![Figure 5.17- Caleri ebb-tidal delta](image-url)
5.2.4.2 Sedimentology

As for Lido inlet, grain size parameters were processed to investigate sediment patterns within the ebb-tidal delta. Elaborations were used to produce maps representing sand-percentage, mean grain size and sorting distributions. Following Kruit-Nota (Nota, 1959) classification, as shown in Figure 5.18, the majority of the samples consists of sand, thus characterized by a mud-percentage lower than 5%. Although five samples consist of pelitic sand, they are characterized by a sand-percentage slightly less than 95%, never reaching values less than 90%.

![Figure 5.18 – Caleri sand-percentage distribution](image)

The analysis of the mean grain size parameter following Udden-Wentworth shows that 44 samples consist of fine sands (Mz between 2\(\phi\) and 3\(\phi\)) while 18 are defined as very fine sand (Mz between 3\(\phi\) and 4\(\phi\)). Figure 5.20 illustrates mean grain size distribution at 0.10\(\phi\) intervals, representing sediment patterns outside the inlet throat. The progressive decrease in mean grain size is due to the process of seaward sediment spreading from the inlet to form the ebb-tidal delta morphology. More in detail, the submerged delta feature consists of sediments
reaching mean grain size values of $2.8\varphi$, not uniformly distributed along the $-2.5m$ bathymetric line. Coarser sediments, reaching the $2.6\varphi$ value, are located inside the inlet and in the ebb-jet spreading area, which exhibit an asymmetrical downdrift configuration. The coarsest sediments (represented by 3 samples) are characterized by mean grain size values $< 2.4\varphi$ and are found within the main channel and in the marginal flood channel flanking Albarella island, the areas interested by highest energetic conditions.

Most of the samples have a sorting coefficient between $0 < \sigma < 0.35\varphi$ and only five samples present values between $0.35 < \sigma < 0.50\varphi$. Data were grouped by three different classes and the distribution is shown in Figure 5.20, in this case IDW or kriging interpolation technique were not used to represent sorting distribution. The exact values were reported in the map, as the low data variability would have not allow an accurate representation. Sorting values comprises between $0.26 - 0.35\varphi$ (very well sorted) characterize in fact the majority of the sample, thus giving evidence of rather strong energetic conditions within the area. Waves approaching the nearshore zone are able to select the deposited material leading to a quite uniform distribution throughout the seafloor.
5. RESULTS

Figure 5.19 – Caleri mean grain size distribution

Figure 5.20 – Caleri sorting distribution
Cluster analysis has been applied, as for Lido study area, through the linkage Ward’s method and by using the statistical software STATISTICA. Data divided in classes of 0.5φ mean grain size values has been processed and the resulting dendrogram is shown in Figure 5.21.

Through the examination of the resulting dendrogram, the number of clusters has been selected. The first step has been to cut the dendrogram at a distance of \((D_{\text{leg}}/D_{\text{max}})*100 = 25\) to obtain 3 clusters, then the dendrogram has been cut at a distance of \((D_{\text{leg}}/D_{\text{max}})*100 = 15\) and 5 clusters were obtained.

- **Cluster 1**: groups the 3 coarsest samples, with mean grain size values of 2.5φ, very well sorted;
- **Cluster 2**: groups 11 samples characterized by a mean grain size values of 3.0φ;
- **Cluster 3**: groups 19 samples, with mean grain size values around 3.0φ, very well sorted;
- **Cluster 4**: groups 9 samples characterized by higher values of sorting and finer grain size, with values reaching 3.5φ;
- **Cluster 5**: groups 15 well sorted samples, with mean grain size values reaching 3.0φ.
Graph 5.3 – Clusters mean frequency distribution

Figure 5.22 – Caleri cluster distribution
In Graph 5.3 the frequency distribution of each cluster is displayed: cluster 1 is characterized by the lowest $\phi$ values thus indicating coarser sediments, mean grain size values decrease from cluster 2 to 3, to 5 and finally to cluster 4. The map elaborated to show the cluster distribution within the seafloor surface is presented in Figure 5.22: sediments in the area relative to the main inlet channel pertain to cluster 1 and are subjected, together with three samples pertaining to cluster 2, to the highest energies. High current velocities develop in the ebb-jet spreading area within the main channel, leading to the transport and following deposition of the coarsest fraction.

The progressive decrease in current velocities and overall energy is represented by sediments grouped in cluster 2, that have been reworked by currents characterized by lower velocities. Cluster 3 and 5 are quite uniformly distributed along the terminal lobe, with better sorted sediments pertaining to cluster 3 located in the updrift area adjacent to the channel, where wave action is able to exert a selection on grain sizes. Cluster 4 is located at higher depths, were prevailing marine currents are responsible for particles movement, thus leading to poorly sorted sediment samples.

5.2.4.3 Management options

Although the borrow site within Caleri ebb-tidal delta has resulted to be characterized by relatively low sand volumes, an evaluation has been conducted in order to identify a potential nourishment site among adjacent beaches.

A first option concerned the potential use of sand trapped at Caleri ebb-tidal delta for the nourishment of Rosapineta beach, a site located approximately 5km north on the updrift coastline. The northern section of the shoreline has been affected since 1962 by a significant erosional process, with trends comprised between 5my$^{-1}$ and 2my$^{-1}$, (DISGAM, 2007). To contrast sediment losses the shoreline has been stabilized through jetties, breakwaters and a detached breakwater. Unfortunately, these interventions have been ineffective in protecting the beach from wave scouring and 22.000m$^3$ of sand was placed on the site in october 2006 to contrast erosion during the winter season. Afterwards, the best solution has been individuated in the hypothesis of a beach renourishment project. The project indicates a total volume of 225.000m$^3$ of sand to be placed on the northern sector of the coastline, thus due to its proximity to the beach Caleri ebb-tidal delta could represent a suitable borrow area. After
processing the bathymetric and grain size data (that were collected also at Rosapineta beach within the same survey and underwent the same analysis) the hypothesis was tested. Grain size parameters of the native and the borrow areas\(^5\) were compared in order to obtain values of \(R_A\) and \(R_j\) (see section 2.4); resulting parameters are reported in the scheme below:

\[
\begin{array}{|c|c|c|c|}
\hline
M_\varphi_n & M_\varphi_b & \sigma_n & \sigma_b \\
\hline
1.91 & 2.49 & 0.27 & 0.3 \\
\hline
\end{array}
\]

On the basis of these values, \(R_A\) resulted >10 and \(R_j = 7.62\), indicating a rather unstable project. Beach sediments resulted in fact significantly coarser than borrow sediments, possibly due to their proximity to the Adige river mouth, and the amount of material to be filled would be in this case so large to make the project unfeasible. Hence, the hypothesis was rejected.

Although at present information about the sedimentology of other adjacent sites are not available, an alternative solution considers the placement of sand trapped within Caleri ebb-tidal delta on southern shorelines, as for example along Albarella island beaches, following an analogue evaluation of grain size compatibility.

5.2.5 Porto Buso ebb-tidal delta

Updated information were collected at Buso inlet in october and november 2006 by OGS within the VECTOR project. Buso inlet is one of the six conduits for daily tidal exchange between the Adriatic sea and the Grado-Marano lagoon and is flanked by S. Andrea and Banchi d’Orio barrier islands, respectively on the eastward and westward sides. Its central location makes it the boundary between the westernmost Marano lagoon and the easternmost Grado lagoon. The channel has been stabilized in 196-1968 through jetties, now reaching the southern the 3.5m water depth, while the northern lays at the 2.5m water depth. Due to the stabilization though jetties, inlet configuration is nowadays markedly asymmetrical. Updrift shoreline extends far offshore, leading to a morphology very similar to that observed at Lido inlet. Of note is that Banco d’Orio adjacent barrier island undergone significant adjustments

\(^5\) In this case only samples located within the ebb-tidal delta deposit with thickness >1m were used to calculate \(M_\varphi_b\) and \(\sigma_b\).
after the new configuration and sand accumulation took place in proximity of the northern jetty.

Figure 5.23 – Buso inlet bathymetric map

The isopach map resulting from the application of the Residual Method is shown in Figure 5.24: sediments appear to be deposited in the westward direction outside the inlet throat and a bypassing process from the eastward to the westward direction possibly takes place. Maximum deposition reaching 2.5m thickness occurs at 6m water depth in front of the inlet throat, and the seaward delta terminal portion appears to be located along the 7m water depth. The overall ebb-tidal delta feature develops at water depths between 3m and 7m, thus in relatively shallow water if compared to the Venice lagoon tidal deltas. This is possibly due to the jetties’ lesser extent, resulting in the ebb-jet spreading area located in shallower waters. However, the resulting morphology at Buso inlet is very similar to that observed at Lido inlet, characterized by a strong asymmetry of the adjacent coastlines and a downdrift development of the ebb-tidal delta feature. Additionally, examination of old historical maps dating back to 1915 prior
to the construction of jetties showed a seafloor morphology interested by a wide shallow platform, on which the present depositional feature could be possibly superimposed.

The estimation of sand volume trapped at Buso ebb-tidal delta provided a value of 1.849.746 m$^3$, whereas the theoretical equilibrium volume calculated through equation (8) is 5.448.732 m$^3$. Hence, it appears that also in this case the sand accumulation feature has not reached equilibrium volume. It would be extremely interesting to apply the Reservoir Model, in order to evaluate the rate of growth of the ebb-tidal after inlet stabilization given the hypothesis of its seaward diversion. Unfortunately, reliable values of $Q_{in}$ for the area are not available, thus not allowing the calculation of $\alpha$ which is an essential parameter for equation (13).

Figure 5.24 – Buso ebb-tidal delta
5.3 Tidal prism – ebb-tidal delta volume relationship

The results of ebb-tidal delta volume calculations have been plotted against tidal prism values (see section 3.2), to obtain a tidal prism ebb-tidal volume relationship valid for the northern Adriatic coastal area. Prior to this research, five ebb-tidal deltas were studied (Fontolan et al., 2007) and following the collection and processing of new data, the relationship has been elaborated for six natural and almost natural inlets, obtaining the following equation:

\[ V = 8.157 \times 10^{-5} P^{1.4636} \]  

(18)

![Figure 5.25 – Tidal prism – ebb tidal delta volume relationship for northern Adriatic inlets (after: Fontolan et al., 2007, modified).](image)

As shown in Figure 5.25, equation (18) well agrees with the relationship elaborated by Hicks and Hume (1996) for the New Zealand inlets, whereas significantly differs from the analogue relationships found for the U.S. study areas. Hence, it was found that the interaction of wave
and tidal energy conditions which characterize the northern Adriatic coastal area tend to
develop smaller ebb-tidal delta features if compared to the U.S coastal areas.

Values relative to jettied inlets (Lido, Malamocco, Chioggia and Buso) were not plotted in the
graph, as calculated volumes at these inlets were found to be significantly different from all
theoretical volumes obtained through the application of empirical relationships. Additionally,
values obtained for Chioggia and Malamocco inlets are based on data that were not considered
sufficiently reliable to provide a final estimation, thus results concerning these inlets are only
preliminary and must be verify by more updated surveys. However, they provided indications
on ebb-tidal delta location, overall shape and a first estimation of the order of magnitude of
trapped sand volumes.

So far, a significant outcome of the research is the identification of a different behaviour
between natural and almost natural inlets and stabilized inlets, where the first follow
predictable relationship concerning ebb-tidal delta growth whereas the latter exhibit a more
complex development. Given the volumes predicted by either equation (8) or equation (18), it
seems that jettied inlets have developed ebb-tidal deltas smaller than expected, as shown in
Table 5.1.

Table 5.1 – Summary of ebb-tidal delta volumes at northern Adriatic inlets and comparison
with empirical relationships.

<table>
<thead>
<tr>
<th>INLET</th>
<th>TIDAL PRISM</th>
<th>VOLUME</th>
<th>HICKS AND HUME</th>
<th>NA RELATIONSHIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGNANO</td>
<td>40×10⁶</td>
<td>10.998.329</td>
<td>9.841.526</td>
<td>10.912.028</td>
</tr>
<tr>
<td>GRADO</td>
<td>23.4×10⁵</td>
<td>5.039.855</td>
<td>4.621.173</td>
<td>4.978.678</td>
</tr>
<tr>
<td>S.ANDREA</td>
<td>3.12×10⁶</td>
<td>269.910</td>
<td>269.722</td>
<td>260.841</td>
</tr>
<tr>
<td>BASELEGHE</td>
<td>5.2×10⁶</td>
<td>269.910</td>
<td>269.722</td>
<td>260.841</td>
</tr>
<tr>
<td>PRIMERO</td>
<td>6×10⁵</td>
<td>593.563</td>
<td>678.190</td>
<td>679.255</td>
</tr>
<tr>
<td>CALERI</td>
<td>9.5×10⁶</td>
<td>1.432.000</td>
<td>1.296.497</td>
<td>1.330.843</td>
</tr>
<tr>
<td>BUSO</td>
<td>26.3×10⁶</td>
<td>1.849.746</td>
<td>5.448.732</td>
<td>5.907.146</td>
</tr>
<tr>
<td>LIDO 2006</td>
<td>1.45×10⁸</td>
<td>5.810.053</td>
<td>60.490.438</td>
<td>71.863.551</td>
</tr>
<tr>
<td>MALAMOCCO 1987</td>
<td>1.36×10⁸</td>
<td>4.387.778</td>
<td>55.264.686</td>
<td>65.430.164</td>
</tr>
</tbody>
</table>
5. RESULTS

The analysis conducted through the application of the Tidal Inlet Reservoir Model were aimed at understanding whether ebb-tidal deltas at jettied inlets would reach theoretical equilibrium volumes. A fundamental assumption in the TIRM is that the growth of the depositional features is determined by the input longshore transport rate, and by the rate between the sediment supply and the equilibrium volume, which is a function of tidal prism. Hence, in presence of small sediment supply and large tidal prism and associated theoretical equilibrium volume, a long time may be required to reach equilibrium volume. For this reason, given the present longshore transport rates, Venice lagoon inlets are far from having reached the theoretical equilibrium volume, which is very large. It should also be emphasized that morphodynamic evolution has been governed by human intervention, thus a new equilibrium state adapted to the changed configuration of the main ebb channel. A marked downdrift asymmetrical morphology of the ebb-tidal delta has been described at Lido, Malamocco, and Chioggia inlets, possibly related to different factors as the magnitude and direction of net longshore transport, the magnitude of tidal prism and the offshore extent of the ebb jet, the presence of a relict ebb-tidal delta feature, dredging operations on the channel and finally wave refraction and diffraction over the offshore bathymetry and delta structure.

In the examined cases, sediment deposition is controlled by the relative strength of the tidal jet within the jettied channel versus the input longshore transport rate. Jetties tend to enhance the ebb-jet velocity and its seaward extension, while the longshore transport in many cases provides sand also to the updrift shores. Once the seafloor bathymetry reaches the local closure depth in correspondence to the jetty’s terminal end, a sand bypass process to the downdrift side may start. Additionally, local wave and transport reversal through wave refraction may occur on the downdrift area, thus originating an asymmetrical morphology.
5. RESULTS

5.4 River delta deposits

The first phase in order to analyse the morphological evolution at the Piave and Adige river mouths was performed by processing the data gathered in the 1970s. This led to a general comprehension of the morphodynamic processes occurring in the areas, mainly related to seasonal cycles of erosion and deposition.

The following phase has been to compare this data with the more recent surveys, in order to investigate the morphological evolution of the delta front features during a time frame of 30-40 years; this allowed the identification of strong scouring processes occurring outside the river mouths. Finally, only the more recent data collected at Piave, Adige and Sile river mouths were used to analyse the present morphological evolution.

5.4.1 Piave river mouth

The results of investigations carried out by the Consiglio Nazionale delle Ricerche (Di Silvio and Lippe, 1976) during autumn 1972 and spring 1973 were used to analyse the main morphological features situated in the nearshore area facing the Piave river mouth. The submerged delta morphology (Figure 5.26 and Figure 5.27) was at that time well developed as represented by the bathymetric pattern, that diverted seaward and reached the depth of 5m. The deflection of the bathymetric contour lines reaches the -10m depth; offshore the contour lines follow a straight configuration. The submerged delta exhibits a south-western orientation, which is related to the existent littoral drift, and large sand bars are located at the downdrift side of the river mouth, adjacent to the coast. By subtracting the two bathymetric maps an isopach map was created (Figure 5.28), from which seasonal variations in the submerged delta morphology could be observed. The main process that had occurred between November 1972 and May 1973 is a process of erosion, possibly due to marine currents scouring the seafloor in absence of significant sediment supply (of note is that no significant flood events were measured within the examined time frame). Sand bars lost a small volume of sediment that was subsequently reworked by waves and marine currents, thus highlighting the relative influence of marine processes versus fluvial processes.
5. RESULTS

Figure 5.26 – Piave river delta bathymetric map, November 1972

Figure 5.27 – Piave river delta bathymetric map, May 1973
5. RESULTS

Updated DEMs has been created using data from the surveys (carried out by Te.Ma snc for the Magistrato alle Acque through its concessionary Consorzio Venezia Nuova) collected in April 2002 and May 2005, as shown in Figure 5.29 and in Figure 5.30. Although these recent surveys did not reach the same depth as the previous ones (only -6m depth versus -10m depth), the submerged delta morphology has been detected, due to the fact that the delta front deposits usually develop in shallow waters. Similarly to the 1972-1973 situation, the delta was found to be more developed in the downdrift direction and the presence of sand bars is more evident in the 2005 survey. By drawing the analysis mask on the more recent data, two comparisons have been made with the older surveys, the first relative to the period 2005-1973 and the second to the period 2002-1972; results are illustrated in Figure 5.31 and Figure 5.32. The resulting maps clearly show that a very strong erosional process has occurred during the last thirty years in the area adjacent to the river mouth, leading to the loss of a significant sediment volume, quantified by the following values:

- **DIFFERENCE 2002-1972**: $2,478,186 \text{m}^3$
- **DIFFERENCE 2005-1973**: $2,134,280 \text{m}^3$
5. RESULTS

Figure 5.29 – Piave river delta bathymetric map, April 2002

Figure 5.30 – Piave river delta bathymetric map, May 2005
5. RESULTS

Figure 5.31 – Piave river mouth, difference 2002-1972

Figure 5.32 – Piave river mouth, difference 2005-1973
Additionally, the more recent morphological evolution has been investigated. Figure 5.33 illustrates the variations occurred between the 2005 and 2002 surveys; a moderate depositional process have taken place, with sediment accumulation estimated to be around 35,000m³. However, this deposition is very modest if compared to the amount of material lost by the system, value the has been quantified around $2 \times 10^6$m³.

River flow measurements available for the period were examined in order to find out to what extent fluvial inputs may have influenced recent morphodynamics. Available data, relative to the period January 2002-February 2003, as already reported in Graph 3.3., show major flood events occurred in November 2002, characterized by maximum discharge values of 2000, 1300 and 1000 m³/s. During these high transport episodes sediments may be deposited within the delta front, and afterwards reworked by wave action and marine currents.

Following these analysis, some considerations were made regarding the opportunity of a hypothetical utilization of sand deposited in the delta front area for beach nourishment projects. First of all, the evaluation of the morphological evolution over the last thirty years has evidenced how strong erosional processes affected the delta front and its associated...
features. Moreover, the analysis of the nearshore morphodynamics developed for the 1972-1973 data had showed the prominent role of marine currents and wave energy in transporting sediments out of the area.

An explanation to the outcomes of the analyses may arise from a simple consideration: the decrease in river supplies which, as reported in detail in section 3.3, originates as a consequence of the heavy human interventions occurred throughout the river basin dating back to the 1950s has strongly affected the depositional processes in the nearshore seafloor area. A decreasing amount of sediments is discharged within the delta front, to be removed by marine currents and waves during storms.

Unfortunately, these considerations may not be confirmed by solid transport measurements and explanations are here provided only by qualitative considerations. However, these achievements has been considered sufficiently reliable to reject the hypothesis of an utilization of delta front deposits for beach nourishment, as sand extraction in the area would certainly lead to an increase in erosional phenomena. Episodically flood events are not considered sufficient to provide adequate sediment supply to the area.

5.4.2 Adige river mouth

Similarly to the analysis provided for the Piave river, data collected during the 1970s at the Adige river mouth were analysed to investigate the general morphology and dynamics of the nearshore area. On the basis of several bathymetric maps, it has been possible to examine river mouth and submerged delta morphology and also to observe seasonal variations of the associated features. As shown in Figure 5.34 and Figure 5.35, in proximity of the river mouth bathymetric lines start to deflect towards north-east, to become more straight around the -9m depth. Submerged bars are present at shallow depths along the northern coastline, while along the southern shoreline a bar-through morphology is evident.

Summarizing results found by CNR (1980), it was reported that between autumn 1973 and summer 1977 alternating erosional-depositional events had occurred, and this process is influenced by episodical flood events and marine forces, as observed for the Piave river mouth. More precisely, it was found that sediment transport capacity by the Adige river has been characterized by strong variations between years, with positive (august 1974-august1975; august 1976-august1977) and negative (august1975-august1976) balances.
Figure 5.34 – Adige river mouth bathymetric map, November 1973

Figure 5.35 – Adige river mouth bathymetric map, May 1975
Recent surveys are available from June 2001 to May 2006 (carried out by Te.Ma snc for the Magistrato alle Acque through its concessionary Consorzio Venezia Nuova); bathymetric data reaching the 9 m water depth were collected and elaborated. Bathymetries in the area located outside the river mouth appear to be strongly deflected in a north-east direction both in June 2001 and in December 2003 (Figure 5.36 and Figure 5.37). The submerged delta, which extends to the 8 m water depth, exhibits a cuspat e morphology which is particularly evident in the map representing the June 2001 situation. In the following years, the morphology appears less extended seaward and becomes more flattened, as clearly shown in the maps presented in Figure 5.38 and Figure 5.39.

Starting from the 1970s, submerged sheet piles have been placed outside the river mouth in order to divert seaward the river flow responsible for a low marine water quality, thus creating a negative impact to recreational activities (i.e. bathing) usually taking place in the area. At the beginning the placement was only experimental, while after 1999 it has become continuous during the summer season, whereas during winter months the sheet pile structures are removed.
Figure 5.37 – Adige river mouth bathymetric map, december 2003

Figure 5.38 – Adige river mouth bathymetric map, may 2005
5. RESULTS

Figure 5.39 – Adige river mouth bathymetric map, may 2006

With the aim to analyse the long-term evolution, the 2005 map and the 1975 map were compared, and an isopach map showing the differences that had occurred over the entire period has been produced. The isopach map is illustrated in Figure 5.40: as for the Piave river, within the thirty years period the delta front area has been subjected to a strong scouring process, leading to a sediment loss of about 1.580.000m$^3$. In chapter 3 a detailed analysis of the variations in the Adige river regime has been presented, highlighting how human activities are responsible for the decrease in both river flow and sediment transport capacity. Strong modifications occurred at the river basin after the 1950s and continue nowadays, leading to decreased sediment supply to the coast. Therefore, the situation illustrated in Figure 5.40 is a consequence of these modifications, that in the nearshore area led to a prevalence of marine currents over fluvial inputs. Episodical flood events, which may transport a large amount of sediment to the coast, are not able to contrast marine erosion.
5. RESULTS

Figure 5.40 – Adige river mouth, difference 2005-1975

Through the examination of the more recent surveys, it has also been possible to observe the occurrence of erosional phenomena developing on a smaller time scale. The comparison between the 2005 and 2001 DEMs, as displayed in the map reported in Figure 5.41, shows that a significant scouring process has occurred during the 4-years period. The estimated sediment loss reaches the value of 800,000 m³, a significantly high value if considering the short period of time. Among the different processes that could be responsible for the phenomenon (i.e. sand extraction for Isola Verde beach nourishment project), it can be easily recognized through the examination of the map that the interaction between waves approaching the shore with the terminal part of the sheet piles is possibly responsible for the creation of a turbulent circulation, more concentrated around the northern structure, leading to a scouring process adjacent to the structures.
In conclusion, it is rather clear that given the present morphological processes occurring at the Adige river mouth, episodical discharges would not be able to positively alter the existing erosional trend. These considerations led to consider inappropriate the application of geostatistical procedures, and the hypothesis of sand extraction from the (potential) depositional features located outside the river mouth was considered not feasible. Similarly to what stated for the Piave river mouth, an intervention in the area would affect an already critical situation which continues nowadays, as resulted from the examination of the more recent data collected in may 2006.

5.4.3 Sile river mouth

The elaboration of data collected at Sile river mouth concern bathymetric profiles gathered in may 2005 and may 2003 by Te.Ma snc for the Magistrato alle Acque through its concessionary Consorzio Venezia Nuova.
5. RESULTS

Figure 5.42 – Sile river mouth bathymetric map, May 2003

Figure 5.43 – Sile river mouth bathymetric map, May 2005
Data taken in May 2002 did not contain an adequate number of profiles to provide reliable elaborations, thus they were not used. As described in section 3.3, the particular flow regime of the Sile river is characterized by a nearly regular discharge throughout the year, and modest values. Moreover, as it does not drain a mountain basin, the transported material mainly comes from bed scouring. Hence, although sediment supply to the coast is regular, values are rather low. The analysis of the river mouth morphology, as shown in Figure 5.42 and in Figure 5.43, gives evidence of a small pronounced delta feature, as a consequence of the low sediment supply. Outside the mouth, which is fixed by small jetties, bathymetric lines are slightly deflected, and tend to reach a straight configuration at shallow water depths. The deflection is quite symmetrical and a bar-trough morphology is evident adjacent to the updrift shoreline. In this case, the elaborations have been negatively influenced by a poor data covering, that led to strongly rectified interpolations. However, through the examination of the map elaborated by subtracting the 2003 DEM from the 2005 DEM, as shown in Figure 5.44, it has been estimated a loss of sediment of 32,271 m³ in proximity of the river mouth.

Figure 5.44 – Sile river mouth, difference 2005-2003.
An accumulation of sediments is evident in the north-eastern portion, probably as a consequence of beach nourishment interventions that took place along the updrift beach at the end of the 1990s. Although the results here presented are influenced by the scarcity in the number of profiles, they clearly show that the Sile river mouth does not present significant morphologies and/or sand accumulation features, as a consequence of its hydrological regime.

5.5 Sand resources geodatabase

All elaborations and final estimations of sand volumes have been integrated into a broad data set, which includes ESRI ArcGIS™ shapefiles and raster files storing bathymetric and grain size data relative to the different study areas. Hence, in order to develop a useful tool for sand resources management, these information have been stored in a personal ESRI ArcGIS™ geodatabase specifically created for the study.

5.5.1 Personal geodatabases

A geodatabase is a container for spatial and attribute data in which it is possible to store existing GIS data. Additionally, it has the capability of supporting multiple data types, in relational tables, with rules that define relationships and behaviour. Most elements and properties in a personal GDB are stored within a Microsoft Access file
Core elements of a geodatabase are the followings:

- feature class: collections of features sharing the same type of geometry and the same attributes;
- feature dataset: collection of feature classes that share the same spatial reference;
- table;
- raster: raster data are seemingly stored in the geodatabase, as either Raster Datasets or Raster Catalogs. A raster dataset is any valid raster format that organizes data into bands and may include mosaics, while a raster catalog is a collection of raster datasets stored in a table, in which each raster dataset keeps its own properties. Additionally, raster data in the personal GDB can be managed or unmanaged by the GDB: managed data are converted to IMG format while unmanaged data are analogous to hyperlinks.

### 5.5.2 Ebb-delta geodatabase

For the evaluation of suitable borrow areas the utility of a geodatabase arises from its large query capacity. Once sand volumes and associated grain size characteristics are appropriately catalogued and the requirements for a specific beach nourishment project are identified, a simple query may identify the best borrow site for the project.

Along the northern Adriatic coastal area the presence of a large number of inlets and associated ebb-tidal deltas provides a potential sand resource for adjacent beaches, with the main advantage of being located in the proximity of the sites to be nourished thus reducing operational costs. Within this context the use of a geodatabase is of primary interest as it allows the identification of the nearest optimal borrow site. A description of the Ebb-delta Geodatabase tool is here provided, in order to illustrate its main features and the overall functioning. The tool can be implemented after new surveys and the collection of more updated data to cover the entire coastal area, by simply loading new GIS items into the existing feature classes and raster datasets. All feature classes and raster datasets refers to the Gauss-Boaga projected coordinate system.
The following elements constitute the Ebb-delta Geodatabase:

- A single feature classes named SAMPLES which groups all shapefiles (point features) relative to grain size characteristics;
- Several single feature classes, each storing bathymetric data relative to a single inlet/tidal delta system;
- Raster datasets relative to the different study areas. As raster datasets do not allow data overlapping, different datasets were created for each location in order to store data relative to ebb-tidal delta deposits; sand percentage distribution; mean grain size distribution and sorting distribution. Study areas were named Grado_Marano; Caorle_lagoon; Venice_lagoon; Caleri_lagoon, as shown in Figure 5.46.

![Ebb_delta_Geodatabase](image)

**Figure 5.46 – Structure and elements of the Ebb-delta Geodatabase**

As previously stated, a GIS query concerning specific grain size parameters identifies the different potential borrow areas within the Geodatabase, thus subsequent actions can be
planned. Owing to the necessity of navigational maintenance of the main ebb channel, in the case of Caleri inlet for example, the use of dredged material could be planned once verified the suitability of the material; in other cases sand extraction could lead to a morphological re-shaping of the ebb-tidal delta by mainly using sand from growing areas, i.e. the channel margin linear bar and the terminal lobe.

On a regional scale, a geodatabase tool could be used to develop a local “Sand Resources Masterplan”, which integrates all existent data and allows the research of the optimal borrow site for each specific requirement.
6 CONCLUSIONS

This study focused on the evaluation of the sand trapping potential of nearshore morphologies along the northern Adriatic coastal area. Investigated features include ebb-tidal deltas associated with tidal inlets, both natural and stabilized, and small river deltas. Summarizing all results presented in the previous sections, the major outcomes of the research are the followings:

1) the seafloor morphologies facing the Piave and Adige river mouths exhibit strong erosional patterns over the last thirty years, possibly as a consequence of a decrease in sediment supply from rivers. Therefore, these areas were not considered suitable sand resources for beach nourishment projects, whereas their morphological evolution testifies that a disequilibrium in sediment supply and deposition is occurring;

2) ebb-tidal deltas represent significant sand sinks along the northern Adriatic coastal area, both the natural and the stabilized ones, with volumes comprised between c.a 270,000m$^3$ and c.a. $10 \times 10^6$m$^3$.

3) the newly-developed semi-automatic procedure (ADP) provided to be a useful analytical tool for the evaluation of ebb-tidal delta volumes; the development of agile geostatistical procedures allowed the integration and processing of newly collected and older bathymetric and grain size data.

Additionally, the study of the morphodynamics of Lido, Chioggia, Malamocco and Buso inlet, provided an analysis of ebb-tidal delta volumes and jetty effects. According to Carr and Kraus (2001) the offshore extent and dimension of the ebb-tidal delta is in great part determined by the magnitude of the tidal prism, the slope of the nearshore shelf, and the ebb-jet confinement caused by jetties. Notwithstanding the limited statistics, the direct proportionality between tidal prism and ebb-tidal delta volumes obtained from the application of the ADP on the bathymetric dataset, as well as the high correlation coefficient, demonstrates that natural or almost natural inlets in the northern Adriatic tend to build ebb-tidal deltas which are strongly influenced by tidal processes. Thus the effects of storm induced wave winnowing and longshore sedimentary drift may be considered uniformly distributed, since scattering in the prism vs. ebb-tidal delta volumes relationship is negligible. The V-P relationship of ebb tidal delta volumes in the northern Adriatic is very similar to that obtained by Hicks and Hume.
(1996), but significantly different from that found by Walton and Adams (1976) and Marino and Mehta (1987) in the United States.

The use of a standardized procedure, as in the case of the geostatistical application here proposed, reduces the subjectivity in the calculation of the ebb-tidal deltamplitude which occurs when using the Dean and Walton method (1973). The ADP could also be a useful method for a step-by-step preliminary test on ebb-tidal delta structure determination as in the case of complicated bathymetric frameworks. Equilibrium conditions based on delta volume vs. tidal prism relationships constructed for natural or almost natural northern Adriatic inlets, may be used to infer the hypothetical delta volume also for jettied inlets. During the past, many northern Adriatic inlets were strongly asymmetrical, because of significant longshore transport processes that gave rise to large updrift coastal offset. Since the 19th Century, owing to great difficulties in navigation through the main channel, some inlets were fixed by jetties. Depending on the jetty length, precisely on the offset between shoreline and jetty apex, the ebb-tidal delta may re-shape or completely erode, and thus begin to re-form offshore, shifting to a distance equal to that of the jetty length. This may cause a delay in ebb-tidal delta formation, since the longshore sediment input is not immediately captured by the inlet system and stored in the ebb delta. In fact, the updrift beach will accrete until the sediments are able to by-pass the jetty, thus entering in the inlet sedimentary budget.

What can be observed is a large variety of new “human-induced” ebb deltas, whose equilibrium volumes may be reached only when a large amount of transported longshore sediment has been trapped for long time. The “immaturity” status of the new ebb-tidal deltas is a major result, for the case of Lido inlet, the largest in the north Adriatic, where jetties were constructed about one century ago. According to Hansen and Knowles (1988) confinement of the flow by jetty construction has resulted in tidal flow abandonment of the natural main ebb channel, swash platform and marginal flood channels, resulting in effects similar to those observed in natural ebb-tidal delta breaching (Fitzgerald et al., 1978). After jetty construction, sediments were stored in the updrift area of Punta Sabbioni and caused the accretion of that beach, resulting in a starved status of the ebb-tidal delta potential area. Considering that the present ebb-tidal delta volume accounts for only 10% of the equilibrium hypothetical volume, Lido inlet can be seen as a typical case of immature ebb-tidal delta, which only recently has significantly grown offshore due to the jetty fixation. Some doubts arise from the possibility that the delta volume will increase, owing to the periodic dredging operations that are done for
6. CONCLUSIONS

Navigational improvement. This practice may lead to a stationary configuration of the ebb tidal delta, that can be tested only through a specific monitoring plan. Additional studies concerning the behaviour of jettied inlets provided similar results in the cases of Malamocco, Chioggia and Buso inlets. Data analysis confirms the limited ebb-tidal delta extension also in these latter cases, and a morphodynamic response comparable to the one observed at Lido.

The ebb-tidal delta sediment inventory that was processed through GIS has very high versatility and can associate type of deposits (grain-size, sorting) with its location and volume “excess”. Once the required physical parameters of the material are known for a beach that needs to be re-nourished, a GIS query could identify different potential borrow areas and subsequent actions can be planned. The suitability of a morphological artificial re-shaping may be planned, by mainly using sand from growing areas, i.e. the channel margin linear bar and terminal lobe, as well as the sedimentary surplus from navigational maintenance located inside the outer part of the main ebb channel. In any case, dredging must be limited both in extension and thickness, in order to minimize the already cited effects on wave and sedimentary dynamics. The use of ebb-tidal delta sediment as a source for beach nourishment material has and will be controversial. However, as suggested by Hansen and Work (1999) there is a natural variability to these inlets systems, and if artificial bypassing practices mimic the natural processes by removing a small percent of the delta on an annual basis, there is likely to be minimal adverse impact to adjacent shorelines. Mining the seaward edge of the delta over a large area would maintain the overall geomorphology of the inlet and would reduce the possibility of severely altering nearshore refraction and sediment transport patterns.
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APPENDIX 1:

Lido samples grain size parameters

Table A. Laboratory analysis results.

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<th>N_sample</th>
<th>D &lt;62.5 mm</th>
<th>62.5mm &lt;D&lt;2mm</th>
<th>tot</th>
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<th>% pelite</th>
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Table B. Grain size parameters after Folk and Ward (1957)

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<th>Sample</th>
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<th>Clay</th>
<th>Mz</th>
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APPENDIX 2:

Caleri samples grain size parameters

Table A. Laboratory analysis results.

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APPENDIX 3:
Publications
Sediment storage at tidal inlets in northern Adriatic lagoons: Ebb-tidal delta morphodynamics, conservation and sand use strategies

G. Fontolan*, S. Pillon, F. Delli Quadri, A. Bezzi

Coastal Group – Dip.to di Scienze Geologiche Ambientali e Marine, Università degli Studi, via E. Weiss 2 – 34127 Trieste, Italy

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Abstract

Several morphological and sedimentological investigations were carried out along barrier islands in the northern Adriatic (Italy) in order to evaluate the sand reservoir potential associated with ebb-tidal deltas. The classical exponential \( A = cP^n \) (cross-sectional area vs. spring tidal prism) relationship was used to draw a synthesis of the hydrodynamic equilibrium conditions and demonstrates that both natural and artificially fixed inlets exhibit the same morphological adaptations to tidal conditions. A new semi-automatic geostatistical GIS procedure was developed to process bathymetrical data. With this, a first estimate of ebb-delta volumes, was obtained. Sand storage potential at natural and almost natural inlets varied considerably, as a function of the tidal prism, from ca. \( 0.27 \times 10^6 \) to ca. \( 11 \times 10^6 \) m\(^3\). The same procedure, applied to the large jettied inlet of Lido, produced 10% of the expected volume that was calculated with the tidal prism. The immaturity status of the ebb delta was confirmed by the application of a simplified version of the Tidal Inlet Reservoir Model, which takes into account the time delay of sand bypassing inside the inlet system. This study also presents the use of GIS as a tool for cataloguing sediment stored in ebb deltas with the potential application of using this material for nourishment plans aimed at restoring neighbouring beaches which are subject to erosion.

Keywords: tidal inlet; ebb-tidal delta; morphodynamics; sediment storage; trend-surface analysis; GIS; northern Adriatic sea

1. Introduction

Tidal inlets are natural openings along barrier coastlines where sea water penetrates land and also provides a connection between the ocean and bays, lagoons, marshes and tidal creek systems. Escoffier (1940) presented a theory concerning the stability of an inlet under the influence of erosional–depositional conditions which tend to enlarge or reduce the size of the inlet cross-section. O’Brien (1931, 1969) showed that the size of a tidal inlet is closely related to its tidal discharge; he demonstrated that a strong correlation exists between an inlet’s tidal prism \( P \) and its throat cross-sectional area \( A \):

\[
A = cP^n \tag{1}
\]

where \( c \) and \( n \) are empirical constants. Many other authors have used this type of analysis to define the equilibrium state of a tidal inlet (Jarrett, 1976; Gao and Collins, 1994; Hughes, 2002; Nishi et al., 2006).

Tidal inlets, particularly when not fixed by jetties, have very high sand trapping capabilities as a consequence of the strong interference generated by tidal currents on the littoral drift. In tide-dominated environments sand is largely stored in the jet spreading area (far field) and this forms the ebb-tidal...
delta. Many studies have been carried out on ebb-tidal deltas in different coastal areas (Mason and Sorensen, 1971; Boot-hroyd, 1978; Hayes, 1979, 1980; Hubbard et al., 1979; Marino and Mehta, 1987, 1988; FitzGerald, 1988; Oertel, 1988; Sha, 1990; Stauble, 1993; Smith and FitzGerald, 1994; Imperato et al., 1988; Davis and FitzGerald, 2004; Elias and van der Spek, 2006). Ebb deltas are important morphological features because: (1) they represent huge sand reservoirs, (2) sand shoals associated with ebb-tidal deltas reduce wave energy on landward beaches, and (3) they affect the bypass process towards downdrift shorelines.

Since many inlets are maritime routes, dredging is periodically planned to maintain accessibility of the pass. Sand which fills the pass comes from the main depositional bodies of the ebb delta, predominantly from the channel margin linear bar located updrift. As a consequence, a possible strategy for channel maintenance would involve the re-shaping of the dominant depositional bodies. A plan focused on the rational use of sand would require ebb-delta volume calculations to identify the shape, size and amount of sand that is stored. Several authors discussed the main concerns when calculating ebb-delta volume and presented large data sets, mainly along the Atlantic coast of the United States (Dean and Walton, 1973; Walton and Adams, 1976; Marino and Mehta, 1987; Stauble, 1998; Powell et al., 2006) and the coastline of New Zealand (Hicks and Hume, 1996). Relationships concerning the hydrodynamic equilibrium of tidal inlets well predict ebb-delta growth in cases where no significant alteration has occurred in the inlet, as a consequence of direct and indirect human activities. Walton and Adams (1976) suggested that, as in the case of inlet cross-sectional areas, the volume of sand contained in the ebb-tidal delta (V) is closely related to the spring tidal prism as follows (pedex of V is referred to the authors’ initial):

\[ V_{WA} = 6.6 \times 10^{-3} P^{1.21} \]  

(2)

Similar formulas, even if using different coefficients, were proposed by Marino and Mehta (1987) and Hicks and Hume (1996):

\[ V_{MM} = 5.6 \times 10^{-4} P^{1.39} \]  

(3)

\[ V_{HH} = 1.88 \times 10^{-4} P^{1.41} \]  

(4)

There was a large variability in the assessment of delta volume using the deterministic approach, and application of the different formulas gave rise to differences of up to one order of magnitude. Despite the need for a more complex approach and detailed information on the bathymetrical framework of each area, precise ebb-delta volume data may be obtained only using Dean and Walton’s (1973) Residual Method. However, this method is somewhat subjective, due to the strong influence of expert judgement required.

Eleven tidal inlets occur in the northern Adriatic lagoon system. This system consists of the Grado—Marano, Caorle and Venice lagoons. Other inlets are located along the barrier islands and inter-distributary bays surrounding the Po delta. These inlets vary in structure, such that some are natural and unjettied, others are laterally embanked, and some are fixed by long jetties. Unjettied or embanked inlets, as well as inlets where short jetties have limited influence on ebb-delta growth, are characterised by well-developed ebb deltas because of the continuous deposition without significant human activity.

Since no detailed information was available for the ebb-tidal deltas occurring in the northern Adriatic, new bathymetrical and sedimentological surveys were carried out. This information was also used to supplement the limited data available on tidal inlet morphology, thus furnishing a complete data set for the northern Adriatic and its A—P relationship. This led to a basis for discussion of ebb-tidal delta equilibrium conditions for natural or almost natural inlets as well as jetted inlets.

Although expert judgement is always a prerequisite in the examination and interpretation of ebb-tidal delta structure and morphodynamics, an improvement in the Residual Method can be obtained using GIS geostatistical procedures. In this study, a newly developed semi-automatic geostatistical procedure was applied to data collected at six inlets in the northern Adriatic sea, in order to evaluate the possibility of standardizing ebb-tidal delta volume calculations.

Finally, this study also shows how GIS can be applied in the cataloguing of sediment stored in northern Adriatic ebb deltas, with the purpose of using this material for nourishment plans addressed at restoring neighbouring beaches subjected to erosion.

2. Study area

The northern Adriatic coastal area, between the Isonzo and Po rivers, mainly consists of lagoon—river delta systems fronted by barrier islands and sandbars fed by tidal inlets (Fig. 1). Despite the microtidal regime, limited wave influence tends to produce tidal inlets of the tide-dominated type (Hubbard et al., 1979).

In regards to frequency and intensity, the wind climate is characterized by a prevalence of winds blowing from the first quadrant, mainly from the ENE (the Bora) (Carrera et al., 1995). South-easterly winds (the Scirocco) that have a longer geographical fetch (over 800 km) are also important. Tides are semi-diurnal and their range is one of the widest in the Mediterranean, with mean spring-tide values of 86 cm in Trieste and 100 cm in Venice, and mean neap-tide values of 22 and 20 cm, respectively (Dorigo, 1965; Polli, 1970). The concomitance of spring tides, seiches, south-easterly winds and low atmospheric pressure can cause a sea-level rise of 160 cm (locally called “acqua alta”). Mean significant wave height during the year is lower than 0.5 m (Dal Cin and Simeoni, 1994), while the highest offshore wave height, both for Bora and Scirocco storms, is about 5 m (Cavaleri et al., 1996).

An estimate of wave energy for the northern Adriatic area in the form of \( H^2T^2 \) (H and T corresponding to the significant wave height and period) was obtained using the complete series of 2000—2003 three-hourly measurements available
Fig. 1. Study area, tidal inlets locations and bathymetrical maps of investigated inlets.
from the RON—APAT wave gauge located offshore Ancona (Latitude 43°37′46″, Longitude 13°30′13″). The annual value is 15.61 m² s⁻².

Longshore drift in the area occurs westward from the Isonzo River to Lignano, eastward and westward along the cuspatc Tagliamento River delta, and southwestward from Baseleghe to Chioggia; along the southern coastline, from the Po delta to Chioggia, the longshore drift is directed northward (Bondesan et al., 1995).

Venice and Grado—Marano lagoons are two large basins, the first 55,000 ha and the second 16,000 ha. They are the only remnants of the formerly huge Adriatic estuary that once extended over 200 km, from the southern Po delta to the Isonzo (Dorigo, 1965).

Six inlets are located along the Grado—Marano lagoon—barrier island system, which extends over 20 km. From west to east, we find Lignano (embanked), S. Andrea (natural), Buso (jettied), Morgo (partially occluded), Grado (embanked—small jetties), Primero (embanked), connected to five main sub-basins. Lignano and Buso are the largest inlets, with tidal prism values of 40 × 10⁶ m³ and 26 × 10⁶ m³, respectively.

Baseleghe is a natural inlet located along the Veneto coast, where water exchange between the Caorle Lagoon and the sea occurs. The tidal prism of this basin has strongly been reduced, from ca. 15.5 × 10⁶ m³ in 1891 to ca. 3.3 × 10⁶ m³ in 1983 (Fontolan, 2004). This is a consequence of the reclamations of most of the surface occupied by tidal marshes for agricultural purposes.

All three inlets, Lido, Malamocco and Chioggia, connecting the Venice lagoon with the Adriatic sea, are fixed by long jetties which extend far offshore. During the period 1808—1840 the jetties at Malamocco inlet were built to avoid shoaling inside the channel and to improve the navigability; for the same reason long jetties were also built at the inlets of Lido (1890—1910) and Chioggia (1911—1933). The mean water volume of the Venice lagoon is approximately 700 × 10⁶ m³, the semi-diurnal volume exchange with the sea is about 350 × 10⁵ m³ during spring tides and 175 × 10⁵ m³ during neap tides (Silvestri et al., 2000). The tidal prism at Lido inlet is about 145 × 10⁶ m³, at Malamocco inlet is 136 × 10⁶ m³ and at Chioggia inlet is 82 × 10⁶ m³ (Consorzio Venezia Nuova, 1989).

More information is available for the Lido inlet, where a detailed morphological investigation was carried out for this study. Until 1882, three different inlets (Tre Porti, S. Erasmo, S. Nicolò) occupied the area of the present Lido inlet. However, after the construction of two long jetties between 1882 and 1910, the three channels were united to form the Lido inlet (Muraca, 1982). The northern jetty is 3635 m long and the southern jetty is 3155 m.

A large ebb shoal and a strongly asymmetric swash platform once existed outside the Lido inlet before jetty construction; when examining the shape and orientation of these sandbars in older data, there is strong evidence of a southward net littoral drift. Due to the great difficulty in navigation and the strong dynamic behaviour of this channel, local authorities decided to fix the lagoon entrance with jetties. As a result, after construction, the ebb shoal quickly eroded (Fig. 2) and the main ebb flow was strongly diverted seaward.

Beach accretion close to the updrift jetty (Fig. 3) also reveals the existence of a southward net littoral drift. Punta Sabbioni beach has accreted at a rate of more than 10 m y⁻¹ since 1886, but more precisely the rate of growth has been 15.8 m y⁻¹ between 1908 and 1933 and 10.7 m y⁻¹ between 1933 and 1968. Since 1968, the rate of beach accretion has decreased, to 8.7 m y⁻¹ in the period 1968—1980, to 8.5 m y⁻¹ in the period 1980—1987 (Consorzio Venezia Nuova, 1989). The littoral drift has been estimated to be between 350,000 and 400,000 m³ y⁻¹ as an average for the whole period (Muraca, 1982) whereas the current longshore input can be estimated to be in the order of 150,000 m³ y⁻¹ (Consorzio Venezia Nuova, 1989).

3. Material and methods

3.1. Tidal inlet database

Six inlets have been studied since 1994 (Fig. 1, Table 1). Investigations have included bathymetrical surveys and sediment sample collection, so that ebb-delta morphology and deposit characteristics could be analyzed.

Unjettied or embanked inlets, as well as inlets where short jetties have limited influence on ebb-delta growth, such as Lignano, S. Andrea, Grado, Primero and Baseleghe inlets, are hereinafter referred to as natural or “almost natural” inlets. An investigation was carried out at Lido inlet (Fig. 1) as a first study case of a jettied inlet strongly influenced by human activity. Lido inlet may be considered a representative case of a jettied inlet in the northern Adriatic since it has the same configuration as Buso, Malamocco and Chioggia, for which there is a lack of updated data, and which are scheduled for future investigation.

Collected data were not homogeneous, because of the different survey techniques and instruments used. In older surveys, an analogue echo-sounder along with a topographic total station were employed, whereas these more recent surveys have benefited from modern technology such as DGPS positioning coupled to a digital echo-sounder. Owing to the time-consuming older survey techniques first used at Primero, S. Andrea and Baseleghe, the bathymetrical data are sparse, and consist of some channel cross-sections, some shoreline normal profiles, and a relatively small number of scattered measurements in intertidal areas, though these were expertly selected to capture the most significant morphologies.

Only the more recent surveys at Grado, Lignano and Lido, have been uniformly covered by a regular sounding grid. The sounding grids were specifically designed, after analysis of the existing bathymetrical data, to capture the most important morphologies of the ebb delta. Data coverage was considered sufficient for the above-mentioned purpose (Hicks and Hume, 1997) and was comparable to data used in similar studies. A GIS system is an optimal way to homogenize and perform analyses of data coming from different sources. ESRI ArcGIS™ Software was used to analyze the bathymetrical data.
A data set for sediment grain size is available for every inlet. Samples were collected by scuba diving or by Van Veen grab, depending on water depth. Grain size analyses were carried out using a Macrogranometer© settling tube and classical grain size statistical parameters ($\phi$ notation) are represented following Folk and Ward (1957).

As with the bathymetrical data, grain size parameters were processed using GIS to produce thematic maps. Sediment properties, such as mean size and sorting are very important in the evaluation of ebb deltas as potential sediment sources. It is assumed that a theoretical sand source must be very similar to the native sand of the beach targeted for nourishment. This assumption is the basic principle of the classical formulas reported in literature for beach nourishment practices (CUR, 1987), and these are based on the comparison between mean grain size ($M_z$) and sorting of native and borrow sediment (James, 1975).

3.2. Ebb-delta volume calculation

A simple estimate of ebb-delta volume can be obtained using formulas available in literature (Walton and Adams, 1976; Marino and Mehta, 1988; Hicks and Hume, 1996). Nonetheless, even when using the same tidal prism value, estimated volumes sometimes doubled depending on the formula adopted. Moreover, these mathematical relations were constructed on data coming from Atlantic inlets, which may be different from those of the Adriatic. Thus, applicability is not guaranteed and other methods must be applied to give more reliable estimates of the sand volume stored in ebb-delta structures.

A methodology was developed to quantify the ebb-delta area and volume of various northern Adriatic inlets. Different techniques exist to evaluate the evolution of inlet ebb-delta structures and calculate ebb-delta volume and area (Stauble, 1998): among these the Residual Method calculates volume in ebb deltas by reference to idealized no inlet contour lines. The Residual Method fits a Digital Terrain Model to a no-delta hypothetical bathymetry. In the manually developed original method, the parallel updrift and downdrift bathymetrical lines of an inlet far from the influence of the channel were assumed as the natural topography of the coast without the inlet (Walton and Adams, 1976). Hicks and Hume (1996, 1997) presented data collected from tidal inlets of New Zealand and developed a procedure for ebb-delta volume calculation using SURFER™ Software.

One of the major challenges of this study was the construction of a reliable virtual no-delta bathymetrical configuration. As the procedure is somewhat subjective, an attempt was made to develop an automatic procedure based on the methodology.

Fig. 2. Ebb-delta evolution during jetties construction at Lido inlet, 1882–1898 (after Lippe, 1984, modified).
first presented by Dean and Walton (1973). To minimize operator intervention in the building of the “no-delta” bathymetry, a GIS geostatistical procedure based on the original depth data was applied and herein referred to as the Semi-Automatic Detrending Procedure (ADP).

The first step involved the manual procedure, followed by an automatic interpolation procedure which was tested through the following steps.

### 3.2.1. Construction of a Digital Terrain Model (DTM) of the real bathymetry

The DTMs were built with the triangulation method (TIN) which is reliable when the available data are not regularly spaced, and thus variable resolution is required. Moreover, it is possible to improve the resulting model by introducing data from different surveys and adding vector elements, inferred from collected data. Efforts were made to improve the models of those inlets lacking complete survey data. These resulting models were considered sufficiently accurate to perform the required calculation. The resulting bathymetry was converted to raster format, a grid of regularly spaced cells. Cell spacing was chosen according to survey data resolution.

### 3.2.2. Construction of the no-delta bathymetry

This is the most crucial stage in the procedure, as stated in previous studies (Hicks and Hume, 1996, 1997; Stauble, 1998), because of the large source of error in the calculation process. One of the main aims of this project was to minimize operator intervention when defining the no-delta bathymetry. Several tests were carried out to compare the results of methods adopted in previous studies and to find an improved, less subjective, methodology. Following Hicks and Hume (1996), representative equilibrium shape profiles from areas outside the ebb-shoal area were used to create an idealized no inlet bathymetry. As a first attempt, 2—4 lateral profiles located in the littoral area not affected by the ebb-delta structure were used to develop different polynomial trend surfaces. Afterwards, the entire data set was used to create different polynomial trend surfaces. The use of the entire data set resulted in a less subjective and more precise procedure, because it avoided operator error when selecting lateral profiles. An example of the procedure is shown in Fig. 4. First, second, and third order polynomial trend surfaces were created and evaluated, both for statistical relevance (Davis, 2002; Grohmann, 2005) and for correspondence with the overall morphology of the coastal area. Higher degree trend surfaces were not considered in the analysis due to the fact that these surfaces are more representative of the true configuration than the idealized no-delta bathymetry. All trend surfaces provided a significant fit to the observations (values of $r^2$ were between 0.83 and 0.90).

It is extremely important to emphasize that in this type of application, as reported by Davis (2002), statistical tests of significance are not a suitable guide when selecting degree of trend surface because the problem is not one of statistical estimation. Rather, the objective is to closely simulate the regional trend of the sub-surface. The application of different polynomial trends can lead to relevant differences in the following steps of ebb-delta volume calculation (up to 40—50%), and at this final step of the procedure, expert judgement is necessary to evaluate which degree of trend surface is the most adequate in the representation of no-delta bathymetry. Several observations and considerations were made to discriminate first, second and third order polynomial surfaces, based on previous knowledge of the morphology of the coastal area. In fact, in cases where jetties possibly alter shoreline...
position, great accuracy must be taken when defining the regional shoreline trend. In almost all analyzed cases, a first order polynomial surface was found to be the most adequate interpretation of the regional trend, since coastal areas in proximity of tidal inlets are normally straight in configuration. In some locations, like Lido, Malamocco and Chioggia inlets, the construction of long jetties extending far offshore has led to substantial accretion of the updrift beach, resulting in high asymmetric configuration of the shoreline near the inlet. As a consequence, the local bathymetry has shifted to a more deflected configuration, and is well represented by a third order polynomial trend surface.

3.2.3. Subtraction of the different no-delta surfaces from the real bathymetry and creation of different residual maps

In order to obtain accurate residual maps, cell-by-cell calculations between the bathymetrical rasters were carried out.
3.2.4 Ebb-delta volume calculation

Volume was calculated for the different configurations using cells with positive values in the residual surface. The Residual Method (Walton and Adams, 1976; Hicks and Hume, 1996) consists of the calculation of the positive anomalies (Fig. 4) while negative anomalies identify mainly channel morphologies. At Lido inlet (Fig. 5) the differences in volume calculation by subtraction of first, second and third order polynomial trend surfaces were estimated to be 40% between first and second order, and around 50% between first and third order. As previously stated, the choice of the third order trend surface (Fig. 5C) was driven by the strong bathymetric offset. As a result, a more precise ebb-shoal residual morphology, as well as a reduced extension of the significant negative values outside the delta domain can be observed (Fig. 5C).

Fig. 5. Ebb-delta volume calculation at Lido inlet. (A) First order polynomial trend surface and associated residual map; (B) second order polynomial trend surface and associated residual map; (C) third order polynomial trend surface and associated residual map. All negative values are below −0.25 m; negative anomalies inside the main ebb channel are not shown.
4. Results

4.1. The northern Adriatic $A-P$ relationship

A regression analysis of the $A-P$ values for the northern Adriatic inlets’ data set (Table 1) is shown in Fig. 6. This regression shows some small differences within the calculations carried out following Jarrett’s (1976) formula. The smaller northern Adriatic inlets were found to have wider hydraulic sections than those calculated by Jarrett’s (1976) general formula. Only the jettied inlets (the largest three along the curve) tend to be well represented by the classical O’Brien’s (1931, 1969) relationship for dual jetties.

4.2. Ebb-delta volume at natural or almost natural inlets

Despite the human modifications, which have occurred at some inlets, mainly the construction of small jetties at Lignano and Grado inlets and the canalization of Primero inlet, these five cases may be considered as representative of natural or almost natural inlets, where direct human activity has not affected the whole ebb-delta structure.

ADP developed with linear interpolation of the whole data set and supported by a regular spatial distribution of depth data has given reliable values of ebb-delta volumes, comparable to those calculated by Hicks and Hume’s (1996) formula (Fig. 7). The relationship for northern Adriatic inlets is represented by:

$$V = 8.157 \times 10^{-5} p^{1.4636}$$

(5)

The correlation coefficient is $r^2 = 0.997$, thus indicating high significance for the results obtained through application of the Residual Method. The sand storage potential values vary considerably from $0.27 \times 10^6$ to $11 \times 10^6$ m$^3$, as a function of the tidal prism.

The complete results of the calculation are reported in Table 2. Comparison of volumes calculated with Walton and Adams (1976), Marino and Mehta (1987) and Hicks and Hume (1996) formulas are shown in Table 3. For the same tidal prism, Walton and Adams’ (1976) together with Marino and Mehta’s (1988) formulas give higher volume estimations, not comparable to results obtained using the ADP application.

4.3. Ebb-delta volume at jettied inlets: the case of Lido

Although a large data set is normally required to obtain statistically significant results, data from this preliminary investigation are herein presented with the aim to demonstrate the impact of jetty structures on ebb-delta formation and development.

The results of the bathymetric survey carried out at Lido inlet are shown in Fig. 1. Due to the confinement of flow by the jetty construction, sand is being deposited at higher depths and new ebb-tidal delta growth has been occurring seaward of the jetties. The modern terminal lobe of the ebb delta at Lido inlet is delineated by the $-13$ m contour. Bathymetrical contour lines south of the southern jetty give evidence of an ebb-delta structure, a cuspate-shaped sand body developing in the northern-updrift direction. Dredging operations are required almost yearly to maintain suitable channel depth for...
Table 3
Results of ebb-delta volume calculations by using classic literature formulas: HH, Hicks and Hume (1996); WA, Walton and Adams (1976) and MM, Marino and Mehta (1987). All values are in m³

<table>
<thead>
<tr>
<th>Tidal inlet</th>
<th>Tidal prism</th>
<th>HH</th>
<th>WA</th>
<th>MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lignano</td>
<td>40,000,000</td>
<td>9,841,526</td>
<td>14,793,731</td>
<td>20,656,247</td>
</tr>
<tr>
<td>Grado</td>
<td>23,400,000</td>
<td>4,621,173</td>
<td>7,650,317</td>
<td>9,803,882</td>
</tr>
<tr>
<td>S. Andrea</td>
<td>3,120,000</td>
<td>269,722</td>
<td>641,733</td>
<td>595,748</td>
</tr>
<tr>
<td>Baseleghe</td>
<td>5,200,000</td>
<td>554,272</td>
<td>1,202,896</td>
<td>1,211,805</td>
</tr>
<tr>
<td>Primero</td>
<td>6,000,000</td>
<td>678,190</td>
<td>1,434,399</td>
<td>1,478,490</td>
</tr>
</tbody>
</table>

Fig. 7. Tidal prism vs. ebb-tidal delta volume experimental results and comparison with literature relationships.

conditions. Ebb deltas store sand and serve as a conduit for sand bypassing in the vicinity of the inlet. Bypassing towards the downdrift beach occurs according to the maturity state of the shoal, wave conditions, magnitude of the tidal prism, and other factors (Kraus, 2002). As far as a newly formed ebb shoal is concerned, after jetty construction, sand is expected to be completely stored in the ebb delta, because this structure is still too immature for bypassing sand to the downdrift area. This difficulty is due to the lower wave effectiveness to winnow the newly formed ebb shoal, which is located far offshore, in an area of greater depth than the natural one.

The original TIRM was used in a simplified form, which ignores the output associated with the bypass. This model predicts time delays in growth of morphological features, such as ebb deltas, through the following formula:

\[ V_E = V_{Ee} (1 - e^{-\alpha t}) \]  

where \( V_E \) = volume of ebb delta, \( V_{Ee} \) = equilibrium volume of ebb delta, \( t \) = time, and \( \alpha = Q_{in}/V_{Ee} \), in which \( Q_{in} \) is the known input transport rate, which is assumed to be constant.

Coefficient \( \alpha \) gives a characteristic time scale for the ebb delta, approximately proportional to \( 1/R \) (Kraus, 2002), where \( R \) is the ratio between tidal prism and the average annual volume of littoral sediment brought to the inlet (Bruun and Gerritsen, 1959). In the case of Lido inlet, the parameters entering the formula are \( Q_{in} = 150,000 \text{ m}^3\text{ y}^{-1} \) and \( V_{Ee} = 7.18 \times 10^7 \text{ m}^3 \), calculated by Eq. (5). The value of \( \alpha \) calculated for these parameters is 0.00209, thus giving an \( R \) value of 479. Since \( R \) values over the conventional limit of 150 indicate poor “by-passers” inlets from the updrift to the downdrift area, mainly stable with deep channel (Bruun and Gerritsen, 1959), this confirms the assumption that sediment losses due to the bypass towards the downdrift beach can be neglected. Giving a time period of 100 years (after the construction of the two jetties), the application of the model gives
a value of \( V_E = 13.5 \times 10^6 \) m\(^3\), while the estimate found through the Residual Method gives a value of \( 5.81 \times 10^6 \) m\(^3\).

A consideration has to be made at this point, with regard to the interruption of the southward net littoral drift by the northern jetty, and the consequent accretion of Punta Sabbioni beach (Fig. 3). From the beginning of 1900 to 1968, the rate of accretion has been high, more than 10 m y\(^{-1}\), thus the entrapment of sand by the seaward extension of the north jetty may have subtracted sediment from the development of the ebb shoal. Since 1968, the rate of growth has been decreasing. Moreover, the beach has nearly reached the end of the jetty (300 m further), once approaching this point the process of sediment bypassing inside the inlet and transport by tidal currents could have begun. This consideration leads to the conclusion that for the application of the above formula a timeline of 40 years should be considered. The result of the application of the Reservoir Model with \( t = 40 \) years gives a value of \( V_E = 5.76 \times 10^6 \) m\(^3\), very close to the volume calculated through ADP.

### 4.4. GIS sediment catalogue

Once significant values concerning sand stored in ebb deltas are calculated, the advantage of a GIS database is its large query possibility, with direct correlations between geographic information, area, volume and grain size characteristics. For the inlets in this study, the use of GIS highlights that a large amount of ebb-delta sediment consists of well-sorted sand, more than 1-m thick, and thus is suitable for dredging and re-use. As an example, a summary of the different lithologies, obtained through specified examination of mean grain size and sorting, may be a useful tool for beach nourishment plans that aim to address erosional problems in neighbouring beaches. Conversely, once the grain size characteristics for nourishment are known the identification of the best potential borrow site can be obtained, and then inserted into a GIS query.

A simple logical calculation, using ArcGIS™ Spatial Analyst, was performed by setting three minimum conditions: deposit thickness, mean grain size and grain size sorting. The minimum thickness of the deposit was assumed to be 1.0 m, in order to take into account dredging machinery limits, while the other two conditions depend on the nourishment site characteristics. GIS queries highlight the presence of a possible dredging area, thus allowing more precise volume calculation and providing a reliable indication of the suitability of the inlet as a sand source. Furthermore, the identified area becomes the preferred site on which further investigations can be performed, such as core sampling and geophysical supplementary surveys.

In the case of Lignano inlet, the identification of a sand deposit with specified thickness (>1 m) and grain size characteristics (\( M_z = 2.4–2.6 \) and sorting < 0.35) which is to be used for a possible local nourishment of ca. 120,000 m\(^3\), leads to a GIS output of 2,700,000 m\(^3\) of sand located near the ebb delta, namely on the terminal lobe and along the updrift channel margin linear bar (Fig. 9). Part of this deposit is currently made up of sand filling the entrance, thus limiting navigation, whereas another part is sand that tends to accumulate on the updrift area, which may be entering the channel as a consequence of NE storms. Thus a very limited dredging operation consisting of the re-shaping of the channel margin linear bar may be planned and accurately studied. Coarser sediments, with mean size between 2.2 and 2.4 \( \phi \) may also be used as borrow material, although they are limited to a small area situated approximately at the channel entrance, with a total volume of ca. 170,000 m\(^3\) (Fig. 9).

### 5. Discussion

#### 5.1. Tidal prism vs. cross-sectional area relationship

Although limited to 11 sites, the \( A-P \) relationship displayed in Fig. 6 for the northern Adriatic shows very little scattering, and this is confirmed by its high correlation coefficient. The data fell within the large amount of data already reported in literature (Jarrett, 1976) and thus any discussion concerning morphodynamics and equilibrium conditions can be only speculative. The variability in the morphology of the different sites is large so they lack comparative parameters and only general observations could be made.

The northern Adriatic \( A-P \) relationship does not appear to exhibit different behaviour at natural, almost natural, and jettied inlets. As a general rule, northern Adriatic tidal inlets with \( P \) smaller than \( 5 \times 10^7 \) m\(^3\) tend to develop wider cross-sectional areas than corresponding inlets with the same tidal prism found in the United States. Conversely, only the three largest inlets (Lido, Malamocco and Chioggia) fell precisely inside O’Brien’s (1931, 1969) proposed relationship for dual jetties.

As suggested by many authors (Bruun and Gerritsen, 1959; Bruun, 1978; Gao and Collins, 1994; Kraus, 1998, 2005), within tidal inlet equilibrium processes, attention should be focused on the dynamic balance between the transport capacity, provided by ebb currents flowing through the inlet, and longshore sand transport that is caused by wave action on the sides of the entrance. According to Kraus (1998), reduced littoral transport leads to a larger equilibrium cross-sectional area for the same tidal prism. As a consequence, in cases of higher littoral drift, the equilibrium cross-sectional area is smaller than under conditions of weak littoral drift because less sediment is removed from the inlet throat during each tidal cycle. This could be explained by taking into account the flow efficiency of the inlet throat in moving sediment through the inlet. In order to increase current speed through the entrance, and to maintain an equilibrium state according to Escoffier’s (1940) closure curve, the inlet is subjected to a reduction in its cross-sectional area.

Kraus (1998) derived a theoretical form for the coefficient \( c \) in the \( A-P \) relationship (Eq. (1)) in which the effects of longshore sediment transport have been included. According to the same author (Kraus, 2005), values of \( c \) obtained with his
formula are in the order of magnitude as those empirically determined. Assuming qualitative validity of the equation, the cross-sectional area depends weakly, but inversely on the gross longshore transport rate, such that for all other factors being equal, the inlet channel cross-sectional area would tend to be larger for areas with smaller transport rates (Kraus, 2005).

Due to the limited influence of longshore transport along the northern Adriatic coastline, in almost all cases the orientation of the main ebb channel is symmetrical, being slightly asymmetrical and rotated downdrift at the terminal end of the channel margin linear bar and the terminal lobe. The inlet showed a typical updrift or downdrift offset configuration only in a few cases. Since a morphological response of the mutual interaction between tidal forces and sediment longshore drift is an inlet's tendency to change orientation or migrate, the overall symmetrical or slightly asymmetrical configuration is evidence of the effectiveness of the tidal current in intercepting the longshore sedimentary load directed towards the main

Fig. 8. Lignano and Grado ebb-tidal deltas: sand deposits catalogue.
ebb channel. Sediment trapping leads to growth of channel margin linear bars located updrift, which tends to curve towards the distal end, thus enhancing the morphological contrast of the terminal lobe shoal.

The examined jettied inlets appear to have reached hydrodynamic equilibrium as their $A-P$ relationship was not significantly different from other cases. This could be due to the fact that these jetties were constructed approximately 100 years ago along the Venice littoral shore, and 40 years prior at Buso, a sufficient length of time for adaptation of the cross-sectional area to the newly restricted conditions.

5.2. Ebb-tidal delta volumes and jetty effects

Apparently the large differences in ebb-delta volume obtained, when using different experimental relationships found in literature, require discussion of the existing differences in physical parameters which occur in different geographical environments. According to Carr and Kraus (2001) the offshore extent and dimension of the ebb delta is in great part determined by the magnitude of the tidal prism, the slope of the nearshore shelf, and the ebb-jet confinement caused by jetties. Notwithstanding the limited statistics, the direct proportionality between tidal prism and ebb-delta volumes obtained from the application of the ADP on the bathymetrical data set, as well as the high correlation coefficient, demonstrates that natural or almost natural inlets in the northern Adriatic tend to build ebb deltas which are strongly influenced by tidal processes. Thus the effects of storm induced wave winnowing and longshore sedimentary drift may be considered uniformly distributed, since scattering in the prism vs. ebb-delta volumes relationship is negligible.

As already stated, the $V-P$ relationship of ebb-tidal delta volumes in the northern Adriatic is very similar to that obtained by Hicks and Hume (1996), but significantly different from that found by Walton and Adams (1976) and Marino and Mehta (1987) in the United States.

Ebb-tidal deltas of coastlines exposed to different degrees of wave action were already examined by Walton and Adams (1976) who proposed three different possible equations, relative to mildly, moderately, and highly exposed coasts, the latter featuring the lowest delta volumes. Similarly, Hicks and Hume (1996) suggested that ebb-delta volume increases with decreasing wave energy, decreasing sand grain size, and increasing sine of the tidal jet angle. Following this last consideration, we expected the northern Adriatic ebb deltas to reach maximum values, since wave energy is quite low, sediments are fine to very fine sand, and the somewhat symmetrical jet configuration leads to a sine of jet angle equal to one.

It is not our intention to discuss the influence of different physical parameters in ebb-tidal delta growth, because our data set is too limited. But any discussion could be ineffective if comparisons do not consider the different sources of error in the determination of ebb-delta volume and tidal prism. First of all, as already pointed out by Valiela (2001, pp. 225–226) a large scatter in the data set may reduce or remove any difference, as in the case of the data reported by Walton and Adams.

Fig. 9. Example of GIS queries to the ebb delta deposit of Lignano.
Therefore different wave exposure cannot be considered statistically significant. In Fig. 10, data sets from classical literature sources, together with a new revised data set from the Florida’s tidal entrances (Powell et al., 2006) are reported for comparison with our data. This comparison shows the limitations of using data sets from large geographical areas, where the margin of error tends to reduce the significance of a unique prism vs. ebb-delta volume relationship. Second, the calculation of the tidal prism value as well as the ebb-delta volume needs to be standardized. Tidal prism values may be determined from current meter data, by the cubature method (Jarrett, 1976) or by basin volume calculation. Following Oertel (1988), volumetric calculations determined from current meter data varied by 100%, compared to calculations based on the other two methods. For this reason, Oertel (1988) compared his data set to the wave-dominated curve of Walton and Adams (1976), using a mean tidal prism, instead of the spring tidal prism, thus reaching a similar result.

In the same manner, ebb-delta volumes were obtained using the Dean and Walton (1973) graphical method. This method leads to variable results since different operators may draw different curves for the same regional trend. Following Mehta et al. (1996) possible human error in these calculations can be in the order of 30%, but typically range from 5 to 15%.

The use of a standardized procedure, as in the case of the geostatistical application proposed here, reduces the subjectivity in the calculation of the ebb-delta volume, which occurs when using the Dean and Walton (1973) method. The ADP could also be a useful method for a step-by-step preliminary test on ebb-delta structure determination as in the case of complicated bathymetric frameworks.

Equilibrium conditions based on delta volume vs. tidal prism relationships constructed for natural or almost natural northern Adriatic inlets may be used to infer the hypothetical delta volume also for jettied inlets. During the past, many northern Adriatic inlets were strongly asymmetrical, because of significant longshore transport processes that gave rise to large updrift coastal offset. Since the 19th Century, owing to great difficulties in navigation through the main channel, some inlets were fixed by jetties. Depending on the jetty length, precisely on the offset between shoreline and jetty apex, the ebb delta may re-shape or completely erode, and thus begin to reform offshore, shifting to a distance equal to that of the jetty length. This may cause a delay in ebb-delta formation, since the longshore sediment input is not immediately captured by the inlet system and stored in the ebb delta. In fact, the updrift beach will accrete until the sediments are able to bypass the jetty, thus entering in the inlet sedimentary budget.

What can be observed is a large variety of new “human-induced” ebb deltas, whose equilibrium volumes may be reached only when a large amount of transported longshore sediment has been trapped for long time.

The immaturity status of the new ebb-tidal delta was the main result, for the case of Lido inlet, the largest in the north Adriatic, where jetties were constructed about one century ago.

According to Hansen and Knowles (1988) confinement of the flow by jetty construction has resulted in tidal flow abandonment of the natural main ebb channel, swash platform and marginal flood channels, resulting in effects similar to those observed in natural ebb-tidal delta breaching (FitzGerald et al., 1978).

After jetty construction, sediments were stored in the updrift area of Punta Sabbioni and caused the accretion of that beach, resulting in a starved status of the ebb-delta potential area. Considering that the present ebb-delta volume accounts for only 10% of the equilibrium hypothetical volume, Lido inlet can be seen as a typical case of immature ebb delta, which only recently has significantly grown offshore due to the jetty fixation.

Some doubts arise from the possibility that the delta volume will increase, owing to the periodic dredging operations that are done for navigational improvement. This practice
may lead to a stationary configuration of the ebb-tidal delta that can be tested only through a specific monitoring plan.

Additional studies concerning the behaviour of jetted inlets are still in progress, and include the remnant cases of Malamocco, Chioggia and Buso inlets. Preliminary data confirm the limited ebb-delta extension also in these latter cases, and the same morphodynamic response observed at Lido.

5.3. Ebb-shoal mining by morphological re-shaping

Since inlets are the only access pathways between a lagoon and the sea, one of the major problems in terms of navigability is their intrinsic incapacity to maintain a predetermined configuration. Due to the longshore drift, the channel can shift and cause continuous filling of abandoned routes. Moreover, during storms landward pushes can increase the natural rise of the terminal lobe of the ebb delta, enhancing the phenomenon of shoaling at the channel entrance.

During the last decades, the practice of ebb-shoal mining (Cialone and Stauble, 1998) has been progressively increasing, with the rising demand for suitable beach fill material along barrier islands. Ebb-shoal mining gives a new outlook on beach re-equilibrium projects since a large amount of sand, well compatible to native adjacent beaches, is stored by the ebb shoal and easily mined at low cost. Dredging of an inlet opening and channel may also represent a good compromise between navigational needs and the rational use of dredged material. The use of ebb-tidal delta sediment as a source for beach nourishment material has and will be controversial. However, as suggested by Hansen and Work (1999) there is a natural variability to these inlets systems, and if artificial bypassing practices mimic the natural processes by removing a small percent of the delta on an annual basis, there is likely to be minimal adverse impact to adjacent shorelines. Mining the seaward edge of the delta over a large area would maintain the overall geomorphology of the inlet and would reduce the possibility of severely altering nearshore refraction and sediment transport patterns.

The ebb-tidal delta sediment inventory that was processed through GIS has very high versatility and can associate type of deposits (grain size, sorting) with its location and volume “excess”. Once the required physical parameters of the material are known for a beach that needs to be re-nourished, a GIS query could identify different potential borrow areas and subsequent actions can be planned. The suitability of a morphological artificial re-shaping may be planned, by mainly using sand from growing areas, i.e. the channel margin linear bar and terminal lobe, as well as the sedimentary surplus from navigational maintenance located inside the outer part of the main ebb channel. In any case, dredging must be limited both in extension and thickness, in order to minimize the already cited effects on wave and sedimentary dynamics.

6. Conclusions

Several tidal inlets are located along the northern Adriatic coastline, and due to the interaction between tidal currents and longshore drift, they develop ebb-tidal delta morphologies at their seaward end.

Newly collected morphological and sedimentological information from the study added substantiality to the previous limited knowledge of tidal inlet characteristics in the northern Adriatic. The local experimental $A-P$ relationship can be used for assessing hydrodynamic equilibrium conditions. This relationship demonstrates the complete adaptation of a cross-sectional area, also in the presence of jetties, the latter because the duration of time following jetty construction was adequate.

A new semi-automatic geostatistical procedure was developed for the calculation of the amount of sand stored in ebb deltas, both for natural or almost natural inlets and jetted inlets.

This procedure allows the calculation of ebb-delta volume with less subjectivity than the manual method originally developed by Dean and Walton (1973). Volumes obtained by geostatistical calculation for natural or almost natural inlets show a good correlation with corresponding spring tidal prisms, and are very similar to the volumes calculated through Hicks and Hume’s (1996) predictive relationship. The automatic geostatistical procedure tested at Lido inlet, gave a reliable prediction of the immaturity status of the ebb delta, which presently accounts for only 10% of the total equilibrium volume, as confirmed by the application of the simplified Reservoir Model by Kraus (2002).

Sand deposits stored at the ebb shoal, mainly in the cases of unjettied or only partially fixed inlets, requires constant dredging in order to guarantee navigability and a rational plan concerning the use of the dredged material. When coupled with sedimentological data, the sand stored in ebb delta may be classified using GIS and catalogued following the volume, mean grain size and sorting, thus providing a useful tool for a preliminary assessment of sediment compatibility for possible re-nourishment of neighbouring beaches subject to erosion.

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References


**Sediment Storage in the Northern Adriatic Ebb-Tidal Deltas, Italy: Sand Use Potential and GIS Database**

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**ABSTRACT**

Tidal inlet morphodynamics have often resulted in conflicting situations with the navigation and maritime uses of the lagoon areas in the northern Adriatic Sea, Italy, where important industries and harbours are located. Many of the inlets are now rigidly stabilised by jetties; others are managed through periodic excavations. A new automatic geostatistical procedure has been developed for the ebb-tidal delta volume calculation and applied on five relatively natural inlets. Sand storage potential varies considerably, as a function of the tidal prism, from ca. 0.27 · 10⁶ to 11 · 10⁶ m³. Our results compare well with the volumes obtained from the application of the Hicks and Hume (1987) relationship. Spatial queries from GIS emphasise that a significant amount of the ebb delta material consists of more than 1-m-thick sand deposits, thus suitable for dredging and re-use. A GIS catalogue of the different lithologies, obtained through specified inquiry about mean grain-size and sorting, may be a useful tool for a beach nourishment plan for the neighbouring erosional beaches.

**ADDITIONAL INDEX WORDS:** Barrier island, Tidal inlet, Delta volume, Geostatistics.

**INTRODUCTION**

Tidal inlets, particularly when not fixed by jetties, have very high sand trapping capabilities, as a consequence of the strong interference generated by tidal currents on the littoral drift. In tide-dominated environments sand is largely stored in the jet spreading area (far field), to form the ebb-tidal delta (ETD).

Since the inlets are the only access pathways between the lagoon and the sea, one of the major problems in terms of navigability is their intrinsic incapacity to maintain a pre-determined configuration. During the last decades the practice of ebb shoal mining (Cialone and Stauble, 1998) has been increasing progressively, in order to make up the lack of sand to use for beach reconstruction along barrier islands. The ebb shoal mining furnishes a new perspective for beach re-equilibrium interventions as a large amount of sand is stored by the ebb shoal, is well compatible with the native adjacent beaches, and is easily mined at low-cost operations. Eleven tidal inlets characterise the North Adriatic lagoon system, including the Grado-Marano, Caorle and Venice lagoons. Inlets present different configurations as natural unjettied, or laterally embanked, or fixed by long jetties. Since many inlets are maritime routes, dredging is periodically planned in order to conserve the navigation pass. Anyway, the sand filling of the pass comes from the main ETD depositional bodies, mainly from the channel margin linear bar located updrift. As a consequence, a possible strategy for channel navigation maintenance would involve the re-shaping of the main depositional bodies that sediments come from.

The rational use of sand requires ETD volume computation in order to identify the shape, size and amount of sand stored in the ETD. Several authors discussed the main issue of ETD volume computation and presented large datasets of ETD volumes, mainly along the Atlantic Coast of the United States (Dean and Walton, 1973; Walton and Adams, 1976; Marino and Metha, 1987; Stauble, 1998; Kraus, 2000) or along the New Zealand coastal area (Hicks and Hume, 1996, 1997).

In this paper the results obtained by the application of a new automatic GIS procedure, developed for the calculation of the amount of sand stored in ETD, are presented and discussed.

**STUDY AREA**

The North Adriatic coastal area between the Isonzo and Po rivers consists mainly of lagoon-river delta systems fronted by barrier islands and sandbars and fed by tidal inlets (Figure 1). Despite the microtidal regime, the limited wave influence tends to produce tidal inlets of the tide-dominated type (Hubbard et al., 1979). Tides are semi-diurnal, with mean spring-tide ranges of 86 cm in Trieste and 100 cm in Venice and mean neap-tides of 22 and 20 cm respectively (Pollì, 1970; Dorigo, 1965). Mean significant wave heights during the year are lower than 0.5 m (Dal Cin and Simeoni, 1994), while highest offshore wave height for both ENE (Bora) and SE (Scirocco) storms, is about 5 m (Cavaleri et al., 1996).

The longshore drift in the area occurs westward from the Isonzo River to Lignano; eastward and westward along the cuspatc Tagliamento Delta; and southwestward from Baselegheto to Chioggia (Bondesan et al., 1995).

Six inlets are located along the Grado-Marano lagoon-barrier island system, which extends over 20 km. From W to E we find Lignano (embanked); S. Andrea (natural); Buso (jetted); Morgo (partially occluded); Grado (embanked-small jetties); Primero (embanked); related to five main sub-basins. Morgo sub-basin, due to the presence of a long sand bank offshore, is almost
Baseleghe basin has strongly reduced its tidal prism during the last 100 years, from ca. 15.5 \times 10^6 m^3 in the 1891 to ca. 3.3 \times 10^6 m^3 since 1983 (FONTOLAN, 2004).

Baseleghe is a natural inlet located along the Veneto coast, which allows the exchange of water between Caorle lagoon and the sea. As a consequence of the reclamation of most of the surface occupied by tidal marshes for agricultural purposes, Baseleghe basin has strongly reduced its tidal prism during the last 100 years, from ca. 15.5 \times 10^6 m^3 in the 1891 to ca. 3.3 \times 10^6 m^3 since 1983 (FONTOLAN, 2004).

**MATERIALS AND METHODS**

**Tidal inlet database**

Five inlets have been studied since 1994 (Table 1). Investigations included bathymetric surveys and sediment samples collection, in order to characterise the ETM morphology and deposits.

Unjettied or embanked inlets, as well as inlets where short jetties have limited influence on ETM growth, were selected because they present well-developed ETDs as a result of a continuous deposition without significant human alteration.

Data were not homogeneous, because of the different survey techniques and instruments adopted. In the older surveys, for example, an analogue echo-sounder along with a topographic total station was used, while the more recent surveys benefited from the newest technology such as DGPS positioning, together with a digital echo-sounder. A GIS system is the optimal way to homogenise data coming from different sources, and to analyse it. The ESRI ArcGIS™ software has been used to perform bathymetric data analysis and processing, taking advantage of its many extensions. A sediment grain size dataset is available for every bathymetric dataset. Sampling (Van Veen grab) and analysis (settling tube) methodology remained the same for every surveyed site; therefore the only necessary operation was the porting of the sample points into the GIS environment to produce thematic maps of the sediment statistical parameters. These thematic maps are very important for classifying the various ETDs as potential sediment sources.

**Ebb-tidal delta volume computation**

A simple estimate of ETM volume can be obtained using the formulas available in literature (WALTON AND ADAMS, 1976; MARINO AND MEHTA, 1987; HICKS AND HUME, 1996). Nonetheless, considering the same tidal prism, estimated volumes may even double depending on the adopted formula. Moreover, these mathematical relations have been constructed by statistics based mainly on Atlantic inlets, which may be different from the Adriatic Sea. Thus the applicability is not guaranteed, and other methods must be applied to give a correct estimate of volumes of sand stored in ETD structures.

A new methodology has been developed in order to correctly quantify ETM areas and volumes of five northern Adriatic inlets. Several techniques exist in order to evaluate the evolution of the inlet ETM and to calculate ETM volume and area (STABLE, 1998). Among these the Residual Method refers to a methodology for calculating volume in ETM by reference to idealised no-inlet contour lines. The residual method fits a Digital Terrain Model to a no-delta hypothetical bathymetry. In the original method (developed manually), the parallel bathymetric lines updrift and downdrift of an inlet away from the influence of the inlet were assumed as the natural topography of the coast without the inlet (Walton and Adams, 1976). Hicks and Hume (1996) presented statistics based on New Zealand tidal inlets, and developed a procedure for ETM volume computation using the SURFER™ software.

One of the major challenges of this study has been the construction of a reliable virtual bathymetric configuration. As the method is somewhat subjective, a geostatistical procedure has been applied through GIS (herein referred as Automatic Detrending Procedure [ADP]), in order to avoid errors in the interpretation of the ‘no-delta’ bathymetry.

The first test involved the use of the manual procedure, then an automatic interpolation procedure has been tested through the following steps:

**Construction of a Digital Terrain Model (DTM) of the real bathymetry:** the DTM has been built through the use of two different interpolation methods - triangulation or kriging - depending on the spatial distribution of the original bathymetric data. As previously stated, the examined sites haven’t the same data distribution due to the different survey techniques adopted, so the best fitting interpolation method has been used. The resulting bathymetry has been converted in raster format. All operations have been performed by ESRI ArcGIS™ 3D Analyst and Spatial Analyst;

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Defences</th>
<th>Tidal Prism ((\times 10^6 m^3))</th>
<th>Cross-sectional area ((m^2))</th>
<th>Date of survey</th>
<th>Ebb volume by GIS calculation ((m^3))</th>
<th>Ebb volume by Hicks and Hume ((1986)) relationship ((m^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primero</td>
<td>embanked</td>
<td>6.00</td>
<td>696</td>
<td>1997</td>
<td>593,563</td>
<td>678,190</td>
</tr>
<tr>
<td>Grado</td>
<td>small jetties</td>
<td>23.40</td>
<td>2,045</td>
<td>2002</td>
<td>5,039,855</td>
<td>4,621,173</td>
</tr>
<tr>
<td>Lignano</td>
<td>small jetties</td>
<td>40.00</td>
<td>3,438</td>
<td>2003</td>
<td>10,998,329</td>
<td>9,841,526</td>
</tr>
<tr>
<td>Baselegh e</td>
<td>natural</td>
<td>3.04</td>
<td>435</td>
<td>1999</td>
<td>595,148</td>
<td>554,272</td>
</tr>
</tbody>
</table>
Construction of the no-delta bathymetry: a first test was done by extracting 2 to 4 lateral profiles (located in the littoral area not interested by the ETD structure) in order to create a first-order trend surface. A more rigorous and effective method consists on the use of the entire bathymetric dataset for the calculation of different polynomial trend surfaces. First, second, third - and in some cases, also fourth - order polynomial surfaces have been created and evaluated, both for statistical parameters as goodness-of-fit and correlation, and for the correspondence with the existing geographic setting of the coastal area. Tests and processing have been carried out by ESRI ArcGIS™ Geostatistical Analyst;

Subtraction of the different no-delta surfaces from the real bathymetry and creation of different Residual Maps: in order to obtain precise residual maps, cell-by-cell calculations between the bathymetric rasters have been carried out. The result obtained consists in a map of hypothetical thickness of the deposit. This task has been performed with ESRI ArcGIS™ Spatial Analyst, using its Raster Calculator.

Ebb-tidal delta volumes calculations: volumes have been calculated for the different configurations considering cells with positive values in the residual surface.

A first-order polynomial surface resulted as the most adequate interpretation of the regional trend, since the coastal area in the vicinity of tidal inlets presents a relatively straight configuration. An example of residual map obtained using the de-trending procedure is reported in Figure 2, where the residual map clearly shows the location of the ETD shoal and the different thickness of the deposit.

A further step has been the identification of the best potential dredging site, assuming the use of the sand for nourishment to an erosional beach located in the neighbourhood. Tests have been carried out both on Lignano and Grado inlets, because sediment data for local erosional beaches are available. A simple logical calculation using the ESRI’s Raster Calculator has been performed, fixing three conditions: a minimum thickness of the deposit; a minimum mean grain size (in phi); and a minimum grain size sorting. The minimum thickness of the deposit has been assumed at 1.0 m (to take into account dredging machinery working limits), while the other two conditions depend on the nourishment site characteristics. GIS query leads to a possible dredging area, thus allowing better volume calculation and giving a precise indication of the suitability of the inlet as a sand source. Furthermore, the identified area becomes the preferred site on which further investigations can be performed, such as core sampling and geophysical supplementary surveys.

RESULTS AND DISCUSSION

The stability of an inlet is due to the balance between the forces that tend to close the opening and those that cause the widening of the cross-section. O’BRIEN (1931, 1969) quantified the relation that the size of a tidal inlet is tied closely to its tidal discharge; he demonstrated that a strong correlation exists between an inlet’s tidal prism ($P$) and its throat cross-sectional area ($A$), according to the following formula:

$$ A = c \cdot P^n $$

where $c$ and $n$ are empirical constants. These types of equations are widely reported by other authors (JARRETT, 1976; GAO AND COLLINS, 1992; HUGHES, 2002; NISHI et al., in press), and can be used to define the equilibrium state of a tidal inlet. On the basis of further studies and statistical analysis, WALTON AND ADAMS (1976) suggested that, like inlet cross-sectional area, the volume of sand contained in the ebb-tidal delta ($V$) is closely related to the spring tidal prism ($P$), as follows ($V$ is followed by the authors’ initials):

$$ V_{WA} = 6.6 \cdot 10^{-3} P^{1.23} $$

(1)

Similar formulas, even if using different coefficients, were elaborated by MARINO AND MEHTA (1987) and HICKS AND HUME (1996):

$$ V_{MM} = 5.6 \cdot 10^{-4} P^{1.39} \quad \text{and} \quad V_{HH} = 1.88 \cdot 10^{-4} P^{1.41} $$

(2)

MARINO AND MEHTA (1987) developed their formula based on a statistic of 19 inlets along the east (Atlantic) coast of Florida, while Hicks and Hume analysed morphology and size of 17 ebb-tidal deltas off natural inlets on the New Zealand North Island coast.

A regression analysis of the A-P values for the northern Adriatic inlets dataset, including data from literature (DORIGO, 1965; CONSORZIO VENEZIA NUOVA, 1989), is shown in Figure 3.

The data statistics for $P$ and $A$ available for the North Adriatic show a significant discrepancy with the calculations carried out following JARRETT’s (1976) indications. All the North Adriatic inlets have hydraulic sections wider than those computed by

![Figure 2. Lignano inlet: example of the de-trending procedure for the definition of the ebb-tidal delta and volume calculation.](image-url)
Jarrett’s general formula. This means that, with equal tidal prism, the Adriatic inlets have lower velocity values than those defined by the relations based on the Atlantic conditions. A lower flow velocity in equilibrium conditions determines a lower competence of the tidal flow, and therefore a lower sand load directed towards the ETD.

ADP developed with the linear interpolation of the whole dataset and supported by a regular spatial distribution of depth data, has given reliable values of ETD volumes comparable with those calculated by the Hicks and Hume (1996) formula (Table 1; Figure 4). Sand storage potential varies considerably from $0.27 \cdot 10^6$ to $11 \cdot 10^6$ m$^3$, as a function of the tidal prism.

For the analysed northern Adriatic inlets, the use of GIS highlights that a large amount of the ETD sediments consists of more than 1-m-thick deposits, thus suitable for dredging and reuse. A GIS catalogue of the different lithologies (obtained through specified inquiries about grain mean-size and sorting) may be a useful tool for a beach nourishment plan addressed to the neighbouring erosional beaches.

In the case of Lignano inlet, the research of a sand deposit with specified thickness (> 1 m) and grain size characteristics ($M_z = 2.4-2.6$ phi and sorting < 0.35 phi) to use for a possible local nourishment of ca. 120,000 m$^3$, leads to the GIS response of a total amount of 2,700,000 m$^3$ of sand located in the area surrounding the ETD, namely on the terminal lobe and along the updrift channel margin linear bar (Figure 5).

Part of this deposit is currently sand that fills the entrance, thus limiting the navigation; part is sand that tends to accumulate on the updrift area, and due to storms from NE, may enter the channel. A possible limited dredging operation through the reshaping of the channel margin linear bar may be thus hypothesised and accurately studied.

CONCLUSIONS

Several tidal inlets exist along the northern Adriatic coastline, where the interaction between tidal currents and longshore drift developed ebb-tidal deltas. The presence of these morphologies in the nearshore areas has caused several problems for shipping facilities, and modifications such as jetty construction has been employed at several inlets.

Sand deposits stored at the ebb shoal mainly in the cases of unjettied or only partially stabilised inlets require constant dredging operations in order to guarantee navigability, and a rational plan concerning the use of the dredged material is required. Different methodologies are available for calculating the volumes of sand that accumulates in ETD structures; a specific and simple geostatistical procedure through GIS has been developed and applied to five inlets. This automatic procedure allows the calculation of ETD volumes with less subjectivity than through the manual method, originally developed by Walton and Adams (1976). Volumes calculated by geostatistical computation present good correspondence with the values calculated through Hicks and Hume (1996) predictive relationship.

When coupled with sedimentological data, the sand stored in ETD may be classified in GIS and catalogued following the volume, mean grain-size and sorting, thus providing a useful tool for a preliminary assessment on sediment compatibility for possible nourishment of neighbouring erosional beaches.

In order to avoid abrupt environmental impact, a possible strategy for channel navigation maintenance could involve the reshaping of the main depositional bodies which act as sediment sources, following a suitability control in the GIS inventory.

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LITERATURE CITED


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