Geomorphology of Irish Estuaries: Inherited and Dynamic Controls

J.A.G Cooper

Coastal Research Group
University of Ulster
Coleraine BT52 1SA
Northern Ireland
United Kingdom

ABSTRACT


The Irish (Republic of Ireland and Northern Ireland) coast contains a diverse range of estuary forms that have developed in response to a combination of contemporary dynamic conditions and inherited factors. Most of the coastline is bedrock-framed and estuaries typically occur in bedrock-confined valleys. The effects of the last glaciation, however, largely control the relative sea-level history of the island. Thus the depths of bedrock valleys are substantially greater in the south, where sea levels fell to at least 60 m below present levels compared to 30 m below present in the north. Further inherited control is imparted through the distribution of glacially-derived sediment on the coast and adjacent shelf. Major sediment sources for contemporary estuarine barriers coincide with known glacial limits and retreat phase stabilisation. Contemporary dynamics vary substantially around the coast with the main contrast being between the exposed Atlantic western coast and sheltered eastern, Irish Sea coast. Tidal range varies around the island from micro- to macrotidal and this too exerts a strong control on estuary morphology. This paper presents a threefold classification of estuary type in Ireland (drowned river valley estuary, river-dominated estuary and bar-built estuary) and attributes the variation in morphology primarily to inherited controls related to the island’s paraglacial setting.

INTRODUCTION

The geomorphology of estuaries is known to vary spatially in response to a combination of inherited factors (geological setting and bedrock framework) and process factors (contemporary dynamics). A number of regional syntheses of estuary morphology have provided insights into the relative importance of various controlling factors (e.g., LANKFORD, 1977, DUFFY et al., 1989, HUME and HERDENDORF, 1988; COOPER, 2003).

In this paper, the geomorphology of Irish estuaries is assessed and a preliminary categorization is presented that is based primarily on genetic factors (mode of origin) and secondarily on contemporary dynamics. The Irish (Republic of Ireland and Northern Ireland) coast, while small in extent, is highly variable in terms of inherited factors and contemporary dynamics and offers an excellent opportunity to investigate the roles of both sets of factors on estuary morphology. The aim is (a) to describe the spatial variability in potential estuary controlling factors and contemporary dynamics, (b) describe the range of estuarine morphology and (c) present a provisional classification based on geomorphic parameters.

Against a highly variable geological and dynamic background, an estimated 400 transitional water bodies of various sizes exist around the Irish coast. The coastal hinterland is low-lying and humid. While there is perennial stream flow, the volume of sediment that is carried, is low because of the hinterland topography and vegetation cover. Marine factors that influence estuary morphology are highly variable, with strong gradients in wave energy and tidal range around the Irish coast. The entire island may be considered paraglacial and the inherited elements of the glacial landscape constrain the physical setting of estuaries.

ENVIRONMENTAL SETTING

Inherited Factors

The whole island comprises a bedrock-framed coast that lacks coastal plains. Estuaries occur in bedrock valleys, which form re-entrants on the coastline and in which coastal sediments occasionally accumulate as barriers.

The island of Ireland has a 3000 km coast located between 50 and 55° N (Figure 1). The entire island was affected by successive glaciations, although the main Midlandian (=Wisconsinan) glaciation glaciation and ice limits formed during deglaciation are the main constraints on contemporary coastal geomorphology. The main ice limits (Figure 2) are important in coastal geomorphology in that they are associated with major sediment sources. Bedrock across the island has been sculpted by glacial processes although fjards are best developed in the north and west of the island. Lough Swilly, for example, has a 130 m-deep bedrock valley, of which about 100 m is filled by glacial sediments. Glacial diamict was deposited on bedrock veneers according to sediment supply during glacial periods. In some areas, a paucity of sediment has left a sculpted bedrock surface while in others, glacial deposits provide soft, coastal lithologies, vulnerable to erosion at present sea level.

The distribution and variable sediment composition of beaches and barriers may be explained in large part by glacial inheritance. Areas located close to ice limits tend to have sandy barriers, the sand having been deposited initially by outwash and subsequently reworked by marine processes. Depositional areas distant from ice margins are instead characterised by coarser sediments (gravel and cobbles) derived largely from reworking by wave action of glacial diamicts. Sediment supply at the Irish coast occurs predominantly from reworking of shelf sands (themselves of glacial origin), locally from erosion of bluffs of glacial sediments, and occasionally from contemporary fluvial sediment supply, although the latter is mainly confined to the steep NE coastal hinterland. Coastal sediment supply is thus strongly related to patterns of ice movement, stabilisation and decay during the last glacial cycle. Contemporary rates of sea level change are equally variable. Tide gauge observations in the north suggest a near stable or slightly falling sea level over the past 50 years, while in the south sea level appears to be rising at c3.0 mm/yr over the same period.

One consequence of highstand shorelines along the north coast is the presence of highstand deltas, which provide potential sediment supply to rivers in the northeast. An additional consequence of this sea level history is the depth to which river channels were incised during the Holocene...
lowstand. Much deeper incision is expected in the south than the north. Against this, valleys throughout the island were scoured by ice and contain overdeepened channels.

Dynamic Variables

The main process variables identified as affecting estuaries include tidal range, wave energy and river discharge (DALRYMPLE et al., 1992; COOPER, 1993). Around the Irish coast there is marked variation in tidal range. The west coast comprises meso- to macrotidal environments, while the east coast ranges from microtidal to macrotidal settings. It is swell-dominated with modally high wave and wind energy and characteristically dissipative sand beaches, or more reflective gravel systems. Large sand dunes characterize many beach systems and these appear to be related to major deglacial depocentres. Superimposed on this variability is a strong east-west gradient in wave energy (Fig.3). The west coast is exposed to high-energy swell waves while the east coast is dominated by locally generated waves produced within the Irish Sea. The east coast is thus more prone to energetic short period waves and longshore sediment transport than the west coast where refraction is typically near complete as swell waves approach the shoreline.

River discharge is an important variable in estuary dynamics. In Ireland most estuaries are of comparatively small catchment size because of the small drainage area of the island as a whole. Most estuaries are fed by rivers with <200km² catchment areas. Only a few rivers have catchment areas greater than 1000 km². By far the largest catchment is that of the Shannon (>11,000 km²). The large rivers drain low-lying areas and supply little coarse-grained sediment to the coast. High vegetation in the hinterland cover also reduces the suspended sediment load.

Irish Estuary Types

Within this highly variable environmental context a range of estuary types may be identified on the basis of contemporary geomorphology and consideration of the contemporary geomorphology in the context of inherited and process variables. Here the term 'estuary' is considered in its broadest context as a transitional fluvio-marine coastal water body.

A threefold classification based initially on genetic (mode of origin) characteristics is presented here. The inherited factors are considered to be the dominant geomorphological control as they set the physical limits within which contemporary processes operate.

Drowned Valley Estuaries (Fjards, River Valleys)

Valleys, both of glacial and fluvial origin, have been inundated during the Holocene rise in sea level to form estuary basins. In terms of contemporary geomorphology the nature of the drowned valley has limited significance. The drowning was accompanied by and succeeded by sedimentation that acts to reduce estuary volume. Because typical fluvial sedimentation rates are low, most of these estuaries are still infilling. Typical estuarine circulation patterns exist in these estuaries and a range of salinity is noted.

Barred Drowned Valley Estuaries

This group of estuaries may be subdivided into those that have barriers and those that lack barriers. The barrier in such cases is not essential to the existence of the estuary, but simply reflects the availability of non-cohesive sediments in the contemporary coastal zone. Examples of such estuaries include the estuaries of Lough Foyle (COOPER and GAULT, 2002), SW Donegal (BURNINGHAM and COOPER, 1998), and Wexford Harbour (ORFORD, 1988) (Fig.4A). Common to all of these estuaries is a local supply of relict sediment for barrier
construct. All of these examples are adjacent to sites of ice margin stabilisation followed by outwash, which provided abundant sandy sediment that was reworked during the Holocene to form estuary barriers. The early formation of barriers is inferred to have caused constricted inlets with flood-tidal dominance and through which shelf sands were transported to act as the main infilling mechanism for these estuaries (Burningham, 1999), coast, the Antrim Glens.

Within this genetic characterisation some variability can be seen that is related to contemporary dynamics. Ebb-tidal deltas are well developed in Castlemaine harbour, Lough Foyle, and the SW Donegal estuaries, despite high wave energy. This suggests that the tidal currents generated by large tidal prisms produce semi-fixed ebb-deltas. At Wexford Harbour, an ebb-delta is present but is less well developed as a result of vigorous wave reworking. Flood-tidal deltas are not easily discernible in the SW Donegal, and Foyle examples where the estuarine basins have been largely infilled by flood-tidal deposition thus limiting accommodation space for distinctive delta features. In Wexford and Castlemaine, flood-deltas attain typical morphologies with a flood ramp, ebb shield and spillover lobes. This development is probably linked to lower sedimentation rates in the back-barrier.

The antecedent morphology of the drowned river valley exerts constraints on the contemporary morphology in that (i) less sediment is needed for barrier development if the valley is narrow, and (ii) those estuaries developed in wide valleys have large internal fetch distances in which estuary waves may modify the shoreline. The latter phenomenon is well demonstrated in Lough Foyle where extensive intertidal flats have developed through erosion and planation on the downwind margin of the estuary.

**Non-barred Drowned Valley Estuaries**

A large number of valleys that were drowned during the Holocene persist as elongate inlets more or less dominated by seawater. They lack barriers and have fully marine salinity. In the upper reaches of some, freshwater discharge reduces salinity and deposits deltaic sediments, which may form intertidal flats. Examples include Belfast Lough, Strangford Lough, Killary Harbour and Cork Harbour (Fig.4B). These examples exhibit marked morphological differences as a result of their mode of origin (fjords are common in the north while rias characterise the south of the island) and surrounding geology but they have in common, their origin as drowned valleys. None has a barrier and they are dominated by seawater. In the upper reaches of Belfast and Strangford Loughs are minor deltaic deposits from the inflowing rivers. Low fluvial and marine sedimentation rates render these valleys still in an immature stage of development. The largest estuary in Ireland, the Shannon, also falls in this category. It too has extensive intertidal flats in its upper reaches, developed through deposition of fluvial sediments. Its lack of a barrier relates to a lack of local sediment supply as much as the strength of tidal and fluvial currents which prohibits barrier development on macrotidal estuaries elsewhere.

Common to all of these estuaries is a substrate dominated by mud or bedrock. Contemporary geomorphological variations within this group arise from the volume of fine-grained sediment deposited. Belfast Lough is rich in fine sediment due to a relatively large inflowing river and potential anthropogenic enhancement of the sediment supply (Orford et al., 1997). Strangford Lough is sediment-poor due to the small catchments of inflowing rivers.

**Bar-Built Estuary/Lagoon**

Several estuaries have developed in low-lying coastal areas where inflowing rivers are small or non-existent. These estuaries exist because of the local availability of sediment from which barriers have been constructed (Fig.4C). They may thus be termed bar-built estuaries. Typically, sediment sources are eroding glacial bluffs (Carter et al., 1984) which yield coarse clasts (gravel). Such enclosed water systems have small volumes and are not associated with major terrestrial drainage systems. Carter et al. (1984) studied several such lagoons in SE Ireland and observed two main forms of interaction between marine and terrestrial waters. Many systems lacked an outlet and communicated via seepage and overwash, while others had sufficient tidal prism to enable semi-permanent inlet/outlets to be maintained.

**Barriers With Inlets**

Several examples exist with inlets. Of these, Tramore in County Waterford is a good example. Here a barrier encloses a
shallow embayment located between two bedrock promontories. The size of the enclosed embayment produces a sufficient tidal prism to maintain an inlet in the barrier, and a small ebb-tidal delta is present. A similar system exists in Ballyteige Bay while the adjacent lagoon at Tacumshin, fluctuates between seepage and channelised water exchange. Bar-built estuaries with surface channels typically exhibit small ebb-tidal deltas and limited or no flood-tidal deltas as a result of the small tidal prism and limited accommodation space for flood-tidal deposition.

Closed/Percolation Lagoon

Several small enclosed systems exist in which the barrier lacks a natural inlet. These systems facilitate exchange of water via percolation through the barriers (Carter et al., 1984). The barriers of the south Wexford coast originate through erosion of adjacent glacial bluffs and the high porosity afforded by their gravelly texture assists in freshwater exchange in a seaward direction. Similar barrier-enclosed systems are developed at several other localities on the south coast including Brandon Bay, and the west coast north of Killylarry Harbour (Delaney and Devoy, 1995). These systems are dominated by freshwater seepage and barrier overwash and are probably best termed lagoons as they lack typical estuarine salinity patterns. At Lady's Island Lake, Healy (1997) noted that such lagoons undergo wide fluctuations in salinity related to barrier overwashing and freshwater discharge volumes. Freshwater discharge in winter caused water levels to rise by over 2m and water levels in the enclosed lagoons were perched several metres above sea level.

River-dominated Estuaries

In the northeast of Ireland in the Antrim Glens, several small rivers discharge across a steep, uplifted hinterland on which high-level, coarse-grained fluvioglacial deltas are present (Fig.4D). They thus deliver appreciable quantities of sand and gravel to the coast, which is reflected in the coarse-grained channel sediment and associated coastal barriers and beaches. These systems discharge fluvial sediment directly into the sea and have minimal tidal prisms as a result of fluvial infilling.

**DISCUSSION**

This preliminary assessment of estuary geomorphology in Ireland reveals the presence of several distinctive types of contemporary estuary, differentiated in terms of their mode of origin and contemporary morphodynamics. The dominant controls on contemporary morphology appear to be inherited features related to the nature of the original valley, and the nature of sediment supply. Barriers across drowned valley estuaries are developed only where relict glacial sediment is available in the immediate vicinity. Barrier development sets up tidal asymmetry in the inlet and may enable estuarine infilling from marine sources. Where sediment is abundant on the shelf, such estuaries are largely infilled and contain broad intertidal flats. In areas of lower sediment abundance, distinctive flood-tidal deltas may be distinguished. Drowned valleys in sediment-poor locations produce essentially marine embayments within which reduced wave energy may permit suspension settling of fine sediments from inflowing rivers. Both types of estuary appear to operate as sediment sinks in the coastal sediment budget.

Barrier-built estuaries occupy pre-existing topographic lows that may or may not be related to fluvial or glacial incision. Their presence is related to the availability of sediment of glacial origin in most instances, and a coastal re-entrant in which barrier sediment may accumulate. The contemporary geomorphology and hydrology of these systems is a function of the relationship between seepage through the barrier, freshwater discharge and frequency of marine overwash overwashing and lack of return flow also mean that these systems act as net sediment sinks river-dominated estuaries are distinctive forms that have developed through fluvial infilling of their valleys and which now act as sediment sources for the adjacent coast. The frontal limits of the resulting channel deposits are reworked to form estuary mouth barrens. The beaches of the northeast coast owe their existence to this fluvial sediment supply.

There is a generalised geographical distribution of estuary type that relates largely to inherited, glacial characteristics (Fig.5). In the northeast, river-dominated estuaries owe their existence to isostatic uplift which gave rise to shallow estuarine valleys, and provided both a ready sediment source (fluvioglacial deltas) and steep rivers in which the sediment could be transported to the adjacent coast. Barred, drowned valley estuaries are located close to major ice limits that occurred during the deglacial phase. At such locations outwash was responsible for depositing the now relict sand and gravel in the vicinity of contemporary barred estuary mouths. On the northwest coast a major ice limit at c14k yr BP produced high volumes of sand and gravel outwash from the adjacent crystalline basement outcrops. Further south, temporary stillstands in the retreating ice front produced similar concentrations of outwash. A north-south increase in the depth of the incised valleys may be responsible for the relative immaturity of development of barred estuaries southwards in that greater volumes of sediment are required to infill the larger volume drowned valleys.

Drowned valleys distant from ice margins have remained as marine indentations in which contemporary fluvial sedimentation may produce bayhead deltas and tidal flats and, if wave action is reduced, fine-grained sedimentation in the drowned valley. Tidal asymmetry is less developed than in barred estuaries. Bar-built estuaries tend to be small in volume and rely on a local supply of erodible glacial diamict that typically supplies downdrift barriers with necessary sediment.

In all cases, inherited factors are a dominant control in contemporary estuary morphology. Patterns of uplift have been important in their control on high-level sediment sources in the northeast and in locating relict glacial outwash in the Holocene active wave zone. The influence of relative sea level history has also determined the depth of Holocene valley incision.

Contemporary dynamics exert a secondary variability on this pattern, which is best investigated by comparison of genetically similar estuaries in contrasting dynamic zones. Clearly further subdivision of estuary type is possible and the physico-chemical characteristics of these estuary types remain to be investigated. This paper, however, presents a preliminary geomorphological classification in which the influence of Inherited factors can be seen to be dominant over contemporary processes in controlling contemporary estuary morphology.
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LITERATURE CITED