# New typologies for estuarine morphology

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## Abstract

New theories to explain how tides and river flow determine estuarine bathymetries have been developed. The range of validity of these theories has been subsequently assessed against a recently available observational data set.

Success in reproducing the evolution of estuarine bathymetries that has occurred over the last 10 000 years provides the basis for the translation, here, of these theories into new typologies. These then provide reference frameworks to enhance our perspective on existing morphologies and identify 'anomalous' estuaries. Further refinement of these new theories requires analyses of causal factors responsible for such anomalies drawing on classical morphological experience. These frameworks can also be used for calculating likely future bathymetric adjustments for prescribed changes in: mean sea level, tidal amplitudes, river flow and sediment supply.

Keywords: estuaries, morphology, tides, river flow, sea-level change

## 1. Introduction

Prandle (2004a) used the equations describing tidal propagation in an estuary to derive expressions for: i) the length of tidal intrusion $L \propto D_0^{5/4}/\zeta^{1/2}$, where $D_0$ is the depth at the mouth and $\zeta$ is the tidal elevation amplitude, and ii) the depth profile $D \propto x^{0.8}$, where $x$ is distance from the head of the estuary. By using an existing expression for the length of tidal intrusion $L_I$, and requiring $L_I/L < 1.0$, it was further shown that $D_0$ is proportional to $Q^{0.4}$, where $Q$ is river flow. Hence the basic estuarine bathymetric parameters of depth profile and tidal length can be directly estimated from the two fundamental 'forcing' parameters namely tidal amplitude and river flow.

Moreover, since the latter are also the most readily available data for many estuaries, wide-scale assessment of the theories is possible.

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A recently available data set (Burgess et al., 2002) for 96 estuaries in England and Wales, shown in Figure 1, proved ideal for this assessment (Prandle, 2006). Results showed that while estuaries include peculiar localised features, statistically their bathymetries correlate with the fundamental 'forcing functions' of $\zeta$ and $Q$ in the form suggested by these new theories. Additionally, for the more bathymetrically dynamic 'Coastal Plain' and 'Bar-built' estuaries there is generally good quantitative agreement between observations and theory – subject to the nature and availability of the prevailing sediment sources.

The further objective here is to construct new typological frameworks, based on the primary 'forcing parameters' $\zeta$, and $Q$ illustrating both theoretical and observed distributions of depth, $D$, and tidal intrusion length, $L$. These typologies provide immediate perspectives of the sensitivity of existing bathymetry to these forcing factors and allow 'anomalous' estuaries to be identified. Likewise, they can be used to indicate likely changes from various climate change scenarios. The typologies also enable broad inter-comparisons between estuaries, potentially allowing additional influences (such as geological type, sediment supply, wave exposure, change in mean sea level, etc.) to be recognised.

Section 2 summarises the theoretical background and Section 3 the observational data. Section 4 describes the new typologies and Section 5 presents conclusions and suggestions as to how these typologies can be both used and refined.

## 2. Morphological theories

Equations for the tidal intrusion length and depth at the mouth are combined with conditions for saline and tidal intrusion, and stratification to establish a range of viable estuarine characteristics, against which observed estuary properties can be compared.

### *2.1. Tidal Length,* L

By assuming a 'synchronous' estuary, where surface gradients generated by tidal phase change predominate over those *via* tidal amplitude variations, Prandle (2004a) derived the following expression for the length of tidal intrusion in an estuary, $L$ (see Figure 3):

$$L = 123\, D^{5/4}/(\zeta f)^{1/2} = 2460\, D^{5/4}/\zeta^{1/2}\ (\mathrm{m}) \tag{1}$$

where $D$ is depth (m), $\zeta$ tidal elevation amplitude (m) and $f$, the bed friction coefficient, is taken as 0.0025.

An alternative perspective for judging the validity of the 'synchronous' assumption is provided (Prandle 2004a) by noting that almost identical expressions are obtained by replacing tidal elevation amplitudes with tidal current amplitudes. Thence where axial variation in (mid-channel) velocity amplitudes vary gradually indicates applicability of the assumption.

### *2.2. Depth at the mouth,* D

Prandle (2004a) compared observed saline intrusion lengths with the following theoretical expression:

$$L_I = 2D^2/f\,U_T\,U_0 \tag{2}$$

where $U_T$ is tidal velocity amplitude and $U_0$ is residual (riverine) velocity. Best agreement followed when the (tidally averaged) location of the centre of the intrusion was as far seaward as possible, subject to maintaining the intrusion length within the estuary. (Note that this latter condition implies bathymetric constraints or highly variable river flows might be characteristic of estuaries with pronounced coastal plumes.) Applying these conditions, the following expression was obtained (see Figure 4):

$$D = 12.8\,(Q\,a)^{0.4} \tag{3}$$

where '$a$' is the lateral slope of an assumed triangular cross section, and $Q$ is the river flow ($m^3\ s^{-1}$). This result is independent of both $\zeta$ and $f$.

### *2.3. Morphological Zone*

The above theories were extended (Prandle, 2004a) to indicate a 'zone of morphological existence' (Figure 2), which is bounded by the requirements that saline intrusion and its associated tidal excursion do not extend beyond the estuary, i.e.

$$\text{Tidal excursion: tidal length} \qquad E_X / L < 1 \tag{4}$$

where $E_X = U_T P/\pi$ and $P$ is the $M_2$ tidal period.

$$\text{Saline intrusion: tidal length} \qquad L_I / L < 1. \tag{5}$$

The additional condition, limiting applications to ‘mixed’ estuaries, is the criterion of Simpson and Hunter (1974):

$$D \,/\, U_T^{\,3} < 55 \ (\mathrm{m}^{-2}\,\mathrm{s}^3). \tag{6}$$

The Simpson-Hunter criterion was derived to explain thermally-generated seasonal stratification in shelf seas. However, Prandle (2004a) shows the criterion corresponds to persistence of salinity-induced stratification over the flood and ebb phase in estuaries. This study also showed that the criterion is closely approximated by $\zeta = 1$ m, as shown in Figure 2.

## 3. Results

### *3.1. Observed bathymetries of English and Welsh estuaries*

Table 1 summarises results based on observed bathymetries from the estuaries of England and Wales shown in Figure 1. The figure also shows the sub-division into the major estuarine types of: Ria, Coastal Plain and Bar-built (Davidson and Buck, 1997). In general, Rias are short, deep and steep-sided with small river flows. Coastal Plain estuaries are long and funnel-shaped with gently sloping triangular cross-sections providing extensive intertidal zones. Bar-built estuaries are short and shallow with small river flows and tidal range. Short estuaries tend to be sandy and long estuaries muddy. In sedimentary terms, Bar-built estuaries are located along coasts with plentiful supplies of marine sediments and, consequently, are closer to present-day equilibrium. Coastal Plain estuaries are continuing to in-fill following ‘over-deepening’ *via* post-glacial river incision whereas Rias are drowned river valleys (with related cross-sections) as a consequence of (relative) sea level rise.

The Future-Coast dataset (Burgess et al., 2002) includes estimates of observed tidal intrusion lengths. A systematic procedure for calculating corresponding representative depths, $D$ was used, namely:

$$D = 0.5\,(V_H \,/\, S_H + V_L \,/\, S_L) \tag{7}$$

where $V$ is net volume and $S$ net surface area at High Water (H) and Low Water (L). Other techniques for estimating $D$ from parameters in this dataset were examined, however equation (7) proved to be the most robust.

### *3.2. River flows*

The subsequent analysis is restricted to estuaries within the three types described above. The only estuaries excluded were those with no river flow data available or those shorter than 2.6 km. (This minimum length corresponds to $U_T \sim 0.2$ ms$^{-1}$, i.e., strongly stratified conditions from equation (6).) The river flow data were extracted from the Future-Coast dataset (Burgess et al., 2002) as being representative of mean flows. An examination was made of the 42 years of daily river flows from 203 rivers, provided by the Centre for Ecology and Hydrology (www.ceh.ac.uk). This showed that, on average, the 90th percentile value was 2.1 times the mean and the 99th percentile was 5.8 times. Noting that equation (3) indicates depth is proportional to river flow to a power of 0.4, these ratios correspond to depth variations of 1.34 and 2.02 respectively. This suggests that the perennial issue of the relative impacts of extreme versus mean conditions in determining estuarine bathymetries may be of secondary importance in respect of river flows.

### *3.3. Comparison with theory*

The 'theory' values in Table 1 correspond to Equations (1) and (2), incorporating the mean values of $\zeta = 1.8$ m and $a = 0.013$. Overall the table shows that the theories are most directly applicable to Coastal Plain and Bar-built estuaries, reflecting their geomorphic modes of generation and their relative independence from control by 'hard geology'. Hence, the subsequent focus is on these morphological types in establishing the new typologies.

*3.3.1. Estuarine length.* The relationships derived from observations between $L$ and $D$ for both Coastal Plain and Bar-Built estuaries agree closely with the theoretical formula – both for the power of $D$ and the related scaling coefficient. Ironically, the derived result for Rias shows even higher correlation, but the scaling coefficient is half the theoretical value.

*3.3.2. Estuarine depth.* Again, the derived relationships between $D$ and $Q$ for both Coastal Plain and Bar-Built estuaries are in reasonable agreement with the theory whereas the scaling coefficient for Rias is more than double the theoretical value. This indication of much broader cross-sections of Coastal Plain and Bar-Built estuaries is highlighted by the values shown for the lateral slope, $a$, where the value for Rias is almost three times the values for the latter.

The significant correlations between observed and theoretical estimates for both $L$ and $D$ for all types of estuaries emphasises that despite the scatter shown in Figures 3 and 4, there remains statistically significant agreement between theoretically derived and observationally fitted expressions.

Having thus established a degree of confidence in equations (1) and (3), we present in Figures 2, 3 and 4, typological frameworks for the 'Morphological Zone', lengths and depths of estuaries.

## 4. Discussion: new estuarine typologies

Figure 2 illustrates the application to the Future-Coast dataset, indicating the ($\zeta$, $Q$) coordinates for the estuaries shown in Figure 1. The background theoretical framework comprises the demarcation lines which bound the likely Morphological Zone. These lines correspond to requirements that saline intrusion and its associated tidal excursion do not extend beyond the estuary, and the Simpson and Hunter (1974) criterion for an estuary to be permanently stratified, i.e., equations (4), (5) and (6). Representative tidal current amplitudes, $U_T$ (from Prandle, 2004a), are also shown.

The distribution of estuaries is overwhelmingly within the anticipated Morphological Zone – with a few 'anomalies' justifying further investigation. Similarly we note that, as expected, Coastal Plain estuaries are generally associated with larger tides and river flows (see Table 1). The strong tidal currents, invariably greater than 0.5 m $s^{-1}$, exclude (permanent) stratification in almost all of the estuaries considered.

Figure 3 shows the distribution of estuarine lengths for each of the estuaries identified in Figure 2. Superimposed are theoretical loci for values of $L$ = 5, 10 and 20 km, based on equations (1) and (2). The correspondence between the observed and theoretical mean values of $L$ indicated in Table 1 is substantiated by the distributions in this figure. (However, note that in Figures 3 and 4, a few clearly erroneous values appear – these may stem from errors in the original data base and in subsequent derivations (see section 5 for further discussion). For future reference, these values are retained rather than omitted or adjusted.) The general trend for longer tidal reaches with larger flows is clearly evidenced.

Perversely, the theoretical result from equation (1) suggests that if $D$ is independent of $\zeta$, larger tides correspond to shorter estuaries. The theoretical basis for equation (3) relies on a requirement for estuaries to be long enough to contain the mixing of salt water. Since the salinity intrusion length, $L_I$, increases markedly for low-tidal stratified regimes, this result appears worthy of further investigation by extending the study to include such estuaries.

The distribution of observed depths is shown in Figure 4 together with loci for $D = 1$, 3 and 10 m based on equation (2). The small depths in Bar-built estuaries are clearly demonstrated.

## 5. Conclusions and further research

While individual estuaries exhibit localised features (related to underlying geology, flora and fauna, historical development and 'intervention') the overall values of depth and length and (funnelling) shape are broadly consistent with the latest dynamical theories. Moreover, the morphological features which characterise Rias, Coastal Plain and Bar-built estuaries can be rationalised by reference to these theories. The new typological frameworks provide perspectives against which to assess the morphology of any particular estuary. Furthermore, 'anomalous' estuaries can be identified, and related causal mechanisms explored. In addition, the formulae and typological frameworks can be readily used to calculate likely bathymetric adjustments to prescribed changes in mean sea level, tidal amplitudes, river flow and sediment supply.

These new typologies are of direct relevance for coastal zone management. For example, the European Water Framework Directive requires classification of all estuaries reflecting their levels of stratification, flushing times, etc. The typologies also usefully extend existing estuarine classification schemes beyond those for tidal response (Prandle and Rahman, 1980), sedimentation (Prandle, 2005) and mixing (Hansen and Rattray, 1966).

Anomalies between observational data and the theories derived for 'synchronous' estuaries might be attributed to many factors, including:

(i) 'interventions', e.g., flood protection, reclamation, dredging, weir and barrier constrictions
(ii) 'hard' geology, pronounced meanders
(iii) non-synchronous dynamics
(iv) inconsistencies in both the Future-Coast dataset and the classifications of Davidson and Buck (1997)
(v) impacts from waves
(vi) type and quantity of sediment supply
(vii) flora and fauna

Fuller consideration of all such factors for all of the estuaries considered here is beyond the present scope. However, it should be possible to identify consistent patterns within the 'anomalies' and link these to one or more of the above factors.

A major question concerns the degree to which present-day morphology is in equilibrium with existing dynamics. Discrepancies between observed and theoretical depths may be used to investigate historical changes that have occurred since the prevailing morphology was established. Thus, for Coastal Plain estuaries, estimates can be made of the much larger flows existent in their post-glacial formation. Likewise the divergence can be used for inferring coastal regions with scarcity of sediment supply for in-filling.

Interestingly, the new dynamical theories for estuarine morphology take no account of the sediment regimes in estuaries. These processes may need to be considered to quantify the related timescales for morphological adjustment. However, the success of these theories provokes a reversal of the customary assumption that estuarine bathymetries are determined by their prevailing sediment regimes. On-going small changes in net sediment movement (determined with great difficulty by extensive field and numerical model studies) may be inconsequential in longer-term morphological evolution. The resultant supposition is that the latter is determined by longer-term changes to the forcing parameters, $\zeta$ and $Q$ (as indicated here). Noting the sensitivity of the new theories to the bed friction coefficient, we also surmise that morphological evolution may be highly dependent on longer-term changes in flora and fauna, primarily through their impacts on the dynamical response of the estuary rather than through their more obvious control on sediment regimes.

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Table 1
Least squares fitted relationships between: i) estuarine length $L$ and depth $D$, and ii) $D$ and mean river flow $Q$; $R$ associated correlation – calculated as Percentage of Variance Accounted for (PVA).
Observed mean values of $L$, $D$, $Q$ and '$a$' (lateral slope).

| Type | No. | $L \sim AD^P$ | $R$ | Mean $L$ (km) | $D \sim AQ^P$ | $R$ | Mean $D$ (m) | Mean $Q$ ($\mathrm{m^3\,s^{-1}}$) | Mean $a$ |
|---|---|---|---|---|---|---|---|---|---|
| *All* | *80* | $1.28\,D^{1.24}$ | *0.69* | *20* | $3.3\,Q^{0.47}$ | *0.55* | *6.5* | *14.9* | *0.013* |
| Ria | 15 | $0.99\,D^{1.10}$ | 0.89 | 12 | $5.1\,Q^{0.31}$ | 0.74 | 9.3 | 6.3 | 0.037 |
| Coastal Plain | 30 | $1.95\,D^{1.12}$ | 0.69 | 33 | $3.0\,Q^{0.38}$ | 0.67 | 8.1 | 17.9 | 0.011 |
| Bar-built | 35 | $1.92\,D^{1.15}$ | 0.66 | 9 | $2.4\,Q^{0.38}$ | 0.72 | 3.6 | 9.5 | 0.014 |
| **Theory** | | $\mathbf{1.83\,D^{1.25}}$ | | **19** | $\mathbf{2.3\,Q^{0.40}}$ | | **6.6** | | |

The 'theory' values correspond to Equations (1) and (3), incorporating the mean values of $\zeta = 1.8$ m and $a = 0.013$.

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   Morphological types from Davidson and Buck (1997). Numbers correspond to the Future-Coast data set (Burgess et al., 2002)

2. ($\zeta$, $Q$) coordinates for Coastal Plain and Bar-built estuaries.

   Morphological Zone bounded by: i) tidal excursion – tidal length $E_X / L < 1$ (Equation 4), ii) saline intrusion – tidal length $L_I / L < 1$ (Equation 5), and iii) the Simpson and Hunter (1974) criterion (Equation 6), $D / U^3 < 55$ ($\mathrm{m}^{-2}\,\mathrm{s}^3$). Dashed contours for tidal velocity amplitude $U = 0.5$ and $1.0\ \mathrm{m\ s}^{-1}$ (Prandle, 2004a).

3. Estuarine Lengths, digits show observed values (km).

   Contours show theoretical values (Equation 1) for $L = 5$, 10 and 20 km.

4. Estuarine Depths, digits show observed values (m)

   Contours show theoretical values (Equation 3) for $D = 1$, 3 and 10 m.

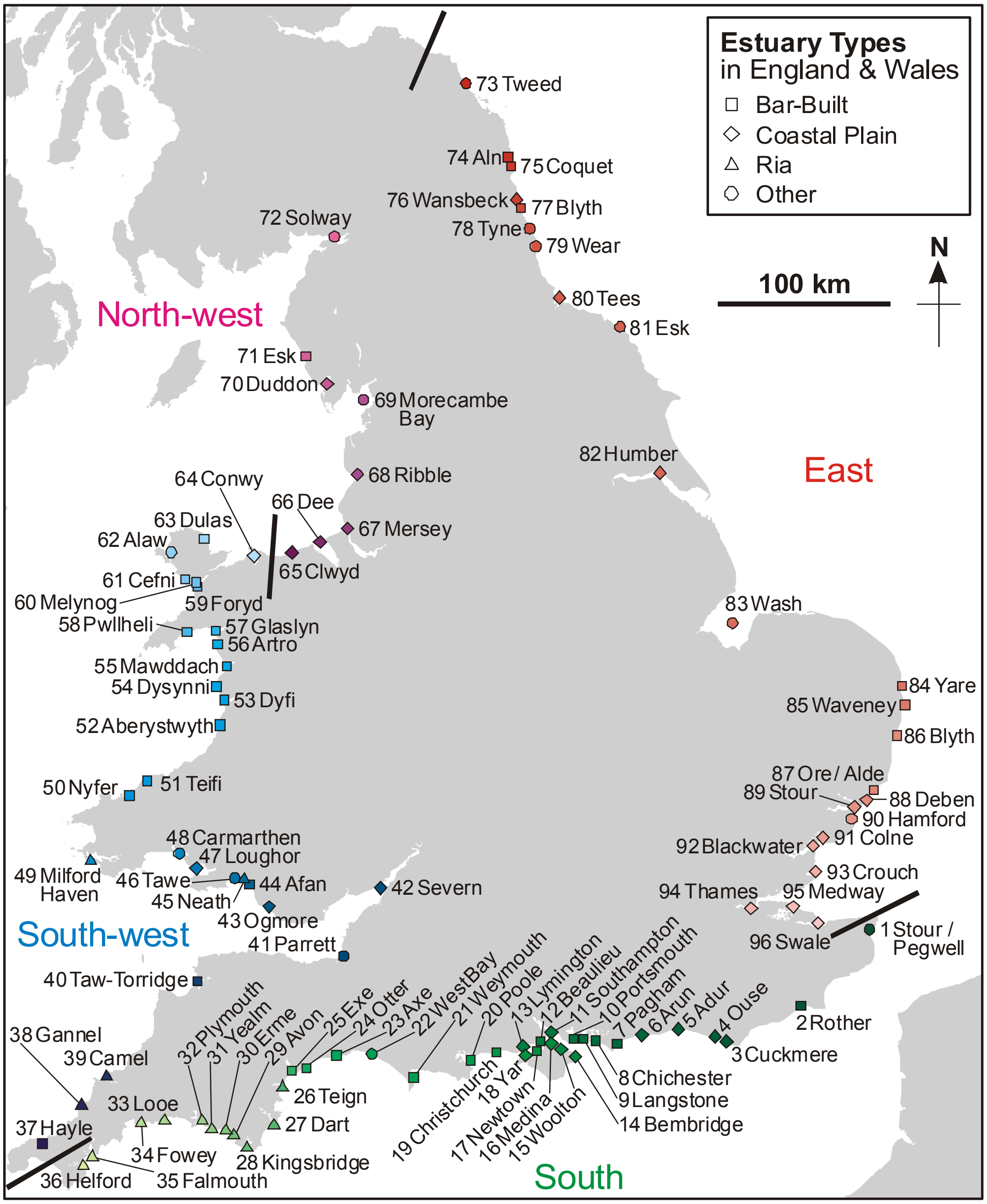

Fig. 1. Estuaries of England and Wales. Morphological types from Davidson and Buck (1997). Numbers correspond to the Future-Coast data set (Burgess et al., 2002).

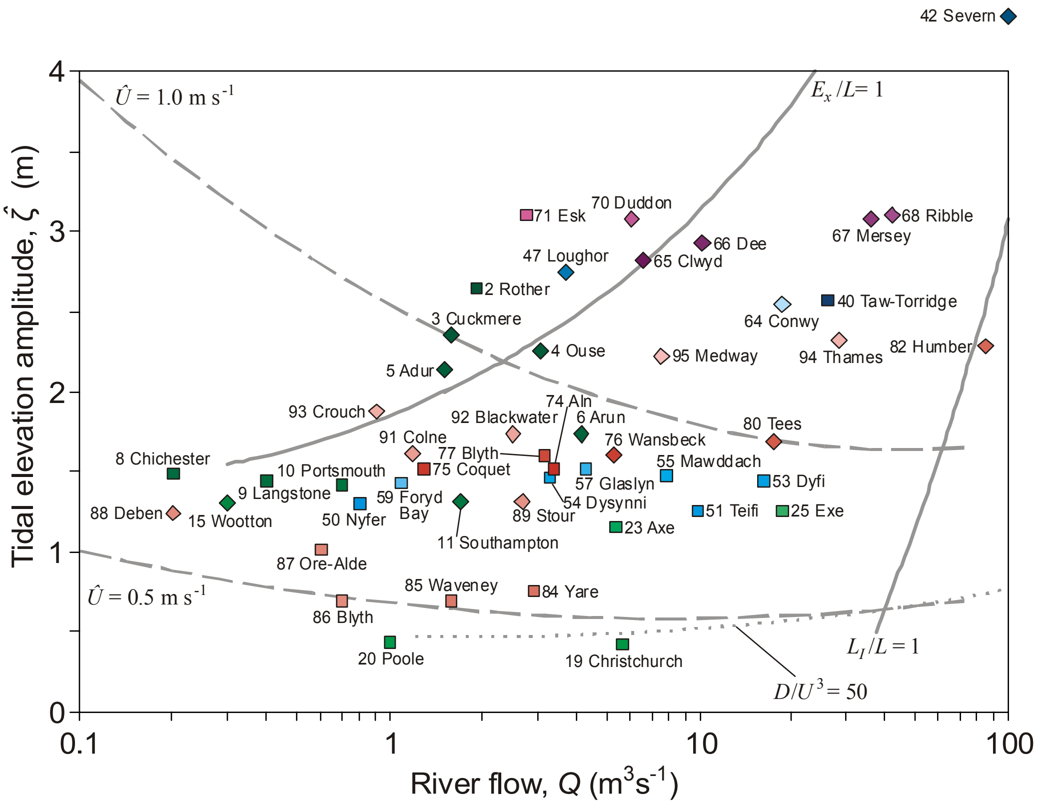

Fig. 2. (ζ, Q) coordinates for Coastal Plain and Bar-built estuaries. Morphological Zone bounded by: i) tidal excursion – tidal length $E_X/L < 1$ (Equation 4), ii) saline intrusion – tidal length $L_I/L < 1$ (Equation 5), and iii) the Simpson and Hunter (1974) criterion (Equation 6), $D/U^3 < 55$ (m$^{-2}$ s$^3$). Dashed contours for tidal velocity amplitude $U = 0.5$ and 1.0 m s$^{-1}$ (Prandle, 2004a).

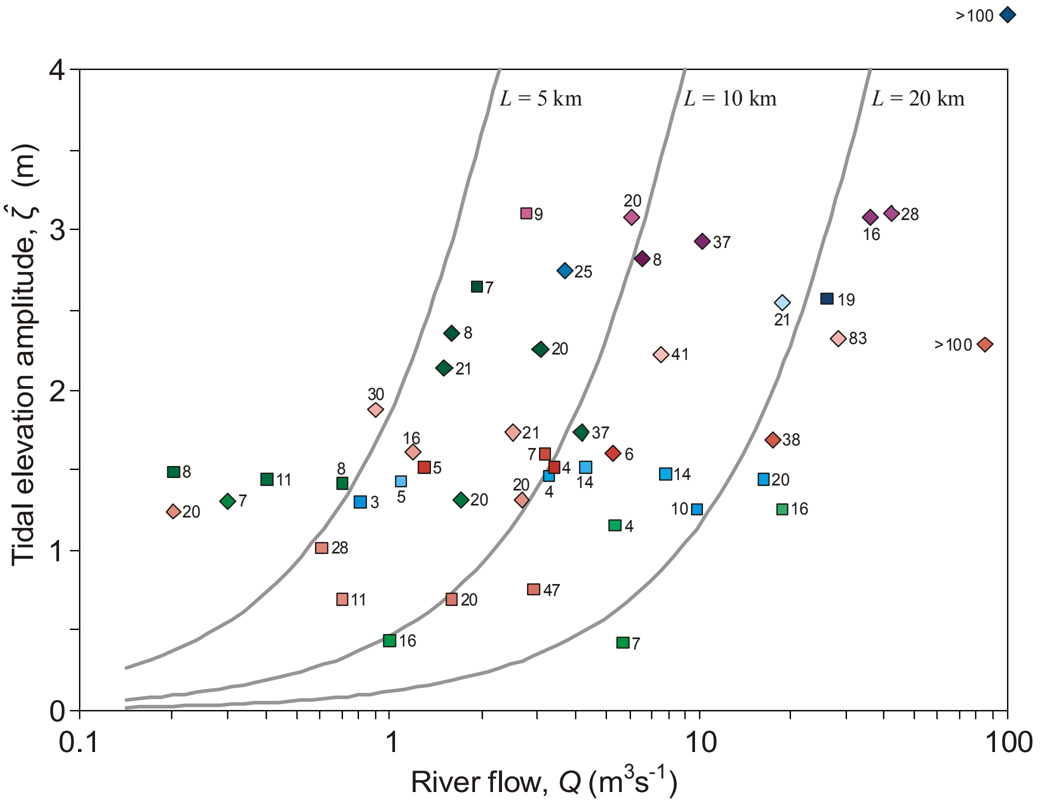

Fig. 3. Estuarine Lengths, digits show observed values (km). Contours show theoretical values (Equation 1) for *L* = 5, 10 and 20 km.

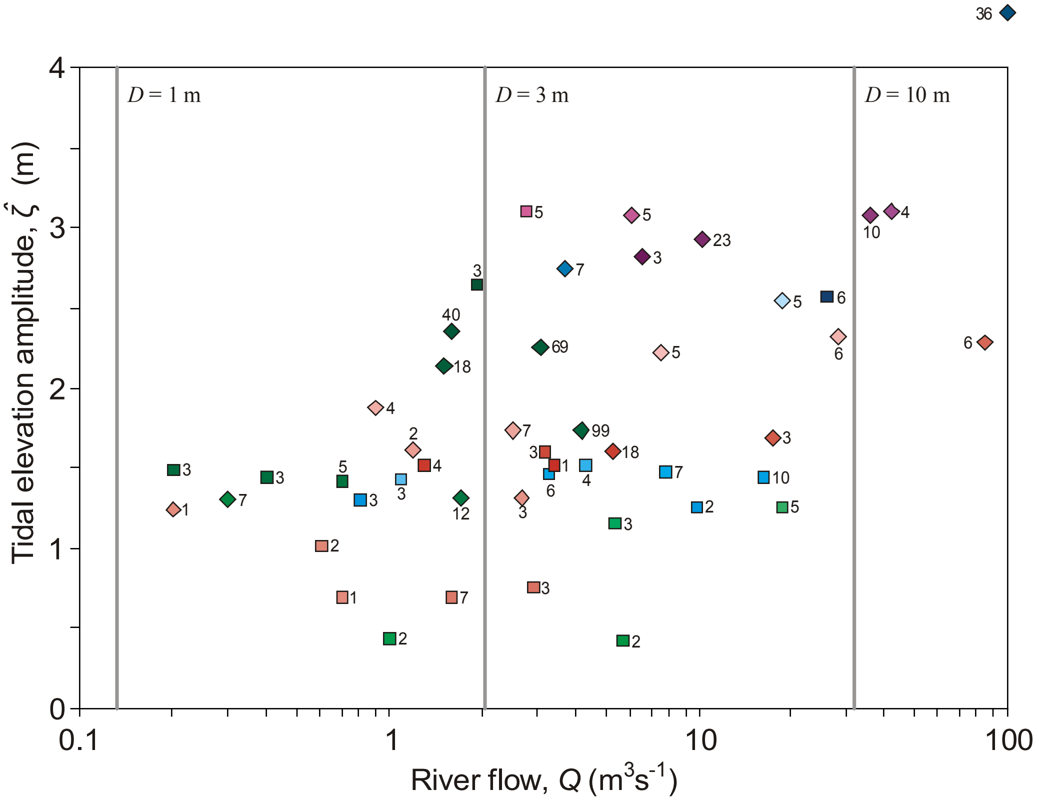

Fig. 4. Estuarine Depths, digits show observed values (m). Contours show theoretical values (Equation 3) for $D$ = 1, 3 and 10 m.