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Artificial barriers and estuarine squeeze: A novel assessment of estuarine vulnerability to climate change and sea level rise

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ABSTRACT

Estuarine ecosystems are threatened globally by changes in climate and catchment land use, with upper estuarine tidal freshwater and low-salinity zones being particularly vulnerable, yet the most poorly understood. These zones play a pivotal role in estuarine structure and functioning but are overlooked in assessments of vulnerability to sea-level rise and climate change. Commonly the tidal limits or landward boundaries of these zones are defined by in-stream barriers, such as weirs and sluices. These barriers restrict the natural inland migration of estuaries, intensifying the risk of saline intrusion as sea levels rise and summer river flows decline – a phenomenon known as 'estuarine squeeze'. This study provides the first estuarine squeeze vulnerability assessment for mainland England and Wales. Using an extensive dataset of salinity and electrical conductivity measurements, we delineate for the first time, tidal freshwater, oligohaline, brackish and marine zones across 85 estuaries. Of these, 59 (69 %) are constrained by in-stream barriers, and 45 (53 %) contain tidal freshwater and oligohaline zones. Nineteen of these 45 estuaries are bound by barriers at their tidal limits, making them susceptible to estuarine squeeze. These estuaries account for 64 % of all tidal fresh and oligohaline waters in mainland England and Wales. The Medway, Exe and Ouse estuaries in the south of England are identified as being most at risk. These zones are vital gateways, supplying and exchanging energy, matter, and organisms to the lower brackish estuary and upper non-tidal freshwater river. Their loss underscores the urgent need for their assessment, monitoring and management. However, it also presents an opportunity to compensate for their loss through for habitat creation, such as tidal freshwater marshes, offering ecosystem benefits and bolstering resilience against climate and other human-induced changes.

1. Introduction

The UK coastline is projected to experience a relative sea level rise of up to 1.15m by 2100 (Weeks et al., 2023), consistent with global sea-level projections (IPCC, 2021). In recent years (1992–2020), UK sea levels have risen by 3.0–5.2 mm per year (Kendon et al., 2022). Rising sea levels are directly associated with the influx of saltwater into estuaries and the inland extension of tidal influence (Costa et al., 2023; Ensign and NOE, 2018). At least 80 % of UK estuaries are likely to be vulnerable to the effects of sea level rise (Prandle and Lane, 2015), and this will be exacerbated by future reductions in river flow and anthropogenic channel modification (Wu et al., 2021; Talke and Jay, 2020; Hoagland et al., 2020). Assessing estuarine vulnerability to future changes in climate and human activity is a crucial first step towards the successful adaptive management of estuarine ecosystems, and the preservation of their benefits and ecosystem services into the future (Little et al., 2017).

A recently identified priority for estuarine management is in relation to 'estuarine squeeze'; the loss of upper-estuarine transitional zones against in-channel, man-made barriers through saline intrusion (Little et al., 2022a, 2022b). This process affects the upper tidal freshwater (<0.5) and low salinity, oligohaline (<5) reaches which exist below the

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landward boundary of estuarine water; the Normal Tidal Limit (NTL), as defined by Dionne (1963), in Fairbridge (1980). These distinct upper estuarine zones form when the momentum of the tide reaches further inland than the saline influence (Odum, 1988; Schuhardt et al., 1993), for example in estuaries with a larger (>1m) tidal range and high river flow input.

In-stream man-made barriers (e.g. weirs, dams, sluices, barrages) are becoming increasingly prevalent in the upper reaches of many estuaries in order to prevent flooding, facilitate water abstraction, and generate electricity (Bice et al., 2023). These structures, however, disassociate river and estuarine channels, thereby disrupting source to sea linkages, as well as potentially restricting the movement of organisms between habitats, and altering environmental conditions (Kukulka and Jay, 2003; Simenstad et al., 2011; van Puijenbroek et al., 2019). With a tidal influx of saltwater through sea level rise, previously fresh and oligohaline habitat becomes increasingly brackish, putting tidal freshwater resources and ecological communities at risk (e.g. Cañedo-Argüelles et al., 2013). Despite concerns around the impact of artificial barriers on estuarine habitats (van Puijenbroek et al., 2019; Bice et al., 2023; Little et al., 2022b), barrier presence has not yet been incorporated into an assessment of estuarine vulnerability to sea level rise and saline intrusion e.g. Prandle and Lane (2015).

The 'squeezing', and associated loss, of tidal freshwater and oligohaline habitat poses a potential threat to the ecology and functioning of the entire estuarine transition (Little et al. 2022a, 2022b). These distinctive, yet poorly-understood, upper-estuarine zones support unique and productive ecological communities (e.g. McLachlan et al., 2019; Little et al., 2017), provide habitat and migratory routes for species of conservation importance (Griffon et al. 2025), enable essential biogeochemical processes (Knights et al., 2017; Xu et al., 2021), and contribute to the wider structure and functioning of estuarine ecosystems (Williams and Williams, 1998; Dias et al., 2016; Young et al., 2021). Failure to include tidal freshwater and oligohaline zones in assessments of estuarine vulnerability could undermine the success of management initiatives and threaten the future provision of ecosystem services (Ensign and Noe, 2018; Little et al., 2022b). However, despite their importance, very little is currently known about the distribution of these zones, or the extent to which they are constrained by in-stream, man-made barriers. There is an urgent need to record the location and extent of tidal fresh and oligohaline waters, and identify which estuaries are likely to be most susceptible to estuarine squeeze. This paper presents the first estuarine squeeze vulnerability assessment for mainland England and Wales, which includes.

- Delineating tidal fresh, oligohaline, brackish, and marine zones in estuaries, using the first comprehensive dataset of UK estuarine salinity and electrical conductivity measurements.
- Identifying which estuaries are bound at their upper limit (NTL) by an artificial, in-stream barrier, and those which are not bound.
- Ranking estuaries in order of their vulnerability to estuarine squeeze using the following indices:
  (1) size of tidal freshwater and oligohaline zones
  (2) projected relative sea level rise at estuarine mouth
  (3) future river flow projections
  (4) future catchment water stress
  (5) depth at estuarine mouth

These findings will identify estuaries most vulnerable to estuarine squeeze, highlighting priority locations for assessment, monitoring and management. The results presented here can also be used to identify areas where habitat restoration and creation (e.g. tidal freshwater marsh) will best mitigate loss from climate change. The delineation of all estuarine waters in mainland England and Wales into salinity zones will also support a range of research and future applications, including species conservation, nature-based solutions, water quality and pollution control, and planning and development projects.

2. Methods

2.1. Summary of data holdings

Surface water salinity and electrical conductivity data for all estuaries in mainland England and Wales were gathered from government monitoring schemes, large-scale funded research projects, and independent researchers (Table 1). Additional, descriptive information regarding water salinity was taken from peer reviewed journals or catchment management plans when numerical data were lacking (Brew et al., 1992; Robinson et al., 1998; Wright, 2002; Pye and Blott, 2010; Dausse et al., 2012; Environment Agency, 2011, Environment Agency, 2012a; Grenfell et al., 2016). Specific details of the data source and sampling year(s) used to delineate the zones of each individual estuary, can be found in the Supplementary Data Table 3.

2.1.1. Data processing

Samples relating to waste, pollution or compliance monitoring were excluded, and entries with obviously erroneous data values or coordinates were removed. Entries with a result qualifier, e.g. <1 ppt, were treated separately as categorical variables, assigned using the site description and verified by the data provider. Any electrical conductivity readings in millisiemens per centimeter (mS/cm) were converted to microsiemens per centimeter (μS/cm). All salinity readings were either expressed using the Practical Salinity Scale, or in parts per thousand (ppt) (used interchangeably for the purpose of this study, as the conversion factor is minimal, Millero, 2010).

A total of 76,630 mean values of salinity or conductivity were calculated for sites across mainland England and Wales. All processing was undertaken in R (v4.3.0; R Core Team, 2021) using the tidyverse package (v2.0; Wickham et al., 2019).

2.2. Delineating estuarine zones

Sampling sites with associated salinity data were coded 'riverine', 'tidal freshwater', 'oligohaline', 'brackish' and 'marine' using the standard Venice system (Anon, 1958. Those with associated conductivity data were similarly coded, according to values that are widely reported in the literature (e.g. Wagner et al., 2006). The boundaries identified are shown in Fig. 1. All analyses were carried out in ArcMap Pro 10.8.1 and QGIS Desktop 3.34.0.

Estuarine water was defined as water located between the Normal Tidal Limit (NTL) and the bay closure line , the latter being the line drawn across the mouth of an estuary to mark its seaward boundary (Davidson and Buck, 1997). The upper limit of each estuary (NTL) was taken directly from the OS OpenData Boundary Line™ (Open Government license) Mean High Water shapefile. The lower limit of each estuary (bay closure line) was taken from the WFD Transitional and Coastal Waterbodies Cycle 2 Shapefile (Open Government License).

Within each estuary, salinity boundaries were identified and digitised with reference to the available salinity and conductivity data. It is important to acknowledge that, whilst all salinity sampling was undertaken as close as possible to local high water or on a falling tide the nature of the data means it is not possible to standardise salinity zone location for a set tide height (i.e. Mean High Water Spring) and river discharge for all estuaries in England and Wales. Some of the sampling was undertaken during (or standardised to) spring tides (i.e. Environment Agency, 2012b, Environment Agency, 2017; Environment Agency, 2024a Little et al., 2017; Uncles et al., 2015) and others over a range of tide heights (i.e. Natural Resources Wales, 2023 ; Tye et al., 2022) and all were recorded over different river discharge conditions.

As estuarine salinity zone location is subject to variations in tide height and river discharge conditions, a conservative approach was adopted when defining their extent to avoid overestimating the size of each zone. The upper limit of each tidal freshwater zone was marked at the Normal Tidal Limit (NTL). The tidal freshwater-oligohaline interface

Table 1
Summary of electrical conductivity and salinity datasets used for delineating estuarine zones. Additional, descriptive sources can be found in the Supplementary Data Table 3.

Description	Source	Usage licence and link	Reference
Water quality data from the Water Quality Archive (Beta), 2000-present	UK Environment Agency (EA)	Available under the Open Government Licence, https://environment.data.gov.uk/water-quality/view/landing	Environment Agency, 2024a
Natural Resources Wales water salinity and conductivity information, 1990-present	Natural Resources Wales (NRW)	Provided under the Open Government Licence following data request	Natural Resources Wales, 2023
Sampling of estuarine chemistry and organic matter for 16 estuaries in Great Britain in 2017/8 as part of the LOCATE project planned and facilitated by Andy Rees, of Plymouth Marine Laboratory	LOCATE (Land Ocean CArbon TransfEr), NERC EDS British Oceanographic Data Centre NOC	Provided by NERC and available under the Open Government Licence, www.bodc.ac.uk/data/published_data_library/catalogue/10.5285/d111d44e-0794-28dc-e053-6c86abc0fc99/	Tye et al., 2022
Water Framework Directive (WFD) classification scheme for marine benthic invertebrates: infaunal quality index (IQI) – associated salinity data, 2004-12	UK Environment Agency (EA)	Provided under the Open Government Licence following data request	Environment Agency, 2012b
Fucoid extent data WFD Cycle 2 TraC macroalgae classification – associated salinity data, 2009-15	UK Environment Agency (EA)	Provided under the Open Government Licence following data request	Environment Agency, 2017
Salinity data for estuaries of Southwest England collected during estuarine surveys planned and facilitated by Reg Uncles (RJU) of Plymouth Marine Laboratory (PML) and undertaken by RJU, John Stephens, Carolyn Harris and Norman Bowley (coxswain) of PML between 1996 and 2001	Reg Uncles, Plymouth Marine Laboratory	Provided by corresponding author	Uncles et al., 2015
Salinity data for the Ouse and Adur estuaries, Sussex, UK, 2008-09	Sally Little, Nottingham Trent University	Provided by corresponding author	Little et al., 2017

was marked at the last consistently ‘fresh’ sample site location (<0.5 or <1000 μs/cm) downstream of the NTL. The oligohaline-brackish interface was marked at the last consistently ‘oligohaline’ sample site location (≤5 or ≤8000 μs/cm) downstream of the NTL. The brackish-marine interface was marked at the first consistently ‘marine’ sampling location downstream of the NTL (>30 or >55,000 μS/cm). Each zone was also assigned a confidence level (high, medium, or low) based on the data used to delineate the zone extents. High confidence was given to zones delineated based on the most recent data (from 2016 onward) and/or scientific literature with specific focus on salinity gradients. Medium confidence was assigned to zones delineated with older data (pre-2015). Low confidence was given to zones where no data was available from within the estuary, but where conditions were conducive to the presence of a tidal freshwater zone (Table 2).

2.2.1. *Vulnerability to estuarine squeeze indices*

At their upper tidal limits, estuaries were classified as either ‘bound’ i.e. all NTL’s defined by an in-stream man-made engineering structure, ‘partially bound’ i.e. one of more NTL defined by an in-stream engineering structure or ‘unbound’ i.e. no in-stream engineering structure present at NTL, using the UK Environment Agency’s River Obstacles dataset (Environment Agency, 2024b), Ordinance Survey maps and satellite imagery. Where possible, the type of structure present was recorded for each bound estuary.

The 19 bound estuaries with tidal freshwater and oligohaline zones were then ranked in terms of their vulnerability to estuarine squeeze, using the following indices.

1 Size of tidal freshwater and oligohaline zones

The smaller the tidal freshwater and oligohaline zone, the more vulnerable it is to loss. The length (km) of each bound tidal freshwater and oligohaline zone was calculated using the OS Mastermap Networks - Water Layer (Ordnance Survey Limited (OS Data), 2023). The area (km^2) of each zone was calculated using a polygon shapefile created from the OS OpenData Boundary -Line™ (Open Government license) Mean High Water line. Only the bound tidal freshwater and oligohaline estuarine sections were included in this calculation. Estuaries were ranked 1–19 in order of the length of their (combined) bound tidal freshwater and oligohaline zones. The estuary with the smallest zone was assigned the highest score (19), indicating high vulnerability to estuarine squeeze. The estuary with the largest zone was assigned the lowest score (1).

2 Relative sea level rise by 2080

Rising sea levels will increase saltwater intrusion into estuaries and the inland extension of tidal influence (Prandle and Lane, 2015). Relative sea level rise (m) projections [95 % anomalies, baseline 1980–2000, RCP 8.5] for each bound estuary were generated using the UKCP User Interface (Met Office) for 2080. Grid squares at the mouth of each estuary were manually selected. Where the mouth of the estuary was covered by more than one grid square, the central-most square was used. Sea level rise anomalies are provided as a range, representing the different model ensemble members, so estuaries were ranked based on the mean of this range. Estuaries were ranked 1–19 with tied systems

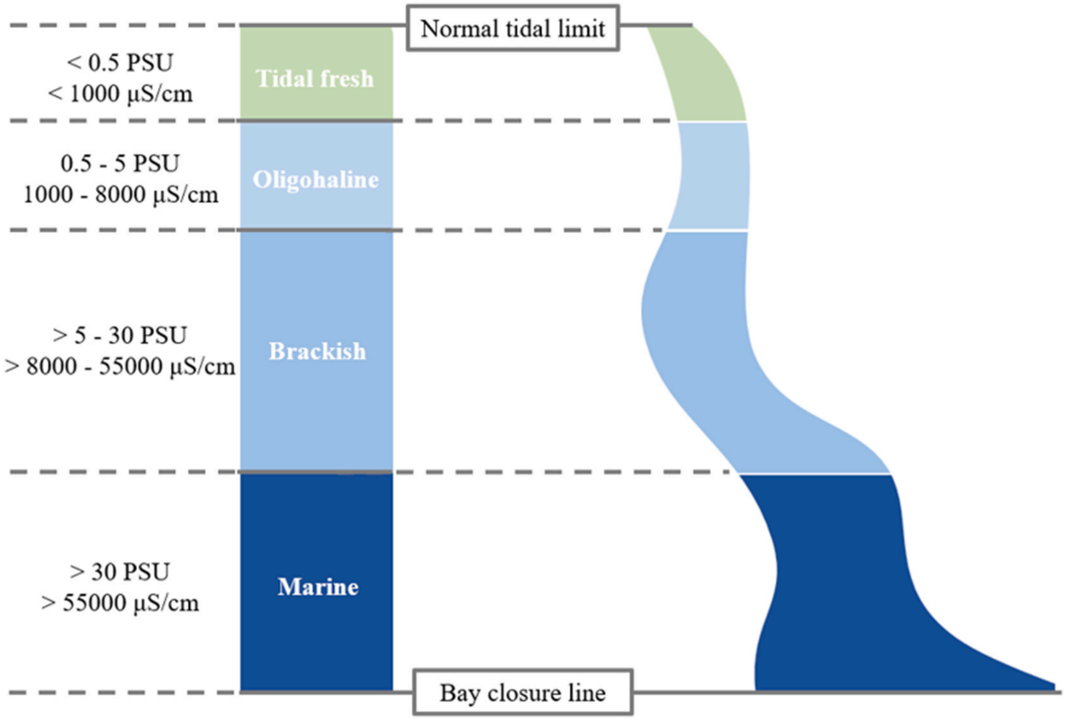

Fig. 1. Salinity and conductivity boundaries used to define each estuarine zone. Tidal waters in mainland England and Wales were classified as 'tidal freshwater' (<0.5 PSU or <1000 µS/cm), 'oligohaline' (0.5–5 PSU or 1000–8000 µS/cm), 'brackish' (>5–30 PSU or >8000–55000 µS/cm), or 'marine' (>30 PSU or >55000 µS/cm).

Table 2
Definitions of the confidence levels assigned to each estuarine salinity boundary.

Confidence level	Definition
High	Salinity and/or conductivity data from 2016 onward and/or the location of salinity boundaries are specifically mentioned in a peer reviewed journal article or official document e.g. catchment management plan
Medium	Salinity and/or conductivity data pre-2015.
Low	No data available, however have conditions conducive to the presence of a tidal freshwater zone i.e. are unbound and have 'fresh' sample sites upstream of the NTL.

Table 3
Total length and area of each estuarine salinity zone – tidal freshwater, oligohaline, brackish, and marine – in mainland England and Wales.

Estuarine zone	Length (km)	Area (km^2)
Tidal freshwater	376.98	19.36
Oligohaline	192.08	16.39
Brackish	2929.01	2097.95
Marine	614.8	516.95

given the same ranking centred between the rankings above and below. The estuary with the largest predicted relative sea level rise was assigned the highest score (19), indicating high vulnerability to estuarine squeeze. The estuary with the smallest predicted relative sea level rise was assigned the lowest score (1).

3 Future river flows

Freshwater river flow acts as an opposing force to saline intrusion and inland tidal extension (Little et al., 2017). Projected reductions in future summer river flows through climate

changes will result in increased saline intrusion into estuaries. Grid-to-Grid model estimates of river flow for Great Britain driven by UKCP18 Regional (12 km) data (1980–2080) (Kay, 2021), were used to predict future summer freshwater inputs (m^3/s) into each estuary. NetCDF raster layers showing mean monthly river flow for summer months (June, July, August) for each ensemble member were created. These were used to extract mean summer river flow for 1980-81, and mean summer flow projections for 2079-80. Estuaries were ranked 1–19 on their predicted total decrease in river flow, with the estuary experiencing the largest decrease being allocated the vulnerability highest score (19). The estuary predicted to experience the smallest decrease was allocated the lowest score (1). Summer river flow figures for the larger estuaries (Humber, Thames and Severn) represent mean values, averaged across all tidal rivers.

4 Catchment water stress 2039-40

Predicted catchment water stress values for each bound estuary were taken from the Environment Agency water stress assessment for 2039-40 (Environment Agency, 2021). These values incorporate water inputs into the catchment, as well as public water supply options, and sustainability reductions. Estuaries were ranked in order of their final supply demand balance (SDB), with the lowest SDB, or most water stressed, estuaries assigned the highest score (19). Catchment water stress was ranked 1–19 with tied systems given the same ranking centred between the rankings above and below. Catchment water stress for the larger estuaries (Humber, Thames and Severn) represent mean values, averaged across all tidal rivers.

5 Depth at estuary mouth

Prandle and Lane (2015) demonstrated that the extent of saline intrusion is related to, and changes with, the depth at the mouth of an estuary. Shallow estuaries (<10m) were shown to be considerably more vulnerable to saline intrusion, when subject to a hypothetical 1m rise in sea level (Prandle and Lane, 2015). For each bound estuary in this study, mean depth (m) values were manually extracted from OceanWise bathymetry data, available on Marine Digimap (British Crown and OceanWise, 2018). Estuaries were ranked 1–19 in order of the depth at their mouth with tied systems given the same ranking centred between the rankings above and below. The deepest estuaries were assigned the lowest rank (1) and the shallowest estuaries were assigned the highest rank (19).

A total rank score (sum of individual ranks) was calculated for each bound estuary with a tidal freshwater and/or oligohaline zone. Those with the highest combined scores are considered most vulnerable to estuarine squeeze. The relationship between these estuaries and the vulnerability indices data were further explored via principal component analysis (PCA) in R using the Vegan package (v4.3.0; R Core Team, 2021). Square root transformation was applied to all vulnerability indices data prior to PCA analysis.

3. Results

3.1. Bound vs. unbound

Across mainland England and Wales, 85 estuaries were included in this study. Of these, 28 were bound at all of their landward limit(s) with an artificial engineering structure, and 26 were completely unbound. A further 31 estuaries were bound on at least one of their landward limits. The distributions of bound, partially bound, and unbound estuaries included in this study are shown in Fig. 2. The lowest proportion of

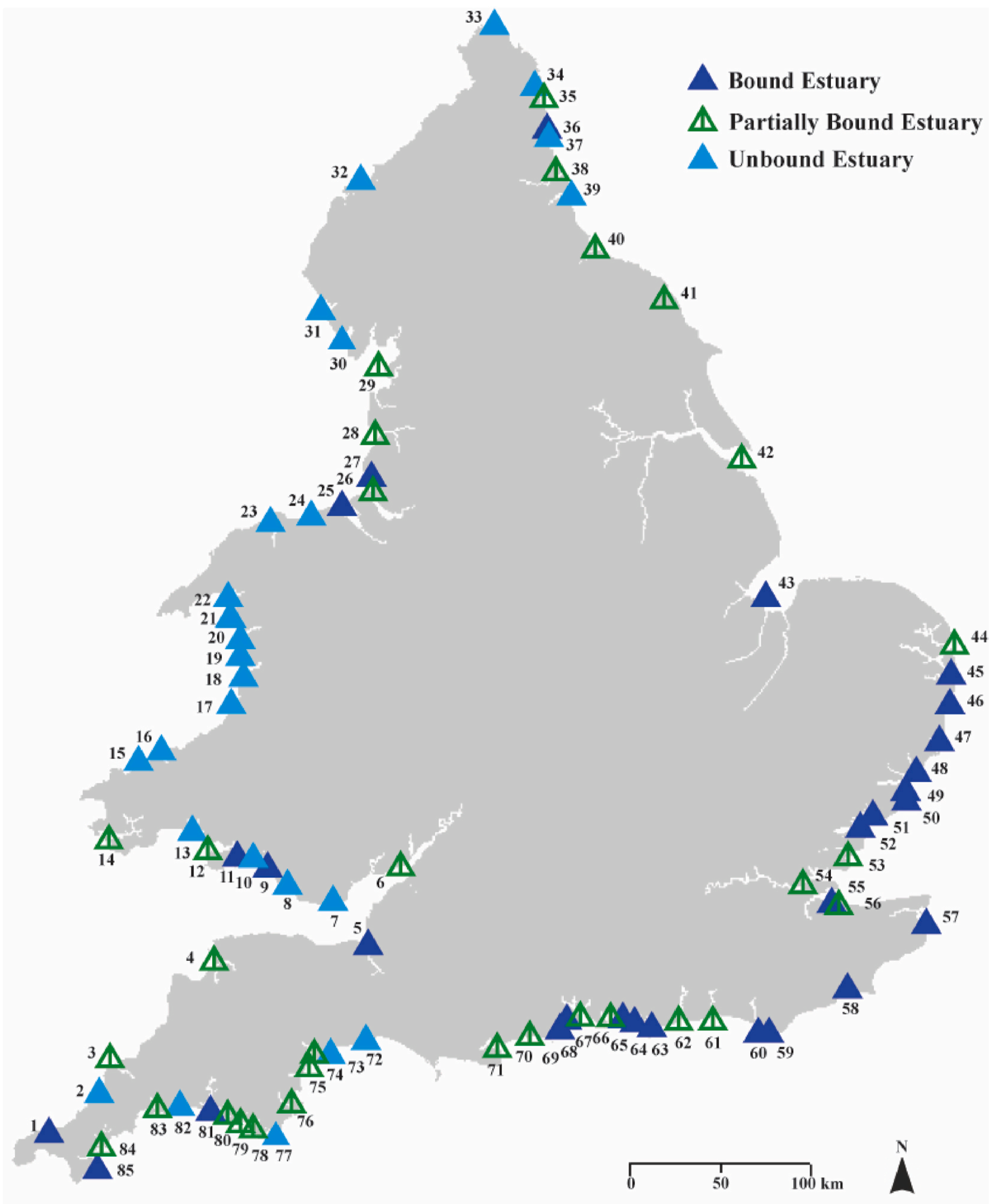

Fig. 2. Distribution of bound, partially bound, and unbound estuaries in mainland England and Wales. Each point represents one estuary. Estuaries are marked as bound if an artificial engineering structure is present at all of their Normal Tidal Limits (NTL), and partially bound if an artificial engineering structure is present in one, but not all of their Normal Tidal Limits. Refer to Supplementary Data Table 1 for estuary names related to numbers 1–85 and Supplementary Data Table 2 for boundary descriptions.

bound estuaries were identified in Wales, where artificial barriers are present in only 26 % of estuaries. This is in contrast to South East England, where all estuaries are bound on at least one of their landward limits. Northern England's estuaries are much less constrained by artificial barriers, however, with only the Wandsbeck estuary in Northumberland fully bound at all of its landward limits.

The most common types of estuarine barrier present in England and Wales are weirs and sluices. A comprehensive breakdown of estuarine barrier presence in each estuary and tidal river, including barrier type (where available), is provided in Supplementary Data Table 2.

3.2. Estuarine zones

Estuarine waters in mainland England and Wales were mapped as either 'tidal freshwater', 'oligohaline', 'brackish' or 'marine' (Fig. 1). The total length and area of each estuarine zone is shown in Table 3, and a detailed breakdown of individual estuaries and tidal rivers can be found in the Supplementary Data Table 3.

Our data show that estuaries in mainland England and Wales have a total tidal freshwater length of 376.98 km and area of 19.36 km^2, and a total oligohaline length of 192.08 km and area of 16.39 km^2. This means that tidal freshwater and oligohaline habitats make up just 9 % and 5 % of the length and 0.7 % and 0.6 % of the area of estuarine waters, respectively. Tidal freshwater and oligohaline zones are present in 45 estuaries. Of these, 19 are bound on at least one of their tidal limits. The majority (64 %) of tidal freshwater and oligohaline waters in mainland England and Wales are found in estuaries that are bound at their tidal limits (Supplementary Data Tables 2 and 3).

Tidal freshwater and oligohaline zones were identified in all regions of England and Wales, across estuaries of all sizes and morphological types (Fig. 3 and Supplementary Data Table 3). In some cases, they make up a significant proportion of an estuary's extent. The tidal River Trent section of the Humber estuary, for example, contains the longest stretch of tidal freshwater in the UK (54.57 km), over 22 km longer than any other estuary, though even this estuary is bound at its upper limits by Cromwell Lock (Fig. 3). The smallest tidal freshwater zone recorded in this study, the Gannel in Cornwall, UK, could be as small as 24m. The three estuaries with the longest stretches of tidal freshwater and oligohaline water – Humber, Thames, Breydon Water – are all found on the East coast of England and are all bound, while the smallest stretches (<0.51 km) – Gannel, Dart, Erme, Otter, Looe and Helford – are all in South West England (Fig. 3). Of these only the Erme and Helford are bound at their tidal limits (Fig. 2).

Thirteen estuaries were identified as potentially containing tidal freshwater and oligohaline zones, or having an expanded extent of these zones if they were already present (Supplementary Data Table 3). However, these zones were ranked with low confidence (Table 2) and are therefore not included in the zone extent values (Table 3 and Supplementary Data Table 3). These estuaries and/or associated tidal rivers were found to have conditions conducive with the presence of a tidal freshwater or oligohaline zone, i.e. they have no data but are unbounded and have fresh points immediately above the NTL. The only exception to this is the Lynher (sub-estuary of the Tamar) where there is high confidence of tidal freshwater and oligohaline zones as recorded by Uncles et al. (2018), however this data was not included in this study. The Tees shows signs of having already lost its tidal freshwater zone, with

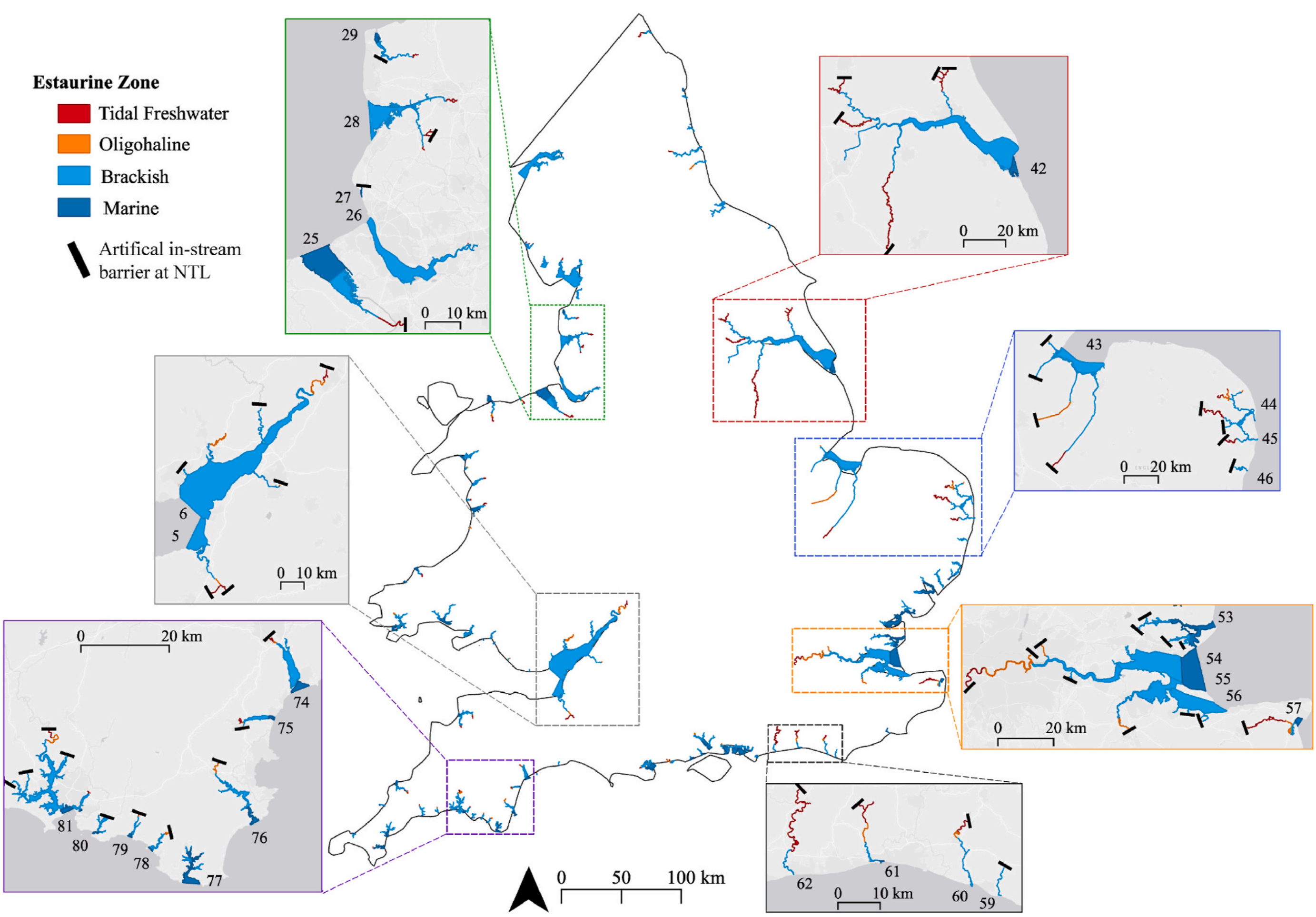

Fig. 3. Mapped salinity zones of all estuaries in mainland England and Wales. Map inserts show selected estuaries and salinity zones and the presence or absence of boundaries at the NTL.

borderline brackish conductivity readings immediately below the tidal limit (i.e. the Tees Barrage).

3.3. Vulnerability to estuarine squeeze

Bound estuaries with tidal freshwater and oligohaline zones were ranked in terms of their vulnerability estuarine squeeze (Figs. 4 and 5). Three estuaries in the South of England (Medway, Exe and Ouse) were ranked as most vulnerable to estuarine squeeze (Fig. 4). Those with the least vulnerable tidal freshwater and oligohaline zones are more dispersed, with the Humber in North East England, the Severn on the border between England and Wales and The Wash in East Anglia (Figs. 4 and 5). Data upon which the vulnerability rankings are based are included in supplementary data table 4.

Trends can be seen in the rankings of each individual vulnerability index. The smallest tidal freshwater and oligohaline zones vulnerable to estuarine squeeze were found in the South West of England, with those of the Helford, Erme and Dart estuaries only ranging from 0.36 to 1.51 km. This is in contrast to the three largest zones – Humber, Thames and Breydon Water – all on England's east coast, which range in length from 37.43 to 102.54 km. Estuaries in the South West are also likely to experience the highest relative change in sea level, as much as 0.85m at the mouth of the Helford estuary. This is 0.11–0.12m greater than estuaries in the North of England, such as the Dee and Ribble.

Both predicted future summer river flow and catchment water stress indices showed the estuaries of Southern England to be most vulnerable. Summer river flows in the Severn, Thames and Ouse are likely to decrease substantially, with reductions ranging from 5.19 to 11.29 m^3/s. Meanwhile, The Wash, Breydon Water and the Thames all have a highly negative catchment supply demand balance of 345-260. The one exception to this geographical pattern is the Dee estuary, on the border between England and North Wales, whose vulnerability ranking is increased by a large future reduction in summer river flow of 11.60 m^3/s, and a catchment water supply demand balance of −236. In contrast the Ribble located to the north of the Dee has a strongly positive catchment supply demand balance of 124.

The PCA showing the relationship between the bound estuaries containing tidal freshwater and/or oligohaline zones (thus susceptible to estuarine squeeze) and the vulnerability data (Supplementary Data Table 4) is shown in Fig. 6. As with the vulnerability rankings, some regional and geomorphological clustering is apparent. Estuaries in the south west (i.e. Helford, Erme, Devon Avon, Exe, Dart, Plymouth Sound and Bridgewater Bay) cluster to the left of PCA axis 1 (shaded blue in Fig. 6). These are ria or bar-built macrotidal estuaries with a wide range of mean river flows (2–23 m^3/s; ABPmer and Wallingford, 2007) and have the smallest extents of oligohaline and tidal freshwaters (0.36–14 km). They are associated with lower projected catchment water stress and lower projected reductions in summer flow, but susceptible to future RSLR (Fig. 6). The estuaries with the longest tidal freshwater and oligohaline zones (10–102 km), deepest mouths and are most susceptible to future catchment water stress are situated to the right of the plot, including The Wash, Humber, Thames, Severn and Dee (Fig. 6). The Ribble appears as an outlier due to lowest susceptibility to future catchment water stress and the lowest susceptibility to future RSLR (Supplementary Data Table 3). These are all coastal plain macrotidal estuaries (with the exception of the Wash embayment) with high mean river flow (20–86 m^3/s; ABPmer and Wallingford, 2007). Estuaries in the south and southeast of England that are susceptible to future RLSR, reductions in summer flow and predicted to experience some catchment water stress, or have deep mouths cluster centrally (Fig. 6). These are mesotidal and macrotidal coastal plain, embayment and bar built estuaries with mean river flows ranging from 1 to 17 m^3/s (ABPmer and Wallingford, 2007) and tidal freshwater and/or oligohaline extents ranging from 5 to 37 km.

4. Discussion

Tidal freshwater and oligohaline zones were identified in all regions of England and Wales ranging in size from just 0.24 km (Gannel, South West England) to 118.28 km (Humber, North East England). In some

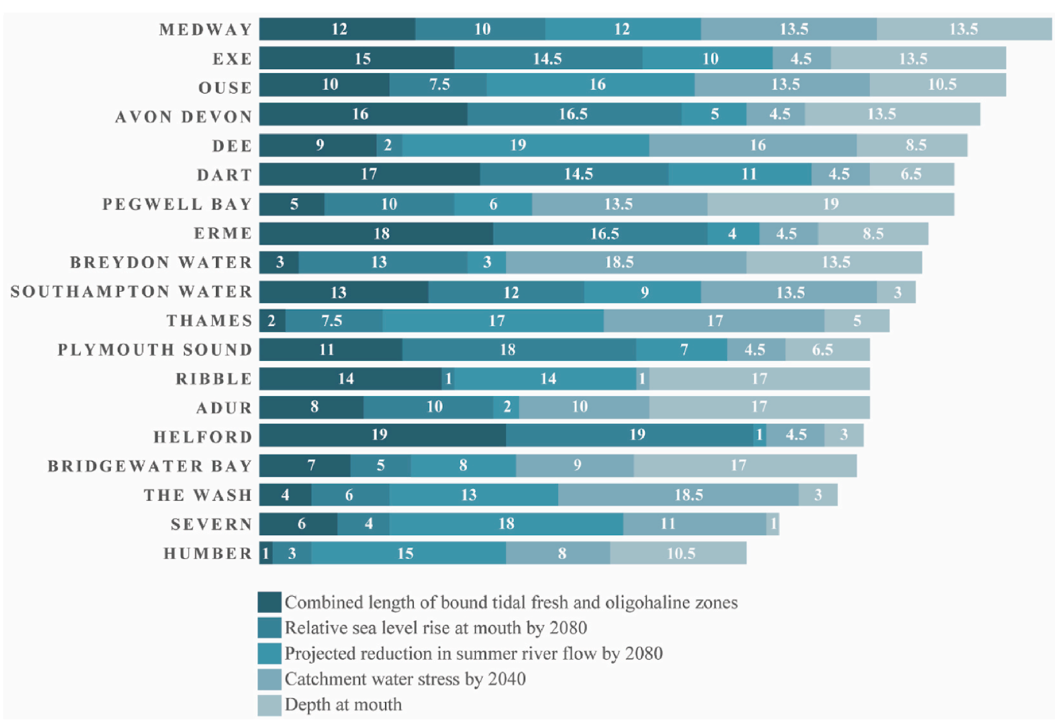

Fig. 4. Ranking of 19 UK estuaries on their vulnerability to estuarine squeeze. Each estuary was assigned a rank (or tied rank, where applicable) for the following indices; combined length of tidal freshwater and oligohaline zones; relative projected sea level rise at the estuary mouth, predicted future river flow, catchment water stress, and depth at mouth (Supplementary Data Table 4). The most vulnerable estuary (Medway) is at the top, and the least vulnerable (Humber) is at the bottom.

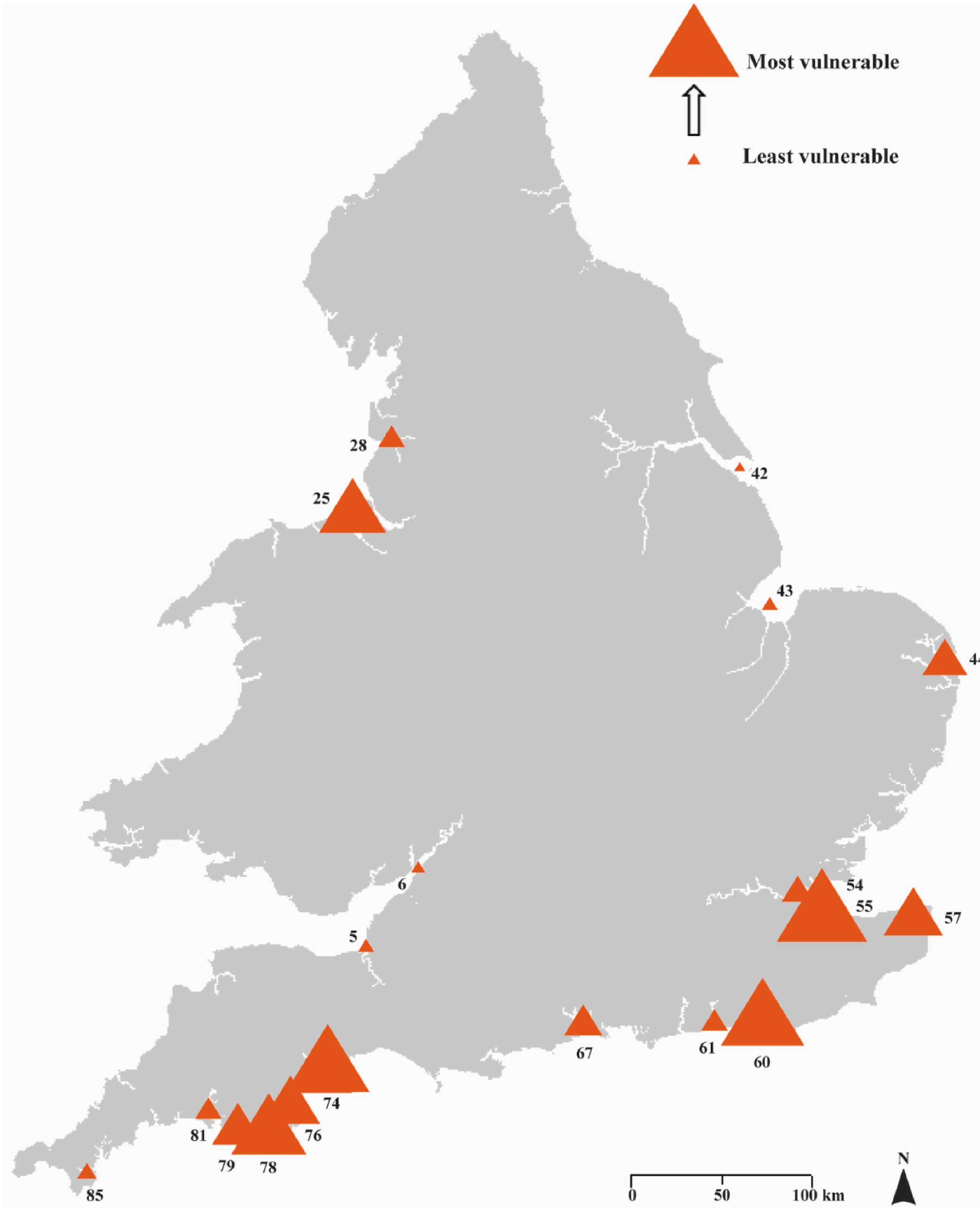

Fig. 5. Vulnerability of the 19 UK estuaries at risk of estuarine squeeze, and their geographic distribution. Triangle scale based on the vulnerability score (Fig. 3), with the most vulnerable estuaries represented by the largest triangles. Refer to supplementary data table 1 for estuary names related to numbers.

cases, these zones make up a significant proportion of the estuary. The tidal freshwater section of the Humber's River Trent, for example, is equivalent to 15 % of the total estuary, or 65 % of the tidal river Trent. While there was insufficient data to delineate the oligohaline zone in the Humber estuary, salinity measurements at Alkborough Flats managed realignment site (at the confluence of the River Trent and River Ouse) suggest that this location may mark the boundary between brackish and oligohaline zones (Franco and Mills, 2019). This implies that the entire tidal River Trent could fall within the tidal freshwater and oligohaline zone, making it by far the largest such zone in England and Wales.

It is generally understood that tidal freshwater zones are more common in mesotidal (1–4m) and macrotidal (>4m) estuaries with high river flow, where there is a relatively flat and long gradient from the estuary mouth inland (Baldwin et al., 2009; Whigham et al., 2019 and references therein). This study has however identified tidal freshwater zones in microtidal estuaries (e.g. the Yare, Waverney, Christchurch Harbour and Poole Harbour), in estuaries with low mean river flow (e.g. the Gannel, Teign, Dart and Waverney <2 m^3/s) and in a range of estuarine geomorphological types in addition to coastal plain (i.e. ria, bar-built, embayment, and complex; ABPmer and Wallingford, 2007). This suggests that globally, tidal freshwater zones may be more ubiquitous than previously realised, which could be significant as in recent years, their importance has been more widely highlighted (Adame et al., 2024; O'Connor et al., 2022; Barendregt et al., 2009). Whilst present across estuaries of all sizes, tidal ranges and morphological types, the results here suggest they are more common in those with larger catchments (recorded in the UK Rivers and Catchments map; Esri UK, 2023). The estuaries in this study with the largest catchment areas – Severn, Humber, The Wash, Thames – for example, support some of the longest stretches of tidal freshwater and oligohaline habitat in mainland

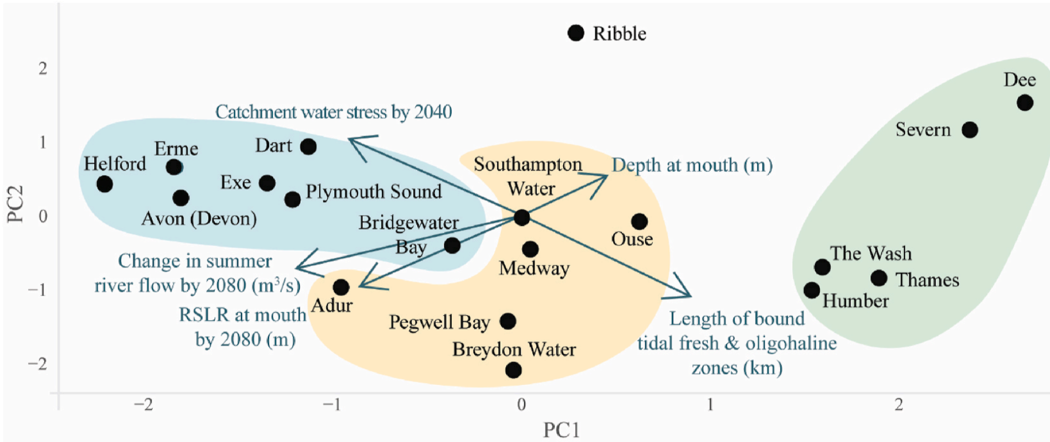

Fig. 6. Principal component analysis (PCA) depicting the relationship between the bound estuaries containing oligohaline and/or tidal freshwater zones and the vulnerability data (shown in Supplementary Data Table 4). Clusters are shaded to aid interpretation. The blue cluster are ria or bar-built estuaries in the south west of England, the green cluster consists of coastal plain and embayment estuaries with deep mouths and large tidal freshwater and/or oligohaline extents and the yellow cluster coastal plain, bar built and embayment estuaries in the south and south east England. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

England and Wales.

Despite this wide geographic distribution, relatively little is known about these zones in comparison to the adjacent brackish estuary and non-tidal freshwater river (Barendregt et al., 2009). This is likely due to their unique physical characteristics – tidal, yet fresh or very low salinity – not aligning directly with either fluvial or estuarine research (Odum, 1988; Schuhardt et al., 1993; Attrill et al., 1996;Rundle et al., 1998; Sousa et al., 2005). A growing body of evidence suggests that the unique environmental conditions (tidal energy and fluvial water chemistry), strategic location (linking catchment and coast), and distinct ecology of these zones make them hotspots of biogeochemical processes and support abundant, productive communities (O'Connor et al., 2022; Little et al., 2022a; Knights et al., 2017; Xu et al., 2021; Whigham, 2009). These zones may provide essential trophic subsidies—organisms, organic matter, and nutrients— to adjacent habitats, primarily the brackish estuary (O'Connor et al., 2022; Williams and Williams, 1998), but also to riparian zones (e.g., through aquatic insect emergence; Dias et al., 2016), and the non-tidal freshwater river (e.g., through migrating species). Given their potential significance (Lehman, 2007; Little et al., 2022b; O'Connor et al., 2022; Schuhardt et al., 1993; Williams and Williams, 1998; Xu et al., 2021), there is an urgent need to understand more about their ecology, function, and role within the wider estuary and beyond. This becomes an even greater issue given that the majority (64 %) of tidal freshwater and oligohaline waters in England and Wales are in estuaries which are bound at one or more of their tidal limits by an in-stream engineering structure, and thus are susceptible to loss through estuarine squeeze.

Barriers were found to be present across all types of estuary, regardless of catchment size and tidal range. This indicates that concerns relating to coastal or shoreline hardening (e.g. Neubauer and Craft, 2009; Gittman et al., 2016; Floerl et al., 2021) and coastal intertidal squeeze (e.g. Torio and Chmura, 2013; Silva et al., 2020) could be affecting aquatic habitats much further inland than previously thought (as highlighted by Little et al., 2022a, Little et al., 2022b). They do, however, appear to be more prevalent in catchments with a higher percentage urban land cover (Digimap, 2024), likely to be associated with flood defence. The most highly urbanised catchments, for example the Mersey (26 % urban land cover), Crouch-Roach (22 %), and the Thames (21 %), are all bound at one or more of their tidal limits. Meanwhile, catchments with <1 % urban cover, such as Nyfer, Duddon, Mawddach and Dyfi, have no artificial barriers at their tidal limits. Whilst researchers have alluded to the fact that the presence of barriers may be an important factor in estuarine response to changes in climate and sea level (Robins et al., 2016 ; Ensign and Noe, 2018), vulnerability assessments to date have focused on the lower reaches of estuaries (see Khojasteh et al., 2021 for overview). Future assessments (cf. Prandle and Lane, 2015) therefore need to include information regarding barrier presence and vulnerability to estuarine squeeze, particularly as placement of dams near the NTL have been shown to be responsible for losses of tidal freshwater zones in the past (i.e. New England, USA; Leck and Crain, 2009). Whilst this research has focussed on barriers at the present-day tidal limits, it is important to note that a 'non-bounded NTL' may still be downstream of a boundary and so has the potential to be subject to estuarine squeeze in the future with rising sea levels. For example, the tidal river Wyre of Morecambe Bay is currently 'unbound', however, the NTL is only 500 m downstream from a weir.

In England and Wales the majority of upper estuarine channels have been heavily modified through channelisation and stream bank modification restricting any intertidal zone, and severing connection to the floodplain (Little et al., 2022a, 2022b, Talke and Jay, 2020). They also face threats from urban, agricultural, domestic and industrial pollution, reducing the current functional value of these zones (Kennish, 2002; Zonneveld and Barendregt, 2009). However, globally, tidal freshwater zones are characterised by their high productivity and rich biodiversity (Whigham et al., 2019), largely due to the presence of intertidal freshwater marshes which in some regions can be extensive (e.g. Alaska; Hall, 2009). These habitats were once widespread and common in northwestern Europe, however they are now exceptionally rare due to human activities (Barendregt et al., 2006; Zonneveld and Barendregt, 2009). In England, extensive diking and draining of tidal freshwater marshes (i.e. fens and peat) took place in the 19th and 20th centuries primarily for agriculture, alongside construction of the first in-stream barriers for flood control and navigation (Verhoeven, 2014). Today, only small fragments of tidal freshwater marsh remain, with tidal freshwaters restricted to embanked channels (Zonneveld & Barendregt, 2009). The loss of this intertidal habitat in England and Wales has reduced the functional value of this zone, however it does provide an important opportunity for large-scale restoration projects to re-create tidal freshwater marsh in suitable estuaries across the UK. This would significantly increase the value of these zones, address biodiversity net gain targets and improve ecosystem services at the landscape scale (Verhoeven, 2014). Habitat restoration and recovery in estuaries in the UK is currently focussed on three priority habitats in the mid and lower brackish estuary (i.e. sea grass, salt marsh and European native oyster reef; Preston et al., 2020; Hudson et al., 2021; Gamble et al., 2021). To the authors' knowledge, no significant habitat restoration has occurred in the upper estuary, apart from small-scale projects such as the creation of less than 0.5 ha of tidal freshwater marsh in the River Trent for eel habitat (J. Lewis, pers. comm.). This is despite tidal freshwater marshes providing higher levels of ecosystem services per unit area than salt marshes (Craft et al., 2009) and similar or larger potential for atmospheric carbon sequestration and storage than saltmarshes and seagrass (i.e. blue carbon; Adame et al., 2024). Additionally, their position within the crucial corridor between catchment and coast indicates that restoring tidal freshwater marshes could be central to holistic management strategies that acknowledge the connections across hydrological systems in a source-to-sea approach (Hoagland et al., 2020).

Through mapping the extent of these zones in England and Wales, this study can be used to identify locations where tidal freshwater marsh creation could provide the most benefits. These could be as compensation for areas that will be lost through estuarine squeeze, but also in systems with significant tidal freshwater extents where habitat creation could for example be used to boost carbon sequestration, important populations of diadromous fish species (i.e. European eel and river lamprey) and habitat for migrating waterfowl (Baldwin et al., 2009 and refs therein). There is significant scope for tidal freshwater marsh creation on the tidal River Trent and River Great Ouse for example, re-creating fenland tidal marsh habitats which would have been ubiquitous in these catchments historically prior to drainage and supported significant eel populations (Greenlee, 2020). It is clearly not cost-effective to recreate tidal freshwater marsh habitat in estuaries where the tidal freshwater zone is at risk of imminent loss from estuarine squeeze, however the argument could be made to compensate for this loss by recreating tidal freshwater marsh in more suitable unbounded or partially bounded estuaries within the local area. For example the Axe, Otter, Avon or Erme estuaries in south west England and all unbound or partially bound and are situated near to some of the estuaries identified here as being most susceptible to estuarine squeeze. Alternatively, in systems at risk of losing their tidal freshwater areas, barrier removal, or bypass channel projects might become priority.

Increasing saline intrusion into the upper estuaries will lead to the loss of freshwater species, disrupting ecosystem functioning and affecting statutory sites designated for their freshwater habitats (Herbert et al., 2015). Even if not directly connected to the estuary channel, these sites could experience pulsed or sustained salinisation through groundwater exchange or surface flooding. Of the 19 estuaries vulnerable to estuarine squeeze, 14 have TFZ and oligohaline zones that run through or parallel to sites with statutory designations (i.e. SSSI, SPA, SAC, Ramsar). Many of these sites are designated due to the importance of their freshwater habitats, including freshwater marshes, reedbeds, floodplains, and the nationally and internationally significant species that rely on them. Stodmarsh SSSI, SAC, RAMSAR on the tidal freshwater section of the Stour (Kent, UK), for example, is renowned for its extensive freshwater marshes and reedbeds, providing habitat for species such as bitterns, marsh harriers, and Desmoulin's whorl snail (Natural England, 1984a). On the Thames, the Inner Thames Marshes and Syon Park SSSI's are both noted in part for their freshwater fauna and flora (Natural England, 1984b; Natural England, 1989). Just small increases in salinity could change the structure of the faunal and floral assemblages of these sites.

Studies have shown that flow regulation in the catchment may have a significant influence on future saline intrusion (Little et al., 2022b and references therein) and therefore estuarine squeeze. Catchments that are highly regulated through reservoirs and abstractions are predicted to be the most water stressed with low flows in the future (i.e. the Dee, the Ouse). This is particularly highlighted in the adjacent catchments of the Adur and Ouse in Sussex. While both are coastal plain estuaries which are comparable in size and extent, and face the same projected relative sea level rise, the Ouse ranks much higher in vulnerability to estuarine squeeze due to the much greater predicted reduction in summer river flows and catchment water stress, likely driven in part by the highly regulated water discharge from Ardingly reservoir at the top of the catchment and Public Water Supply abstraction at Barcombe Mills just above the tidal limits (Little, 2012).

Despite the potential detrimental impact of estuarine squeeze, increasing saline intrusion remains largely overlooked in estuarine and catchment management. Of the management plans relating to the 19 estuaries vulnerable to estuarine squeeze, only the Adur and Ouse Catchment Management Plan (Adur and Ouse Partnership, 2012) acknowledges the risk of increasing saline intrusion. Concerns about saline intrusion in this catchment have persisted for over two decades , dating back to the 2003 summer drought, when reduced flows and increased freshwater abstraction led to increased salinities in the upper Ouse estuary, affecting coarse fisheries in the TFZ (Environment, 2005b; Environment Agency, 2005a).

4.1. *Future research priorities and global significance*

Presented here is the most comprehensive, detailed account of estuarine salinity and electrical conductivity data available for all of mainland England and Wales. We acknowledge that improved, real-time salinity data from estuaries, especially those with conditions conducive to the presence of tidal freshwater and oligohaline zones, could improve mapping and variability monitoring. The data presented here suffer similar problems inherent in any large-scale, multi-study big dataset in terms of coverage and consistency, largely due to the need for more comprehensive underlying data. We also acknowledge that for some estuaries tailored studies will have collected additional salinity data that could be useful for further refining zone boundaries. However, extraction of all salinity data available for estuaries in mainland England and Wales across all academic and grey literature was beyond the scope of this study. We, therefore, focussed on broader scale, long-term salinity data collected where possible from consistent multi-estuary sampling programs to generate best coarse estimates for all zone areas. The challenge now is to further integrate and monitor finer-scale salinity conditions through collaborations with local experts and water quality monitoring teams following standard protocols to improve our understanding of zone boundaries and their temporal variability. Incorporating this with longer-term data, covering extreme drought and precipitation events, as well as the impacts of variables such as wind and topography, would allow us to build powerful models to assess the vulnerability of these systems. Detailed ecological, sedimentological and chemical monitoring of these systems is the next step towards more fully determining the importance of upper estuarine habitats, and their functioning within the wider estuary. Nevertheless, this is a powerful starting point upon which to build a better understanding of upper estuarine ecosystems and their stressors. The more data that becomes available on these systems, the more informed and effective their future management and conservation will be.

The data presented here identifies areas of tidal freshwater and oligohaline waters in England and Wales, and highlights which may be most vulnerable to future changes in climate and human activity. We can now more accurately assess the structure of the ecological communities present in these zones, and begin to consider their potential function within the wider estuary and their relationship with adjacent zones. Although these data have been presented for England and Wales, the techniques and their significance are applicable to estuaries worldwide. This is especially critical given the lack of a global inventory or estimates of the worldwide geographic distribution of tidal freshwater and oligohaline zones (Whigham, 2009. Globally, 9.7 % of estuaries and deltas have dams or weirs at their tidal limits and these in-stream barriers are likely to become increasingly common (Figueroa and Son, 2024). Determining the extent of these zones and their vulnerability to estuarine squeeze and saline intrusion is the essential first step in managing estuarine ecosystems and the source-to-sea system holistically. The goal must be to, where possible, protect and restore these typically overlooked habitats in order to maintain and enhance their provision of ecosystem services into the future.

CRediT authorship contribution statement

Helen Pietkiewicz: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Robert J.G. Mortimer:** Writing – review & editing. **Andrew G. Hirst:** Writing – review & editing. **Jonathan P. Lewis:** Writing – review & editing. **Lucy Clarke:** Writing – review & editing, Visualization, Data curation. **Sally Little:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2025.109299.

Data availability

The GIS shapefiles of salinity zones for all estuaries in mainland England and Wales are available via licensed open access at https://doi.org/10.5281/zenodo.15164383.

References

ABPmer and HR Wallingford, 2007. The Estuary-Guide: a website-based overview of how to identify and predict morphological change within estuaries (online). Website prepared for the joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme November 2007 https://www.estuary-guide.net/. (Accessed 4 April 2025).

Adame, M.F., Kelleway, J., Krauss, K.W., Lovelock, C.E., Adams, J.B., Trevathan-Tackett, S.M., Noe, G., Jeffrey, L., Ronan, M., Zann, M., Carnell, P.E., Iram, N., Maher, D.T., Murdiyarso, D., Sasmito, S., Tran, D.B., Dargusch, P., Kauffman, J.B., Brophy, L., 2024. All tidal wetlands are blue carbon ecosystems. Bioscience 74 (4), 253–268.

Adur and Ouse Partnership, 2012. Adur and Ouse Catchment Management Plan. Available at: https://adurandousecatchment.org.uk/wp-content/uploads/2020/06/Adur_and_Ouse_Catchment_Management_Plan-1.pdf (Accessed: 15 March 2025).

Anon, 1958. The Venice system for the classification of marine waters according to salinity. Limnology and Oceanography 3, 346–347.

Attrill, M.J., Rundle, S.D., Thomas, R.M., 1996. The influence of drought-induced low freshwater flow on an upper-estuarine macroinvertebrate community. Water Research 30 (2), 261–268.

Baldwin, A.H., Hammerschlag, R.S., Cahoon, D.R., 2009. Evaluation of restored tidal freshwater wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Brinson, M.M. (Eds.), Coastal Wetlands: an Integrated Ecosystem Approach. Elsevier Science, Amsterdam, pp. 801–832.

Barendregt, A., Whigham, D.F., Baldwin, A.H., van Damme, S., 2006. Wetlands in the tidal freshwater zone. In: Bobbink, R., Beltman, B., Verhoeven, J.T.A., Whigham, D. F. (Eds.), Wetlands: Functioning, Biodiversity Conservation, and Restoration. Springer-Verlag, Berlin, Germany, pp. 117–148.

Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), 2009. Tidal Freshwater Wetlands. Backhuys Publishers, Leiden.

Bice, C.M., Huisman, J., Kimball, M.E., Mallen-Cooper, M., Zampatti, B.P., Gillanders, B. M., 2023. Tidal barriers and fish–Impacts and remediation in the face of increasing demand for freshwater and climate change. Estuar. Coast Shelf Sci. 289, 108376.

Brew, D.S., Funnell, B.M., Kreiser, A., 1992. Sedimentary environments and Holocene evolution of the lower Blyth estuary, Suffolk England, and a comparison with other East Anglian coastal sequences. Proc. Geologists' Assoc. 103, 57–74.

British Crown and OceanWise, 2018. Marine Digimap. [online] Edinburgh: Digimap, EDINA. Available at: https://digimap.edina.ac.uk/ [Accessed 15 March 2025].

Cañedo-Argüelles, M., Kefford, B.J., Piscart, C., Prat, N., Schäfer, R.B., Schulz, C.J., 2013. Salinisation of rivers: an urgent ecological issue. Environ. Pollut. 173, 157–167.

Costa, Y., Martins, I., de Carvalho, G.C., Barros, F., 2023. Trends of sea-level rise effects on estuaries and estimates of future saline intrusion. Ocean Coast Manag. 236, 106490.

Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., Machmuller, M., 2009. Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment 7, 73–78. https://doi.org/10.1890/070219.

Dausse, A., Garbutt, A., Norman, L., Papadimitriou, S., Jones, L.M., Robins, P.E., Thomas, D.N., 2012. Biogeochemical functioning of grazed estuarine tidal marshes along a salinity gradient. Estuar. Coast Shelf Sci. 100, 83–92.

Davidson, N.C., Buck, A.L., 1997. An Inventory of UK Estuaries, Volume 1: Introduction and Methodology. Joint Nature Conservation Committee, Peterborough, UK.

Dias, E., Morais, P., Cotter, A.M., Antunes, C., Hoffman, J.C., 2016. Estuarine consumers utilize marine, estuarine and terrestrial organic matter and provide connectivity among these food webs. Mar. Ecol. Prog. Ser. 554, 21–34.

Digimap, 2024. Land cover map. Available at: https://digimap.edina.ac.uk. (Accessed 5 April 2024).

Ensign, S.H., Noe, G.B., 2018. Tidal extension and sea-level rise: recommendations for a research agenda. Front. Ecol. Environ. 16, 37–43.

Environment Agency, 2005a. Adur and Ouse catchment abstraction management strategy. Final Strategy March 2005. Environment Agency, Bristol, UK.

Environment, Agency., 2005b. Transitional waters ecology studies. Sussex Area Ecological Appraisal Team. In: Rep, No. D24LR053. Environment Agency, Bristol, UK.

Environment Agency, 2011. Survey of Gamma Dose Rates in Air Around the Esk Estuary Related to Radioactivity Levels in Sediments. Almondsbury, Bristol. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291201/scho0211btlm-e-e.pdf. (Accessed 18 November 2024).

Environment Agency, 2012a. Lower Tidal River Arun Strategy Environmental Report. Worthing, West Sussex. Available at: https://assets.publishing.service.gov.uk/media/5a7d8954ed915d497af7008e/Lower_Tidal_River_Arun_final_strategy_report.pdf. (Accessed 18 November 2024).

Environment Agency, 2012b. Water Framework Directive (WFD) Classification Scheme for Marine Benthic Invertebrates: Infaunal Quality Index (IQI) – Associated Salinity Data. UK Government Open Data Portal, pp. 2004–2012.

Environment Agency, 2017. WFD Cycle 2 TRAC Macroalgae Classification. UK Government Open Data Portal. Available at: https://www.data.gov.uk/dataset/3cf8b01f-665c-4f8d-995d-0d7def4b93fb/wfd-cycle-2-trac-macroalgae-classification#licence-info. (Accessed 15 November 2024).

Esri UK, 2023. Esri UK Rivers and Catchments [online]. Available at: https://www.arcgis.com/apps/instant/media/index.html?appid=10a33673687a4bb0a4af12a18883af3d (Accessed: 15 March 2025).

Environment Agency, 2021. Appendix 3: water stress assessment methodology. V1.0. 1-10. Available at: https://assets.publishing.service.gov.uk/media/601c08d78fa8f5146c96b162/Appendix_3_Assessment_of_water_stress_methodology.pdf. (Accessed 8 March 2024).

Environment Agency, 2024a. Water quality data [online]. UK government open data portal. Available at: https://environment.data.gov.uk/water-quality/view/landing. (Accessed 15 November 2024).

Environment Agency, 2024b. River Obstacles Dataset. Available at: River Obstacles - data.gov.uk (Accessed 15 March 2025).

Fairbridge, R.W., 1980. The estuary: its definition and geodynamic cycle. In: Olausson, E., Cato, I. (Eds.), Chemistry and Biochemistry of Estuaries. Wiley, New York, pp. 1–35.

Figueroa, S.M., Son, M., 2024. Estuarine dams and weirs: global analysis and synthesis. Mar. Geol. 477, 107388.

Floerl, O., Atalah, J., Bugnot, A.B., Chandler, M., Dafforn, K.A., Floerl, L., Zaiko, A., Major, R., 2021. A global model to forecast coastal hardening and mitigate associated socioecological risks. Nat. Sustain. 4, 1060–1067.

Franco, A., Mills, M.J., 2019. Fish monitoring at Alkborough flats managed realignment site, humber estuary, spring 2018 and autumn 2019. A technical report by the Institute of Estuarine and Coastal Studies, University of Hull, for ABPmer. Report number YBB383-F-2019 53. July 2019.

Gamble, C., Debney, A., Glover, A., Bertelli, C., Green, B., Hendy, I., Lilley, R., Nuuttila, H., Potouroglou, M., Ragazzola, F., Unsworth, R., Preston, J. (Eds.), 2021. Seagrass Restoration Handbook. Zoological Society of, London, UK. London, UK.

Gittman, R.K., Scyphers, S.B., Smith, C.S., Neylan, I.P., Grabowski, J.H., 2016. Ecological consequences of shoreline hardening: a meta-analysis. Bioscience 66, 763–773.

Greenlee, J.W., 2020. Seeing All the Anguilles: Eels in the Cultural Landscape of Medieval and Early Modern England. Cornell University. PhD thesis. https://www.proquest.com/docview/2415426741?pq-origsite=gscholar&fromopenview=true&sourcetype=Dissertations%20&%20Theses.

Grenfell, S.E., Callaway, R.M., Grenfell, M.C., Bertelli, C.M., Mendzil, A.F., Tew, I., 2016. Will a rising sea sink some estuarine wetland ecosystems? Sci. Total Environ. 554, 276–292.

Griffin, K.R., Holbrook, C.M., Zielinski, D.P., Cahill, C.L., Wagner, C.M., 2025. Not all who meander are lost: migrating sea lamprey follow river thalwegs to facilitate safe and efficient passage upstream. Journal of Experimental Biology 228 (4), JEB249539.

Hall, J.V., 2009. Chapter 16. Tidal freshwater wetlands of Alaska. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys Publishers, Leiden, The Netherlands, pp. 179–184.

Herbert, E.R., Boon, P., Burgin, A.J., Neubauer, S.C., Franklin, R.B., Ardón, M., Hopfensperger, K.N., Lamers, L.P.M., Gell, P., 2015. A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. Ecosphere 6, 1–43.

Hoagland, P., Beet, A., Ralston, D., Parsons, G., Shirazi, Y., Carr, E., 2020. Salinity intrusion in a modified river-estuary system: an integrated modelling framework for source-to-sea management. Front. Mar. Sci. 7, 425.
Hudson, R., Kenworthy, J., Best, M. (Eds.), 2021. Saltmarsh Restoration Handbook: UK and Ireland. Environment Agency, Bristol, UK, p. 105.
IPCC, 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 2391.
Kay, A.L., 2021. Simulation of river flow in Britain under climate change: baseline performance and future seasonal changes. Hydrol. Process. 35, e14137. https://doi.org/10.1002/hyp.14137.
Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Sparks, T., Garforth, J., Kennedy, J., 2022. State of the UK climate 2021. Int. J. Climatol. 42, 1–80.
Kennish, M.J., 2002. Environmental threats and environmental future of estuaries. Environ. Conserv. 29, 78–107.
Khojasteh, D., Glamore, W., Heimhuber, V., Felder, S., 2021. Sea level rise impacts on estuarine dynamics: a review. Sci. Total Environ. 780, 146470.
Knights, D., Sawyer, A.H., Barnes, R.T., Musial, C.T., Bray, S., 2017. Tidal controls on riverbed denitrification along a tidal freshwater zone. Water Resour. Res. 53, 799–816.
Kukulka, T., Jay, D.A., 2003. Impacts of Columbia River discharge on salmonid habitat: 1. A nonstationary fluvial tide model. J. Geophys. Res. 108, 3293.
Leck, M.A., Crain, C.M., 2009. Northeastern North American case studies – New Jersey and New England. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys Publishers, Leiden, The Netherlands, pp. 145–156.
Lehman, P.W., 2007. The influence of phytoplankton community composition on primary productivity along the riverine to freshwater tidal continuum in the san joaquin river, California. Estuaries Coasts 30, 82–93.
Little, S., 2012. The Impact of Increasing Saline Penetration upon Estuarine and Riverine Benthic Macroinvertebrates, Department of Geography, vol. 742. Loughborough University, UK. Available at: https://dspace.lboro.ac.uk/2134/9737.
Little, S., Wood, P.J., Elliott, M., 2017. Quantifying salinity-induced changes on estuarine benthic fauna: the potential implications of climate change. Estuar. Coast Shelf Sci. 198, 610–625.
Little, S., Lewis, J.P., Pietkiewicz, H., Mazik, K., 2022a. Estuarine tidal freshwater zones in a changing climate: meeting the challenge of saline incursion and estuarine squeeze. In: Humphreys, J., Little, S. (Eds.), Challenges in Estuarine and Coastal Science. Pelagic Publishing, London, pp. 94–112.
Little, S., Lewis, J.P., Pietkiewicz, H., 2022b. Defining estuarine squeeze: the loss of upper estuarine transitional zones against in-channel barriers through saline intrusion. Estuar. Coast Shelf Sci. 278, 108107.
McLachlan, J.R., Haghkerdar, J.M., Greig, H.S., 2019. Strong zonation of benthic communities across a tidal freshwater height gradient. Freshw. Biol. 64, 1284–1294.
Millero, F.J., 2010. History of the equation of state of seawater. Oceanography 23 (3), 18–33. https://doi.org/10.5670/oceanog.2010.21.
Natural England, 1984a. SSSI *Citation for Stodmarsh site 1003639* [online] Available at: https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1003639.pdf. (Accessed 5 April 2025).
Natural England, 1984b. SSSI *Citation for Syon Park site 1004281* [online] Available at: https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1004281.pdf. (Accessed 5 April 2025).
Natural England, 1989. SSSI *Citation for inner Thames Marshes site 1001732* [online] Available at: https://designatedsites.naturalengland.org.uk/PDFsForWeb/Citation/1001732.pdf. (Accessed 5 April 2025).
Natural Resources Wales, 2023. Wales Water Salinity and Conductivity Information. UK Government Open Data Portal. Natural Resources Wales. Available at: https://naturalresources.wales/evidence-and-data/accessing-our-data/access-our-data-maps-and-reports/. (Accessed 15 November 2024).
Neubauer, S.C., Craft, C.B., 2009. Global change and tidal freshwater wetlands: scenarios and impacts. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys Publishers, Leiden, The Netherlands, pp. 253–266.
O'Connor, J.A., Erler, D.V., Ferguson, A., Maher, D.T., 2022. The tidal freshwater river zone: physical properties and biogeochemical contribution to estuarine hypoxia and acidification - the "hydrologic switch". Estuar. Coast Shelf Sci. 268, 107786.
Odum, W.E., 1988. Comparative ecology of tidal freshwater and salt marshes. Annu. Rev. Ecol. Systemat. 19, 147–176.
Prandle, D., Lane, A., 2015. Sensitivity of estuaries to sea level rise: vulnerability indices. Estuarine. Coast Shelf Sci. 160, 60–68.
Preston, J., Gamble, C., Debney, A., Helmer, L., Hancock, B., zu Ermgassen, P.S.E. (Eds.), 2020. European Native Oyster Habitat Restoration Handbook. The Zoological Society of, London, UK, p. 61. London, UK.
Pye, K., Blott, S.J., 2010. Morphological change in carmarthen bay and adjoining estuaries: further analysis. In: Annex A2 in: Halcrow (2010) Swansea Bay and Carmarthen Bay Shoreline Management Plan, vol. 2.
R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. URL: https://www.R-project.org/.
Robins, P.E., Skov, M.W., Lewis, M.J., Gimenez, L., Davies, A.G., Malham, S.K., Neill, S.P., McDonald, J.E., Whitton, T.A., Jackson, S.E., Jago, C.F., 2016. Impact of climate change on UK estuaries: a review of past trends and potential projections. Estuar. Coast Shelf Sci. 169, 119–135.
Robinson, A.D., Nedwell, D.B., Harrison, R.M., Ogilvie, B.G., 1998. Hypernutrified estuaries as sources of N_2O emission to the atmosphere: the estuary of the River Colne, Essex, UK. Mar. Ecol. Prog. Ser. 164, 59–71.
Rundle, S.D., Attrill, M.J., Arshad, A., 1998. Seasonality in macroinvertebrate community composition across a neglected ecological boundary, the freshwater-estuarine transition zone. Aquatic Ecology 32, 211–216.
Schuchardt, B., Haesloop, U., Schirmer, M., 1993. The tidal freshwater reach of the Weser estuary: riverine or estuarine? Neth. J. Aquat. Ecol. 27, 215–226.
Silva, R., Martínez, M.L., van Tussenbroek, B.I., Guzmán-Rodríguez, L.O., Mendoza, E., López-Portillo, J., 2020. A framework to manage coastal squeeze. Sustainability 12, 10610.
Simenstad, C.A., Burke, J.L., O'Connor, J.E., Cannon, C., Heatwole, D.W., Ramirez, M.F., Waite, I.R., Counihan, T.D., Jones, K.L., 2011. Columbia River Estuary Ecosystem Classification—Concept and Application. U.S. Geological Survey Open-File Report, p. 54, 2011-1228.
Sousa, R., Guilhermino, L., Antunes, C., 2005. Molluscan fauna in the freshwater tidal area of the River Minhoestuary, NW of Iberian Peninsula. *In: Annales de Limnologie-International*. Journal of Limnology, EDP Sciences 141–147.
Talke, S.A., Jay, D.A., 2020. Changing tides: the role of natural and anthropogenic factors. Ann. Rev. Mar. Sci 12, 121–151.
Torio, D.D., Chmura, G.L., 2013. Assessing coastal squeeze of tidal wetlands. J. Coast Res. 29, 1049–1061.
Tye, A.M., Balfour, C.A., Bowes, M., Brown, I.J., Evans, C.D., Felgate, S.L., Fishwick, J., Hargreaves, G., Harris, C., Kitidis, V., Lapworth, D.J., Martin, A.P., Matthews, R., Mayor, D.J., Mounteney, I., Nightingale, P.D., Pickard, A., Rees, A., Sanders, R., Spears, B.M., Stephens, J., Stinchcombe, M.C., Williams, P., Williamson, J., Woodward, E.M.S., Boothroyd, I.M., Bowes, M.J., Breimann, S., Burden, A., Callaghan, N., Gilbert, P.J., Ives, S., Juergens, M.D., Keenan, P., Hughes, L., Lichtschlag, A., Mack, S., Mallin Martin, D., Mawji, E., McDonald, R., Olszewska, J. P., Parkes, D., Pearce, C.R., Peel, K.E., dos Santos Pereira, M.G., Pugh, J.P., Worrall, F., Yarrow, D.M., 2022. Sampling of Estuarine Chemistry and Organic Matter for 16 Estuaries in Great Britain in 2017/8 as Part of the LOCATE Project. NERC EDS British Oceanographic Data Centre NOC. https://doi.org/10.5285/d111d44e-0794-28dc-e053-6c86abc0fc99.
Uncles, R.J., Stephens, J.A., Harris, C., 2015. Estuaries of Southwest England: salinity, suspended particulate matter, loss-on-ignition and morphology. Prog. Oceanogr. 137, 385–408.
Uncles, R.J., Hooper, T., Stephens, J.A., Harris, C., 2018. Seasonal variability of turbidity, salinity, temperature and suspended chlorophyll in a strongly tidal sub-estuary: the Lynher Marine Conservation Zone. Estuar. Coast Shelf Sci. 212, 253–264.
van Puijenbroek, P.J.T.M., Buijse, A.D., Kraak, M.H.S., Verdonschot, P.F.M., 2019. Species and river specific effects of river fragmentation on European anadromous fish species. River Res. Appl. 35, 68–77.
Verhoeven, J.T.A., 2014. Wetlands in Europe: perspectives for restoration of a lost paradise. Ecol. Eng. 66, 6–9.
Wagner, R. J., Boulger Jr. R. W., Oblinger, C. J. and Smith, B. A. 2006. Guidelines and standard procedures for continuous water-quality monitors: Station operation, recordcomputation, and data reporting: U.S. Geological Survey Techniques and Methods 1–D3, pp. 51. Available from http://pubs.er.usgs.gov/publication/tm1D3.
Weeks, J.H., Fung, F., Harrison, B.J., Palmer, M.D., 2023. The evolution of UK sea-level projections. Environmental Research Communications 5, 032001.
Whigham, D.F., 2009. Tidal freshwater wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Brinson, M.M. (Eds.), Coastal Wetlands: an Integrated Ecosystem Approach. Elsevier, Amsterdam, p. 515.
Whigham, D.F., Baldwin, A.H., Barendregt, A., 2019. Chapter 18 - tidal freshwater wetlands. In: Perillo, G.M.E., Wolanski, E., Cahoon, D.R., Hopkinson, C.S. (Eds.), Coastal Wetlands, second ed. Elsevier, Amsterdam, pp. 619–640.
Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the tidyverse. J. Open Source Softw. 4, 1686.
Williams, D.D., Williams, N.E., 1998. Seasonal variation, export dynamics and consumption of freshwater invertebrates in an estuarine environment. Estuarine. Coastal and Shelf Science 46, 393–410.
Wright, J.P., 2002. Water Quality in Estuarine Impoundments. Durham University. Doctoral thesis. http://etheses.dur.ac.uk/4027/. (Accessed 18 November 2024).
Wu, W., Yang, Z., Zhang, X., Zhou, Y., Tian, B., Tang, Q., 2021. Integrated modeling analysis of estuarine responses to extreme hydrological events and sea-level rise. Estuar. Coast Shelf Sci. 261, 107555.
Xu, X., Wei, H., Barker, G., Holt, K., Julian, S., Light, T., Melton, S., Salamanca, A., Moffett, K.B., McClelland, J.W., Hardison, A.K., 2021. Tidal freshwater zones as hotspots for biogeochemical cycling: sediment organic matter decomposition in the lower reaches of two south Texas rivers. Estuaries Coasts 44, 722–733.
Young, M., Howe, E., O'Rear, T., Berridge, K., Moyle, P., 2021. Food web fuel differs across habitats and seasons of a tidal freshwater estuary. Estuaries Coasts 44, 286–301.
Zonneveld, I.S., Barendregt, A., 2009. Human activities in European tidal freshwater wetlands. In: Barendregt, A., Whigham, D.F., Baldwin, A.H. (Eds.), Tidal Freshwater Wetlands. Backhuys, Leiden, pp. 11–20.