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Human disturbance is a primary discriminator of coastal lagoon typology in sedimentary barrier lagoons located in southern UK and France

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ABSTRACT

The environmental heterogeneity of coastal lagoons makes their classification challenging. Historically, lagoons have been characterised unilaterally according to their geomorphological, hydrological, saline or biotic features. While these characteristics are important, they independently fail to capture the nuanced complexity of coastal lagoons as multistressor environments. The vulnerability of these ecologically important, but neglected, habitats to continued climate change and anthropogenic pressure remains largely undetermined because of their inadequate appraisal. A systematic approach is therefore needed to facilitate their classification and improve assessment. Here, we developed a holistic, multivariable-driven classification using 16 environmental and anthropogenic variables to characterise 37 sedimentary barrier lagoon systems across the UK and southern France. Hierarchical clustering was employed to identify clusters naturally *a posteriori*, without imposing a predefined number of clusters. Five distinct lagoon clusters were revealed, with human disturbance emerging as the key discriminator of lagoon typology. Hydrology, temperature and naturalness were also identified as strong predictors, while salinity showed no discriminative power. This categorisation offers a reproducible means for the assessment of coastal lagoons to facilitate and prioritise field surveys. Furthermore, it provides a baseline for evaluating the biological and ecological consequences of lagoon type, including impacts on biodiversity, water quality and individual organisms, which may support conservation prioritisation and management decision making.

1. Introduction

Coastal lagoons are highly productive ecosystems found along 13% of the world's coastlines (Colombo, 1977). Characterised as shallow bodies of salt or brackish water partially separated from the adjacent sea by natural (or manmade) barriers, seawater exchange is restricted via channels, inlets, percolation or overtopping sufficient to deviate from a normal marine salinity of 35 (Angus, 2017; Barnes, 1980; Colombo, 1977; Kjerfve, 1994). In contrast to the lagoon-dense coastlines of microtidal regions (tidal range <2 m) like the Mediterranean, the dynamic macrotidal coastlines (tidal range >4 m) of the UK challenge the development of the persistent barriers and retention of water needed for lagoon formation, making them less common habitats (Barnes, 1980, 1994b). Sediment barrier-enclosed lagoons have typically formed along the low-lying eastern and southern UK coastlines through the transportation of glacially deposited shingle with rising interglacial sea levels and wave action, or through sediment entrapment in growing spits (Barnes, 1980, 1994b). Other lagoons reflect relicts of historic human land claim activities in centuries past (e.g. Holkham Salts Hole, Norfolk, UK, established in the 1700s; Hunt, 1971). These rare habitats manifest diverse sizes, shapes and depths, which influence their physical, biological and chemical properties (Bamber et al., 1993; Colombo, 1977), providing a myriad of highly individual poikilohaline habitats.

The ephemeral nature of these, often small and shallow, systems limits their existence to hundreds of years or less, ultimately transitioning into freshwater lakes through complete isolation from the sea or obliteration through barrier erosion (Bamber et al., 1993; Barnes, 1980). Rising sea levels are likely to further increase the vulnerability of coastal lagoons to barrier erosion through increasingly destructive storm surges and coastal flooding (Boateng et al., 2020; Carrasco et al., 2016). With approximately 38% of the global human population living within 100 km of the coastline (Cosby et al., 2024), coastal lagoons are increasingly exposed to anthropogenic-induced pressures, including climate change, urbanisation, land claim and eutrophication, in addition

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to recreational and commercial exploitation (Amora-Nogueira et al., 2023; De Wit, 2011; Ligorini et al., 2023; Lloret et al., 2008, 2018; Padedda et al., 2019; Pérez-Ruzafa et al., 2019). Infrastructure-mediated coastal squeeze is severe along global coastlines with median infrastructure-free widths of just 131 m, 151 m and 402 m in Europe, Asia and North America, respectively (Lansu et al., 2024). End-of-century predictions suggest the complete loss of 31% of European, 28% of Asian and 22% of North American infrastructure-free zones under Representative Concentration Pathway [RCP] 4.5 (Lansu et al., 2024). Human infrastructure prevents the natural retreat of coastal habitats, like coastal lagoons, and their natural development, while also increasing the risk of large scale coastal erosion (De Wit, 2011; Lansu et al., 2024). Many coastal lagoons are integrated into these urban environments and have experienced anthropogenic modification with direct consequences on hydrological and ecosystem function, often in addition to significant degradation (Barnes, 1994b; Beer and Joyce, 2013).

There is much controversy in the literature regarding how these unique habitats should be categorised (Pérez-Ruzafa et al., 2011; Tagliapietra et al., 2009). Some studies have considered coastal lagoons as transitional environments akin to estuaries (e.g. Kjerfve, 1989; Tagliapietra et al., 2009), while others have highlighted their physical heterogeneous distinction (Bamber et al., 1992; Joyce et al., 2005; Oliver, 2005; Pérez-Ruzafa et al., 2011; Tagliapietra et al., 2009). The high spatial diversity of lagoon systems and their often unpredictable nature have presented a conundrum regarding their management globally, with ambiguity regarding the responsibility of these specialised habitats falling within terrestrial or marine domains (Beer and Joyce, 2013; Gaertner-Mazouni and De Wit, 2012). Societal pressures on coastal lagoons further augment the challenges of their management and conservation (Davies-Vollum et al., 2025; Elliott et al., 2019). Despite their ecological and economic importance, the development of standardised monitoring frameworks remains challenging. Integrated multidisciplinary approaches that depend on stakeholder input have been explored for the management and monitoring of West African (Davies-Vollum et al., 2025) and Italian (Massarelli et al., 2023) lagoon systems, though bureaucratic barriers continue to impede such approaches (Boutin et al., 2025). Furthermore, the complexities of these habitats often require site-specific consultations (Bamber, 2010; Beer and Joyce, 2013). Coastal lagoons are considered a priority habitat in the UK (1150; JNCC, 2025), and although 26 km^2 of their estimated 52 km^2 areal extent are designated as Special Areas of Conservation or Sites of Special Scientific Interest (Jones et al., 2011), the focus within these designations is often not on the lagoons themselves but the broader protected landscapes they sit within, e.g. saltmarshes, mudflats and estuaries (Beer and Joyce, 2013; JNCC, 2025). Following Barnes' (1980) appraisal of these neglected habitats, a series of surveys ensued in the late 20th century to assess biodiversity and environmental condition (e.g. (Bamber, 2010, 1998, 1997; Barnes, 1994a, 1989, 1987; Downie, 1996; Sheader and Sheader, 1985). The survey of UK coastal lagoons has since, however, been infrequent and fragmented, which has led to their inequitable management during this period of intense and rapid climate and environmental change, despite their ecological importance (Bamber, 2010; Joyce et al., 2005, 2013).

Important and defining characteristics of coastal lagoons include their geological (Lankford, 1977), geomorphological (Kjerfve, 1986; Pérez-Ruzafa et al., 2007, 2011) and hydromorphological (Barnes, 1989; Kjerfve and Magill, 1989) features, in addition to their variable salinity, depth, size and morphology (Bamber et al., 1993). Building on earlier classifications of lagoons by their mode of origin (Barnes, 1980, 1989; Healy, 1998; Kjerfve, 1986), the UK's Joint Nature Conservation Committee categorises coastal lagoons into five main subtypes according to their physiographical relationship to the adjacent sea (Brown et al., 1997; JNCC, 2025). Brackish environments have also been routinely classified by salinity according to the Venice system established in 1958, where salinities of <0.5 are considered fresh, 0.5–4 as oligohaline, 5–18 as mesohaline, 19–30 as polyhaline, 31–40 as euhaline and >40 as hyperhaline (UNESCO/ICES/FAO Working Group, 1958). However, this systematisation neglects the inherent variability of coastal lagoons, in which salinity can fluctuate from mesohaline during periods of high precipitation and hyperhaline during periods of low precipitation (Barnes, 1980; Kennish and Paerl, 2010).

Barnes (1989) was among the first to consider a more holistic approach for evaluating the conservation importance of lagoons, adapting the Nature Conservancy Council's criteria for the assessment of marine communities to the specific context of lagoonal habitats. Bamber et al. (1992) extended this approach through the multivariate analysis of 166 UK lagoons to identify relationships between biological communities (particularly lagoon-specialist taxa) and environmental characteristics, including salinity range, depth, area, shape and substrate type. These findings supported the subsequent ranking of lagoons according to conservation importance (Bamber et al., 1992) and informed criteria for the optimal management of lagoon habitats (Bamber et al., 1993). Joyce et al. (2005) applied similar methods to determine the biotic communities of 28 coastal water bodies, both freshwater and brackish, found along the southern coastline of the UK in the county of Sussex, while Oliver (2005) classified Irish lagoons primarily according to their floral communities, and then subsequently characterised them more broadly using faunal assemblages and salinity regimes. Although these approaches highlight important distinguishing features of lagoon systems, they relied on laborious taxonomic identification as the primary basis for lagoon classification before identifying the associated environmental correlates.

Our understanding of coastal lagoon responses to the continued destabilisation of the Earth's systems and usurpation of land and resources is limited by the inadequate survey of lagoon systems over the last two critical decades of climate change. An environmental-based classification of the lagoon systems themselves could provide a beneficial tool for lagoon assessment and management to complement biological surveys. A systematic approach is needed to enable a reproducible and comprehensive periodic evaluation of these rare habitats to facilitate their management and predicted outlook, in addition to assisting with the classification of new lagoon formations. Using an amalgamation of new and existing criteria, while also capturing environmental variability, this study uses hierarchical clustering to discover, *a posteriori*, the natural grouping of UK, nontidal, sediment barrier coastal lagoons and their discriminating factors. This approach attempts to capture the interplay among shared environmental stressors on these complex and diverse systems to expedite a systematic approach for lagoon research.

2. Methods

2.1. Lagoon surveys

Potential lagoons for inclusion in the categorisation were identified by examining published reports (Bamber, 1998, 2010; Barnes, 1980, 1987; Boyden and Russell, 1972). Two lagoons (Marsh Farm 1 and 2) were identified using scanning satellite imagery available in Google Earth Pro (Google Earth Pro, 2025). Lagoons were surveyed across the coastal regions of southern England and Wales (n = 31) and southern France (n = 6) between May 2023 and October 2025 (Table S1). A total of 37 lagoons (Fig. 1) with complete environmental data were included in the analysis.

2.2. Variables included for categorisation

Coastal lagoon habitats were characterised using a combination of continuous (n = 9) and categorical (n = 7; Table 1) descriptors that are outlined in detail below. Continuous variables were z-standardised before running the cluster analysis to account for heterogeneous units and variances, while categorical variables were treated as unordered

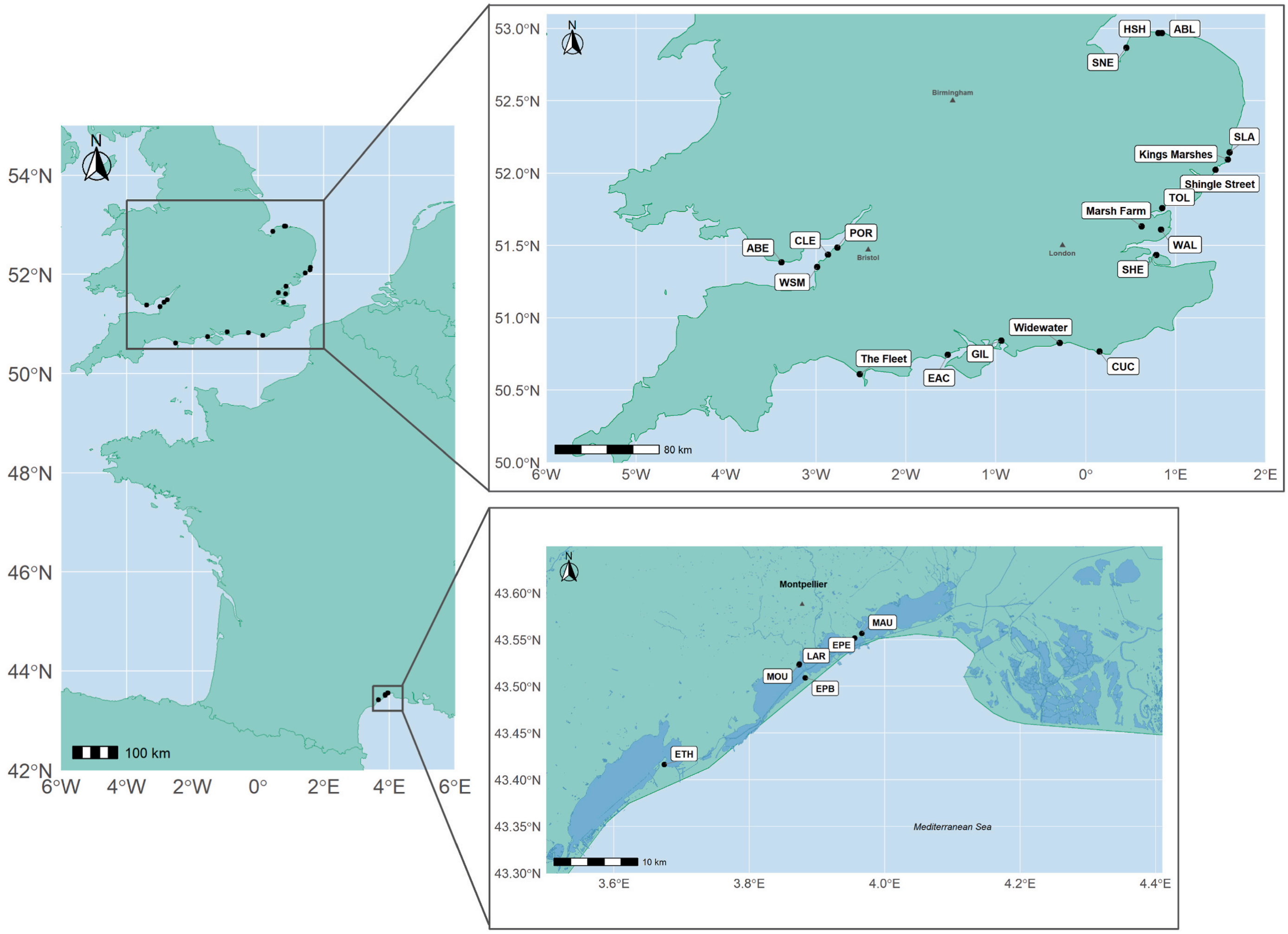

Fig. 1. Coastal lagoons included in the categorisation. Lagoons were surveyed in the a) UK and b) southern France. Some of the labelled locations include multiple coastal lagoons: Kings Marshes, KM1, KM2, KM2a, KM13, KM16, KM23 and KM25; Marsh Farm, SWF1 and SWF2; Shingle Street, OR0a, OR0b, OR1, OR4, OR5, OR6.

factors (Zuur et al., 2010).

2.2.1. *Environmental variables*

2.2.1.1. Meteorology. UK daily air temperature and rainfall records from between 2022 and 2025 were downloaded from the Centre for Environmental Data Analysis (www.ceda-wps-ui.ceda.ac.uk/processes). The Met Office Integrated Data Archive System (MIDAS; www.archive.ceda.ac.uk/tools/midas_stations) was used to search for weather stations located in close proximity to the surveyed lagoons with available daily temperature (°C) and rainfall (mm) records (Met Office, 2006). For French localities, an online source was used to obtain daily temperature and rainfall records (www.extremeweatherwatch.com). Monthly average temperature and rainfall were calculated across the 3 years prior to the survey year, i.e. for the collection year of 2024, monthly averages were calculated for the years 2022, 2023 and 2024.

2.2.1.2. Salinity. In addition to recording the salinity at each lagoon on the day of the survey using a handheld salinity tester (HI-98319, Hanna Instruments), salinity records from within 20 years of the survey were collated from the literature and published reports to capture a more accurate and seasonal picture of the salinity regimes across lagoon systems (Cases and Manresa, 2019; Cataudella et al., 2015; Elbaz-Poulichet et al., 2014; Huyse et al., 2006; Ifremer, 2010, 2007; Joyce et al., 2013; Syndicat Mixte des Etangs Littoraux, 2008). At select lagoon sites (Holkham Salts Hole, Abraham's Bosom, Marsh Farm 1 and 2, Slaughden and Shingle Street lagoons), historical records of salinity were supplemented with intermittent multiseason visits made across an average of seven times over the 3 year survey period. Vertical salinity stratification was considered unlikely to represent a significant source of variability given the shallow mean depth of surveyed lagoons (mean = 1.2 m).

2.2.1.3. Variability. To capture temperature, rainfall and salinity variability among the lagoon systems, separate principal component analyses (PCAs) were employed following the methods outlined by Kroeker et al. (2013) and Telesca et al. (2020). Descriptive statistics for salinity, temperature and rainfall were calculated (i.e. minimum, maximum, mean, median and standard deviation values) for each lagoon. These were then fed into separate PCAs to reduce dimensionality and capture independent summary variables to characterise mean trends and the variability of the abiotic factors across the lagoon systems. The first two principal components (PCs) for each variable were extracted to use as input variables for the clustering analysis (Fig. S3).

2.2.2. *Morphometric variables*

2.2.2.1. Area. Satellite imagery available on Google Earth Pro (Google Earth Pro, 2025) was utilised to calculate the area of individual lagoons. The polygon tool was used to draw along the perimeter of individual lagoons by clicking vertices to form a complete polygon that mirrors their areal shape. A measurement for area in m^2 was then determined from the complete polygon.

Table 1
Categorical variables and character levels used in the categorisation of lagoon environments.

Variable	Characters
Crabs	Present: real-time observation of *Carcinus maenas* in the field, or identification of discarded carapaces or appendages, damage on shells (both repaired and unrepaired) or significant fragmentation of shell material in the substrate (see Fig. S1). Absent: no observation of *C. maenas* or evidence of predation.
Ephemerality	Stable: no seasonal change in water level. Minimal: limited amount of seasonal exposure of the lagoon basin (<0.5 m). Moderate: marked seasonal exposure of the lagoon basin (>0.5 m) Significant: conspicuous seasonal exposure of the lagoon basin (>1m) to the extent that the lagoon may disappear completely during warmer months, also evidenced by desiccation cracks in the substrate.
Human disturbance	Pristine: remote and totally undisturbed with negligible human influence. Low: some human activity, e.g. proximity to a public footpath or location within a public nature reserve like Holkham Salts Hole or the Marsh Farm lagoons. Moderate: anthropogenic activity within the lagoon, i.e. boating, paddle boarding, fishing, relative to size, but no visible refuse or ecological degradation. Significant: heavy recreational use, relative to size, and/or showing clear evidence of degradation, i.e. algal blooms, turbid water, noxious odours, reduced biodiversity, refuse in the lagoon, etc.
Hydrology	Sea inlet: natural channel allowing seawater exchange with tides. Percolation: seawater enters by gradual filtration through the shingle barrier or occasionally by overtopping. Sluiced: regular and frequent seawater exchange via a managed system, i.e. a sluice gate (a type of valve or sliding gateway that controls water flow), or feeder pipes like those at Widewater lagoon to draw in seawater at high tides. Seawater is retained at all states of the tide. Natural channel: a natural waterway or canal system in microtidal regions maintaining a direct connection with the adjacent sea. Artificial channel: artificially created waterway or canal system in microtidal regions to restore or maintain a direct connection with the adjacent sea.
Naturalness	Natural: the lagoon is completely natural with no artificial infrastructure. Semi-natural: basin or outlet (i.e. the installation of an exit pipe) are manmade. Artificial: lagoon basin and outlet are entirely manmade (e.g. the concrete basin at Clevedon Marine Lake, UK), this also includes the frequent desilting and dredging of a basin.
Bank slope	Sloping: gradual inclined transition into lagoon. Variable: areas of sloping shoreline and vertical edges. Steep: vertical edge surrounding the lagoon.
Vegetation	Absent: no submerged vegetation observed. Cha: identification of free-floating mats of the green filamentous alga *Chaetomorpha linum* (see Fig. S2a). Rup: identification of the fine-rooted tasselweed, *Ruppia* spp. (*R. maritima* or *R. cirrhosa*) (see Fig. S2b). Rup_Cha: identification of both *C. linum* and *Ruppia* spp. Zos: identification of the grass-like flowering eelgrass *Zostera marina* (see Fig. S2c).

2.2.2.2. Circularity. The polygon tool on Google Earth Pro (Google Earth Pro, 2025) was also used to obtain perimeter measurements recorded in meters. Perimeter and area could then be applied to Equation (1) to obtain a circularity index. This index was then inverted (1 – *circularity*) with a value of 1 reflecting an irregular shape versus circular (0).

$$Circularity = (4\pi \times area) \div perimeter^2 \qquad \text{Equation 1}$$

2.2.2.3. Depth. Depth was evaluated on the day of the survey and corroborated, where possible, with depth records in the literature from published surveys or reports (Bamber, 1998; Cataudella et al., 2015; Downie, 1996; Hunt, 1971; Joyce et al., 2013).

2.2.2.4. Bank slope. All lagoons (both natural and artificial) were assessed as having sloping, variable or steep banks, depending on the gradient of the shoreline. Those with sloping banks exhibited a gradual, low-gradient incline, while those with steep banks exhibited vertical edges that surround the lagoon. Lagoons with both sloping and steep banks were determined as variable.

2.2.3. Biological variables

2.2.3.1. Crabs. The presence of crabs (predominantly the green shore crab, *Carcinus maenas*) was determined based on the observation of living crabs, discarded moults and dead carapaces or appendages, damage on collected shells (both repaired and nonrepaired; Alexander and Dietl, 2001; Mascaro and Seed, 2000) or the significant fragmentation of shell material in the substrate (Calderwood and Sigwart, 2017) (Fig. S2).

2.2.3.2. Vegetation. Observations were made for the presence of submerged lagoon-specialist flora (Fig. S2). This included the tasselweed, *Ruppia* spp., and filamentous green alga, *Chaetomorpha linum*, in isolation or co-occurring. Because both *R. maritima* and *R. cirrhosa* are found in lagoon environments and are often taxonomically confused, identification was at genus level (Verhoeven, 1979). *Zostera marina* was also included as a sub-character to capture its abundance in the Fleet.

2.2.4. Hydrological variables

2.2.4.1. Hydrology. The hydrology of a sediment-based lagoon system was determined by its primary source of seawater input, including: sea inlet, an exchange of seawater with each tide through an open natural channel; percolation, lagoons fed by the gradual filtration of seawater through the shingle barrier or occasionally by overtopping; sluiced, regular and frequent seawater input via a managed system, such as a sluice gate or feeder pipe, that retains water at all states of the tide; natural channel, also known locally in France as a grau, these narrow, naturally formed waterways connect lagoons in microtidal regions to the adjacent sea; and artificial channel, a manmade waterway created to restore or maintain a connection to the adjacent sea in microtidal regions. This categorisation did not include silled or rock-basin lagoons, which are generally restricted to the north and west of Scotland, and retain tidal water via a rock sill or within a rock basin.

2.2.4.2. Ephemerality. The natural, not artificially managed, ephemerality (susceptibility to desiccation) of lagoon systems was assessed through seasonal visits where possible or the observation of desiccation cracks on the substrate surface. This was also supported by utilising the historical imagery function in Google Earth Pro (Google Earth Pro, 2025) that has aerial images reaching back to the 1940s. Lagoons were assessed as: stable, where there appeared to be no, or negligible, seasonal change in water level; minimal, where exposure of the lagoon basin was restricted to within 0.5 m of the outer margins; moderate, where more than 0.5 m of the lagoon basin area was exposed seasonally; and significant, where more than 1m of the lagoon basin was exposed seasonally and includes lagoons that may even disappear completely during warmer months.

2.2.5. Anthropogenic variables

2.2.5.1. Naturalness. Naturalness was defined as the degree of human intervention affecting lagoon morphology and hydrological connectivity since 1900. Lagoons that have not been altered in any way from their natural state during this period were classified as natural (n = 20), including those with historical features predating 1900, such as salt-marsh relicts from pre-1900 agricultural land claim. Lagoons with either an artificial outlet (e.g. fitted with an exit pipe to reduce flooding and manage water levels) or modified basins (including regularly dredged or desilted systems) were determined as semi-natural (n = 13), while lagoons possessing both manmade basins and outlets were classified as artificial (n = 4).

2.2.5.2. Human disturbance. Human disturbance was defined as the degree of degradation resulting from direct anthropogenic impact and was assessed using criteria adapted from those described by Barnes (1989). Lagoons located in remote areas with no evidence of direct human influence were classified as pristine (n = 16). Lagoons exhibiting minimal disturbance, e.g. proximity to a frequently used footpath or location within a public nature reserve, were categorised as low disturbance (n = 4). Lagoons used for active recreation, such as boating,

Table 2
Summary of the mean characteristics for each cluster. Cluster 1 was characterised by semi-natural, percolation lagoons with low levels of human disturbance; Cluster 2 was characterised by sluice-managed, semi-natural/artificial lagoons with significant levels of human disturbance; Cluster 3 was characterised by the hot, dry French étangs; Cluster 4 was characterised by solely the Fleet capturing its sea inlet hydrology and natural state; and Cluster 5 was characterised by pristine, natural, percolation lagoons.

Variable (95% CI)	Cluster (n)				
	1 (7)	2 (9)	3 (6)	4 (1)	5 (14)
Salinity PC1	−1.20 (-2.48, 0.08)	0.17 (−0.97, 1.32)	0.72 (−0.68, 2.12)	−0.75 (-4.18, 2.68)	0.23 (-0.68, 1.15)
Salinity PC2	0.11 (-0.86, 1.08)	−0.69 (−1.54, 0.17)	0.71 (−0.34, 1.76)	1.04 (−1.53, 3.61)	0.01 (−0.68, 0.69)
Temperature PC1	−0.64 (−0.99, −0.30)	−0.01 (−0.32, 0.29)	5.77 (5.39, 6.15)	0.12 (−0.80, 1.04)	−1.26 (−1.51, −1.01)
Temperature PC2	−0.55 (-1.02, −0.08)	0.49 (0.08, 0.90)	−1.13 (−1.64, −0.62)	1.65 (0.41, 2.89)	−1.28 (−1.61, −0.95)
Rainfall PC1	−0.08 (−0.88, 0.71)	−0.60 (−1.30, 0.10)	4.22 (3.36, 5.08)	−2.10 (−4.20, 0.00)	−0.24 (−0.80, 0.32)
Rainfall PC2	0.38 (-0.01, 0.77)	−0.42 (−0.76, −0.07)	0.21 (-0.21, 0.63)	2.05 (1.02, 3.08)	−0.72 (-1.00, −0.44)
Area (ha)	1.51 (−759.96, 762.97)	5.69 (−665.86, 677.24)	2104.39 (1281.91, 2926.87)	55.00 (−1509.65, 2519.65)	0.43 (−538.01, 538.87)
Depth (m)	1.37 (0.70, 2.04)	1.30 (0.71, 1.89)	1.47 (0.74, 2.19)	5.20 (3.42, 6.98)	0.57 (0.09, 1.04)
Circularity	0.56 (0.41, 0.71)	0.48 (0.35, 0.61)	0.65 (0.49, 0.82)	0.93 (0.53, 1.33)	0.66 (0.55, 0.77)
Crabs (%)					
Present	57.1	100.0	100.0	100.0	21.4
Absent	42.9	0.0	0.0	0.0	78.6
Mode	Present	Present	Present	Present	Absent
Bank slope (%)					
Sloping	28.6	44.4	100.0	0.0	64.3
Variable	28.6	22.2	0.0	100.0	7.1
Steep	42.9	33.3	0.0	0.0	28.6
Mode	Steep	Sloping	Sloping	Variable	Sloping
Vegetation (%)					
Absent	28.6	30.0	16.7	0.0	21.4
Ruppia	28.6	22.2	16.7	0.0	14.3
Chaetomorpha	28.6	22.2	66.7	0.0	50.0
Ruppia & Chaetomorpha	14.3	22.2	0.0	0.0	14.3
Zostera	0.0	0.0	0.0	100.0	0.0
Mode	Absent	Absent	*Chaetomorpha*	*Zostera*	*Chaetomorpha*
Naturalness (%)					
Artificial	0.0	44.4	0.0	0.0	0.0
Semi	100.0	44.4	33.3	0.0	0.0
Natural	0.0	11.1	66.7	100.0	100.0
Mode	Semi	Artificial	Natural	Natural	Natural
Hydrology (%)					
Sea inlet	0.0	11.1	0.0	100.0	0.0
Percolation	100.0	0.0	0.0	0.0	100.0
Sluiced	0.0	88.9	0.0	0.0	0.0
Natural channel	0.0	0.0	66.7	0.0	0.0
Artificial channel	0.0	0.0	33.3	0.0	0.0
Mode	Percolation	Sluiced	Natural channel	Sea inlet	Percolation
Human disturbance (%)					
Pristine	14.3	11.1	0.0	0.0	100.0
Low	57.1	0.0	0.0	0.0	0.0
Moderate	0.0	0.0	0.0	100.0	0.0
Significant	28.6	88.9	100.0	0.0	0.0
Mode	Low	Significant	Significant	Moderate	Pristine
Ephemerality (%)					
Stable	57.1	77.8	50.0	100.0	7.1
Minimal	14.3	0.0	0.0	0.0	21.4
Moderate	0.0	11.1	33.3	0.0	42.9
Significant	28.6	11.1	16.7	0.0	28.8
Mode	Stable	Stable	Stable	Stable	Moderate

paddle boarding or fishing, relative to their size, but lacking visible refuse or ecological degradation were classified as moderately disturbed (n = 1). Lagoons experiencing heavy recreational use, relative to their size, and/or showing clear evidence of degradation, such as visible refuse, algal blooms, turbid water, noxious odours, were classified as significantly disturbed (n = 16).

2.3. Cluster analysis

Our methodology is based on the framework for clustering and feature selection developed by Chavent et al. (2021). All analyses were performed in R (version 4.4.1; R Core Team, 2024). We used unsupervised hierarchical clustering to cluster lagoons, *a posteriori*, without the requirement for predefined clusters. Dissimilarities between lagoons were quantified using a Gower pairwise distance matrix to handle the mixed continuous and categorical variables, with Ward's linkage to minimise within-cluster variance (Murtagh and Legendre, 2014). Clustering was performed using the *cluster* and *stats* packages (Maechler, 2018; R Core Team, 2024). The optimum number of clusters was evaluated by visually identifying potential clusters on a dendrogram and using the *factoextra* package (Kassambara and Mundt, 2020) to visualise elbow plots and calculate Silhouette scores (Rousseeuw, 1987). Analysis of similarities (ANOSIM) and permutational multivariate analysis of variance (PERMANOVA) were used to statistically validate the clusters using the *anosim* and *adonis* functions in the *vegan* package, respectively (Oksanen et al., 2001).

2.4. Cluster characterisation

A conditional inference forest (CIF) was used descriptively to identify the most important variables for determining cluster membership. Unlike traditional random forest analyses that can exhibit bias towards variables with many categories or those correlated with other predictors (Strobl et al., 2007), CIFs calculate conditional variable importance, quantifying the change in prediction accuracy when each variable is permuted while accounting for correlations with other predictors (Strobl et al., 2008). CIF was performed using the *cforest* function in the *partykit* package (Hothorn and Zeileis, 2015). Continuous and categorical lagoon descriptors were used as predictors and the hierarchical cluster assignments were used as the response variables. Variables with higher positive conditional importance values were considered to be more important in the discrimination of lagoon clusters. Clusters were then characterised using cluster-specific summaries of the descriptor variables. Mean values with 95% confidence intervals were evaluated for continuous variables, while categorical variables were reported as the proportion of lagoons exhibiting each sub-character within a cluster in addition to identifying the modal level for each cluster (Table 2; *eemeans* package; Lenth et al., 2025).

To examine the multivariate structure among lagoon clusters and their associated characters, factor analysis for mixed data (FAMD), an extension of PCA dedicated to handling datasets of mixed data types, was implemented using the *FactoMineR* package (Lê et al., 2008). FAMD results were plotted in an ordination plot with 95% confidence ellipses grouped by cluster, with the distribution and strength of quantitative variables visualised using vector arrows and the modalities of categorical characters used to visualise categorical relationships.

Finally, to aid the classification of new lagoons, a conditional inference tree (CIT) was fitted via the *partykit* package (Hothorn and Zeileis, 2015). Unlike traditional decision trees, CITs use permutation-based significance tests to select input variables and determine data splits. The CIT was used to estimate lagoon cluster using the six most important characters identified by the CIF as explanatory variables. Statistical significance was set at $p < 0.05$. The minimum split and bucket sizes were both set at 1 to accommodate clusters represented by a single observation.

3. Results

3.1. Environmental characteristics

PCA of summary statistics for salinity, temperature and rainfall records (Table S2–4) revealed significant heterogeneity across lagoon sites (Fig. S3). The first two PC values were extracted for inclusion in the analysis, capturing 91.6%, 94.7% and 95.5% of the variation in salinity, temperature and rainfall, respectively. Increasing PC1 values reflected increasing mean levels of salinity and temperature, but decreasing mean levels of rainfall. PC2 captured variability in salinity and temperature, with positive PC2 values reflecting increasing variability in salinity, while negative values reflected increasing variability in temperature. Positive rainfall PC2 values reflected drought conditions (Table S5).

3.2. Cluster analysis

Hierarchical clustering on the standardised environmental data (raw data in Table S6) revealed five distinct clusters across the 37 coastal lagoon sites, with a distinct separation between the UK lagoons (four clusters) and French étangs (one cluster) (Fig. 2). An average silhouette score of 0.36 revealed moderate separation among clusters. Individual silhouette scores of 0.14, 0.26, 0.47, 0.00 and 0.50 for clusters 1, 2, 3, 4 and 5, respectively, showed distinct discrimination for clusters 3 and 5, but weaker clustering structure between clusters 1, 2 and 4. A Dunn index of 0. 61 indicated more compact and separate clusters, while a cophenetic correlation of 0.73 indicated the clusters to exhibit a good representation of the original pairwise dissimilarity matrix. Furthermore, ANOSIM revealed clusters to be significantly different ($R = 0.83$, $p < 0.001$) and PERMANOVA ($R^2 = 0.59$, $F = 17.91$, $p < 0.001$) revealed moderate separation between groups.

3.2.1. Cluster membership

Conditional importance values revealed human disturbance to be the most important predictor of cluster membership for lagoon environments with a conditional importance of 0.056, followed by hydrology (0.047) and temperature PC1 (0.045). While these were the dominant drivers, naturalness (0.025), rainfall PC1 (0.020) and area (0.015) (Fig. 3) also made meaningful contributions, falling at or above a threshold of 0.015 in the ranked importance distribution. The remaining variables temperature PC2, rainfall PC2, crabs, ephemerality, depth and salinity PC2 fell below this threshold and were considered uninformative for cluster discrimination. Meanwhile, bank and salinity PC1 were negligible, and circularity and vegetation were negative indicating a potential decrease in model accuracy.

Cluster-specific statistics (Table 2) guided by the CIF results revealed Cluster 1 to be defined by lagoons with low levels of human disturbance (57.1%), percolation hydrology (100%) and semi-natural states (100%). Cluster 2 was defined by lagoons with significant levels of human disturbance (88.9%), sluice-controlled hydrology (88.9%) and semi-natural (44.4%) to entirely artificial (44.4%) states with manmade basins and/or outlets. Cluster 3 comprised the French étangs, characterised as natural (66.7%) lagoons with seawater input via natural channels (66.7%), but experiencing significant levels of human disturbance (100%), high temperatures (mean temperature PC1 = 5.77 [95% CI 5.39–6.15]) and low rainfall (mean rainfall PC1 = 4.22 [95% CI 3.36–5.08]). Cluster 4 represented only the Fleet, characterised by moderate levels of human disturbance (100%), sea inlet hydrology (100%) and retention of its natural state (100%). Finally, Cluster 5 was characterised by pristine (100%), natural (100%) lagoons with percolation hydrology (100%) (Figs. 4 and 5).

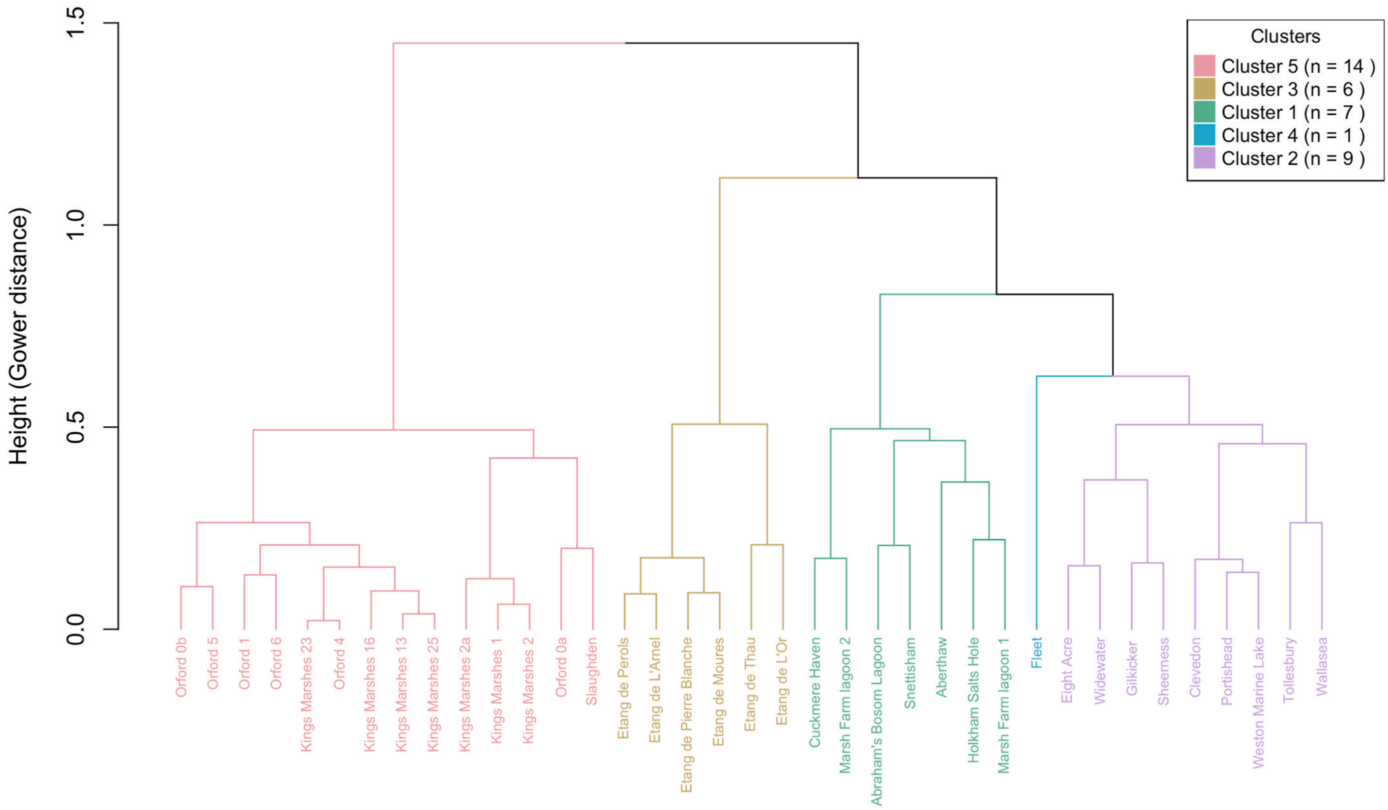

Fig. 2. Dendrogram visually representing the five distinct clusters determined by hierarchical clustering. Clusters included lagoons defined by: pristine, natural, percolation lagoons (cluster 5; n = 14); hot, dry French étangs with natural or artificial channels and significant levels of human disturbance (cluster 3; n = 6); low levels of human disturbance, percolation hydrology and semi-natural state (cluster 1; n = 7); the Fleet with sea inlet hydrology, moderate levels of human disturbance and natural state (cluster 3; n = 1); and significant levels of human disturbance, sluice-controlled hydrology and semi-natural state (cluster 2; n = 9).

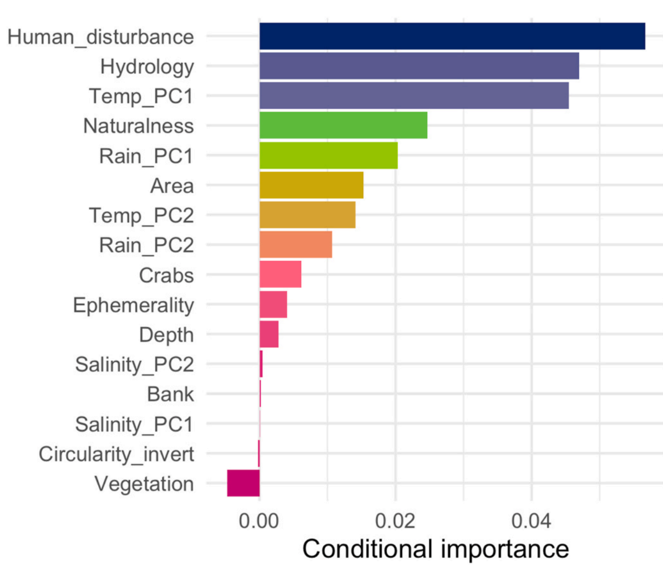

Fig. 3. Conditional importance of variables revealed from the descriptive conditional inference forest, which quantified the change in prediction accuracy of lagoon cluster allocation as each character variable is permuted while accounting for correlations with other predictors.

3.2.2. Multivariate structure of lagoon clustering

The first two dimensions of the FAMD, accounting for 32.3% of the total variation, revealed human disturbance and hydrology as the primary categorical contributors for dimension 1 (17.1% and 14.6%, respectively), with depth the primary quantitative contributor (11.2%). Hydrology was the primary categorical contributor for dimension 2 (20.5%), with rainfall and temperature PC1s (19.6% and 14.10%, respectively) the primary quantitative contributors. Visualisation of the multivariate space revealed the clear separation of lagoons in clusters 3 and 4. Cluster 5 clustered distinctly from clusters 1 and 2, which exhibited partial overlap (Fig. 6).

3.2.3. Decisive characters for cluster assignment

Results from the CIT revealed human disturbance ($p < 0.001$), hydrology ($p < 0.001$), temperature PC1 ($p = 0.005$) and naturalness ($p < 0.001$) to significantly influence cluster membership (Fig. 7). The first split (node 1) showed a significant difference between pristine lagoons and those with low, moderate or significant levels of human disturbance. The next split (node 2) further distinguished percolation lagoons from other hydrological systems, clustering pristine, percolation lagoons into Cluster 1. At node 4, the split separated non-percolation lagoons by temperature PC1 values, with lagoons with a temperature PC1 of more than 0.073 (corresponding to a mean temperature of approximately 13 °C) clustering into Cluster 3 (Mediterranean lagoons), while cooler lagoons formed the UK clusters 2 or 4. Pristine lagoons at node 7 were split by their naturalness, with entirely natural lagoons clustering into Cluster 5, and artificial or semi-natural lagoons clustering into Clusters 1 or 2.

4. Discussion

The categorisation of coastal lagoons has often relied on a single characteristic or intensive biological surveys, which fail to capture the inherent variability of these dynamic and multistressor habitats. Here, we used a multivariate matrix of 16 environmental and anthropogenic variables to determine the natural categorisation of 37 sedimentary

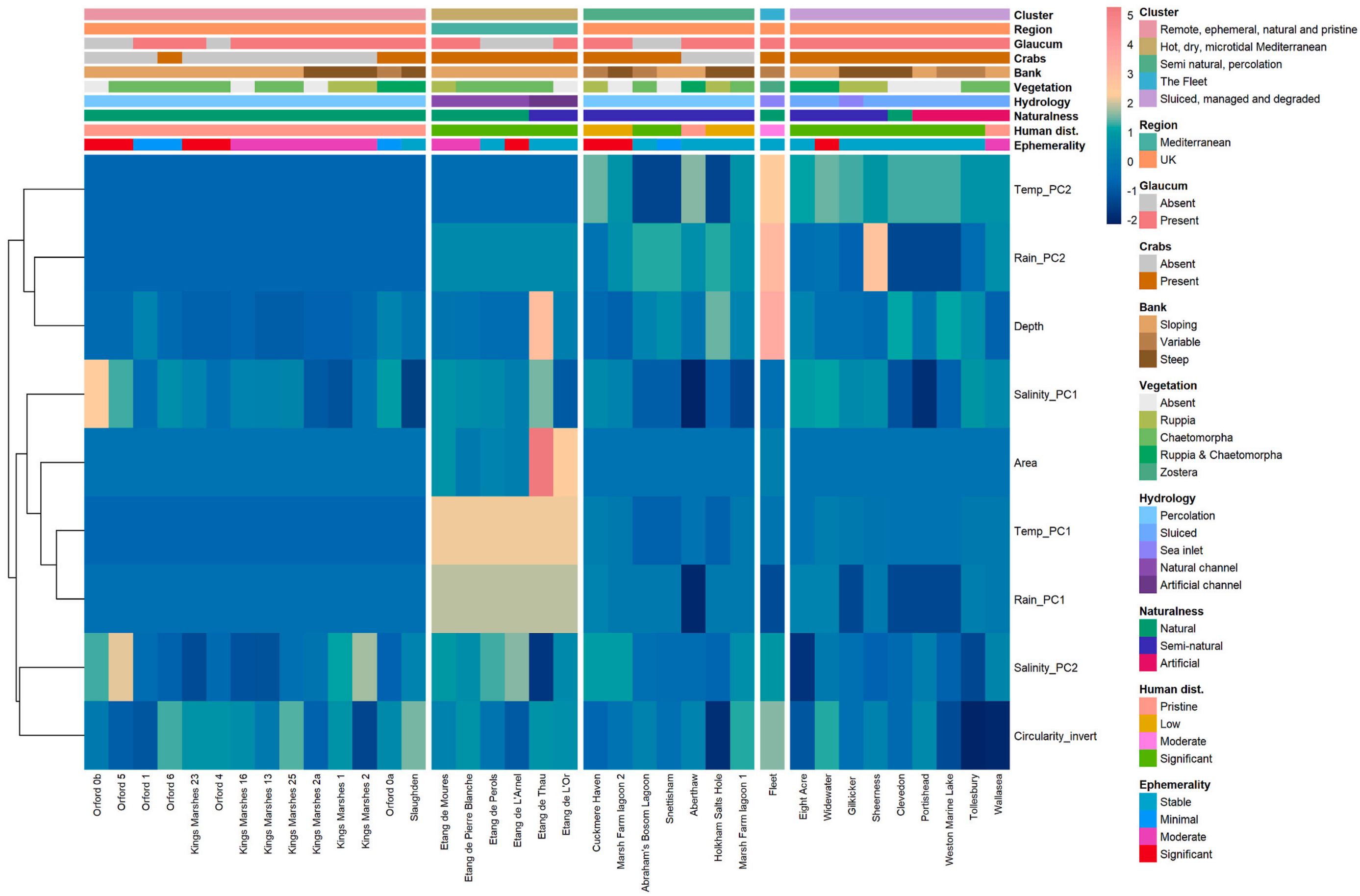

Fig. 4. Heat map visualising cluster membership and characteristics of each of the individual lagoons. The presence of the lagoon-specialist cockle, *Cerastoderma glaucum*, is also included.

barrier coastal lagoons located in the UK and southern France. Five discrete lagoon clusters were revealed, differentiated primarily by their levels of human disturbance, hydrology, mean temperature and naturalness. While this study does not assess the ecological consequences of cluster membership, it serves as a baseline for future studies to examine the influence of cluster membership on lagoon environments and their inhabitants. Furthermore, it may facilitate a comprehensive appraisal of UK sedimentary barrier coastal lagoons, and possibly further afield, and compensate for a two-decade gap in systematic national surveys. Discriminating factors for lagoon typology will be considered here in approximate order of importance.

4.1. Primary discriminators

4.1.1. Human disturbance

The detrimental consequences of inimical human activity are well documented in the literature and are most significant among the urbanised coastlines of the northern hemisphere (Kennish and Paerl, 2010). Coastal defence systems and the land claim of saltmarshes for agriculture have restricted the natural dispersal pattern of lagoon specialists, localising their distribution and increasing species vulnerability to extinction (Bamber et al., 1992; Williams, 1975). Eutrophication from sewage and agricultural runoff can degrade water quality, trigger mass mortality events, anoxia and algal blooms (Kennish et al., 2008; Pérez-Martín, 2023). Furthermore, the recreational use of lagoons for activities such as boating and swimming is often accompanied with deleterious practices, including the chemical control of macrophytes using algaecides (Barnes, 1989; McArthur, 1996), or the draining, dredging and desilting of the lagoon substrate causing significant disruption to the benthos (Fratini et al., 2025; Ponti et al., 2009). Evidence of anthropogenic impact was conspicuous at several of the surveyed lagoons and included evidence of refuse and debris, recreational activities (boating, swimming, crabbing), reduced biodiversity, water discoloration and turbidity, anoxic substrates and algal blooms. Examples of the progressive deterioration of lagoon systems can also be traced through the literature. The severely polluted state of Abraham's Bosom lagoon found enclosed within a caravan site in Norfolk, UK, was first recorded by Williams (1973), and its continued decline was chronicled throughout the following decades (Bamber, 1997; Barnes, 1987; Dipper and Whyte, 2006; McArthur, 1996; Williams, 1975). Indeed, our survey of Abraham's Bosom concluded its ecologically impaired state, appearing to host only polychaetes and a necropolis of *Cerastoderma glaucum* shells.

The categorisation presented here identified four UK clusters, each corresponding to a distinct level of human disturbance, forming a gradient from pristine natural lagoons to significantly disturbed. There is a stark contrast between lagoons coalesced within urban areas and those found on remote stretches of protected coastline. The rapid urbanisation and population growth in the catchments surrounding the French étangs have contributed to significant eutrophication, resulting in their uniform classification as significantly disturbed (Ouisse et al., 2022; Quignard et al., 1983; Syndicat Mixte des Etangs Littoraux, 2008). Barnes (1989) was the first to incorporate the detrimental potential of day-to-day anthropogenic disturbance in their assessment criteria of coastal lagoons, noting specifically their exploitation for waste disposal and recreation in a score-based system. Studies have since incorporated anthropogenic pressures into their analyses of lagoonal environments, particularly factors affecting water quality (Bamber et al., 1992;

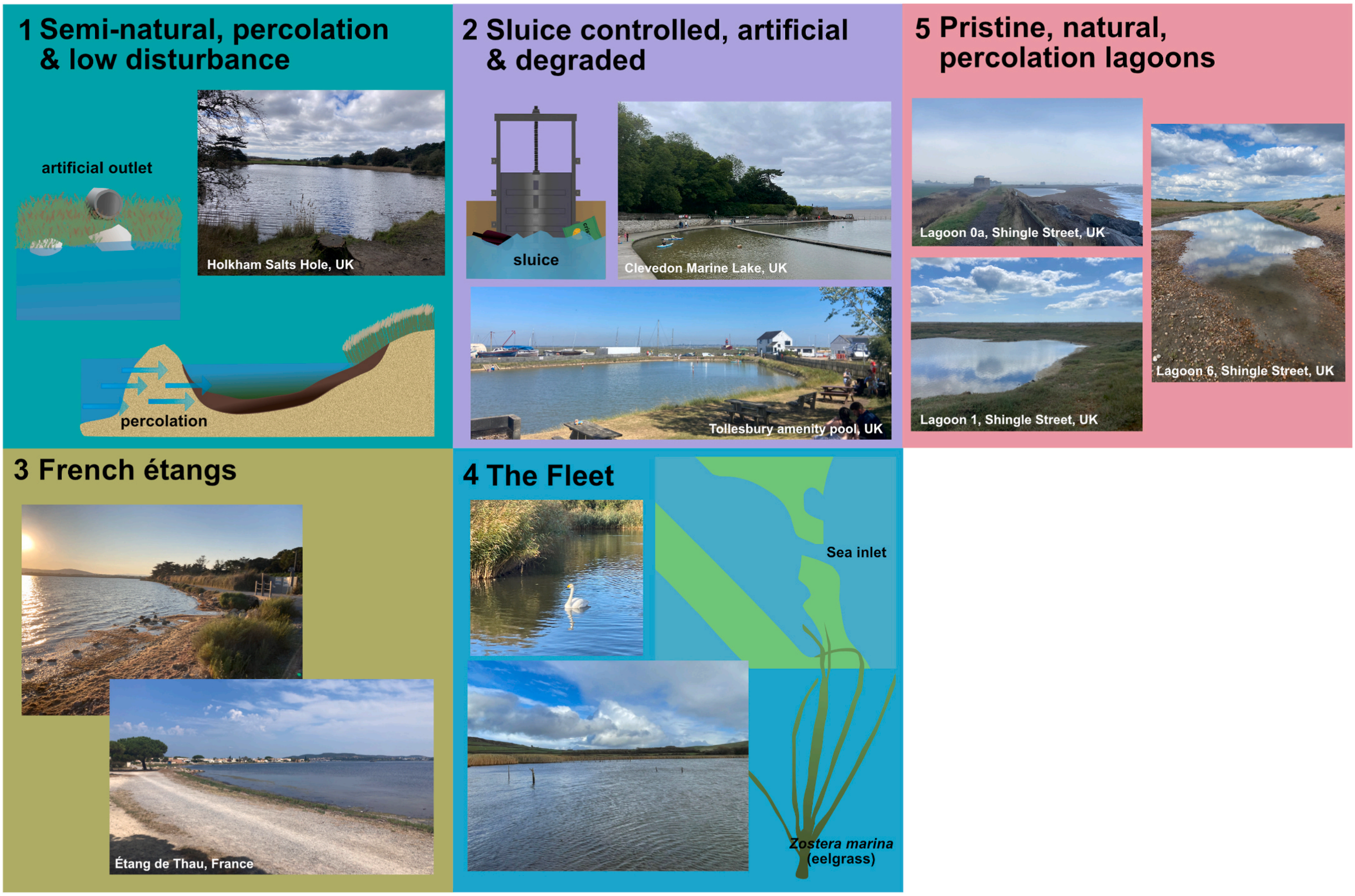

Fig. 5. Lagoon typology. Key characteristics and examples of lagoons included within each cluster.

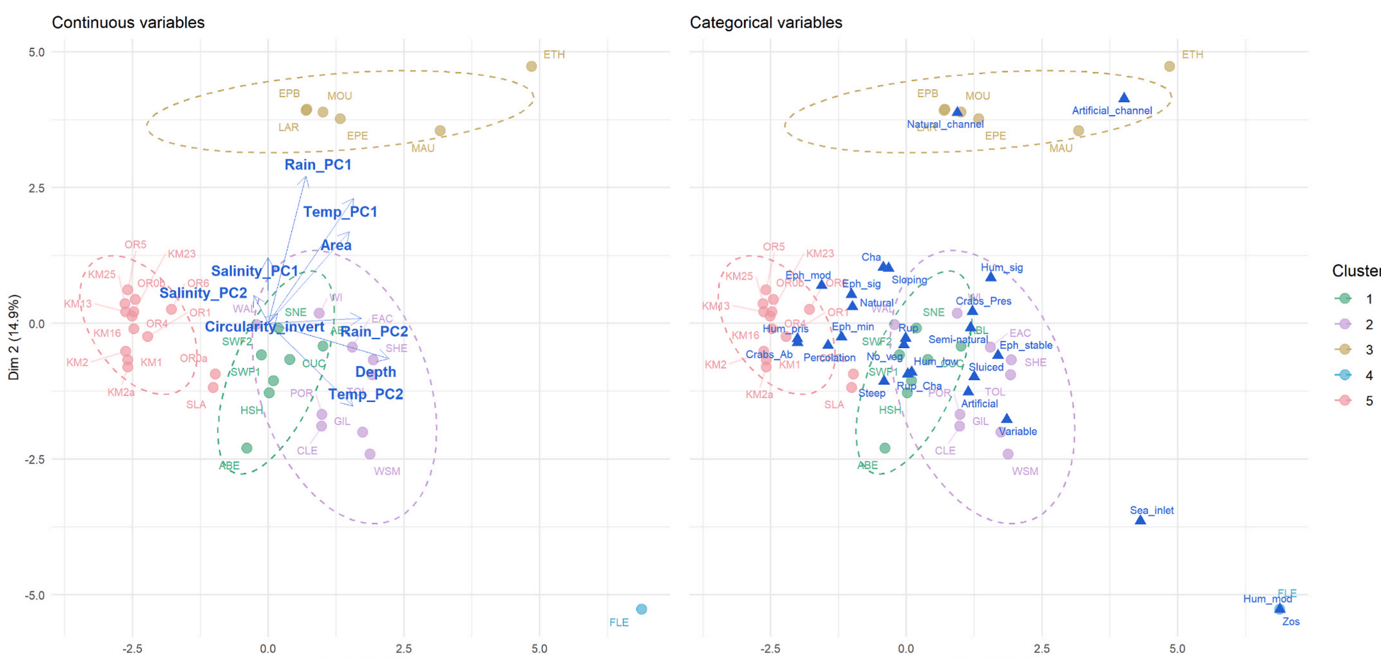

Fig. 6. Factor analysis of mixed data ordination plot displaying lagoon clusters and the distribution and strength of a) quantitative and b) categorical variables. Vector arrow directions represent the relationships among lagoons and variables, and arrow length represents the strength of the relationship. Modalities of categorical characters are displayed to visualise categorical relationships.

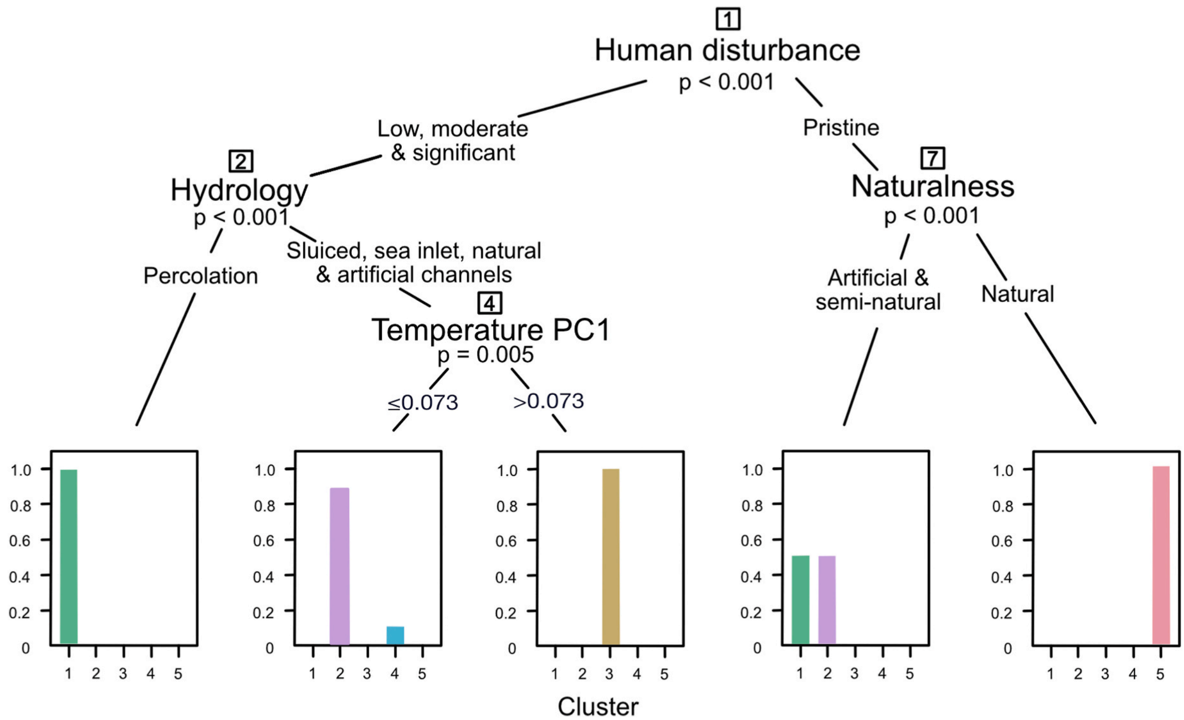

Fig. 7. Conditional inference tree of lagoon cluster allocation. Human disturbance, hydrology, temperature pc1 and naturalness were identified as significant split nodes. The terminal nodes show the predicted lagoon cluster. Temperature PC1 of 0.073 reflects a mean temperature of approximately 13 °C. *p* values represent the statistical significance of each split. Numbers represent node.

Cañedo-Argüelles et al., 2012; Gamito et al., 2012; Jones et al., 2024). Interestingly, Ligorini et al. (2023) conducted a human disturbance-based categorisation, by selecting lagoons of contrasting anthropogenic contexts before assessing their hydroecological functioning, revealing more disturbed lagoons to have high phytoplankton densities, but low diversity, low overall biomass and potentially harmful dinoflagellate booms. Our findings further highlight the importance of considering anthropogenic activity simultaneously with ecological condition, particularly using quantitative and holistic approaches to improve data-driven management (Martínez-Megías and Rico, 2022; Solé Figueras et al., 2024).

4.1.2. Hydrology

A defining feature of coastal lagoons is their salinity and its variability, which requires a level of seawater exchange with the adjacent sea that is determined by their hydrology (Barnes, 1980; Colombo, 1977). UK lagoons formed by their natural separation from the sea by a sedimentary barrier generally receive seawater via percolation through the barrier or occasionally overtopping (Barnes, 1980). The Fleet is distinct in its hydrology, primarily receiving seawater with each tide through an inlet channel at its mouth, in addition to secondary percolation across the shingle barrier (Boyden, 1970; Whittaker, 1981). In the microtidal regions of the Mediterranean, narrow natural or manmade canal systems, known locally as graus, maintain the connection of the étangs to the adjacent sea (Quignard et al., 1983; Syndicat Mixte des Etangs Littoraux, 2008). As a result of their natural ephemerality, many coastal lagoons now rely on anthropogenic mediation to maintain water levels or saline condition (Bamber et al., 1992; Beer and Joyce, 2013). Widewater lagoon in Sussex, UK, was identified as at risk of complete desiccation because of high summer temperatures and drought driving evaporation rates exceeding water input in the 1990s (Joyce et al., 2013). In 2003, as part of coastal defence works, two feeder pipelines were installed through the shingle barrier allowing the ingress of seawater with high tides (mean high water springs: 6.7 m, mean high water neaps: 5.2 m at Newhaven; National Tidal and Sea Level Facility, 2026) to restore the lagoon habitat (Joyce et al., 2013). In 2025, monitoring revealed that the pipelines had become blocked, causing water levels to diminish once again (G. Purnell, Chair of World of Widewater Committee, personal communication, 2025). Following clearance of the blockage, water levels were restored, demonstrating the importance of the sustained management of artificial infrastructure. Without human intervention, lagoons face natural eventualities including their total eradication, e.g. lagoons formed within the transient shingle at Shingle Street, Suffolk, UK, or transformation into freshwater habitats, e.g. Benacre, Suffolk and Broadwater, Norfolk, UK (Barnes, 1980; Barnes and Heath, 1980; Downie, 1996). Indeed, at the end of the last century, Barnes (1989) expressed concern regarding the managerial and conservational neglect of these important and specialist habitats. Beer and Joyce (2013) revisited this issue some decades later expressing the need for more specific management and monitoring protocols that align with the rapidly changing climate, though the implementation of this is not apparent. This categorisation revealed the most degraded lagoons to be those associated with human-managed hydrological systems, which raises questions about causality.

The benefits of anthropogenically managed lagoons might include water level regulation, salinity mediation and reductions in water residence time to prevent anoxia or the accumulation of excessive nutrients and pollutants (Bamber et al., 1993; Duck and Da Silva, 2012). Amor-a-Nogueira et al. (2023), however, found that artificial channels are associated with increased levels of lagoon eutrophication and infilling. Furthermore, while the stabilisation of salinity regimes might appear beneficial, it may encourage shifts in the biotic community as the environmental variability that provides an important niche for lagoon-specialist species is reduced (Boscolo Brusà et al., 2022). The installation of artificial channels might also facilitate colonisation by new species. For example, the arrival of the predatory green shore crab, *C. maenas*, and common eel, *Anguilla anguilla*, in Widewater lagoon, UK, following the installation of feeder pipes, likely altered community structure and function.

4.1.3. Climate

As global mean temperatures continue to increase rapidly, we are simultaneously breaking (even shattering) historical climate records (Fischer et al., 2025). Daily hot temperature and precipitation extremes are significantly more frequent and intense than those predicted in a stationary climate void of human influences (Fischer et al., 2025; IPCC, 2023). In addition to the significant effects of temperature and rainfall on the salinity regimes of coastal lagoons, the consequences for the inhabiting fauna and flora can also be significant. Rising temperatures and unpredictable seasonal variability are driving species to their thermal tolerance limits (Fernandes et al., 2023; Fusi et al., 2024), while also decreasing the capacity for dissolved oxygen saturation (Hutchings et al., 2024; Whitney, 2022). Meanwhile, extreme rainfall events have the potential to eradicate entire populations (Yurimoto et al., 2024; Zamora-López et al., 2025) and disturb vegetative growth because of margin erosion and reduced bottom light (Odebrecht et al., 2010). Given the substantial influence of temperature and rainfall on coastal lagoon environments, it is surprising that these stressors have not previously been considered in the categorisation of these generally small, shallow and subsequently dynamic environments. Here, we used a PCA to reduce the dimensionality of temperature and rainfall data to capture mean trends (PC1 values) and variability (PC2 values) across the surveyed lagoons. Mean climate trends were revealed to be discriminatively more powerful than variability, likely because the inherent variability of lagoon systems masks differences between clusters. Mean temperature across UK lagoons was 11.8 °C compared to 16.5 °C across the French étangs, and the contrast in rainfall was even more substantial, with an average monthly rainfall of 105.6 mm in the UK compared to just 0.1 mm in southern France. These records reflect the more rapid and intense climate change occurring in the Mediterranean, driving reduced winter precipitation and temperature increases of considerable magnitude (Lionello and Scarascia, 2018; Tuel and Eltahir, 2020), in addition to their distinct and distant clustering from UK coastal lagoons in the multivariate space (Fig. 6). Variability, however, particularly seasonal variability, is already an inherent and shared characteristic for these spatially heterogeneous and niche environments (Bamber, 2010).

4.1.4. Naturalness

Human intervention extends beyond the management of lagoon hydrology. A number of lagoon basins have been fabricated for the benefit of recreational consumers with several coastal lagoons exploited for swimming. Clevedon Marine Lake in the UK underwent a transformation in the 1920s when its natural sediment basin was replaced with concrete, and has since been regularly desilted and dredged to maintain inviting swimming conditions (Clevedon Marine Lake, 2025a). Other examples include Weston-Super-Mare Marine Lake and Tollesbury amenity pool, which are also periodically emptied, desilted and dredged for recreational use. While most lagoons do retain their natural basins, artificial outlet/inlet pipes are commonly installed to manage water levels and prevent flooding of the surrounding farmland, public attractions and residential areas (Barnes, 1989). Saltmarsh and wetlands provide a third line of defence to attenuate flooding during extreme weather and storm events, and offer a natural, and often superior, solution for coastal flood prevention (Fairchild et al., 2021; Inácio et al., 2023). Human interventions that prevent natural flooding are contributing to a global loss of protective wetlands (Fairchild et al., 2021), with significant consequences for habitat availability and biodiversity, in addition to reducing carbon sequestration potential, storm damage mitigation and encouraging coastal erosion (Hughes, 2004; Li et al., 2018). Projects to restore these natural and important habitats are however emerging. The Wallasea Island Wild Coast Project in the UK has successfully transformed 650 ha of farmland into a biodiverse wetland comprising saltmarsh, lagoons and mudflats (Cross, 2017). Such schemes highlight the potential for human-led projects to restore natural habitats that subsequently require minimal active management.

4.1.5. Morphology

The typically small and shallow nature of UK coastal lagoons fosters their dynamism and vulnerability to environmental fluctuations. High surface area to volume ratios encourage greater evaporative loss compared to larger, deeper lagoon systems (Meredith et al., 2022), heightening desiccation risk during hot, dry summers and hypersalinisation. By contrast, heavy precipitation events may lead to freshening and introduce pollutants through increased freshwater and agricultural runoff (Kennish and Paerl, 2010; Tweedley et al., 2019). Although size and depth interactively affect the heat and water exchange processes that drive the physical properties of coastal lagoons (Bouin et al., 2012), depth was found to be less influential than area in distinguishing lagoon typology. However, its importance as an ecological gradient was evident in the FAMD. The greater importance of area as a predictor is likely driven by the expansive French étangs and atypically large size of the Fleet compared to the other much smaller UK lagoons included in this study. In addition to increased physical stability and extended life spans, lagoons of greater size have also been revealed to host higher levels of biodiversity and proportions of lagoon specialists (Barnes, 1989). Although Bamber et al. (1992) proposed that this correlation is specific to irregularly shaped lagoons, circularity was not identified to be an important discriminator in this study. Lagoons with high aspect ratios (longer and more slender in shape) experience less turbulent mixing and provide increased shelter from the effects of wind and storm events compared to more circular morphologies (Bamber et al., 1993). While larger lagoons may host higher species diversity, the heterogeneity among smaller, dynamic lagoon systems increases regional diversity through their mosaic of varied habitats (Ligorini et al., 2023). Despite being severely overlooked in the literature, small coastal lagoons may in fact be some of the most active ecosystems globally with the potential for high carbon sequestration rates (Downing, 2010; Ligorini et al., 2023). The emergence of lagoon area as an important discriminator among coastal lagoon habitats captures the distinct ecological benefits for lagoons of all sizes at local and regional scales.

4.2. Secondary variables

Variables of less discriminatory value for lagoon classification included temperature and rainfall PC2 (see section 4.1.3.), crabs, ephemerality, depth and circularity (see section 4.1.5.), salinity PC1 and PC2, bank and vegetation. While these variables were not identified as strong predictors for lagoon typology, they are nevertheless important aspects of ecological function.

4.2.1. Crabs

The durophagous shore crab, *C. maenas*, is prominent across European coastal habitats, including lagoons, and are especially abundant in estuaries and saltmarshes (Crothers, 1968). *C. maenas* predates on a wide variety of organisms including molluscs, crustaceans and annelids, and forms part of the established ecological community of lagoon systems (Crothers, 1968; Frid and James, 1988; Howson et al., 2014; Reise, 1977), in addition to driving morphological and behavioural adaptations in prey species (Boulding, 1984; Romano et al., 2011). In the Mediterranean, the rapid expansion of the invasive, non-native, blue crab, *Callinectes sapidus*, from the western Atlantic Ocean is, however, significantly impacting local ecosystems (Gavioli et al., 2025; Vasconcelos et al., 2019). *C. sapidus* has a strong preference for crustaceans, fish and bivalves, disrupting multiple trophic levels of benthic communities and leading to declines in native species while also driving significant economic damages, including the damage of fishing gear and competing with fishermen for economically valuable species (Gavioli et al., 2025; Vasconcelos et al., 2019; Vivas et al., 2025). Due to their proximity to ports and urban environments, coastal lagoons and estuaries are among some of the most vulnerable habitats to invasion by non-native species (Garside et al., 2014). The potential for invasion also correlates with the frequency of exchange with the sea (Garside et al., 2014), which may similarly influence the presence of durophagous predators within coastal lagoon systems. Indeed, we identified crabs to be present at all lagoons receiving seawater via direct channels (i.e., sluices or feeder pipes, natural or artificial channels, sea inlets). These connections facilitate their introduction to these otherwise isolated environments, which is supported by the predominant absence of these predators at remote, percolation lagoons.

4.2.2. Ephemerality

Coastal lagoons are geologically ephemeral, persisting for only tens to hundreds of years before their eventual reclamation by the sea, sediment infilling or colonisation by plants (Barnes, 1980; Barnes and Heath, 1980). Even within their short lifetimes, coastal lagoons, particularly those that are small and shallow, can experience natural cycles of extinction and rejuvenation with evaporation–precipitation cycles (Bamber et al., 1992; Barnes, 1989). The ephemerality of these systems can drive marked variations in population size resulting in population bottlenecks (Pearson, 2003), threaten the survival of immobile lagoon dwellers and may rely on their recolonisation as these habitats become restored following recovery from complete desiccation (Bamber et al., 1992). Increasing summer temperatures as a result of anthropogenic climate change will only continue to exacerbate desiccation risk (Jones et al., 2011), in addition to an increasing extent of hypersalinity (Tweedley et al., 2019). While artificial ephemerality was not considered, it should be noted that many anthrodependent lagoons used recreationally, particularly for swimming, such as those at Tollesbury, Clevedon and Weston-Super-Mare, UK, have been regularly drained for maintenance and water renewal (Boyden and Russell, 1972; Clevedon Marine Lake, 2025b).

4.2.3. Salinity

Historically, salinity has been an important discriminator among brackish environments like coastal lagoons (UNESCO/ICES/FAO Working Group, 1958) and for defining the natural grouping of species inhabiting these environments (Bamber et al., 1992). Salinity strongly influences the biotic structure of aquatic systems, as species are naturally filtered according to their osmoregulatory capabilities (Attrill, 2002; Joyce et al., 2005; Remane and Schlieper, 1971). Barnes (1989) estimated that salinity, together with lagoon area, accounts for 21% of the variation in macrofaunal species richness in coastal lagoons. In estuarine systems, salinity variance, rather than mean salinity, has also been found to correlate with benthic diversity (Van Diggelen and Montagna, 2016). Our results suggest that salinity is less critical for lagoon classification than for determining species distributions. In naturally dynamic coastal lagoons with widely fluctuating salinities, mean trends do not adequately reflect the true heterogeneous environmental conditions. However, salinity variability, captured here by salinity PC2, did not demonstrate predictive power likely because environmental heterogeneity is a shared characteristic across lagoon systems. Changes to the oceanic water cycle are becoming increasingly apparent with ongoing climate change, with an amplification of rainfall in northern latitudes and drought in regions like the Mediterranean, driving a global "wet gets wetter, and dry get drier" pattern (Held and Soden, 2006). Salinity may become an increasingly sensitive indicator of hydrological change, becoming fresher in regions where freshwater input is high, and saltier where evaporation exceeds rainfall under warming (Durack et al., 2012). Furthermore, there is growing evidence supporting the need to consider the interactive and additive effects of multiple stressors, such as salinity and temperature, on coastal ecosystems (Krishna et al., 2025; O'Brien et al., 2023). The clusters revealed here provide a useful baseline for examining the interactive and additive effects of biotic and abiotic factors associated with lagoon typology on the functioning of these heterogeneous systems.

4.2.4. Bank slope

Coastal lagoons typically exhibit banks that either slope gradually into the lagoon or form steep vertical edges (Bamber et al., 1993). Since the specialist lagoon fauna and flora are almost entirely sublittoral, they do not benefit from shallow sloping littoral zones, which can instead encourage the encroachment of surrounding marsh plants, such as *Phragmites australis,* which has a low Ellenberg salinity indicator value of 2 and a salinity threshold of around 30 (Bamber et al., 1993; Packer et al., 2017). Although Joyce et al. (2005) revealed a weak but positive correlation between slope gradient and the floral composition of lagoons, bank was not identified as an important predictor of lagoon type in this categorisation.

4.2.5. Vegetation

Two distinct lagoon-specialist flora, the green filamentous alga, *C. linum*, and the tasselweed, *Ruppia maritima and R. cirrhosa*, were conspicuous at select sites during the spring and summer months. The macrophytes were most often found in isolation, co-occurring at only a handful of lagoons. Of particular interest was the abundance of small molluscs, including the lagoon specialists *C. glaucum* and *Ecrobia ventrosa*, found entangled within the floating mats of *C. linum* (Fig. S2). This climbing behaviour is considered an advantageous adaption enabling organisms to escape not only predators but also the high quantities of decaying detritus that deplete oxygen levels and drive anoxic conditions at the substrate–water interface (Barnes, 1994b; Sheader et al., 1997). *C. linum* also stimulates the production of oxygen in its surface layers where light is abundant, however, the lower layers of the algal mats can become anoxic and may significantly alter denitrification processes (Krause-Jensen et al., 1999). *Ruppia* spp. have been reported to increase macrobenthic biodiversity and improve substrate quality (Munari et al., 2023), and indeed rare species of lagoon fauna, such as the starlet sea anemone *Nematostella vectensis*, have been observed attached to its grass-like morphology (Sheader et al., 1997). At the Fleet, the common eelgrass, *Z. marina,* was abundant and also provides ecological benefits, including a refuge for fish nurseries, substrate stabilisation and mitigation of eutrophication (Kraufvelin et al., 2025). While vegetation was a negative predictor of lagoon clustering, the highest proportion of unvegetated habitats occurred in the anthropogenically managed and degraded Cluster 2 lagoons, suggesting potential impacts on specialist fauna and communities. Drifting plant material may also aid the colonisation of these isolated environments through the transgressions of seawater or via attachment to the feet of aquatic birds (Bamber et al., 1993).

4.3. Conclusions

This holistic data-driven categorisation of coastal lagoon systems highlights the importance of considering the combined effects of multiple stressors, including anthropogenic pressures, in habitat assessments. Our findings challenge conventional geomorphological approaches and emphasise the potential for human-driven pressures to restructure lagoon ecosystems, overriding natural environmental gradients, such as salinity, in these intrinsically stressed and heterogeneous habitats. The survey of coastal lagoons has historically been sporadic and fragmented, resulting in their inequitable management. The decisive characteristics revealed here suggest that an initial classification of coastal lagoons could be undertaken through the utilisation of tools such as Google Earth Pro to assess proximity to urban infrastructure, existing literature and reports to evaluate salinity regimes and management levels, in addition to publicly available meteorological data, especially in relation to direct human impact. This systematic approach could facilitate the prioritisation of coastal lagoons for appraisal and monitoring, supporting conservation assessment, restoration planning and evidence-based policy or management. However, we acknowledge that the classification of subjective variables, including human disturbance and naturalness, will in many cases require on-site validation and the approach described here is complementary and facilitative to, rather than a replacement for, biological surveys. A limitation of this study is the inclusion of only sedimentary barrier lagoon systems, omitting, for example, some of the larger, rock-basin lagoons found in Scotland (Angus, 2017; NatureScot, 2025). This methodology should be expanded in future to include a broader range of lagoon types with greater spatial reach. Furthermore, this categorisation aids the examination of the biological and ecological consequences of cluster membership through in-depth assessments of biodiversity, water quality and species-level responses, across representative lagoons from each cluster. As environmentally responsive habitats and valuable indicators of climate change, the surveillance of these vulnerable ecosystems is essential as environmental conditions continue to destabilise under accelerating climate change.

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CRediT authorship contribution statement

Bethany F. King: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Lloyd S. Peck:** Conceptualization, Supervision, Writing – review & editing. **Elizabeth M. Harper:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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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.2026.109980.

Data availability

Data is available here: https://github.com/bethanyfrancesking/LagoonCategorisation

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