Estuarine, Coastal and Shelf Science 303 (2024) 108811

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Overview and evolutionary path of Estonian coastal lagoons

Ülo Suursaar[a,b,*], Kaire Torn[a], Helle Mäemets[c], Alar Rosentau[d]

[a] University of Tartu, Estonian Marine Institute, Tallinn, Estonia
[b] Tallinn University, School of Natural Sciences and Health, Institute of Ecology, Estonia
[c] Estonian University of Life Sciences, Institute of Agricultural and Environmental Sciences, Tartu, Estonia
[d] University of Tartu, Institute of Ecology and Earth Sciences, Tartu, Estonia

ARTICLE INFO

Keywords:
Coastal change
Postglacial uplift
Sea level
Bottom vegetation
Succession
Holocene
Baltic sea

ABSTRACT

Coastal lagoons are highly productive and biologically diverse landscape features that sustain a range of valuable natural services to societies. Acting as an interface between land and sea, they evolve naturally, but are also vulnerable to various forms of human activity. Based on old cartographic material, LiDAR elevation data, Holocene sea level histories, and shoreline modelling, we study the development of coastal lagoons on the post-glacially uplifting, tideless coast of the brackish water Baltic Sea. Ecological succession of habitats along the path from bays to semi-enclosed lagoons, coastal lakes or bogs is discussed utilizing community structure analysis of habitat building bottom vegetation. There are about 600 lagoons in Estonia, but they are typically small (bigger ones up to 6 km^2) and mostly <1 m deep. Due to ongoing postglacial uplift (1.5–3.4 mm/a), lagoons are just a relatively short (50–500-years long) transitional phase in a long (up to ~10 000-years) succession. Locating at an altitude of up to 20–30 m, some older, more resilient palaeolagoons can be nowadays distinguished as lakes or bogs, while smaller ones have blended into the surrounding landscape. The contemporary lagoons are ephemeral too, because the emerging terrain has already been flattened by erosion and sedimentation. After separation from the sea, the brackish water habitat is gradually replaced with freshwater habitat and both biodiversity and plants coverage usually increases. As organic deposits build up, low-growth shores are replaced with high-growth vegetation; reedbeds expand. Detached from their marine past, communities typical for lakes, fens, bogs or forests are finally formed. As a result of eutrophication, ongoing climate change and sea level rise, the balance between emergence of new lagoons and their disappearance due to distancing and swamping has shifted over the past 100 years.

1. Introduction

Coastal lagoons are among the most important, vital, and yet vulnerable ecosystems in the coastal zone. Over decades, many definitions of coastal lagoons have been proposed (e.g., Kjerfve, 1994; Tagliapietra et al., 2009). Combining some of these, the coastal lagoons can be called as shallow lake-like water bodies that are nearly isolated from an adjacent sea by a sedimentary barrier, but which nevertheless receive an influx of water from that sea. Because of their transitional nature between land and sea, they are vulnerable to various forms of human activity (Elliott et al., 2007; Duck and da Silva, 2012). Being among the most productive ecosystems in the world and sustaining important environmental services, they are threatened by eutrophication, pollution, urbanization, and various effects of the climate change (Borja et al., 2010; Carrasco et al., 2016; Inácio et al., 2018).

About 13% of the world's coastline is faced by sedimentary barriers, separating some kind of lagoons, bar-built estuaries or coastal lakes behind them (Barnes, 2001). They vary considerably in size, morphology and genesis, which is also reflected by their confusingly mixed-up naming in different countries and languages (McLusky and Elliott, 2004; Tagliapietra et al., 2009). For instance, besides "lagoon", equivalent terms to both freshwater (lake) and marine water bodies (sea, estuary, bay, cove, fjord, sound, harbour etc.) are used. While an important unifying aspect seems to be "restricted" water exchange with the ocean, it may still vary considerably – from being nearly constant (impeded filtration through the barrier or flow through permanent inlets or tidal channels), temporary (e.g. fluvial breaches occurring episodically due to high water on rivers entering the lagoon; sea water breaches during storm surges or high tides), or practically absent (in basins recently separated from the sea, but still remembered as a former part of

* Corresponding author. University of Tartu, Estonian Marine Institute, Tallinn, Estonia.
E-mail address: ulo.suursaar@ut.ee (Ü. Suursaar).

https://doi.org/10.1016/j.ecss.2024.108811
Received 20 June 2023; Received in revised form 25 April 2024; Accepted 23 May 2024
Available online 25 May 2024

the sea). Consequently, coastal lagoons as habitats are mostly young and vulnerable, where ecological conditions may change both in natural and anthropogenically modified succession, but also through more rapid event-driven shifts (Duck and da Silva, 2012; Soria et al., 2022; Davydov and Karaliūnas, 2022).

In Europe, coastal lagoons are declared as habitats (type 1150*) of high natural value (denoted by asterisk, *) in the EU-s nomenclature for the Habitats Directive (European Communities, 1992; European Commission, 2013). Although it is a pan-European agreed habitat type, the objects classified under this code may vary considerably country-wise and slightly adjusted guidance documents have been used in different countries (Paal, 2007; Haapamäki, 2021; Corbau et al., 2022). Lagoons can be genetically and ecologically rather diverse even within one sea. A good example is the brackish water Baltic Sea, where the focus area of this study, the Estonian coast (Fig. 1), is located. The practically tideless Baltic Sea occupies the margin of the Fennsocandian uplift area (Vestøl et al., 2019), and considerable regional differences both in the uplift rates and in sedimentary conditions give rise to completely different-looking coastal lagoons. In the skerry northern part with high (4–9 mm/a) uplift rates, the coastal lagoons are small, and quite ephemeral (Tolvanen et al., 2004; Salomonson et al., 2006). In contrast, in the southern Baltic Sea, on the coasts of Denmark, Germany, Poland, Lithuania and Russia's Kaliningrad Oblast, the global sea level rise is already balancing out or exceeding the postglacial uplift (Hünicke et al., 2015); abundance of sandy sediment has enabled the formation of relatively large coastal lagoons and estuaries behind long spits and duned coastal barriers (Andrulewicz, 1997; Inácio et al., 2018; Kaminskas et al., 2019). About in the middle, where also Estonia is located, the relative sea level lowering (1–4 mm/a) has dominated at least over the past 7000 years (7 ka = 7 kyr) (Harff et al., 2020; Suursaar et al., 2022), but the global sea level rise (1.7 mm/a in 20th century but 3–4 mm/a in the last decades: IPCC, 2021) is catching it up. Availability of movable sediment is mostly scarce or mosaic due to lack of large river inflows and lithological constraints (Raukas, 2000; Orviku et al., 2003), and hence, some unique types of coastal lagoons have evolved in this brackish water and functionally tideless marine area.

In the era of fast environmental change – accelerating sea level, increasing storminess, rising air and water temperatures, and anthropogenic stress on the coastal zone – also formation prerequisites of coastal lagoons, as well as their further development pathways, are about to change (Carrasco et al., 2016; Weisse et al., 2021). Despite their exceptional ecological and conservational value, there are only a few overviews of coastal lagoons in the Baltic Sea or in its parts, yet (Munsterhjelm, 1997; Salomonson et al., 2006; Kose, 2012). Moreover, studies not only on their current status fixation, but also their development as dynamic and transitional water bodies, are needed. The aims of this study are: (1) to give an overview of Estonia's coastal lagoons with the most recent updates in their distribution and ecology, and (2) focusing on shifts in morphology and habitat forming benthic species, to analyse evolutionary path of lagoons from their formation to the probable future.

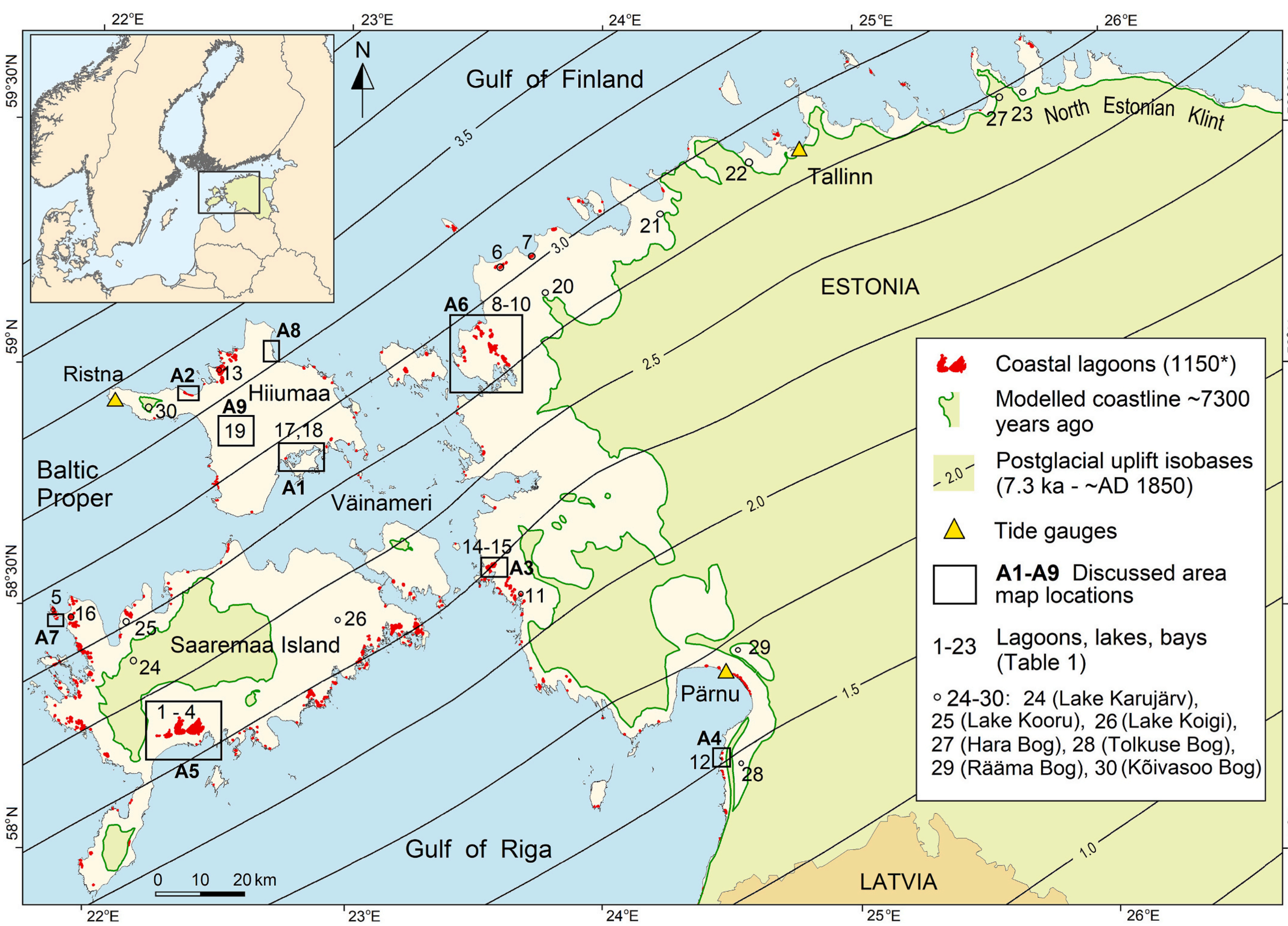

Fig. 1. Distribution of coastal lagoons (1150*) on the Estonian coast of the Baltic Sea. The background shows isobases of geocentric uplift (mm/a) according to the NKG2016LU_lev model (Vestøl et al., 2019). Locations of tide gauges, map fragaments (A1–A9), specific (1–23; Table 1) and other (24–30) mentioned lagoons, lakes, bays or bogs.

2. Study area

Estonia is a small country (45 227 km^2) with long (~3800 km) shoreline on the northeastern coast of the Baltic Sea (Fig. 1). Its coastal zone is strongly indented by peninsulas, islands and bays, and the postglacially uplifting coastal terrain is gently sloping and relatively flat. The bedrock, composed mostly of Ordovician and Silurian limestones and Devonian sandstone, is covered with Quaternary deposits from the last (Weichselian) glacial period. The Holocene (last 11.7 ka) deposits are mostly represented by marine sands, which have been subjected to erosion and transport by waves and wind (Raukas, 2000).

Climatically, Estonia lies in the westerlies zone of temperate latitudes with pronounced seasonality, where hemiboreal forests, meadows and wetlands dominate (Kont et al., 2007). Water level variations are predominantly meteorologically forced. At Estonian tide gauges, about 95% of the sea level data fall between −50 and + 60 cm in relation to the long-term average. Still, the instrumental era variability range is up to 3−4 m. High sea level events are mainly associated with North European cyclonic (winter) storms, whereas persistent east winds lower the sea level (Jaagus and Suursaar, 2013). Due to the indented coastline and low nearshore relief gradient, high waves normally do not reach the shoreline. Swash height during storms may reach 3 m on the coasts that are exposed to the Baltic Proper (Soomere et al., 2008; Suursaar et al., 2008). Within the Gulf of Riga (Fig. 1) and in the bays, low-energy coasts can be found (Eelsalu et al., 2022). Salinity mostly varies between 1 (in shallow bays with riverine inflow) and 7. Annual mean precipitation (550−800 mm) slightly exceeds evaporation and therefore sustains coastal and inland wetlands. Freshwater input is the largest in spring after snow melt, and after heavy rains. Being lastly deglaciated between ca. 14.7 and 12.7 ka (e.g., Kalm, 2006), the evolutionary history of Estonian landscapes has been relatively short.

3. Material and methods

3.1. Field work and data analysis

Because of considerable conservational value, coastal lagoons, among other protected habitats, are subjects of detailed inventory and reporting, which is carried out (or supervised) by ministries of environment of the EU member states (Paal, 2007; Torn et al., 2017). However, this reporting obligation somewhat contradicts with the fast natural evolvement of coastal lagoons in Estonia, and from time to time, some reassessments of the lagoons list in databases, such as the EELIS (Estonian Nature Information System), are needed. A targeted study including an extensive field sampling of coastal lagoons was performed in 2018–2022. During the study, 90 potential lagoons were visited, 75 of which were subsequently classified as lagoons. Some, discarded objects, were either too well connected to the open sea or appeared to be damp areas without a permanent water table. In the lagoons, data from three transects were collected. Smaller waterbodies were studied in their entirety. For each lagoon, maximum depth, sediment type, salinity, and species list of macrovegetation (incl. submerged, emerged and floating-leaved plants) were registered. Widely considered as habitat builders, this group of vegetation holds a specific importance in aquatic ecology. Sampling of vegetation was performed by dredging with a hook from a boat or, due to shallowness, by hand while walking (Torn, 2020).

Additional data from databases of the Centre of Limnology (Estonian University of Life Sciences) and Estonian Marine Institute (University of Tartu) were used to evaluate evolvement of vegetation communities. Hence, data of 18 lagoons (from 2010–2018) was added to the statistical analysis (93 lagoons in total). Also, data from 2010–2019 on 23 lakes (locating less than 20 km inland) and from 32 sheltered soft-bottom coastal bays (2019–2022) were included in the analysis. The depth of the bays was mostly below 1.5 m (3 m as a maximum). Sampling in the bays was performed by SCUBA diving from a boat or directly from the shore. For comparability, only soft bottom vegetation of the bays was included.

Because of relatively small salinity differences, a number of the same macrovegetation species can be found both in the coastal sea and in lakes in Estonia (Mäemets et al., 2016; Torn et al., 2019). Therefore, a community-wide statistical analysis was performed. Analysis of similarities (ANOSIM; one-way permutation test using the Bray-Curtis index) and multidimensional scaling (nMDS) for assessing dissimilarities between the data sets was performed using the PRIMER software package (Clarke and Gorley, 2015). SIMPER functions were used to determine species that contribute the most to the dissimilarity. A matrix of 148 individual waterbodies versus presence (or absence) of 98 registered aquatic vegetation taxa served as input.

A total number and basic morphometric data of coastal lagoons and lakes in Estonia was downloaded from the EELIS database (https://keskkonnaportaal.ee), or obtained from institutional databases, reference books and collections of papers (Mäemets, 1977; Kose, 2012; Laarmaa et al., 2019).

3.2. Land uplift and relative sea level variations

Genesis and development of coastal lagoons was studied using both relative sea level modelling over the past 10 ka and tide-gauge based sea level data from the last hundred years. The early stages of the development history of the Baltic Sea included (from ca. 15 to 7 ka) considerable water level variations due combination of global eustacy, postglacial rebound, and alteration between marine and dammed up limnic conditions (Baltic Ice Lake, Ancylus Lake; e.g.: Raukas, 2000; Harff et al., 2020; Rosentau et al., 2021). In Estonia, however, the relative sea level lowering has been nearly linear over the period starting from ca. 7 ka ago (e.g., Grudzinska et al., 2013; Vassiljev et al., 2015; Suursaar et al., 2022) and ending with the industrial revolution era in about 1850. For that period, modelled geocentric uplift rates (e.g. from the NKG2016LU_lev model; Vestøl et al., 2019, Fig. 1) can be used for calculating the age.

An updated analysis of relative sea level variations and high sea level occurrence statistics was based on data from Tallinn, Pärnu and Ristna tide gauges (Fig. 1). Linear trends, seasonal variations and empirical return period graphs for annual maximum sea levels were calculated (Fig. 2). In Tallinn, the series were discontinued due to port construction in 1996. Therefore, with some gaps, the mean sea level series span from 1842 to 1995, and from 1899 to 1995 for maxima at Tallinn. The series span from 1924 to 2022 at Pärnu, and from 1950 to 2022 at Ristna. Here, the sea level data are presented in the BK77 system (relative to the Kronstadt zero), because this zero is currently close to the long-term mean sea levels around the Estonian coastal sea (Suursaar and Kall, 2018). Since 2018, Estonia changed its height system to the European (EH2000) system. Compared to the BK77, this zero is higher by 24 cm at Tallinn, 19 cm at Pärnu, and 26 cm at Ristna.

3.3. Changes in morphology of coastal lagoons

Morphological study of selected coastal lagoons, potential lagoons and lakes (previous lagoons) was performed using GIS analysis of LiDAR based elevation data, old cartographic material, and palaeocoastline modelling. Digitized maps have recently been made available for public on the website of the Estonian Land Board (ELB), where they are overlain in the same coordinate system in the web-GIS service (ELB, 2024a). The maps vary in scale and quality and not all are useable for every location. Among them, the oldest ones are the Mellin's Atlas of Livonia (1796, not very accurate) and Russian topographic map in 1:42 000 scale (different sheets from 1894–1913). Not covering the entire Estonia, there are also fragments of charts from 1839, 1866 and 1884.

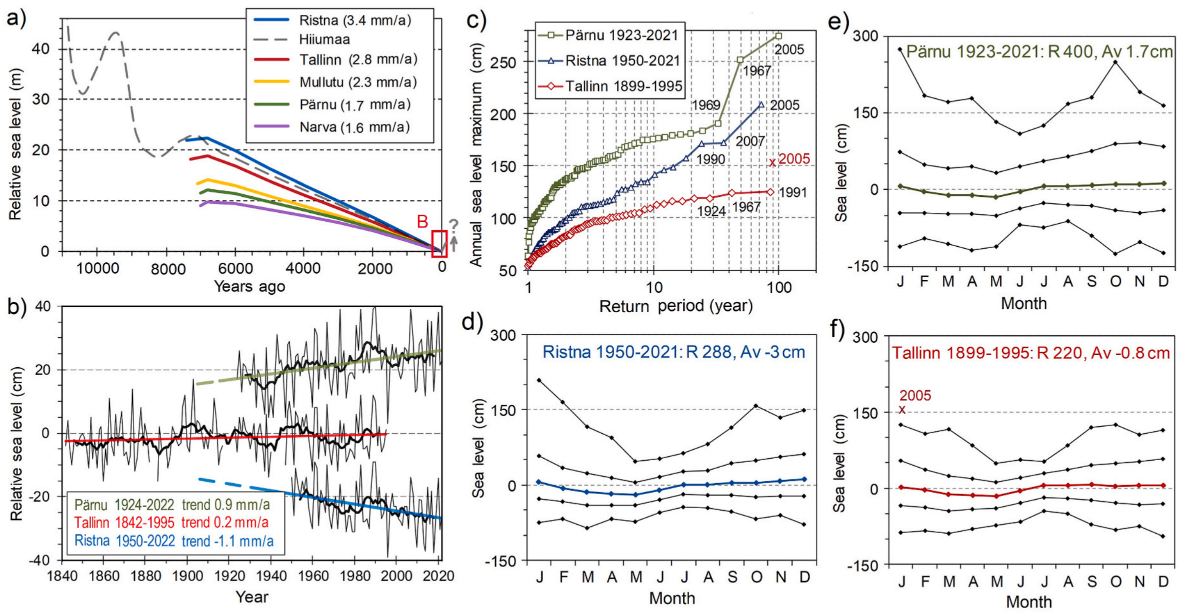

Fig. 2. Variations in relative sea level at selected locations in Estonia in two different time scales. **a**): Sea level curves over the past 11 ka with corresponding modelled uplift values indicated in the legend (see also isobases on Fig. 1); Hiiumaa – indicative water level curve for central Hiiumaa Island generalized from Raukas (2000), Rosentau et al. (2020) and Suursaar et al. (2022). **b**): Recent sea level variations; data from different tide gauges shifted relative to each other by 20 cm. **c**) Empirical return period graphs for annual maxima; years of three extreme events are marked on each graph. (**d**–**f**): Seasonal variations in monthly sea level statistics. Lines from top: absolute maximum, average maximum, average, average minimum, absolute minimum. Sea level variation range (R) and long-term averages (Av) in BK77 system. X – maximum sea level estimate at Tallinn during the 2005 January storm (on **c** and **f**).

Surface areas of lagoons were measured using an area tool by encircling the shorelines on the most recent (2004–2020 survey) and the oldest map sources (with reasonable quality). Areal decrease rates (AD; % per year) and expected lifetimes (EL; years) relative to present time (2022) were calculated. The EL is simply an extrapolation of the current AD rate without considering potential changes in water balance or terrain properties in the future:

$$AD = (100(a1-a2))/(a1(t2-t1));\ EL = 100/AD - (2022-t1),$$

where: a1 – initial measured surface area, a2 – latest surface area, t1 – initial survey year, t2 – latest survey year. For recent coastal developments, also aerial photographs can be used (e.g., Tõnisson et al., 2008), which can be found in another dedicated web-service of the ELB.

LiDAR based digital terrain models (DTMs) were constructed using the GIS software to identify beach ridges, coastal barriers and imprints of past sediment fluxes (e.g., Habicht et al., 2017; Suursaar et al., 2022). LiDAR surveys of land surface altitudes over the entire Estonian territory have been carried out by the ELB since 2008 and the data can be publicly accessed (ELB, 2024b). The measurements used an aero-laser scanner mark Riegl VQ-1560i. The data resolution has varied in time, but currently it averages 2.1 points/m^2. LiDAR-based DTMs with resolution of 1 × 1 m were used to assess historic coastline changes. The palaeogeographic reconstructions for the time slices at year 1400 CE (Kuressaare area in Saaremaa; Fig. 1, A1) and at 1600 CE (Noarootsi area: Fig. 1, A6) were based on the GIS approach, whereby the palaeo-sea-level surfaces were subtracted from the DTM (Rosentau et al., 2011). The interpolated water-level surfaces for the Baltic Sea were based on geocentric uplift rates data (Vestøl et al., 2019, Fig. 1). Reconstruction of the Litorina Sea highest shoreline (Fig. 1) was based on subtraction of Litorina Sea water-level surface (Saarse et al., 2003) from the LiDAR based DTM with spatial resolution 100 × 100 m. In case of lagoons that have turned into mires (fens, bogs, pine bogs), the Estonian peat database and (1 : 10 000) soil map layer of the ELB website (ELB, 2024c) were used to outline the initial lagoon configurations.

4. Results

4.1. An overview and distribution of coastal lagoons as habitat type 1150*

It is difficult to give an unambiguous detailed overview of Estonia's coastal lagoons, partly because of their changeable nature and frequent needs for revisions. Also, the natural habitat handbooks leave a considerable room for different interpretations. It is stated that lagoons in Estonia (Paal, 2007; Kose, 2012) are "shallow coastal lakes and lagoons that have separated from the sea relatively recently or still in temporary contact with it, that have numerous chlorides and sulphates in their water. The bottom is covered by a thick layer of mud and charales (*Chara* spp.)". Not all lagoon-like coastal areas are 1150* habitat listees in Estonia. Due to land uplifting or sediment barrier formation, there are some marine areas which are potential coastal lagoons. However, some of the 1150* listees, which have been turned into lake or disappeared, should be excluded from the list. At the same time, the names of those objects do not necessarily reflect the natural changes. Usually, the historic names (including Estonian affixes referring to "sea", "bay" etc.) are retained even if they are not such geographical objects anymore. For instance, "sea" can actually be a lake or a marsh. Terms like "lagoon" or "coastal lagoon" are rarely used in the names of the water bodies of Estonia. Instead, local and dialect words like *meri* (sea), *laht* (bay), *järv* (lake), *abajas* (cove), *tarn* (sedge), *lõugas, viik, sonn, silm, auk,* and some others are used.

The majority of lagoons are located in western Estonia and on the islands (Fig. 1). Based on current study, there were in total 579 No. 1150* objects in the list (as of in May 2023). Their total area was 42 km^2. Lagoons in Estonia are relatively small and very shallow. The largest 10% of the lagoons had a combined area of 35 km^2. The number of >0.01 km^2 lagoons was 269, which means that there still was a large number of very small objects, which minimal size was not even unambiguously set. The mean depth of lagoons is mostly 0.5–1 m and even the larger lagoons/lakes are rarely up to 2–3 m deep (Table 1). This means that open water surfaces areas of the lagoons have considerably

Table 1
Basic data and areal decrease rates of selected lagoons (No. 1–16), some relatively isolated bays (17–18) and palaeolagoons/lakes (19–23) discussed in this study (data from: Kose, 2012; EELIS database; this study). No – number on Fig. 1; Area – water surface area (km^2); MD – maximum depth (m); D – minimum distance from the sea (km); E – water surface elevation (m a.m.s.l.); Age – estimated age from separation from the sea (years); AD – areal decrease rate (% per year); ADB – AD calculation base (years); EL – expected lifetime (after 2022). AD estimated from maps (past ~100 years) or modelled palaeocoastlines (1b, 3b, 9b).

No	Name	Lat. (N)	Lon. (E)	Area	MD	D	E	Age	AD	ADB	EL
1	Suurlaht	58°15′20″	22°24′44″	5.39	2.1	2.0	0.5	400	0.13	100	630
1b	-’’-								0.08	600	585
2	Mullutu Bay	58°15′24″	22°21′37″	4.11	1.7	2.1	0.5	400	0.12	600	213
3	Linnulaht	58°14′57″	22°26′32″	0.75	2.0	0.8	0.6	500	0.43	100	115
3b	-’’-								0.10	600	360
4	Vägara Bay	58°14′23″	22°18′59″	1.17	1.1	2.2	0.5	400	0.15	600	47
5	Laialepa Bay	58°29′6″	21°51′26″	0.64	1.0	0.1	1.5	500	0.06	100	1501
6	Pikane Lake	59°12′19″	23°35′45″	0.20	1.0	1.3	1.5	500	0.15	100	531
7	Lepaauk	59°13′44″	23°43′6″	0.19	2.3	0.2	0.5	150	0.24	100	306
8	Vööla Sea	59°4′25″	23°30′54″	0.68	1.0	0.4	0.0	50	0.57	100	60
9	Sutlepa Sea	59°2′25″	23°34′1″	1.86	1.5	2.7	0.5	200	0.52	100	78
9b	-’’-								0.19	400	106
10	Saaremõisa Bay	59°1′8″	23°36′42″	0.42	1.0	0.8	0.5	200	0.21	400	56
11	Käomardi Bay	58°32′4″	23°40′58″	0.11	0.7	0.3	0.5	200	0.35	100	169
12	Võiste	58°12′20″	24°28′11″	0.09	0.7	0.2	0.0	20	0.84	70	32
13	Kirikulaht	58°59′8″	22°29′12″	1.14	2.0	0.1	0.0	0	0.16	100	510
14	Mõisalaht	58°34′21″	23°34′12″	0.72	1.9	0.0	0.0	0	0.41	80	125
15	Kasse Bay	58°35′45″	23°34′32″	0.69	0.5	0.2	0.5	100	0.26	80	265
16	Sarapiku Lake	58°28′34″	21°55′35″	0.39	2.0	0.9	2.5	1000	0.24	100	306
17	Käina Bay	58°48′29″	22°47′17″	7.80	0.7	0.3	0.0	20	0.31	90	216
18	Vaemla Bay	58°49′32″	22°51′24″	2.65	0.4	0.0	0.0	0	0.39	90	149
19	Tihu Lake	58°51′9″	22°33′25″	0.49	0.2	5.6	14.0	4800	0.02	4800	250
20	Nõva Veskijärv	59°10′15″	23°45′36″	1.85	3.0	6.1	16.5	5400	0.01	5400	4600
21	Klooga Lake	59°18′19″	24°14′8″	1.31	3.6	2.6	11.8	4100	0.02	4100	450
22	Harku Lake	59°25′0″	24°37′6″	1.63	2.5	2.0	2.0	1200	0.01	1200	~10 ka
23	Lohja Lake	59°32′55″	25°41′30″	0.56	3.7	1.3	6.0	2500	0.002	2500	~40 ka

varied in the past, and they also fluctuate seasonally and occasionally. The largest lagoons are: Suurlaht (5.31 km^2), Mullutu Bay (4.13 km^2), and Undu Bay (2.27 km^2). In addition, there are some lagoon-like aquatic areas like Käina Bay (7.8 km^2) and Vaemla Bay (2.65 km^2; Table 1), which are not yet included in the 1150* list, but may become lagoons in the future. Table 1 includes a list of selected lagoons which evolution is exemplified in the following chapters. In addition to the largest ones, some smaller lagoons, disputable objects and also some palaeolagoons were included.

The main factors that form ecological conditions in the Estonian lagoons are morphometry (size, depth, water volume), bottom substrate, intensity of water exchange with the sea, and age. The other properties (salinity, thickness and organic content of mud layer, hydrochemistry etc.) largely depend on these (e.g., Kose, 2012). Water exchange can be vastly different among coastal lagoons and lakes, ranging from about 1 to 100 turnovers per year (Loopmann, 1984). It is a function of morphometry (mean depth or water volume), exchange with open sea, and freshwater input. Some lagoons have inputs via springs, rivers, ditches or bogs, especially in spring or after heavy rains. Others are affected by inundation due to storm surges from the sea. Such surges may occasionally reach 2 m above the long-term mean sea level in some westerly exposed shallow bays of West Estonia, but up to ca 1.5 m along the straight North Estonian coastal section (Fig. 2).

Generally, 1 m sea level rise can be expected roughly once a year in Western Estonia, where most of the coastal lagoons are located. On the other hand, in dry and hot summers, the area of shallow lagoons may markedly diminish due to strong evaporation and missing contact with the sea, as the sea level occasionally lowers 0.5–1 m below the long-term mean (Fig. 2). Concurrently, evaporation may rise salinity higher than it is in the neighbouring sea. Salinity is mostly 2–7 in lagoons which are well connected to the sea, around 1–2 in more recently separated ones, and down to freshwater in older lagoons. Water in lakes is fresh in Estonia (salinity <0.2). Once separated from the sea, lakes in Western Estonia and on islands are usually considered halotrophic in Estonian typology (Ott and Kõiv, 1999) even if the water salinity is negligible. Hydrochemical properties (hardness, colour, concentration of nutrients and organic substances) partly depend on the above mentioned factors, but may still individually vary from one lagoon to another due to local conditions without any universal explanation.

4.2. *Genesis of coastal lagoons; land uplift*

In the Baltic Sea as a whole, the two main processes for lagoon development are the postglacial uplift (dominating in the northern part of the sea) and formation of sediment barriers (mostly in the southern Baltic Sea). In Estonia, the two processes combine (e.g., Kessel, 1968).

Coastal lagoons have formed both in transgressive and regressive phases of the Baltic Sea development. A transgression took place when the Ancylus Lake was dammed up 10.7–10.2 ka ago, and again, when Litorina Sea level eustatically rose 8.5–7.3 ka ago (Fig. 2a). During transgressions, terrain depressions were inundated, and new bays and lagoons were formed. In sediment rich conditions, sediment barrier evolvement helped to define the borders of lagoons. Such palaeolagoons were relatively large and resilient (e.g., Habicht et al., 2017; Nirgi et al., 2020). Their surface areas started to diminish after the transgression turned into regression, as excessive water drained out to the sea through channels, and the remnant lagoons or lakes started to paludify. In turn, lagoons were also formed during regressive phases, as underwater depressions or embayments in the coastline gradually became isolated from the sea. A monotonic regression has occurred since 7.3 ka BP (Fig. 2a). Hence, lagoons-lakes with unidirectional geomorphic succession can only be found on up to 20 m elevation on Hiiumaa Island, 15 m on West Estonian coastal plain and on Saaremaa, and 10 m in the Pärnu area (see the green line in Fig. 1). Running along the northern coast of Estonia, the nearly 50 m high klint (clint) leaves a little room for coastal lagoons.

Uplift during the “cartographic era” (~150 years) has been up to 0.5 m in Estonia and even together with siltation and vegetation growth, the up to 1 m terrain rise is only visible on low-lying coasts. On the relatively sheltered coasts of the Väinameri Sea and the Gulf of Riga, a large number of such primarily uplift-driven lagoons can be found (Figs. 3, 4). The 19.3 km^2 Kassari Island (Fig. 4ab; essentially a peninsula) was

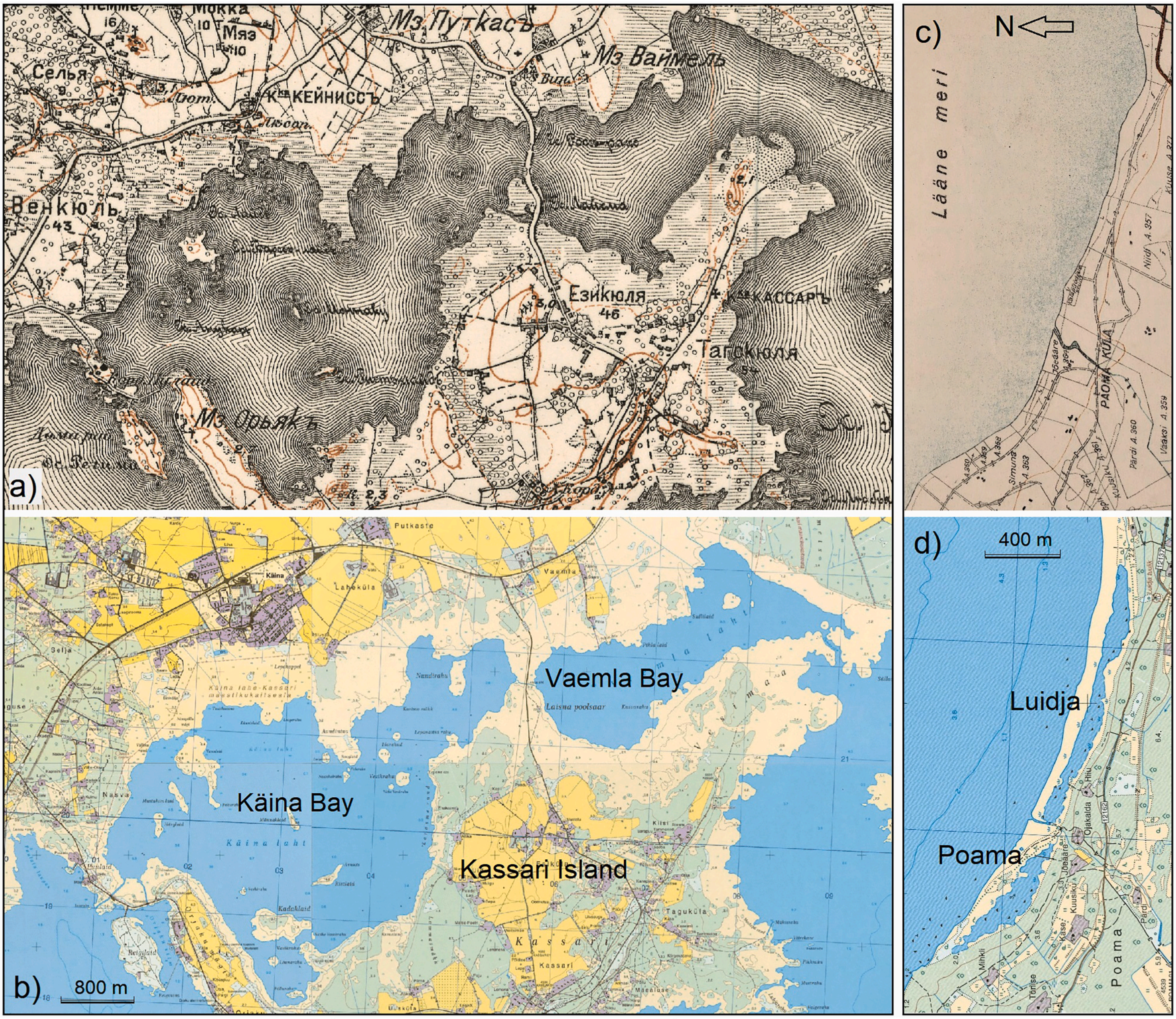

Fig. 3. Map fragments from 1915 (**a**) and 2004 (**b**) covering identical area in the southern Hiiumaa (A1; Fig. 1). The area of the Käina Bay has diminished by 28% and the Vaemla Bay by 35%. Map fragments from 1937 (**c**) and 2004 (**d**) for the Poama – Luidja coast (northern Hiiumaa) (Fig. 1; A2). The Poama Lake exists since the 1970s−1980s, the barrier separating the Luidja Lake grew (from west to east) through 1980s−1990s and by rejoining the mainland, separated the lagoon by 2004.

connected with Hiiumaa mainland firstly by fords and then by causeways (since the 1880s−1890s). The former strait has been replaced by two waterbodies with limited waterflow, the bays of Käina (7.7 km^2) and Vaemla (2.6 km^2).

Because more than 100−150 year-old maps are not reliable and detailed enough, coastline modelling and LiDAR relief analysis was used to identify palaeocoastlines (Fig. 1) and palaeolagoons (Fig. 5). Most of the lakes and some of the mires (bogs) below 20−30 m can be considered as palaeolagoons. For instance, on Saaremaa Island, the lakes of Mullutu and Suurlaht (Fig. 5a; Table 1) gradually isolated from the sea 200−500 years ago, and are still considered as 1150* lagoons. They are randomly (once in a year or two) inundated by storm surges (Fig. 2). Today's Noarootsi Peninsula was an island a few hundred years ago (Fig. 5b), which is also corroborated by old (yet not very detailed) maps, such as Mellin's Atlas from 1782 to 1810. The former strait has turned into a string of gradually shrinking lagoons and wetlands (Fig. 5b; Table 1).

4.3. Lagoons behind sediment barriers

The sediment barrier formation as the process of secondary importance mostly functions on the coasts exposed towards the Baltic Proper, where wave action is stronger and sea level variations are more substantial (Fig. 2). Although it occurs on the background of land uplift, too, such lagoons separate from the open sea much quicker (within 20–100 years) than the apparent uplift alone would have allowed. One of such fast evolving examples of alongshore sediment transport and barrier forming onshore accumulation is Poama-Luidja coast at northern Hiiumaa (Fig. 3cd). Differently from the barriers encountered in the southern Baltic Sea, the sand or gravel built barriers are not long (up to 2 km) in Estonia and the lagoons behind are small (Fig. 6). Sediment input from rivers is mostly negligible in these areas.

There are not many such barriers, but their development has been closely studied in the past decades, mainly in storminess related coastal studies. The most illustrious of them, the Kelba spit (Fig. 6a) on Harilaid

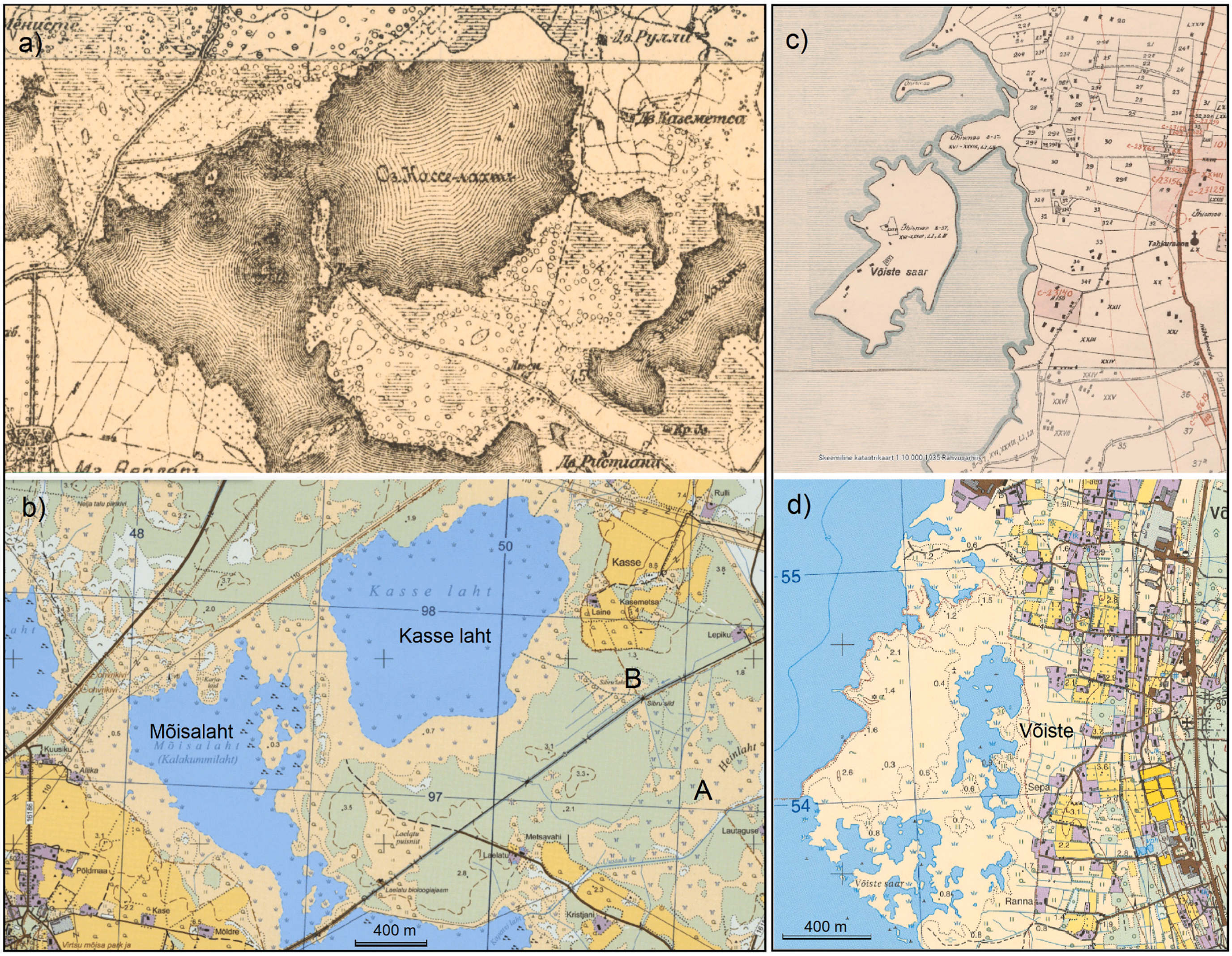

Fig. 4. Map fragments covering identical areas near Virtsu from 1903 (**a**) and 2021 (**b**), and near Võiste (Pärnu County) from 1935 (**c**) and 2004 (**d**) (Fig. 1; A3, A4). A and B on (**b**) marks lagoons which were ameliorated between 1943 and 1992. The areas of two larger lagoons, the Mõisalaht and Kasse Bay have dimished by 46% and 30%, respectively. On (**c**) and (**d**), the shallow lagoon closed between 1996 and 2002 and the aquatic area at the lagoon is diminishing fast.

Peninsula (Saaremaa Island) has elongated annually by ca 20–80 m, mostly after winter storms (Orviku et al., 2003; Tõnisson et al., 2008; Suursaar et al., 2015). Analysis of LiDAR data, aerophotographs and cartographic material have revealed how incremental sediment fluxes have created a series of rhythmic beach ridges and spits. Small lagoons at different phases can be seen (Fig. 6a). The largest (0.34 km^2) and the most recent lagoon was formed after a storm in spring 2022, when the 2 km long Kelba spit (composed of shingle and boulders) eventually rejoined the mainland. The spit is nearly 1 m high at its lowest part. Assuming typical sea level variations in the area, it is probably inundated a couple of times per year. The up to 1.5–2 m high barrier that separates a lagoon (the Laialepa Bay; Table 1) on the same peninsula, has been occasionally breached during extreme storms like in 2005 and 2007 (Tõnisson et al., 2008; Suursaar et al., 2008).

A similar series of barrier built lagoons can be seen at Tõrvanina (Tareste) on Hiiumaa Island (Fig. 6b). Exposed to northerly storms, the currently 1.5 km long Tõrvanina spit is absent on maps until at least 1943. It probably emerged in 1980s and since 1990, it has grown by 1.2 km with an average rate of 40 m/a. The proto-lagoon is not closed yet, but the LiDAR revealed similar patterns with older sediment flows landward. There, an overgrown lagoon (J on Fig. 6b) is located at 2 m above sea level, which has probably passed its lagoon phase ca. 500 years ago.

A former lagoon, the Tihu Lake in Hiiumaa Island (Fig. 7), has formed in combination of land uplift (3.2 mm/a) and once occurred strong sediment fluxes (Suursaar et al., 2022). The LiDAR image shows a multitude of fan-like rhythmic beach ridges, spits and barriers. This part of Hiiumaa emerged from the sea ca. 7–6 ka ago. There was a strait-like marine area which turned into a semi-enclosed lagoon and isolated from the sea 4.8 ka ago (Vassiljev et al., 2015). Today, the very shallow Tihu Lake occupies just 5% of the original lagoonal depression (Fig. 7; Table 1), whereas the rest is filled with mud and up to 2.5 m deep peat layer.

4.4. *Distancing and ageing*

Succession in a broader meaning is a time dependent, evolutionary change. After formation and isolation from the sea, the morphological succession of lagoons on the uplifting coast involves distancing from the sea and a decrease in its water surface area. Although older lagoons usually locate farther from the sea, the main indicator of distancing is altitude. Based on basins water surface altitude (or separating thresholds

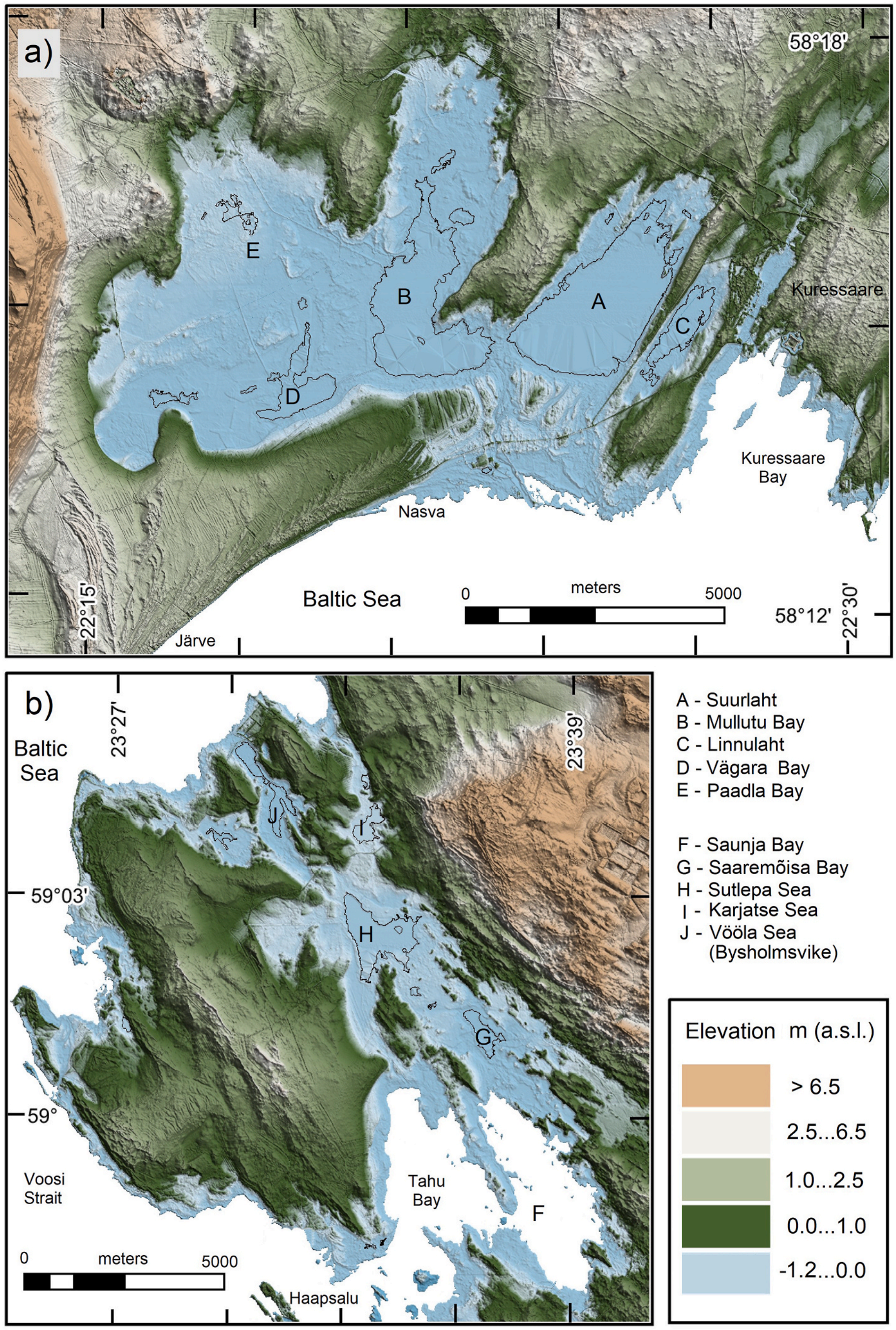

Fig. 5. a): Relief-shaded LiDAR based palaeo-DTM of the area to the west of Kuressaare city (southern Saaremaa; Fig. 1; A5) showing the inundated coastal area as around 1400 CE (considering 2.3 mm/a uplift and ca. 1.5 m relative sea level lowering). Contemporary coastal lakes and lagoons (A–E, see also Table 1) and large paludified areas (e.g., around D and E). Imprints of contemporary roads and other built infrastructure are not removed from this DTM. **b):** Palaeo-DTM of the Noarootsi Peninsula (Fig. 1, A6) and the ancient strait (as of around 1600 CE; 2.8 mm/a uplift) where a string of overgrowing lagoons (F–J) is located.

height), the basins isolation time (roughly: age) can be calculated using local uplift rates (Figs. 1 and 2). Out of nearly 1400 lakes in Estonia, only those locating on the altitude below Litorina Sea limit (about 15–25 m; Fig. 1) can be considered as former lagoons. Some older palaeolagoons (now bogs) could have existed somewhat landward from the 7.3 ka line (Fig. 1), too, but they were subjected to one or several inundation-drainage cycles, and meanwhile swamping and paludification.

The age of a lagoon or coastal lake (Table 1) cannot be defined exactly. Generally, a depression on the terrain precedes isolation and the isolation itself mostly is a 100−300-year process. For instance, on the seacoast of Estonia, 0.5−1 m high separation (threshold) from the sea is usually needed, which can be created by uplift within 200–300 years. If wave-driven sediment accumulation is involved, the process can take 10−50 years, but still a distal part of the spit or barrier tends to remain lower (e.g., Fig. 6), occasionally allowing seawater to penetrate into the lagoon.

The areal decrease rate (AD, Table 1) varies in time. It has been generally faster within the past ~100 years. As an average, the areas of recently separated lagoons have decreased with a rate of 27% per century. Small and very shallow lagoons shrank with faster pace (Figs. 4 and 6) or have even disappeared. Relief flattens in time. In addition to the areal decline during the uplift-driven separation, the main other reasons

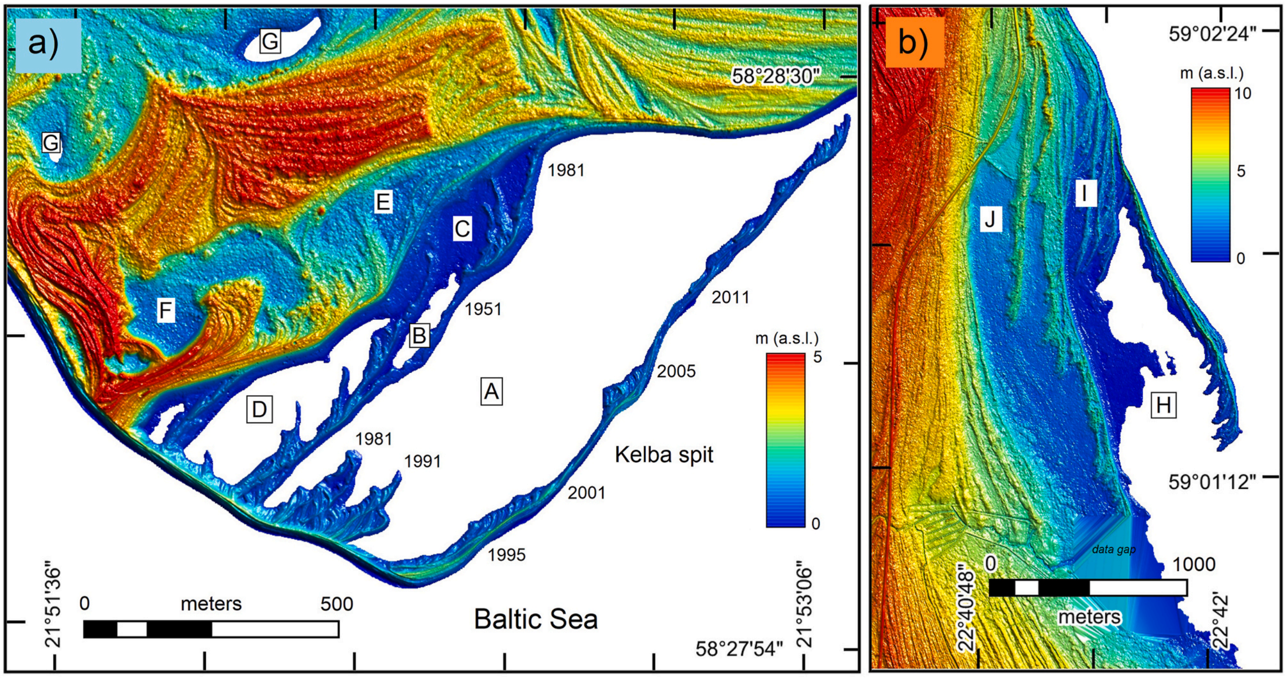

Fig. 6. Relief-shaded DTM of the Kelba spit (**a**) and the Tõrvanina spit (**b**) (Fig. 1, A7, A8). The Kelba spit, shown as of 2021 (**a**), has gradually elongated (years indicated) and closed the lagoon A in 2022. The lagoons B and C closed between 1951 and 1980, D closed in the 1920s, the forest covered E−F isolated 300−500 years and G ca. 500 years ago. The Tõrvanina spit (**b**) started to form in the 1980s because of intensified coastal processes (Buynevich et al., 2023) and ice-free winters. Due to the very shallow sea, aeolian deposition and amelioration, the lagoons (H–J) are ephemeral.

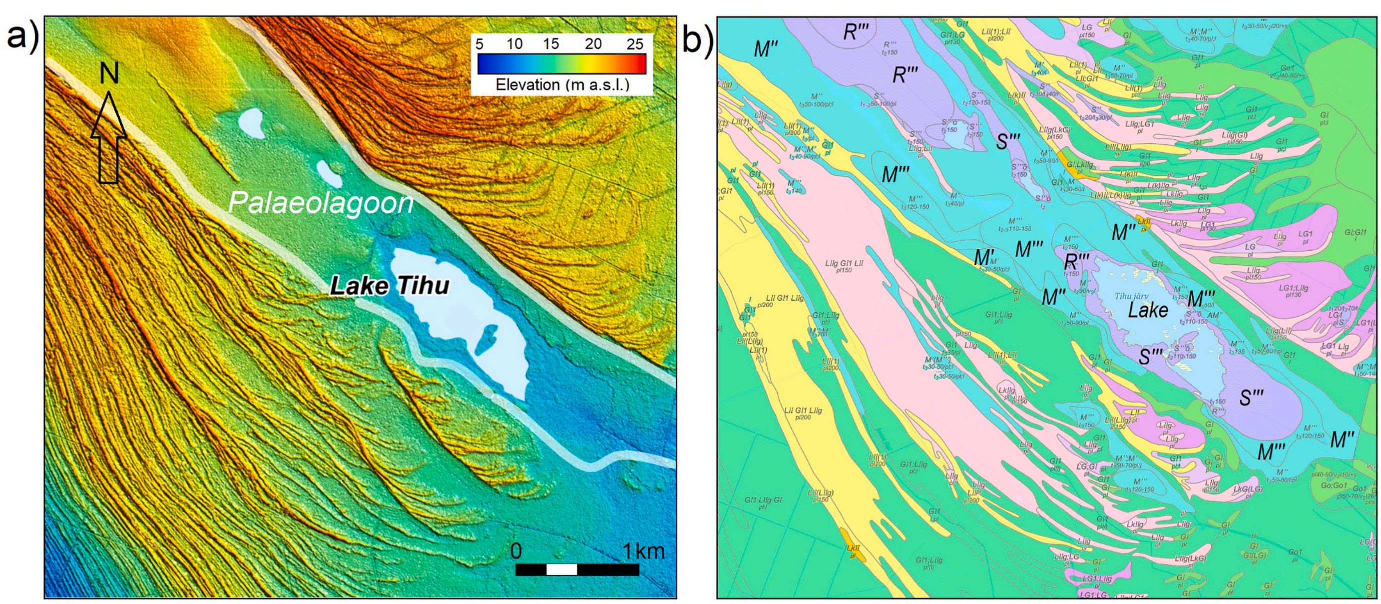

Fig. 7. a): Relief-shaded DTM of the Tihu Lake area (Fig. 1, A9; modified from: Suursaar et al., 2022). The palaeolagoon borders at 5 ka ago were drawn from the Estonian soil map (ELB 2024c; a modified fragment **(b)**). Soil types that encircle the lake and characterise palaeolagoon are fens (M), mesotrophic mires (S), and bogs (R) with peat layer thicknesses <0.5 m ('), 0.5−1 m (''), and >1 m (''').

are subsequent overgrowing by vegetation, mud formation, accumulation of sediments to the lagoon bottom, and occasionally also amelioration (e.g., Kose, 2012). The palaeolagoon decrease rates estimated from soil maps are 10–100 times lower (order of 0.01 % per year; Table 1), because the surviving, bigger lakes (palaeolagoons) are much more resilient than today's ephemeral lagoons. The morainic terrain freshly emerging from the sea 15−10 ka ago included some relatively steep and up to ~10 m deep depressions. Therefore, larger palaeolagoons are detectable even today as lakes or bogs, whereas smaller ones have disappeared without leaving a trace. Quite differently, the emerging (marine) terrain today has been flattened by denudation and the nearshore depressions have already been filled with sediment for hundreds or thousands of years. Consequently, the expected lifetime of contemporary, emerging lagoons is much shorter (Table 1). On contrary, small inland lakes, especially when being oligotrophic and shores fixated with vegetation, have largely retained their size and depth (which may reach up to 38 m in Estonia; Mäemets, 1977).

A number of relict lagoons have been identified and investigated in Estonia for archaeological or palaeoclimatological purposes. Sometimes, their isolation times were estimated on the basis of sedimentary proxies or archaeological findings (Grudzinska et al., 2013; Rosentau et al., 2011, 2020; Vassiljev et al., 2015; Sander and Kriiska, 2022), but these can be now confirmed or adjusted by relating the lake (or threshold) elevations on contemporary relief with local uplift rates over the Holocene (Figs. 1 and 2a). Along the northern coast of Estonia, there is the Tänavjärv group of soft-water lakes (Mäemets, 1977) at an elevation of 16.5–18 m a.s.l. (which also includes Lake Veskijärv; Table 1), and the lakes of Klooga, Harku, and Lohja (Table 1). On Saaremaa Island, a large number of palaeo- and contemporary lagoons at different development stages can be found, the oldest one being Karujärv (33 m), which developed ca. 11−10 ka ago. More recent ones are the Lake Koigi (8.5 m, ca. 3.6 ka), and Lake Kooru (4.5 m, 1.8 ka).

Some of the bogs are genetically old lagoons, too. For instance, Hara Bog (Fig. 1) with up to ca 7 m thick peat layer (Kessel, 1968), probably isolated as a lagoon from the sea ca 9 ka ago. In Pärnu County, a 55 km^2 Tolkuse Bog (Fig. 1) with up to 6 m thick peat layer (peat surface at 10 m elevation) and 17 km^2 Rääma Bog (7 m thick peat, 17 m elevation) are also former lagoons (Habicht et al., 2017; Nirgi et al., 2020). On Hiiumaa Island, Kõivasoo Bog (surface elevation 27 m) has passed the initial formation and subsequent isolation from the sea 8.8 ka ago, a new inundation 7.6−7.4 ka ago, final isolation 7.4 ka ago, and overgrowing and swamping since ca. 5.6 ka BP (Rosentau et al., 2020).

Hence, the "coastal lagoon" stage (satisfying the present 1150* criteria) in Estonia, as in the rest of the world, is only a relatively short time slice in the long succession. In Estonia it begins with a bay or simply shallow sea area, continues with becoming a lagoon, which further distances and rises to become a "proper" lake or perish as a bog (Fig. 8). Out of up to 10−13 ka of landscape history, the contemporary lagoon stage typically lasts for 50−500 years in uplifting Estonia, or even less in case of very small lagoons. However, palaeolagoon phase of older lagoons during transgressions could have lasted longer – at least while the sea level was still rising, stable or not much lowered yet.

4.5. Changes in communities

Along with geomorphic development and distancing, biological communities undergo a series of profound changes (Figs. 8 and 9; Table 2). This evolvement has occurred as a primary succession with minor disruptions on active, sedimentary coasts. The full post-glacial succession path in Estonia cannot be longer than ca. 10−14 ka (Rosentau et al., 2009; Blaus et al., 2021), but it is much shorter on bits of

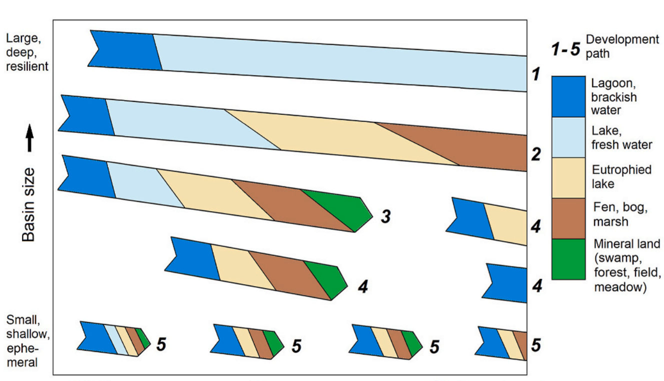

Fig. 8. Generalized geomorphical-ecological succession paths since 7.3 ka. Old (large) palaeolagoon can today be: a lake (1; oligo-, meso-, eutrophic), fen or bog (2; sometimes including small eutrophied remnant lakes), or mineral land (3; hardly distinguishable on today's terrain). Medium size lagoons can currently exist in various stages (3, 4), but with shorter age; small lagoons (5) are overgrowing rapidly or have been disappeared without a trace.

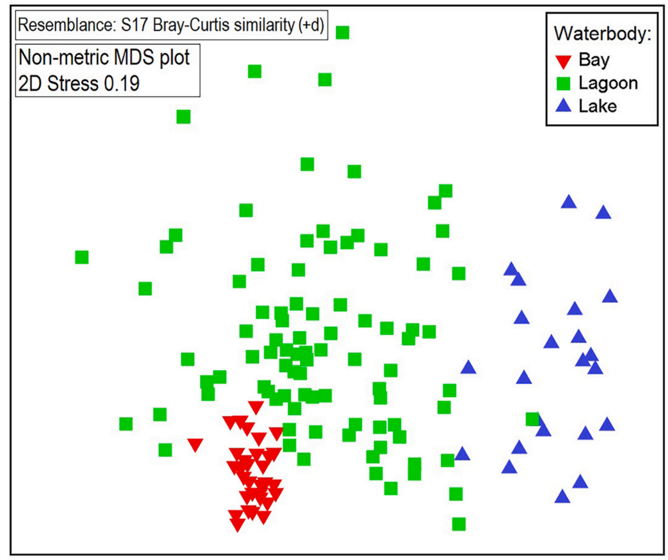

Fig. 9. Multidimensional scaling (nMDS) plot describing grouping and differences between selected 154 water bodies according to the ANOSIM analysis (Clarke and Gorley, 2015) of the soft substrate vegetation.

newly emerging coast. In palaeolagoons, plant macrofossil, pollen, and diatom analyses have been used to assess climatic, palaeoenvironmental and successional changes (e.g., Veski et al., 2005; Habicht et al., 2017; Nirgi et al., 2020; Blaus et al., 2021). However, all these changes overlap and can be hard to distinguish from each other.

Basically, all contemporary and palaeolagoons, large and small, can be divided under general paths (Fig. 8) and their sub-types for different trophic levels or separation phases. In Estonia, the "parent" habitat types for (contemporary) coastal lagoons (1150* according to the EU-s Habitats Directive) belong to group 11, being mostly estuaries or shallow bays (1160) but can also be sandbanks (1110) or salt marshes (1310) (Torn et al., 2017). On gently sloping sandy coasts, also humid dune slacks (2190) or humid meadows (6410) can evolve either directly or subsequently from small lagoons. When distancing from the sea, the lagoons eventually lose any contact with the sea and turn into a lake (habitat group 31, types 3110, 3140, 3160). In time, the open water area of lakes reduces (Table 1) and lake is replaced by a calcareous fen (72) or sphagnum bog (71). Disconnected from the marine past, the general succession vector proceeds from wetland (71, 72) to forest (90; 9030, 9080), humid meadow (6410) or mesophile grassland (6500) (Fig. 8). However, one should bear in mind that not every habitat (e.g., lake, bog, forest) necessarily has a code according to the Habitats Directive.

Aquatic vegetation largely reflects general ecological status of a water body, indicates its development stage within an ecological succession path, and also largely determines other features of fauna and flora. It appeared from field work and database analysis, that the list of taxa was the longest (73 names) in lagoons, where both brackish and freshwater species can be found, followed by lakes (68 species). The list of soft substrate vegetation was the shortest (27) in bays (Table 2). Several species of higher plants and charophytes occurred both in brackish and fresh water. However, their occurrence statistics revealed some differences (Table 2). In general, submerged vegetation dominated in brackish water bodies, whereas in lagoons and lakes the share of emergent species (e.g., *Typha, Carex, Lysimachia*) was much larger. The three habitat types differentiated well on the nMDS plot (Fig. 9). Community structures largely overlapped between bays and lagoons ($R = 0.14$), somewhat overlapped between lagoons and lakes ($R = 0.55$), while bays and lakes were highly dissimilar ($R = 0.96$). SIMPER analysis showed that occurrence of most frequent species in bays and lakes contributed most to dissimilarities between the groups, while the species

Table 2
Occurrence (%) of the most common soft substrate plant taxa in 23 shallow bays, studied 93 coastal lagoons, and in 23 small (not far inland) lakes. Based on SIMPER analysis, species that contributed the most in dissimilarities with other waterbody types are indicated with superscript in bold (B – bay, LG – lagoon, LK – lake). * free-living form.

Bay	%	Lagoon	%	Lake	%
Chara aspera **LK**	100	*Phragmites australis*	76	*Phragmites australis*	91
Stuckenia pectinata	100	*Stuckenia pectinata*	71	*Comarum palustre* **B**	83
Myriophyllum spicatum **LG**	94	*Schoenoplectus tabernaemontanii*	63	*Typha latifolia* **B, LG**	83
Phragmites australis	97	*Chara aspera*	58	*Equisetum fluviatile* **LG**	78
Schoenoplectus tabernaemontanii **LK**	97	*Chara aculeolata*	34	*Potamogeton natans* **LG**	78
Chara canescens **LK, LG**	88	*Chara tomentosa*	34	*Carex rostrata* **LG**	74
Chaetomorpha linum **LG**	78	*Typha angustifolia*	33	*Lysimachia thyrsiflora* **LG**	74
Ruppia maritima **LG**	69	*Bolboschoenus maritimus*	26	*Nuphar lutea*	65
Zannichellia palustris **LG**	66	*Comarum palustre*	23	*Schoenoplectus lacustris*	61
*Fucus vesiculosus**	59	*Najas marina*	22	*Menyanthes trifoliata*	48
Chara connivens	53	*Carex elata*	20	*Polygonum amphibium*	48
Chara baltica	50	*Typha latifolia* **LK**	19	*Potamogeton perfoliatus*	48
Potamogeton perfoliatus	50	*Lysimachia thyrsiflora* **LK**	18	*Typha angustifolia*	48
Najas marina	44	*Utricularia australis*	17	*Nymphaea candida*	39
Chara horrida	38	*Potamogeton gramineus*	16	*Iris pseudacorus*	35

that were more frequent in lagoons, were also common in bays and lakes (Table 2).

The replacement of marine vegetation with the communities typical of lagoons and of inland water bodies is gradual and it occurs at different pace, depending on various morphometric, substrate and other conditions. In the initial phase of separation, the water's edge may have a sandy-pebbly beach with very sparse vegetation or low-grass vegetation of a beach meadow. When there is a high-growth zone, it mainly consists of the sea club-rush and grey club-rush (*Bolboschoenus maritimus, Schoenoplectus tabernaemontanii*) and sometimes also common reed (*Phragmites australis*). In the water, species with a wide ecological amplitude (*Chara aspera, C. tomentosa*, *C. canescens*, *Stuckenia pectinata*) are common. Holly-leaved naiad (*Najas marina*) is also sporadically present.

Notable shifts in species composition occur when a brackish water habitat (salinity 2–7) turns into sheltered and less saline (usually 0.5–2) embayment or lagoon. At salinity <0.5, which is usually considered as the sea/freshwater boundary, *Ruppia maritima, C. canescens* and *C. baltica* disappear. *Chara aspera* and *C. tomentosa* are still important, but *C. aculeolata* becomes a characteristic species of 1150* on limestone bedrock. In lagoons formed on sandstone, submerged vegetation is generally poor in charophytes. In lagoons or their parts at higher trophic level, horned pondweed (*Zannichellia palustris*) and fennel pondweed (*S. pectinata*) are abundant. In eutrophic lagoons with steeper slopes, hornworts (*Ceratophyllum demersum* and *C. submersum*) as well bladderworts (*Utricularia*) may occur abundantly.

The next phase has also been classified as 1150* in terms of habitat type in Estonia. Some features of these lagoons (species composition of elodeids and charophytes, presence of nymphaeids etc.) are close to inland water bodies: mesotrophic, hard water-lakes with benthic vegetation of *Chara* spp or naturally eutrophic lakes. Low grassy vegetation can occur at the water's edge. On limestone or thin sand substrate, saw-sedge (*Cladium mariscus*) is common. More often, saw sedge appears alongside with the above mentioned high-growth species and sedges (*Carex*). Low-growth shores are mostly replaced with high-growth vegetation. Club-rush and reedbeds gradually expand and narrow-leaved cattail (*Typha angustifolia*) appears in the muddy areas. As overgrowing proceeds, fens appear on the edges of lakes, including the protected habitat of calcareous fens (with *C. mariscus*). Fens, where the edifier is tufted sedge (*Carex elata*), can quickly occupy the whole area of smaller lagoons. In somewhat deeper water bodies, there are also plants with floating leaves, especially the broad-leaved pondweed (*Potamogeton natans*) and the white water-lily (*Nymphaea alba*). Charophytes (*C. aspera, C. tomentosa, C. aculeolata*) and bladderworts (*Utricularia australis, U. intermedia, U. minor*) are common.

5. Discussion

5.1. Past and present

Our study has shown that coastal lagoons in Estonia are rather specific. Differing from the lagoons bordering with oceans (e.g., Barnes, 2001; McLusky and Elliott, 2004), the sea is practically tideless and the brackish water salinity differences are small. The lagoons are mostly small and very shallow, and due to ongoing land uplift (Fig. 2a), rather ephemeral. As such, they somewhat resemble lagoons in fast uplifting Canada (Boisson and Allard, 2020), Finland or northern Sweden, where the main development stages are called juvenile flad, flad, glo-flad, glo and glo-lake (Munsterhjelm, 1997; Haapamäki, 2021), but sedimentary and ecological conditions are rather different (e.g., Kessel, 1968). Moreover, contemporary lagoons (1150* habitats) in Estonia mostly do not resemble commonly perceived "lagoons" and are even not called so traditionally. "Lagoon" is widely used in the case of corresponding water bodies in other seas and countries, although their variety is huge and the definition itself may vary (Kjerfve, 1994; Tagliapietra et al., 2009; Soria et al., 2022). It is interesting to note that the term "lagoon" is still used in Estonia for past water bodies – a number of palaeolagoons have been identified and their development has been studied in Estonia (e.g., Vassiljev et al., 2015; Nirgi et al., 2020; Rosentau et al., 2020; Sander and Kriiska, 2022).

Tracking of morphological changes in coastline (Fig. 4–7) showed that the transition between the different development stages is often vague. Even larger problems arise when ecology is also involved and following the EU directives, type 1150* habitats must be identified. At the time of writing, there were 579 listees in the lagoons (1150*) database in Estonia. However, the number changes in time both naturally (due to appearance and disappearance), and subjectively, depending on how we perceive and classify the transitional waterbodies, and how small objects are included. It was shown that the lagoon – lake – bog transition speed and the succession length foremost depends on the morphometry (size, depth) of the initial orographic depression (Fig. 8). Larger (deeper) ones are more resilient. Out of older palaeolagoons, the smaller ones are guessable only from soil maps. Morphological succession is mainly a geomorphic process at the beginning, but it gradually becomes overwhelmed by ecological succession, which can ultimately reshape the physical morphology of water bodies. Quite straightforward ecological succession along the transitional phases of waterbodies (bay-lagoon-lake) was observed on the basis of habitat building vegetation (Fig. 9; Table 2). There was an overlap in neighbouring groups, but the differences between the two ends of the analysis were clear. At first stages, the composition of communities by species is similar to the nearby coastal sea and as the lakes grow older, differences increase.

Mainly because of shallowness, coastal lagoons often suffer from hectic variations in their ecological conditions and are sometimes considered as not good habitats for fish and some other animal groups (Kose, 2012; Pursiainen et al., 2021). However, larger lagoons are known as suitable spawning grounds for fish (Laarmaa et al., 2019). Moreover, coastal lagoons and wetlands are highly valuable habitats and nursery grounds for birds, particularly due to their prime position on the bird migratory route (the East Atlantic Flyway). Bird diversity is relatively low on open coasts, it increases as lagoons separate from the sea and low-growth shore vegetation is replaced by high-growth vegetation and reeds, and decreases again in swamped lakes or overgrown land (Kose, 2012). In Estonia, coastal lagoons and wetlands are mostly under protection, either by the EU-s Natura 2000 network or by UNESCO-s Ramsar Convention (the convention of wetlands), or by both. There are 17 Ramsar sites in Estonia, nine of which include current or past lagoons. Considering the large proportion (18.7%) of protected areas and relatively low population density of the country (30 people per km^2), coastal lagoons are not heavily exploited in Estonia. Their future as valuable habitats depend on balance between sea level rise and uplift, changes in climatic conditions, and on society's choices (Kont et al., 2007).

5.2. Future

With the continuing uplift, the constant renewal of lagoons as a habitat type has taken place so far. However, the balance between emergence of new lagoons (e.g., Fig. 3−5) and disappearance due to their distancing and swamping (Fig. 5−7) has shifted over the past 100 years. Firstly, because the relative sea level lowering has essentially stopped on the Estonian shores (Fig. 2b). Secondly, because ecological succession and anthropogenic intervention gradually makes lagoons "older" (Fig. 8). Future projections suggest global sea level rise for 0.5−1.1 m relative to 1900 (but also large uncertainty) by the end of 21st century (IPCC, 2021). Out of it, 0.25 m global sea level rise has already occurred since 1900. Depending on location (Figs. 1), 0.15−0.35 m rise will be compensated by regional uplift, which still leaves, depending on emission pathway, 0.1−0.6 m relative sea level rise to occur on Estonian coast. There is also a low likelihood high impact storyline for up to ca. 2 m sea level rise by the end of 21st century (IPCC, 2021).

Over the last millennia, climate variations have been rather substantial in the Baltic Sea area. The climate was 2–3° warmer than today during the Holocene climate optimum ca. 8−4 ka ago, and it was a few degrees colder during the Little Ice Age (1300 CE–1850). The present time air temperatures are, again by ca. 2° warmer than a century ago in Estonia (BACC, 2015; Harff et al., 2020). The projected global temperature increase by the end of 21st century (scenario-wise range 1.5–5 °C; IPCC, 2021) does not differ much from the Estonian regionalized scenarios (including a 4−5 °C increase by the steepest RCP8.5-pathway; e.g., Sepp et al., 2018). Along with the Baltic Sea water temperature increase, the number of seasonal sea ice days has declined by 50–60 days at Estonian coasts (BACC, 2015). Considering continuation of sea surface temperature rises (for 1.8−3.1 °C by the end of 21st century; e.g., Meier et al., 2022), the seasonal sea ice cover will continue to shrink to almost nothing at some Estonian coastal sections. Due to the lack of protective ice cover, seacoasts are more exposed to storm surges and increasing waveloads, which leads to intensification of coastal processes (Orviku et al., 2003). Most likely the North Atlantic cyclones and storm surges along west Estonian coast will become just slightly stronger by the end of 21st century, though the uncertainty will also increase (Mäll et al., 2020). Also precipitation will likely increase (by ca. 20%; Sepp et al., 2018; Mäll et al., 2020). A large degree of uncertainty in Northern Europe is related to the Atlantic meridional overturning circulation (AMOC) weakening (or possible collapse) due to increased freshwater input from Greenland ice sheet melt (e.g., Armstrong McKay et al., 2022). The tipping points, stability conditions and impacts are still under heavy debate, but according to recent IPCC reports (e.g., IPCC, 2021), the most likely impact from the AMOC decline would result in limited, relative (~1 °C) cooling (on top of general warming) in Europe and increase in storminess. The more extreme projections for the AMOC shutdown and severe regional cooling in Europe is considered unlikely, but the chaotic nature of the climate system also makes future largely unpredictable and uncertain (e.g., Lohmann and Ditlevsen, 2021).

All the above discussed changes (temperature rise, ice cover decline, increase in precipitation but also in storm-breach likelihood) will modify biological succession in nearshore areas and lagoons (Fig. 8). Predictive modelling (Torn et al., 2019) has shown that changes in species distribution and community structure are expected to occur in the future as a result of climate change, but also due to changes in salinity, turbidity, and hydrochemistry (Meier et al., 2022). The Baltic Sea hosts a mixture of organisms of marine, brackish and freshwater origin, living often close to their physiological limits, and even small changes in the abiotic environment can dramatically impact competition rules and species distribution.

Finally, the future will also depend on human actions and management choices (Elliott et al., 2007) – for instance, either by accelerating or mitigating eutrophication, draining or rewilding wetlands. At least since the 19th century, human intervention has been substantial with amelioration, deforestation, grazing, discharging pollutants and nutrients. Although eutrophication and ageing of water bodies occurs in natural reasons, too, in Estonia, it has accelerated since the second half of the 20th century. In lowland Estonia, most of the lakes are flanked with fens or bogs, which gradually take over aquatic space (Mäemets, 1977; Blaus et al., 2021). Coastal wetlands are mostly under protection in Estonia and do not suffer much from direct human intervention, yet. However, the situation is very different in the case of palaeolagoons, which have been turned into fields, forests or peat mines. Over the last few decades, progress in environmental protection and changes in people's mindset have hopefully turned the balance back to a more natural evolvement course.

6. Conclusions

1) An evolutionary approach in description of coastal lagoons was proposed and exemplified on the Estonian coast of the Baltic Sea. The use of old cartographic material and GIS based shoreline modelling (which utilizes sea level histories throughout Holocene) was demonstrated in studying uplift-driven evolution of lagoons. The role of sediment barrier formation was shown using LIDAR based DTM-s, and ecological succession through different development stages was analyzed statistically.
2) Lagoons have quite specific character and development story on the brackish water, tideless, low-energy, uplifting (1.5−3.4 mm/a) morainic coasts of Estonia. Although "lagoon" (as mostly understood) is not a typical landscape feature on the Estonian coast, the heavily indented and low-lying seashore includes a large number of enclosed and semi-enclosed aquatic areas, which according to the EU-s protected habitats directive have been classified as lagoons (type 1150*). Hence, they are subjected to regular study and reporting. However, censuses made at different times have produced slightly varying lists, as lagoon-like marine areas, coastal lakes and 1150* listees do not relate straightforwardly to each other. The main reason is small size, shallowness and transitional nature of those objects. Currently, there are about 600 lagoons with a total area of about 42 km^2.
3) Because of a deficit in movable sandy sediment in that section of the Baltic Sea, uplift driven lagoon formation is the main process in Estonia. Sediment barrier-built lagoons can be found on relatively high-energy coasts exposed to the Baltic Proper, but they are also subjected to subsequent uplift. Small size of lagoons (in average 0.1 km^2, maximum ~6 km^2) can be explained by flat postglacial morainic terrain that has emerged from the sea. Geomorphic

succession has occurred without disruptions (sea transgressions) for about 7300 years. Hence, in lowland Estonia (<15 … 25 m), elevation of a palaeolagoon/lake reflects age.

4) Due to ongoing uplift, most of the lagoons are just a relatively short (50−500 years long) transitional phase in a long (up to ~10 ka) succession. Locating at the altitude of up to 20−30 m, some older palaeolagoons can be nowadays distinguished as lakes often flanked by bogs. Larger (deeper) lagoons/lakes are more resilient. Smaller and shallower ones are blended into surrounding landscape. The currently evolving lagoons are all very shallow (mostly 0.5−1 m, maximum 2−3 m deep) because the terrain that is emerging from the sea today has been already flattened by marine erosion and sedimentation.
5) Community-level statistical analysis of macrovegetation species revealed some specific shifts as lagoons develop in time. When a lagoon is formed through separation from the sea, the original brackish water habitat is gradually replaced with freshwater habitat. At first, biodiversity of emergent species increases. Further on, high-growth vegetation and club-rush gradually expands, becoming thus a valuable nesting and staging areas for birds. Disconnected from their marine past, communities typical for lakes, fens, bogs, meadows or forests are ultimately formed.
6) As a result of ongoing climate change and sea level rise, the balance between the emergence of new lagoons and disappearance due to their distancing and swamping has shifted over the past 50−100 years. Firstly, because the relative sea level lowering has essentially stopped on the Estonian shores. Secondly, ecological succession gradually makes lagoons "older"; amelioration has been intensive in the second half of the 20th century and letting extra nutrients into watercourses has accelerated eutrophication.

CRediT authorship contribution statement

Ülo Suursaar: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Kaire Torn:** Writing – review & editing, Visualization, Resources, Investigation, Data curation. **Helle Mäemets:** Writing – review & editing, Validation, Resources, Investigation. **Alar Rosentau:** Writing – review & editing, Visualization, Resources, Investigation.

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.

Data availability

Data will be made available on request.

Acknowledgements

The study was supported by the Estonian Research Council grant PRG1471 and by the KIK projects No. 15521 and 18518. We are grateful to the Estonian Land Board and Estonian Nature Information System.

References

Andrulewicz, E., 1997. An overview on lagoons in the Polish coastal area of the Baltic Sea. Int. J. Salt Lake Res. 6, 121–134. https://doi.org/10.1007/BF02441889.

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377, 6610.

BACC, 2015. Second Assessment of Climate Change for the Baltic Sea Basin. Springer, Cham, p. 501.

Barnes, R.S.K., 2001. Lagoons. In: Steele, J.H. (Ed.), Encyclopedia of Ocean Sciences. Academic Press, pp. 1427–1438. https://doi.org/10.1006/rwos.2001.0091.

Blaus, A., Reitalu, T., Poska, A., Vassiljev, J., Veski, S., 2021. Mire plant diversity change over the last 10,000 years: importance of isostatic land uplift, climate and local conditions. J. Ecol. 109 (10) https://doi.org/10.1111/1365-2745.13742.

Boisson, A., Allard, M., 2020. Morphological and evolutionary patterns of emerging arctic coastal landscapes: the case of northwestern Nunavik (Quebec, Canada). Arct. Sci. 6 (4), 488–508.

Borja, Á., Elliott, M., Carstensen, J., Heiskanen, A.-S., van de Bund, W., 2010. Marine management – towards an integrated implementation of the European marine strategy framework and the water framework directives. Mar. Pollut. Bull. 60, 2175–2186.

Buynevich, I.V., Tõnisson, H., Suursaar, Ü., Pupienis, D., Davydov, O.V., Kont, A., Palginõmm, V., Koit, O., Luik, K., 2023. Diverse erosional indicators along a rapidly retreating Holocene strandplain margin, leeward Hiiumaa Island, Estonia. Baltica 36 (1), 79–88.

Carrasco, A.R., Ferreira, Ó., Roelvink, D., 2016. Coastal lagoons and rising sea level: a review. Earth Sci. Rev. 154, 356–368. https://doi.org/10.1016/j.earscirev.2015.11.007.

Clarke, K.R., Gorley, R.N., 2015. PRIMER V7. User Manual/Tutorial. PRIMER-E, Plymouth.

Corbau, C., Zambello, E., Nardin, W., Simeoni, U., 2022. Secular diachronic analysis of coastal marshes and lagoons evolution: study case of the Po River delta (Italy). Estuar. Coast Shelf Sci. 268, 107781.

Davydov, O., Karaliūnas, V., 2022. Genetic diversity of inlet systems along non-tidal coasts: examples from the Black Sea and Sea of Azov (Ukraine). Baltica 35 (2), 125–139.

Duck, R.W., da Silva, J.F., 2012. Coastal lagoons and their evolution: a hydromorphological perspective. Estuar. Coast Shelf Sci. 110, 2–14.

Eelsalu, M., Parnell, K.E., Soomere, T., 2022. Sandy beach evolution in the low-energy microtidal Baltic Sea: attribution of changes to hydrometerological forcing. Geomorphology 414, 108383.

Elliott, M., Burdon, D., Hemingway, K.L., Apitz, S.E., 2007. Estuarine, coastal and marine ecosystem restoration: confusing management and science – a revision of concepts. Estuar. Coast Shelf Sci. 74 (3), 349–366.

ELB, 2024a. Estonian land board: maps. https://xgis.maaamet.ee/xgis2/page/app/ajalooline. (Accessed 24 April 2024).

ELB, 2024b. Estonian land board: elevation data. http://geoportaal.maaamet.ee/eng/Maps-and-Data/Topographicdata/Elevation-data-p308.html. (Accessed 24 April 2024).

ELB, 2024c. Estonian land board. Soil Map. https://xgis.maaamet.ee/xgis2/page/app/mullakaart. (Accessed 24 April 2024).

European Commission, 2013. Interpretation manual of European Union habitats. Interpret. Man. - EUR 28. DG Environ. 146. https://inpn.mnhn.fr/docs/natura2000/Manuel_d_interpretation_EUR_28.pdf. (Accessed 24 April 2024).

European Communities, 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. O. J. Ser. L. 206, 7–49. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1992L0043:20070101:en:PDF. (Accessed 24 April 2024).

Grudzinska, I., Saarse, L., Vassiljev, J., Heinsalu, A., 2013. Mid- and late-Holocene shoreline changes along the southern coast of the Gulf of Finland. Bull. Geol. Soc. Finland 85 (1), 19–34.

Haapamäki, J., 2021. Protection of the Natura 2000 Habitat Coastal Lagoons and Glolakes in Finland. MSc. Thesis. Novia, Raseborg, p. 34. https://www.theseus.fi/handle/10024/512054.

Habicht, H.-L., Rosentau, A., Jõeleht, A., Heinsalu, A., Kriiska, A., Kohv, M., Hang, T., Aunap, R., 2017. GIS-Based multiproxy coastline reconstruction of the eastern Gulf of Riga, Baltic Sea, during the stone age. Boreas 46 (1), 83–99.

Harff, J., Jöns, H., Rosentau, A., 2020. Geological, paleoclimatological, and archaeological history of the Baltic Sea region since the last glaciation. In: Oxford Research Encyclopedia of Climate Science. Oxford University Press, pp. 1–50. https://doi.org/10.1093/acrefore/9780190228620.013.621.

Hünicke, B., Zorita, E., Soomere, T., Madsen, K.S., Johansson, M., Suursaar, Ü., 2015. Recent change − Sea level and wind waves. In: The BACC II Author Team (Ed.), Second Assessment of Climate Change for the Baltic Sea Basin. Springer, Cham, pp. 155–185.

Inácio, M., Schernewski, G., Nazemtseva, Y., Baltranaite, E., Friedland, R., Benz, J., 2018. Ecosystem services provision today and in the past: a comparative study in two Baltic lagoons. Ecol. Res. 33, 1255–1274. https://doi.org/10.1007/s11284-018-1643-8.

IPCC, 2021. AR6 climate change 2021. Phys. Sci. Basis. https://www.ipcc.ch/report/ar6/wg1/.

Jaagus, J., Suursaar, Ü., 2013. Long-term storminess and sea level variations on the Estonian coast of the Baltic Sea in relation to large-scale atmospheric circulation. Est. J. Earth Sci. 62 (2), 73–92.

Kalm, V., 2006. Pleistocene chronostratigraphy in Estonia, southeastern sector of the Scandinavian glaciation. Quat. Sci. Rev. 25, 960–975.

Kaminskas, D., Rudnickaitė, E., Vaikutienė, G., Bitinas, A., Grigienė, A., Buynevich, I.V., Damušyte, A., Pupienis, D., Šinkūnas, P., 2019. Middle and late Holocene paleoenvironmental development of the curonian lagoon, Lithuania. Quat. Int. 501, 240–249. https://doi.org/10.1016/j.quaint.2017.09.016.

Kessel, H., 1968. Formirovanye ozer na podnimayuchemsya poberezhye Estonii. Eesti NSV Tead. Akad. Toim. Keem. Geoloogia 17 (1), 59–66 (in Russian).

Kjerfve, B. (Ed.), 1994. Coastal Lagoon Processes, vol. 60. Elsevier Oceanographic Series, p. 577.

Kont, A., Endjärv, E., Jaagus, J., Lode, E., Orviku, K., Ratas, U., Rivis, R., Suursaar, Ü., Tõnisson, H., 2007. Impact of climate change on Estonian coastal and inland wetlands – a summary with new results. Boreal Env. Res. 12, 653–671.

Kose, M. (Ed.), 2012. Coastal lagoons in Estonia and in the central Baltic Sea region. Development History, Geology and Hydrology, Biodiversity and Nature

Conservation Value. University of Tartu Pärnu College, p. 145. https://www.digar.ee/arhiiv/nlib-digar:122087. (Accessed 24 February 2024).
Laarmaa, R., Ott, I., Timm, H., Maileht, K., Sepp, M., Mäemets, H., Palm, A., Krause, T., Saar, K., 2019. Eesti järved. Varrak, Tallinn, p. 256 (in Estonian).
Lohmann, J., Ditlevsen, P.D., 2021. Risk of tipping the overturning circulation due to increasing rates of ice melt. Proc. Natl. Acad. Sci. USA 118, 8.
Loopmann, A., 1984. Suuremate Eesti järvede morfomeetrilised andmed ja veevahetus. Eesti NSV Teaduste Akadeemia, Tallinn, p. 152 (in Estonian).
McLusky, D.S., Elliott, M., 2004. The Estuarine Ecosystem: Ecology, Threats and Management. Oxford University Press, Oxford, p. 214.
Meier, H.E.M., Dieterich, C., Gröger, M., Dutheil, C., Börgel, F., Safonova, K., Christensen, O.B., Kjellström, E., 2022. Oceanographic regional climate projections for the Baltic Sea until ~2100. Earth Syst. Dyn. 13, 159–199.
Munsterhjelm, R., 1997. The aquatic macrophyte vegetation of flads and gloes, S coast of Finland. Acta Bot. Fennica 157, 1–68.
Mäemets, A., 1977. Eesti NSV järved ja nende kaitse. Valgus, Tallinn, p. 264 (in Estonian).
Mäemets, H., Palmik, K., Haldna, M., 2016. Eutrophication-driven spatial and temporal changes in macrophyte diversity in Lake Peipsi. Proc. Est. Acad. Sci. 65 (4), 394–407.
Mäll, M., Nakamura, R., Suursaar, Ü., Shibayama, T., 2020. Pseudo-climate modelling study on projected changes in extreme extratropical cyclones, storm waves and surges under CMIP5 multi-model ensemble: Baltic Sea perspective. Nat. Hazards 102 (1), 67–99.
Nirgi, T., Rosentau, A., Habicht, H.-L., Hang, T., Jonuks, T., Jõeleht, A., Kihno, K., Kriiska, A., Mustasaar, M., Risberg, J., Suuroja, S., Talviste, P., Tõnisson, H., 2020. Holocene relative shore-level changes and Stone Age palaeogeography of the Pärnu Bay area, eastern Baltic Sea. Holocene 30, 37–52.
Orviku, K., Jaagus, J., Kont, A., Ratas, U., Rivis, R., 2003. Increasing activity of coastal processes associated with climate change in Estonia. J. Coast Res. 19, 364–375.
Ott, I., Kõiv, T., 1999. Estonian Small Lakes: Special Features and Changes. Tallinn, p. 128.
Paal, J., 2007. Loodusdirektiivi elupaigatüüpide käsiraamat. Teine, parandatud ja täiendatud trükk. Tallinn, Auratrükk. p. 308 (in Estonian). https://dspace.ut.ee/items/0c27cc7d-f9cd-4a3f-8aa0-e220ff352dad (Accessed 24 April 2024).
Pursiainen, A., Veneranta, L., Kuningas, S., Saarinen, A., Kallasvuo, M., 2021. The more sheltered, the better – coastal bays and lagoons are important reproduction habitats for pike in the northern Baltic Sea. Estuar. Coast Shelf Sci. 259, 107477.
Raukas, A., 2000. Rapid changes of the Estonian coast during the late glacial and Holocene. Mar. Geol. 170 (1–2), 169–175. https://doi.org/10.1016/S0025-3227(00)00072-4.
Rosentau, A., Vassiljev, J., Hang, T., Kalm, V., 2009. Development of the baltic Ice Lake in the eastern baltic. Quat. Int. 206, 16–23.
Rosentau, A., Veski, S., Kriiska, A., Aunap, A., Vassiljev, J., Saarse, L., Hang, T., Heinsalu, A., Oja, T., 2011. Palaeogeographic model for the SW Estonian coastal zone of the Baltic Sea. In: Harff, J., Björck, S., Hoth, P. (Eds.), The Baltic Sea Basin. Springer, Heidelberg, Dordrecht, Berlin, New York, pp. 165–188.
Rosentau, A., Nirgi, T., Muru, M., Bjursäter, S., Hang, T., Preusser, F., Risberg, J., Sohar, K., Tõnisson, H., Kriiska, A., 2020. Holocene relative shore level changes and stone age hunter-gatherers in Hiiumaa island, eastern Baltic Sea. Boreas 49 (4), 783–798.
Rosentau, A., Klemann, V., Bennike, O., Steffen, H., et al., 2021. A Holocene relative sea-level database for the Baltic Sea. Quat. Sci. Rev. 266, 107071.
Saarse, L., Vassiljev, J., Miidel, A., 2003. Simulation of the Baltic Sea shorelines in Estonia and neighbouring areas. J. Coast Res. 19, 261–268.
Salomonson, A., Katajisto, J., Sedin, A., 2006. Coastal lagoons in Sweden and Finland. In: Hurford, C., Schneider, M. (Eds.), Monitoring Nature Conservation in Cultural Habitats. Springer, Dordrecht. https://doi.org/10.1007/1-4020-3757-0_34.
Sander, K., Kriiska, A., 2022. An integrated result of GIS-based approach to palaeogeographical reconstructions and archaeological surveys of coastal palaeolagoons at the mouths of the rivers Vihterpalu, Teenuse and Velise (western Estonia). Est. J. Archaeol. 26 (2), 184–208.
Sepp, M., Tamm, T., Sagris, V., 2018. The future climate regions in Estonia. Est. J. Earth Sci. 67 (4), 259–268. https://doi.org/10.3176/earth.2018.19.
Soomere, T., Behrens, A., Tuomi, L., Nielsen, J.W., 2008. Wave conditions in the baltic proper and in the Gulf of Finland during windstorm gudrun. Nat. Hazards Earth Syst. Sci. 8, 37–46.
Soria, J., Pérez, R., Sòria-Pepinyà, X., 2022. Mediterranean coastal lagoons review: sites to visit before disappearance. J. Mar. Sci. Eng. 10, 347.
Suursaar, Ü., Jaagus, J., Kont, A., Rivis, R., Tõnisson, H., 2008. Field observations on hydrodynamic and coastal geomorphic processes off Harilaid Peninsula (Baltic Sea) in winter and spring 2006−2007. Estuar. Coast Shelf Sci. 80 (1), 31–41.
Suursaar, Ü., Jaagus, J., Tõnisson, H., 2015. How to quantify long-term changes in coastal sea storminess? Estuar. Coast Shelf Sci. 156, 31–41.
Suursaar, Ü., Kall, T., 2018. Decomposition of relative Sea Level variations at tide gauges using results from four Estonian precise levelings and uplift models. IEEE JSTARS 11 (6), 1966–1974.
Suursaar, Ü., Rosentau, A., Hang, T., Tõnisson, H., Tamura, T., Vaasma, T., Vandel, E., Vilumaa, K., Sugita, S., 2022. Climatically induced cyclicity recorded in the morphology of uplifting Tihu coastal ridgeplain, Hiiumaa Island, eastern Baltic Sea. Geomorphology 404, 108187.
Tagliapietra, D., Sigovini, M., Ghirardini, A.V., 2009. A review of terms and definitions to categorise estuaries, lagoons and associated environments. Mar. Freshw. Res. 60, 497e509.
Tolvanen, H., Numminen, S., Kalliola, R., 2004. Spatial distribution and dynamics of special shore-forms (Tombolos, flads and glo-lakes) in an uplifting archipelago of the Baltic Sea. J. Coast Res. 20 (1), 234–243.
Torn, K., Herkül, K., Martin, G., Oganjan, K., 2017. Assessment of quality of three marine benthic habitat types in northern Baltic Sea. Ecol. Indicat. 73, 772–783.
Torn, K., Peterson, A., Herkül, K., Suursaar, Ü., 2019. Effects of climate change on the occurrence of charophytes and angiosperms in a brackish environment. Webbia 74 (1), 167–177.
Torn, K., 2020. Väärtuslike mereliste elupaigatüüpide hindamise puudujääkide kõrvaldamine. KIK. Tallinn, p. 61. https://www.envir.ee/media/446/download. (Accessed 24 February 2024) (in Estonian).
Tõnisson, H., Orviku, K., Jaagus, J., Suursaar, Ü., Kont, A., Rivis, R., 2008. Coastal damages on Saaremaa island, Estonia, caused by the extreme storm and flooding on January 9, 2005. J. Coast Res. 24 (3), 602–614.
Vassiljev, J., Saarse, L., Grudzinska, I., Heinsalu, A., 2015. Relative sea level changes and development of the Hiiumaa Island, Estonia, during the Holocene. Geol. Q. 59, 517–530.
Veski, S., Heinsalu, A., Klassen, V., Kriiska, A., Lõugas, L., Poska, A., Saluäär, U., 2005. Early Holocene coastal settlement and palaeoenvironment on the shore of the Baltic Sea at Pärnu, southwestern Estonia. Quat. Int. 130, 75–85.
Vestøl, O., Ågren, J., Steffen, H., Kierulf, H., Tarasov, L., 2019. NKG2016LU: a new land uplift model for Fennoscandia and the Baltic region. J. Geodyn. 93, 1759–1779.
Weisse, R., Dailidiene, I., Hünicke, B., Kahma, K., Madsen, K., Omstedt, A., Parnell, K., Schöne, T., Soomere, T., Zhang, W., Zorita, E., 2021. Sea level dynamics and coastal erosion in the Baltic Sea region. Earth Syst. Dyn. 12, 871–898.