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SPATIOTEMPORAL FEATURES OF COASTAL WATERS IN SOUTHWEST FINLAND

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TURUN YLIOPISTON JULKAISUJA – ANNALES UNIVERSITATIS TURKUENSIS
Sarja - ser. A II osa - tom. 305 | Biologica - Geographica - Geologica | Turku 2015

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ISBN 978-951-29-6151-1 (PRINT)
ISBN 978-951-29-6152-8 (PDF)
ISSN 0082-6979
Painosalama Oy - Turku, Finland 2015

ABSTRACT

In coastal waters, physico-chemical and biological properties and constituents vary at different time scales. In the study area of this thesis, within the Archipelago Sea in the northern Baltic Sea, seasonal cycles of light and temperature set preconditions for intra-annual variations, but developments at other temporal scales occur as well. Weather-induced runoffs and currents may alter water properties over the short term, and the consequences over time of eutrophication and global changes are to a degree unpredictable. The dynamic characteristics of northern Baltic Sea waters are further diversified at the archipelago coasts. Water properties may differ in adjacent basins, which are separated by island and underwater thresholds limiting water exchange, making the area not only a mosaic of islands but also one of water masses.

Long-term monitoring and *in situ* observations provide an essential data reserve for coastal management and research. Since the seasonal amplitudes of water properties are so high, inter-annual comparisons of water-quality variables have to be based on observations sampled at the same time each year. In this thesis I compare areas by their temporal characteristics, using both inter-annual and seasonal data. After comparing spatial differences in seasonal cycles, I conclude that spatial comparisons and temporal generalizations have to be made with caution. In classifying areas by the state of their waters, the results may be biased even if the sampling is annually simultaneous, since the dynamics of water properties may vary according to the area. The most comprehensive view of the spatiotemporal dynamics of water properties would be achieved by means of comparisons with data consisting of multiple annual samples. For practical reasons, this cannot be achieved with conventional *in situ* sampling. A holistic understanding of the spatiotemporal features of the water properties of the Archipelago Sea will have to be based on the application of multiple methods, complementing each other's spatial and temporal coverage. The integration of multi-source observational data and time-series analysis may be methodologically challenging, but it will yield new information as to the spatiotemporal regime of the Archipelago Sea.

Keywords: Baltic Sea, Archipelago Sea, water quality, time series, waves, salinity, turbidity

TIIVISTELMÄ

Rannikkovesien fysikaalis-kemialliset ja biologiset ominaisuudet vaihtelevat eri ajanjaksoissa. Saaristomerellä veden ominaisuuksia ja aineiden kiertoa säätelee ennen kaikkea valon, lämpötilan ja biologisen toiminnan voimakas vuodenaikaisuus. Sää vaikuttaa lyhytaikaisesti jokien valumiin ja meren virtauksiin, toisaalta ravinteiden ylimäärä on johtanut vedenlaadun pitkäaikaismuutoksiin ja hitaasti etenevät globaalimuutokset vaikuttavat osin tuntemattomalla tavalla. Saaristomeren vesien dynamiikkaan vaikuttavat lisäksi vedenalaiset kynnykset ja saaret, jotka ohjaavat vesien kulkeutumista. Saaristomeri ei siis ole pelkästään saarten, vaan myös altaiden ja vesimassojen mosaiikki, jossa harva veden ominaisuus on pysyvä.

Vesien tilan pitkäaikaisseuranta tarjoaa taustatietoa monille tutkimusaloille sekä välttämättömän tietovarannon vesien hoidon ohjaamiseksi. Pitkäaikaismuutosten seuraaminen edellyttää vertailukelpoisia, vuosittain samaan aikaan kerättyjä havaintoja. Lyhyeen vuosittaiseen jaksoon perustuva otanta voi kuitenkin johtaa erilaisiin johtopäätöksiin kuin siinä tapauksessa, että alueita vertailtaisiin niiden koko vuoden kehityksen perusteella. Vuodenaikaiskierrossa voi tapahtua muutoksia mm. ajoituksessa ja vaihteluväleissä, eikä näitä muutoksia pystytä seuraamaan muuten kuin ajallisesti riittävän tiheällä näytteenotolla.

Väitöskirjani keskeisin kysymys on, miten yleisimpien meriveden ominaisuuksien vuodenaikaiskierrot vertautuvat alueellisesti. Esimerkiksi pintaveden lämpötilan vuodenkierto toistuu samankaltaisena sijainnista riippumatta, sameuden vuodenkiertoon vaikuttavat puolestaan useat tekijät, joiden merkitys vaihtelee alueittain eri aikoina. Yleistyksien tekemisessä on siis oltava varovainen, kun veden ominaisuuksia kuvaavia havaintotietoja käytetään päätöksenteon tai tutkimuksen taustatietoina. Alueiden luokittelu koko vuodenaikaiskehityksen mukaan on osoittautunut haastavaksi tehtäväksi, sillä se mm. edellyttää useiden, toisiaan alueellisesti ja ajallisesti täydentävien aineistolähteiden käyttöä. Vuodenaikaisvaihteluiden kehityskulkujen alueellinen vertailu avaa kuitenkin uusia näkökulmia rannikkovesitutkimukseen, ja se saattaa auttaa selvittämään Saaristomeren vedenlaatuun vaikuttavien tekijöiden syy-seuraus suhteita.

Avainsanat: Itämeri, Saaristomeri, vedenlaatu, aikasarjat, aallot, suolapitoisuus, sameus

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LIST OF ORIGINAL PUBLICATIONS

This thesis consists of a summary and the following five articles, referred to in the text by Roman numerals:

I Tolvanen, H. & T. Suominen 2005. Quantification of openness and wave activity in archipelago environments. *Estuarine, Coastal and Shelf Science* 64, 436-446.

II Suominen, T., H. Tolvanen & R. Kalliola 2010. Geographical persistence of surface-layer water properties in the Archipelago Sea, SW Finland. *Fennia* 188, 179–196.

III Suominen, T., Tolvanen, H. & R. Kalliola 2010. Surface layer salinity gradients and flow patterns in the archipelago coast of SW Finland, northern Baltic Sea. *Marine Environmental Research* 69, 216-226.

IV Tolvanen, H., T. Suominen & R. Kalliola *2013.* Annual and long-term water transparency variation and the consequent seafloor illumination dynamics in the Baltic Sea archipelago coast of SW Finland*. Boreal Environment Research* 18, 446-458.

V Suominen, T. & H. Tolvanen. From fragmental remote sensing imagery to information in a heterogeneous environment: temporal analysis of turbidity in a coastal archipelago. Submitted manuscript.

1. INTRODUCTION

In coastal waters marine and fresh water characteristics may alternate, and physico-chemical water properties interact with the living environment accordingly (Gasiūnaitė et al. 2005, Hoikkala 2012, Kowalczuk 1999). Fresh waters carry substances filtrated through the natural environment and human activities. As they end up in the sea, these substances start their four-dimensional cycle; some accumulate on the seafloor, others dissolve or remain in the form of suspended solids in the water, yet others are altered by physical, chemical or biological processes. Prevailing currents, waves, and the climate, with variable weather conditions, induce vertical and horizontal water movements, induced by the shoreline and by bathymetry (Danielson et al. 2007, Siegel et al. 2004, Soomere & Viška 2014). There is consequently little that is static in coastal seas, since at any given moment the waters are subject to ongoing long-term developments, cycles of varying lengths, and random variations.

With time, however, some patterns or trends may become detectable. Assessments based on long-term data series provide a wider view, allowing future predictions and making it possible to react to unwanted developments (e.g. Carstensen et al. 2011, Erkkilä & Kalliola 2007, Ferreira et al. 2011, Dupont & Aksnes 2013, Fleming-Lehtinen & Laamanen 2012). It is not only the values of sea-water properties that change over the long term. Seasonal cycles reflect climate-driven, annually repeated chains of interactions; physico-chemical processes interact with the living environment; and seas are affected by their adjacent basins in a predictable manner. The timing and magnitude of these seasonal patterns may alter due to global changes, climate change in particular (BACC Author team 2008, HELCOM 2013), and these responses cannot be recognized without a holistic view of coastal processes, in both a spatial and a temporal sense.

In this thesis I scrutinize temporal aspects of selected physico-chemical properties of the coastal waters in the Archipelago Sea, located off the southwest coast of Finland. The emphasis is on seasonal development, more specifically on the open-water season. Seasonal changes during the ice-free period can be wide-ranging and rapid, but many of these processes have temporal and spatial patterns which are to a degree predictable. Physico-chemical water properties still play an important role in contemporary monitoring designs, which emphasize the health of the living environment as a measure of the state of the marine environment (EC European Commission 2000, EC European Commission 2008). Without knowing the abiotic components of habitats, it is impossible to form a comprehensive view as to the interactions between biological, chemical and physical environmental processes.

The existing scientific literature concerning the water properties of the Archipelago Sea region lacks assessment of its dynamic spatiotemporal nature, due in part but not entirely to a lack of observational data; observations of water properties for the Archipelago Sea and its neighboring basins are available for example in the databases of the Finnish Environment Institute (SYKE), the Swedish Meteorological and Hydrological Institute (SMHI), and the International Council for the Exploration of the Sea (ICES). Water quality off the Finnish coasts is mainly assessed by regular observations at 150 sites collected two to four times a year, at a minimum in February and in July (Niemi 2009). Seasonal developments are monitored at sixteen sites, located along the coast and sampled 15-20 times annually. Especially a few decades ago the focus was on the detection of eutrophication, as indicated by seawater chemistry. Monitoring programs were designed accordingly, and variables related to eutrophication continue to be foregrounded. One challenge relating to the use of Finnish monitoring data is their inconsistency; in addition to the 166 observation sites mentioned, the databases also include data from numerous short-lived sites, whose applicability for scientific purposes is limited (Erkkilä & Kalliola 2007).

Using *in situ* methods alone, it is difficult to collect adequate data for an analysis of cyclical water properties (Raateoja et al. 2005, Rantajärvi et al. 1998). In the absence of continuous data, and in coastal waters with large seasonal cycles, only observations sampled during the same period of the year can be compared; otherwise long-term trends will be obscured by seasonal variation. The late summer has become a more or less accepted period in terms of many other data needs in addition to long-term monitoring, despite the narrow and in some cases inadequate view it offers.

A variety of integrated methods is needed to extend the spatial and temporal coverage of observations. Satellite imagery and ocean remote sensing data products are now available from various web services mandated by the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). There are prejudices against the use of remote sensing in operative coastal zone monitoring and management (Schaeffer et al. 2013), but methodological advances in the remote sensing of coastal waters have extended their use in new research domains (Alvera-Azcárate et al. 2013). The focus in ocean color studies has been on instrument and algorithm development; together with the more liberal data policy, it has greatly improved the applicability of remote sensing to practical coastal management (Kratzer al 2014 , Ferreira et al. 2011, Gohin et al. 2008).

Spatial data with rich marine information is also available from web- based map services (O’Dea et al. 2011), many of them also covering the Baltic Sea (e.g. HELCOM, EMODnet). However, despite such technical advances and their relevance to visualizing the issue, at present it is challenging to apply many of these sources in scientific research; their usefulness is limited due to their unsuitable spatial or temporal coverage and their limited accuracy, processing level, and/or provision of metadata. This reflects the dynamic nature of the study area, and of coastal waters in general; it is impossible to represent all the dimensions of coastal seas in a single map or publication. If we need accurate information as to how the water properties in the Archipelago Sea vary in the course of the year, the answer must thus essentially be sought from the databases or from remote sensing data at lower processing levels. In the papers included in this thesis, I present methods whereby aspects of the spatiotemporal characteristics of the area may be clarified; eventually, however, the methods of data analysis are determined by the research question at hand in each specific case.

The focus of the thesis has evolved in the course of the work. Initially it was clear that I would deal with the water properties and their time series analyses. The further the research progressed, the more interested I became in the question of how different types of seasonal cycles within the Archipelago Sea can be compared spatially and how persistent they are.

The objectives of the study thus are:

1. To identify areas of spatially divergent seasonal development in the Archipelago Sea.
2. To find means to define and visually display temporal characteristics in its water properties.
3. To evaluate the impact of different temporal developments on the features of coastal habitats and the physical environment.

The themes associated with these goals are dealt with in the five original scientific papers, summarized below.

Paper I: Wave exposition. Waves induce geomorphological processes in littoral zones, but in the Archipelago Sea the quantification of wave exposure is hindered by the fragmental shoreline shapes. We applied GIS for cartographic fetch calculations, weighted acquired fetches with wind data, and evaluated wave power on a selected shoreline. Intensive storm events can influence habitats and geomorphological processes, and inter-annual variations in total wave power were found to be substantial.

Paper II: Spatial persistence. We selected five variables reflecting the properties of surface layer waters (temperature, salinity, Secchi, chlorophyll and acidity) and studied their spatiotemporal characteristics from May to October 2007. The fieldwork involved 22 observation sites in the inner and middle Archipelago Sea, which were visited eight times during open water season. Our purpose was to determine whether spatial properties are temporally persistent through the summer: in other words, whether we would find regular relative differences in water properties between observation sites or spatially divergent seasonal developments. To widen the temporal view, we also used long-term data to evaluate the inter-annual persistence of water properties.

Paper III: Salinity. Field observations of salinity from paper II, observations from the water quality database HERTTA, and additional data obtained from the Åland Environmental and Health Protection Authority were applied to evaluate salinity gradients, their seasonal development and water flow patterns in the Archipelago Sea. We tailored an interpolation method to the complex archipelago environment and found that the general spatial salinity patterns reflect the common conception that waters flow northward through the area. There was seasonal fluctuation in salinity, but we also found non-seasonal salinity fluctuations in the long term data, probably reflecting broader developments in the Baltic Sea. Using salinity as a tracer, we also determined a mean residual flow rate through the Archipelago Sea.

Paper IV: Underwater light conditions. We evaluated seasonal changes in the area of euphotic seafloor in the Archipelago Sea, based on bathymetry and several transparency maps during the open water season. Since the Secchi depth varies considerably during the growing season and the seafloor slopes are gentle, areal changes in the euphotic seafloor were also found to be considerable. We also estimated the historical development from the 1930s to the present, concluding that the euphotic seafloor has diminished to half of its original extent in less than a hundred years. This sharp a decrease in the euphotic seafloor cannot leave the benthic ecosystems unchanged.

Paper V: Turbidity. The Archipelago Sea is topographically fragmented, its water properties dynamic and its waters optically complex. All these characteristics hinder the usability of remote sensing data in water-quality mapping and monitoring. Remote sensing, with its extensive spatial and temporal coverage, is nevertheless the most efficient way to form a holistic view of selected water properties in coastal waters as well. We applied linear temporal averaging to produce turbidity time series applicable in temporal image compilations, and identified zones with different turbidity dynamics. The relevance of seasonal variation for monitoring design as well as habitat formation is also discussed.

2. COASTAL SEAS AS AREAS OF INTEREST

2.1 Pressures, research and management

Coastal areas are locales of interaction among multiple simultaneous processes, the equilibrium of which is sensitive to disturbances. Waves, tides and ocean currents, with the addition of aeolian and fluvial processes, are physically shaping the shoreline. Due to the resulting erosion, transport and accumulation, coastal areas are high in geodiversity, including sedimentary and rocky coasts, tidal flats, salt marshes, estuaries and deltas.

Water itself has unique physico-chemical properties, and is able to transport both matter and energy. Suspended and solute matter and compounds are moving in three dimensions, and coastal waters have typically transitional characteristics, where the terrestrial influence on the properties of sea water gradually diminishes with distance from the shore. Coastal water exchange may be limited due to geomorphology, making them particularly vulnerable to global changes, such as higher temperatures, floods, and changes in sediment dynamics (Newton et al. 2014).

The natural and economical values of the coastal seas are significant from a human perspective, providing both material and immaterial ecosystem services (Barbier et al. 2011). Geodiversity, the availability of nutrients, and diverse habitats facilitate high biodiversity in the littoral zone. Biodiversity and high rates of primary production, transportation facilities and an often favorable climate have led to concentrations of human populations in coastal areas (DiDonato et al. 2009, UNEP 2007, Wheeler et al. 2012). With increasing pressure toward economic exploitation of the seas, human activities may confront issues of environmental values. Eutrophication, pollution, and losses in biodiversity are examples of syndromes encountered by the coastal seas and shores (Newton et al. 2012). Direct threats are concentrated on coasts which are heavily affected by human influence, but coasts are also targets of long-range problems: estuarine eutrophication has its origin in river basins, pollutants are diffused along coasts, and invasive species travel globally (Korpinen et al. 2012, Newton et al. 2012).

The consolidation of different objectives therefore requires ecosystem-based planning and management (Douvere 2008). The importance of accurate knowledge concerning seawater properties is obvious; planning and management cannot be carried out without information as to the interactions and development of the biotic and abiotic marine environment. Despite the planning and management of the last decades, environmental degradation has not been reversed, since economic and social changes operate increasingly at greater temporal and spatial scales than management regimes (Mee 2012). While we know a great deal about the structures of marine systems, our knowledge concerning their functions is much less developed (Borja et al. 2010). Understanding marine functions and interactions requires accurate observational data on physical, chemical and biological water properties. In this context the temporal aspects of sampling have to be considered. Typically sampling is designed to capture problematic time periods, although ideally samples would be taken year round to observe also the baseline (Ferreira et al. 2011). In areas for example with less well developed seasonality, a sampling of the whole annual cycle may be more appropriate; despite limited resources, new technologies, such as remote sensing, facilitate a multi-source approach to data gathering, with more extensive spatial and temporal coverage (Ferreira et al. 2010, Gohin et al. 2008). Building a chain from remote-sensing scientists to coastal zone managers requires constant feedback in both directions, but the process has proved to be very useful (Kratzer et al. 2014).

2.2 The Baltic Sea

The Baltic Sea is a brackish marginal sea, with one outlet via the Danish Straits in the south. Sills in the Danish straits are shallow, 18 meters at their deepest. The water exchange with the North Sea usually depends on sea-level differences, and these minor in- and outflows maintain the salinity conditions in the Baltic Sea. Larger intrusions of oceanic waters occur on average at ten-year intervals (Leppäranta & Myrberg 2009). Hänninen et al. (2000) connected the occurrence of saline water intrusions and alterations in fluvial inputs to climatic factors of the Atlantic, and ultimately to the Northern Atlantic Oscillation (NAO). The high net freshwater supply (480 km^3/yr an average) to the Baltic Sea, combined with inflows of oceanic waters from the south, leads to vertical stratification, mainly due to salinity differences. Horizontally, surface layer salinity gradually decreases from 8-12 ‰ near the entrance of the Baltic Sea to less than 3 ‰ at the end of the Bothnian Bay and the Gulf of Finland in the north and east (Rodhe 1999). In the main basin, the halocline typically forms at depths of 40-80 m. The halocline is at its weakest in the Gulf of Bothnia, where the waters are more shallow, but it still prevents the mixing of the entire water body (Leppäranta & Myrberg 2009). There is a relatively persistent cyclonic, i.e. counter-clockwise upper-layer circulation pattern in the Baltic Sea, with an average speed of approximately 5 cm s^{-1}, and weak cyclonic circulation also occurs in the sub-basins of the Baltic Sea (Palmén 1930, Leppäranta & Myrberg 2009). Due to this circulation pattern, waters off the eastern coasts of the Baltic Sea are slightly warmer and more saline than those off the western coasts.

Located at relatively high latitudes, between 54° N and 66° N, the seasonal variability of solar radiation, temperature and available light regulate the seasonal cycles of many physical, chemical and biological features in the Baltic Sea. The northern parts of the sea are ice-covered during winters; in normal winters the northernmost Bay of Bothnia freezes by mid-January and the sea areas south to the Gulf of Riga a month later, but in mild winters freezing affects only the Bay of Bothnia and the easternmost Gulf of Finland (Leppäranta & Myrberg 2009). Surface layer temperatures are accordingly highly variable. In the summer months temperatures in the open sea rise to 15-20 C°. Waters above the halocline become thermally stratified in the summer, forming a thermocline at a depth of 10-20 m. In the autumn, surface layer waters grow colder and thermal stratification ends, resulting in vertical mixing of the water column above the halocline. In shallow waters, where a halocline does not form, mixing reaches the seafloor.

Optically the Baltic Sea is classified as Case-2 waters (Kratzer et al. 2008, Attila et al. 2013), indicating that the optical properties of the water are affected not only by the chlorophyll concentration, but also by suspended particulate matter (SPM) and colored dissolved organic matter (CDOM) (Morel & Prieur 1977). In the open sea, optical properties are dominated by CDOM, originating from both autochthonous biological production and allochthonous sources along with high freshwater input of the Baltic Sea. Cyanobacterial blooms are also frequent (HELCOM 2009, Kahru et al. 2007, Rantajärvi et al. 1998), notably affecting the optical properties of the seawater typically in the late summer. Near the coast, river loads increase the concentrations of CDOM (Asmala et al. 2012, Kowalczuk et al. 2006). Inorganic suspended matter and sediment resuspension from shallow bottoms occur especially off the eastern coast of the Baltic Sea basin (Danielsson et al. 2007). Ice cover, inorganic and organic suspended matter, CDOM and algal blooms affect the spatial and temporal distribution of water transparency, which has shown a long-term decreasing trend (Dupont & Aksnes 2013, Fleming-Lehtinen & Laamanen 2012). The availability of underwater PAR in coastal zones thus has a highly varying inter-annual cycle (Luhtala et al. 2013).

The mean depth of the Baltic Sea is 54 m and its surface area is 393 000 km^2. Its low volume (21 200 km^3), limited water exchange and densely populated drainage area, with 85 million inhabitants, makes the Baltic Sea vulnerable to environmental threats. Human-induced eutrophication, i.e. increased primary production due to excessive flow of nutrients to seawater, is a distinctive and commonly acknowledged environmental problem in the Baltic Sea (Bonsdorff et al. 2002, HELCOM 2009), and is one of the key agents promoting pelagic and littoral ecosystem change in the region (Rönnberg & Bonsdorff 2004).

Global warming has induced extensive studies of sea temperature in the Baltic Sea too. The BACC Author team (BALTEX Assessment of Climate Change for the Baltic Sea Basin 2008) presented a comprehensive report on past and present climatological and hydrological features of the Baltic Sea, and projected the effects of future climate change on the physical and living environment. Siegel at al. (2006), basing their observations on remote sensing data from 1990 to 2004, reported an increase of 0.8 K in surface layer temperatures over 15 years. Lehmann et al. (2011), using the years 1990-2008, presented an increase of 0.8 to 1°C $decade^{-1}$ for the Gulf of Bothnia and the Gulf of Finland. The largest changes in Baltic Sea surface temperatures are projected to occur in the Gulf of Bothnia in the summer and in the Gulf of Finland in the spring, together with a decrease in sea-ice coverage in winters (HELCOM 2013). The total impact of climate change is still unclear, but model projections predict that especially winter precipitation will increase and the melt season may be earlier. The predicted changes in precipitation and discharges may lead to decreased salinity, increased nutrient loads, and consequent changes in other biogeochemical cycles in the Baltic Sea (HELCOM 2013).

2.3 Study area of this thesis: the Archipelago Sea

The three major basins of the Baltic Sea — the Gotland Basin in the south, the Gulf of Finland in the southeast, and the Gulf of Bothnia in the north – meet in the Archipelago Sea (Fig. 1). This sea area consists of 25 000 islands larger than 500 m^2 and 14 400 km of shoreline, in an area of approximately 10 000 km^2 (Granö et al. 1999). The area is structured by fragmental bedrock, with an elevation range of about two hundred meters. The bedrock is partly covered with till, glaciofluvial deposits and marine sediments. The average depth of the Archipelago Sea is approximately 20 meters, typically ranging from 0 to 50 m, with some deeps and fault lines exceeding 100 m.

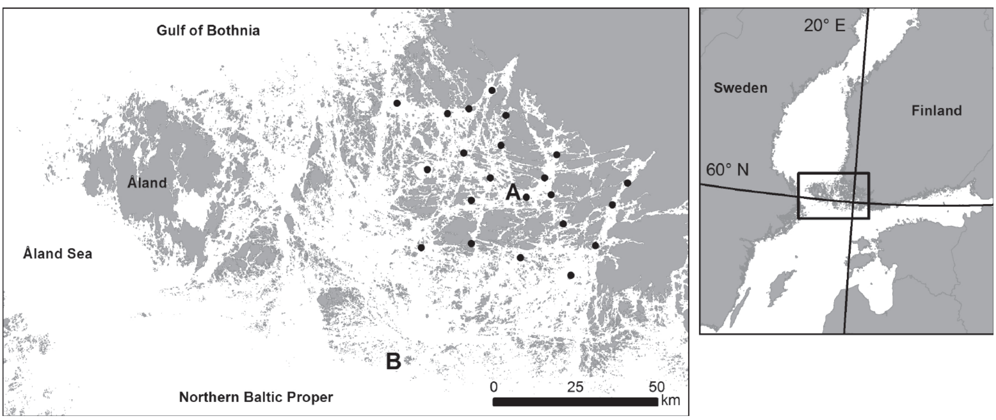

Fig. 1. Archipelago Sea in northern Baltic Sea. Black dots indicate observation sites of fieldwork carried out in 2007. A and B indicate two sites of intensive water quality monitoring.

Water flow velocities are typically less than 10 cm s^{-1} (Virtaustutkimuksen neuvottelukunta 1979). The counter-clockwise upper-layer circulation pattern in the Baltic Sea basin causes a net flow from south to north through the Archipelago Sea and a southward flow along the Swedish coast and in the upper layer of the Åland Sea (Hietala et al. 2007, Myrberg & Andrejev 2006). The water exchange through the Archipelago Sea is estimated as low compared to the Åland Sea (Kullenberg 1981, Omsted et al. 2004). Islands and underwater sills form numerous local sea basins at various scales in the archipelago, resulting in a complex transitional system where the fresh water runoff mixes with the brackish sea water of the adjacent main basins.

For the most part there is no permanent halocline in the Archipelago Sea (Leppäranta & Myrberg 2009). In normal sea-ice years, a permanent ice cover forms for a period of 3-4 months. In the summers the surface layer temperature in the turbid and shallow inner bays may rise to over 20 °C. A thermocline forms at a depth of 10-20 m in the early summer. In November-December this summer stratification is interrupted by vertical circulation, resulting in a mixing of the water column.

Southwest Finland is an agricultural landscape: almost a third of the continental drainage area consists of fields, the rest mainly of forest (Fig 2). River basins with outlets on the coast of the Archipelago Sea are small but many, and they are rather evenly distributed along the coast (Fig. 2). With their drainage areas in forest, in fields on fine-grained former sea-bottom sediments, and in peatlands, the rivers collect SPM and CDOM. The river estuaries are thus turbid; as the waters are shallow and mosaic, turbidity persists until more open sea is reached, where the terrestrial waters mix with the surrounding marine waters. The resuspension of marine sediments also occurs in shallow waters, where the seafloor may be disturbed by wave activity.

Agriculture is responsible for 64 % of the phosphorus load and 37 % of the nitrogen entering the area (Varsinais-Suomen ELY-keskus 2011). The next largest source involves long-range air loads (12 % of P and 37 % of N). These numbers, however, do not include nutrient exchange processes with adjacent basins. It is also worth noting that the amount of nutrients and sediments carried to the sea by rivers during the autumn and winter months was higher in 1990-2009 than in 1970-1989, due to the milder winters; this may signal the changes accompanying climate change (Varsinais-Suomen ELY-keskus 2011). The Archipelago Sea retains much of the nutrients in the waters that flow through the area (Varsinais-Suomen ELY-keskus 2011). Due to nutrient loads from agriculture and forestry, long-range air loads, municipal waste waters and natural river loads, the effects of eutrophication are severe in the Archipelago Sea as well (Bonsdorff et al. 2002, Rönnberg & Bonsdorff 2004, Varsinais-Suomen ELY-keskus 2011). Excessive primary production in the euphotic layer induces a high rate of decomposition in bottom-layer waters. During the summer the thermocline hinders vertical mixing, resulting in possible hypoxic conditions. This is harmful to the bottom fauna, but under hypoxic conditions the flux of dissolved inorganic phosphorus from the sediments to the overlying waters may increase as well (Conley et al. 2011, Puttonen et al. 2014, Virtasalo et al. 2005). When this internal nutrient load ends up in the surface waters, in the autumn at the latest, it may further perpetuate the cycle of eutrophication.

While the term "eutrophication" refers to the biological state of waters, it has implications for the chemical and physical environment as well. Underwater Photosynthetically Active Radiation (PAR) is insufficient for photosynthesis in the winters and under ice. The scarcity of phytoplankton in the winters leads to the accumulation of nutrients in the seawater. The annual peak for phytoplankton is in the spring, when underwater light increases sharply, due to both increasing PAR and ice melt. Combined with the turbid melting waters, this process leads to increased turbidity. The waters grow clearer in late May-early June, after the nutrients are consumed and the zooplankton starts to regulate the phytoplankton. In July-August, however, cyanobacteria start to dominate in the warmed surface waters, reducing the subsurface PAR. Eutrophication is signaled by algal blooms, which are frequent especially in the southern parts of the Archipelago Sea. Towards autumn the abundance of phytoplankton gradually decreases.

The developments described above are visible in surface layer (1 m) temperature, salinity and Secchi depth at two long-term monitoring sites, indicated as A and B (Fig. 1 and 3). Site A (NAU2361) is located in the middle Archipelago Sea, some 30 kilometers from the city of Turku. Further off, some 60 km to the southwest, site B (KORP200) is located at the edge of the pelagic Baltic Proper, near the island of Utö. Both sites are sampled 15-20 times annually for a wide range of variables. The data for this example were downloaded from the water quality database HERTTA (Finnish Environment Institute 2014c). In the left-hand panel, the annual cycle is shown as the weekly means for 1999-2013; in the right-hand panel, the developments of the past 15 years are shown as the means for five-week periods in early and late summer.

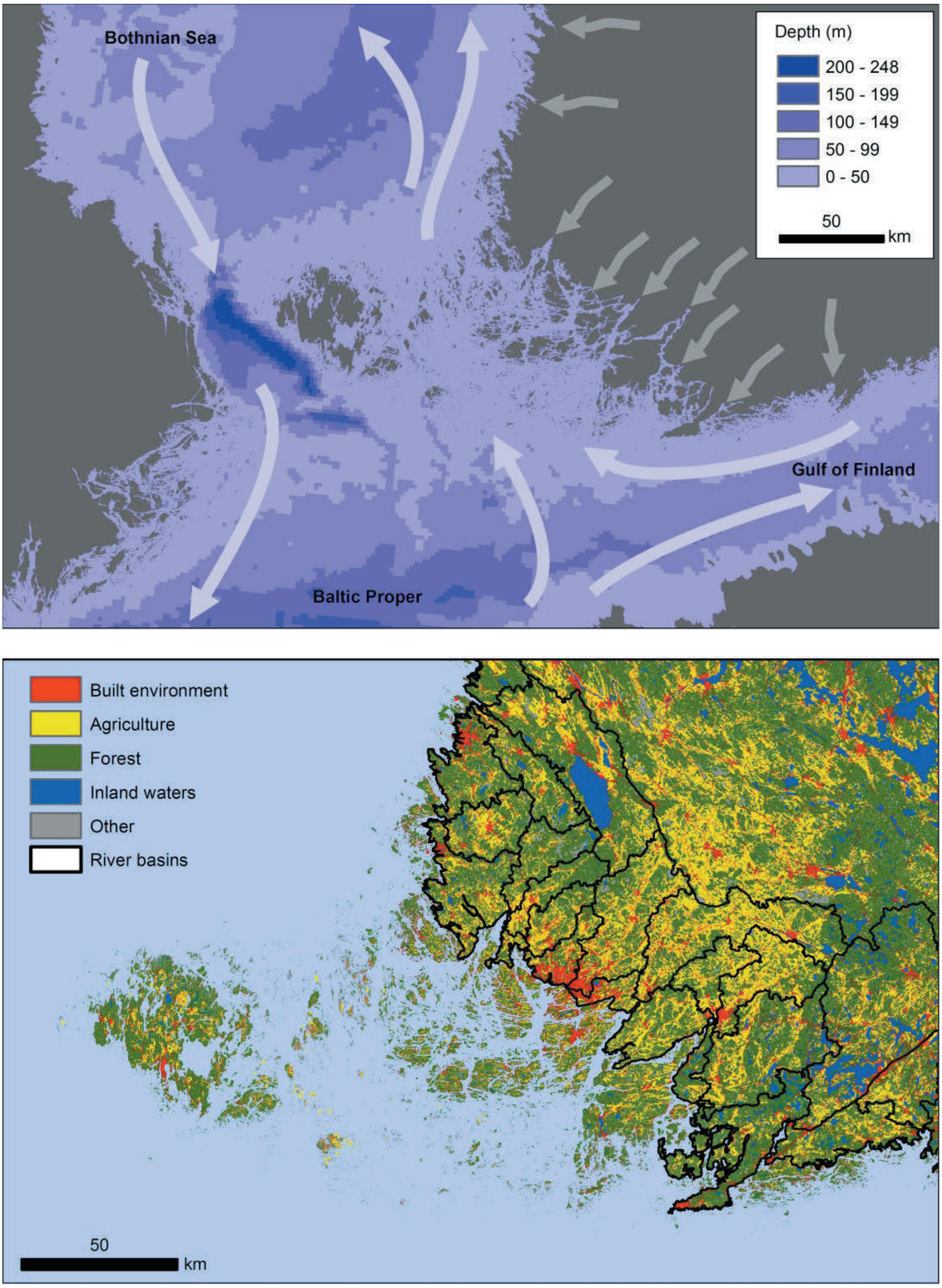

Fig. 2. Upper panel: Baltic Sea circulation pattern surrounding the Archipelago Sea, and rivers discharging into the coastal waters of SW Finland. Lower panel: Land use and catchment areas of SW Finland (Finnish Environment Institute 2014a and 2014b).

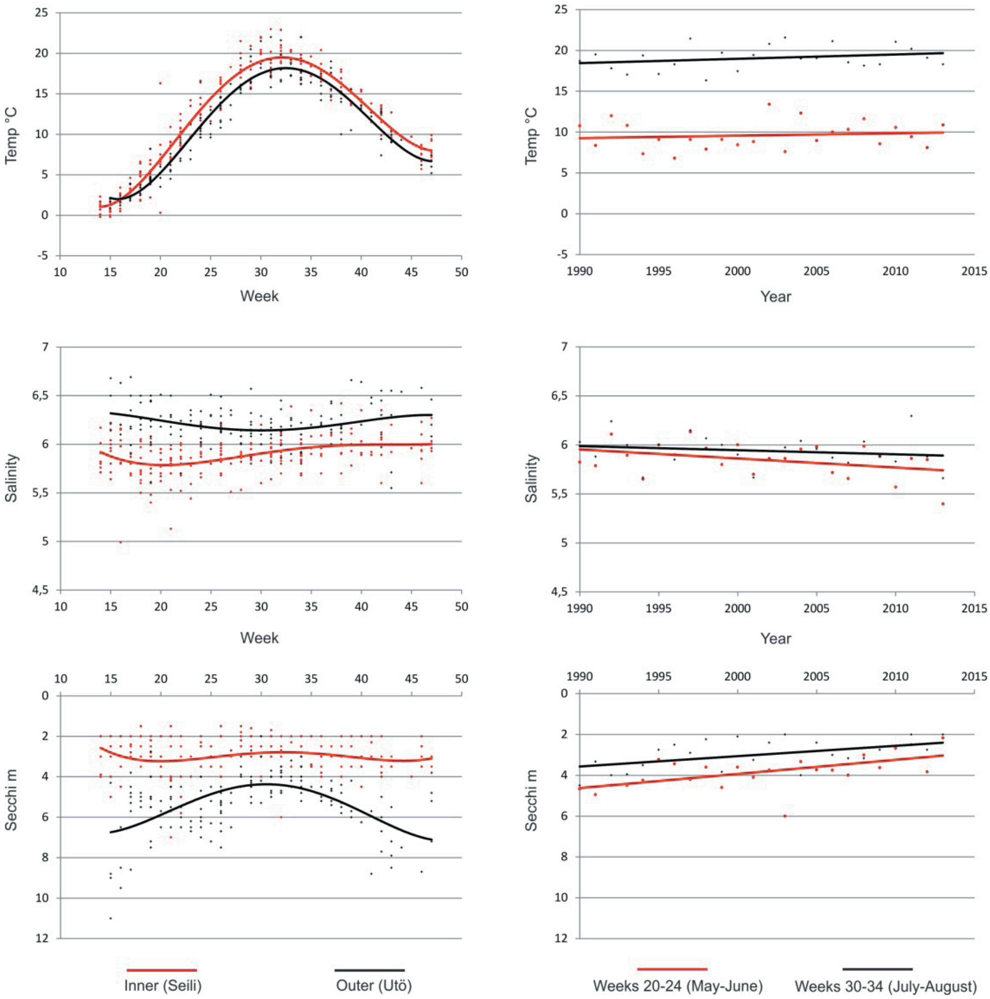

Fig 3. Left panel: Seasonal development at two observation sites, located in the inner (site A in Fig. 1) and outer Archipelago Sea (Site B in Fig. 1). Observations from 1999-2013 (dots) and 4th-order polynomial trend line. Right panel: Long-term changes in water properties at observation sites A and B. Dots indicate mean of five weeks' observations in early (red) and late summer (black).

Temperature changes in the surface layer are considerable, and the highest temperatures in the Archipelago Sea occur in July-August. The rise in temperature after ice melt is slower in the outer area, where the waters are deeper and the volumes greater. The diffusion of fresh melting waters from the terrestrial runoff and from the sea ice is recognizable from the lower salinity readings in the spring and early summer, although in practice such alteration may be obscured by larger-scale fluctuations. The Secchi depths are affected by SPM, CDOM and phytoplankton abundance. In the middle archipelago, Secchi depths vary moderately. In the outer regions water clarity is diminished by the occasionally abundant phytoplankton and the amplitude is wider. There tends to be an increasing trend in surface-layer temperatures and a decreasing trend in salinity. The sampling is insufficient to allow conclusions, but the decrease in transparency is more obvious.

3. MATERIAL AND METHODS

3.1 Material

Access to large digital data sets has become easier since 2007, due to the EU directive "Infrastructure for spatial information in the European Community" (INSPIRE, EC European Commission 2007). It facilitates greater efficiency to obtain the data. In this thesis too, the digital archive data sources used are mainly freely accessible. The main types of digital data sources used in Papers I-V are listed in Table 1.

Table 1. Source of materials in the five papers included in this thesis.

	Paper I: Waves	Paper II: Persistence	Paper III: Salinity	Paper IV: Light	Paper V: Turbidity
Water quality databases		x	x	x	x
Fieldwork		x	x	x	
Remote sensing					x
Topographic data	x		x	x	x

3.1.1 Water quality databases

One feature common to all but one of the papers was the use of a water-quality database as a data source, either as material for analysis (II, III, IV) or in error assessment (V). Physico-chemical water quality data from national monitoring programs are stored in the centralized databases HERTTA, maintained by Finnish Environmental Institute (SYKE). The database consists of both marine and freshwater observations from the 1960s to the present. In 2009 there were some 25 million results from various types of analysis and measurements, obtained from 2.4 million water samples collected during one million sampling events (Finnish Environment Institute 2014d). These data are available without restrictions from the web-based OIVA service (Finnish Environment Institute 2014c), which is an excellent resource for water quality studies in Finnish coastal waters and provides the necessary background data for basic research and change detection studies (e.g. Asmala et al. 2012, Lundberg et al. 2009, Rinne et al. 2011). The data are mainly collected by the Centres for Economic Development, Transport and the Environment (ELY) and SYKE, but also by other research institutes and universities in both the public and the private sector.

The data used in this thesis (turbidity,[1] secchi,[2] salinity and conductance,[3] temperature,[4] chlorophyll a[5] and pH[6]) have been analyzed in different laboratories using standardized methods (see Näykki et al. 2013 for details). Some questionable outliers, however, were found in a handful of data after they were downloaded to a desktop database and quality-checked by basic statistical analyses (Papers II, III, IV and V). Observations in the HERTTA database do not cover the western parts of the Archipelago Sea. In Paper III, additional salinity data were obtained from the Åland Environmental and Health Protection Authority.

3.1.2 Fieldwork

An intensive fieldwork campaign, with sampling every third week, was carried out in the Archipelago Sea during April-October 2007. The campaign consisted of sampling within a network of 22 observation sites located in the eastern part of the Archipelago Sea, 6–15 km apart. We prioritized open sea areas with no nearby point source pollution; the sampling regime covered the transition from inner bays close to the mainland to the border of the outer archipelago areas (see Fig. 1). The locations of the sites were defined so as to coincide with the actively used monitoring sites stored in the HERTTA database. This linkage helped tie the field data to the results of earlier samplings, and increased the seasonal coverage of information from the selected sites in the database. At each station, three depth profiles were measured in a constellation of an isosceles triangle with sides of 300 m. Sampling included measuring the vertical profile of conductivity, temperature, depth, chlorophyll-a, pH and turbidity with a multi-parameter sonde YSI 6600 V2 from the surface layer of ten meters. Water sampling and laboratory analysis of conductivity, chlorophyll-a and pH were performed for data evaluation; these data are now publicly available in the HERTTA database. The sampled data were used in three papers (II, III, IV) to evaluate seasonal changes, along with long-term data from the water quality database.

3.1.3 Remote sensing

Medium Resolution Imaging Spectrometer MERIS (ESA), along with MODIS and SeaWiFS (NASA), is one of the most widely used polar-orbiting multi-spectral ocean-color instruments of the last decade. Access to spatially and temporally full resolution data has recently improved, and at present the facilities for processing for example the MERIS

[1] Standardized nephelometric method EN 27027 1994
[2] From the white cap of the Limnos sampler
[3] SFS-EN 27888 1994
[4] Thermometer inside the Limnos sampler
[5] Spectrophotometrically from ethanol extract SFS 5772 1993
[6] SFS 3021 1979

data are versatile. Full-resolution and calibrated sensor data (Level 1) can be browsed and downloaded, free of charge, from well-organized databases EOLi, (EOLi 2014) and MERCI (MERCI 2014). In terms of the applicability of remote sensing data, it is not only a matter of improved access to data but also of providing remotely sensed data in useful formats and processing levels. The focus in remote-sensing ocean-color studies has been on using Level 1 data for assessing geophysical variables, but the availability of well documented Level 2 geophysical variables has also been enhanced; for example the MERCI service facilitates the downloading of Level 2 full-resolution geophysical variables, produced by the CoastColour project (Brockmann et al. 2012, CoastColour 2014). If more detailed options are needed in assessing geophysical variables from Level 1 data, the free and downloadable software packages ODESA (ODESA 2012) and BEAM (BEAM 2014) can be used, both of which have diverse functionalities for processing data from MERIS.

Ready-made ocean color data and geophysical data products are also available for the Archipelago Sea, but the fragmented and dynamic environment of the area calls for high-precision products and localized pre-processing to produce satellite imagery applicable in time-series and other analyses. Using satellite-imagery time series leads to the use of rather large data sets, but the above-mentioned tools facilitated an effective work flow. MERIS data (Level 1P/b calibrated sensor data) were downloaded from the server of the CoastColour project and were further processed with the freeware BEAM 4.11 (Paper V).

3.1.4 Topographic information

Shoreline data originating from the topographic database of the National Land Survey of Finland (NLS), on a scale of 1:10 000 (or 1:20 000 in earlier papers), were used in all but one paper. Precise topographic data are indispensable because the Archipelago Sea's topographical details influence many of the spatiotemporal features of the water. Geological and bathymetric surveys have a long history, and water depth has been mapped extensively. The availability of bathymetric and geological data, however, is restricted by the National Territorial Surveillance Act. Spatially sparse bathymetric data are available from digital nautical charts by the Finnish Maritime Administration. In paper IV we used a bathymetric model, created by combining the topographic database and the chart based bathymetric data (Stock et al. 2010).

The importance of topographic details was particularly focal in paper I, which dealt with the effect of the fragmental shoreline on wave power in the littoral zone, and in paper IV, where the euphotic seafloor area was defined by combining estimated underwater light attenuation and bathymetry. Shoreline dimensions played a key role in paper III as well, as it defines the borders restricting the anisotropic water diffusion scheme that prevails in the area. In paper V, accurate shoreline data were needed in masking cells on land from water surfaces in remote sensing imagery.

3.2 Methods

3.2.1 Notes on methodology

GIS analysis and modeling was used in all papers except Paper II. The methods included calculations of angles and distances (Paper I), spatial (III, IV) and temporal (V) interpolations, and data combination of Geographical Information (GI) data (III, IV, V). As the basic functions of the used ArcGIS software did not offer sufficiently effective tools to process spatially extensive and/or multi-temporal data, additional scripts (in Python scripting language) were also developed. In paper I, a suitable tool had already been written as part of a previous study concerning wave exposition (Ekebom et al. 2003). In papers III and IV, new scripts were written for spatial interpolation of salinity and Secchi depths. In Paper V, scripts were used to perform temporal linear averaging of satellite image time series and in various batch-processing tasks.

Scripting and batch processing facilitated data mining from large data sets. The importance of scripting lies in its repeatability. A single map layer or statically extracted data present only one view of phenomena, and have limited usability. By scripting the process can be developed further to find multiple aspects; this was an important theme throughout my research and writing, especially in the latter papers. This means, first of all, identifying specific and relevant spatiotemporal problems concerning the dynamic and fragmental archipelago coast; then defining suitable GIS methods to study them; and finally, applying the methodology thus developed to phenomena in the real world, and evaluating its applicability and accuracy.

Multiple data sources were another feature common to all the studies of this thesis. Collecting and combining spatially and temporally extensive data requires extensive pre-processing in order to make the data as compatible and consistent as possible, with regard to coordinate systems, measurement units, and spatial and temporal extents. Pre-processing formed a notable part of the analysis process, although in many cases this stage received only brief mention in the final papers. The optimal starting point for an analytical process consisted of quality-assured but otherwise unprocessed numerical data. A low level of previous processing offered better possibilities of subsequent control over a study. Typically the pre-processing of data included some or all of the following steps: 1) searching databases and GI data; 2) registration and acquiring the required permissions and downloading; 3) making the data technically uniform, in terms for example of file format, numerical and geographical format, units, time-tags; 4) storing the data in a single numerical or spatial database; and 5) data mining the combined data.

The purpose in all the papers was to bring out basic features of physical water properties from a new perspective, by identifying spatial divergence in their temporal behavior. Many of the water properties dealt with in the thesis were multidimensional in space and time. Time series graphs were used to illustrate how water properties changed as a function of time. These graphs were nevertheless insufficient to illustrate spatial causalities, for which spatial visualizations of both statistics and time series data were developed. These included for example image series of successive time steps, surfaces of statistical measures over space, and change detection maps. Extensive visualizations were produced in connection with various steps of the data analysis.

Table 2. Summary of analysis methods used and forms of result presentation.

	Paper I: Waves	Paper II: Persistence	Paper III: Salinity	Paper IV: Light	Paper V: Turbidity
Analysis					
Spatial/GIS Modeling	x		x	x	x
Statistics	x	x	x	x	x
Results					
Graphs	x	x	x	x	x
Tables of statistics	x			x	x
Visualizations	x	x	x	x	x

3.2.2 Descriptions of methods used in papers I-V

In paper I, GI methods were used to calculate fetch lengths for the Archipelago Sea. Exposition is conventionally calculated with cartographic methods and presented with fetches, i.e. the distances over which wind affects a sea surface (e.g. Ekebom et al. 2003, Kiirikki 1996, Murtojärvi et al. 2007) or with the Baardseth index, based on the number of free open water sectors around a given point (Baardseth 1970, Ruuskanen & Nappu 2005, Westerbom & Jattu 2006). At the time of writing, a need to assess wave exposition measures for wide areas emerged due to habitat-modeling initiatives. Distances from points on the shoreline, and on water to the nearest shoreline, were extensively calculated in the Archipelago Sea for the first time. Based on fetch lengths and wind data, we calculated measures of exposure and wave power. The algorithm, written in Avenue scripting language (Jenness 2001) turned to be rather slow for a larger number of origin points; subsequently, Murtojärvi et al. (2007) published an enhanced algorithm written with Java, which was used in Suominen et al. (2007) to calculate fetch values to 4.6 million points, following the principles introduced in Paper I.

Linear fetch-based approaches have obvious limitations in topographically fragmental environments, where bottom friction may affect overpassing waves before they reach the shoreline, and diffraction bends wave fields around obstacles. For this reason neither linear fetches nor the Baardseth index were optimal for open shorelines with long fetches (Ruuskanen & Nappu 2005). More advanced cartographic methods, including algorithms for diffraction and bottom friction (Bekkby et al. 2008, Wijkmark & Isæus 2010), were published soon after the publication of Paper I, and have been used to measure exposure in an ecological context in the Baltic Sea. Numerical hydrodynamic models have also been introduced (see Sundblad et al. 2014), and accounting bathymetry proved to enhance the performance of exposure models. Despite its obvious weaknesses, the principle of the fetch approach is simple and robust, thus increasing the applicability of the resulting GI data sets.

The data used in Paper II originated from both the HERTTA database and the fieldwork campaign of 2007. The analysis of the seasonal and long-term geographical persistence of five surface-layer properties (temperature, salinity, Secchi, chlorophyll a, and pH) used the time stability method, which evaluates how steadily observations on a site are located under or over the global median of all observations made at the same time (Keim et al. 2005, Starr 2005, Vachaud et al. 1985, Zimmermann et al. 2007). GIS was not used in the analyses, but played a considerable role in preparing the visualizations of the large data sets produced.

In paper III, we hypothesized that salinity levels within the Archipelago Sea would reflect water movements through and within the area. To evaluate this assumption, a new GIS-based approach was developed to cope with the fragmental structure of the study area and with the anisotropic water diffusion due to diverse barriers and both prevailing and ephemeral flow patterns. Salinity, and its easily measurable counterpart conductivity, are frequently covered in various monitoring programs. We applied a procedure based on the inverse distance weighted (IDW) method (e.g. Longley et al. 2001). The IDW weights the values of sample points according to the inverse distance from known data points to the raster cells to be estimated; instead of using Euclidean distances, however, we calculated path distances along the water surface. We named the method the Inverse Path Distance Weighted Interpolation (IPDW). The script was written with Python, and was later modified for the R package (Stachelek 2014).

In paper IV we defined seasonal and long-term changes in the spatial coverage and patchiness of the photic seafloor in the inner and middle archipelago areas. In the seasonal analysis, we combined bathymetric data from the Finnish Maritime Administration with elevation data from the National Land Survey of Finland (Stock et al. 2010), and Secchi depths from our fieldwork campaign from 2007. Light attenuation was estimated according to the Secchi depths measured, interpolated to surfaces with the IPDW method introduced in Paper III. This yielded eight estimations of areal light attenuation from May to October, which were overlaid with bathymetric data. The method allowed estimation of the spatial coverage and patchiness of the photic seafloor at different stages of the open water season. We made a rough estimation as to the circumstances prevailing in the 1930s, and compared the present seafloor dynamics to the era prior to large-scale eutrophication.

In paper V we dealt in particular with issues encountered in using remote sensing data in a fragmented archipelago, and executed a chain of analyses to refine spatially and temporally scattered remote sensing instrument MERIS Level 1 data (corrected top-of-atmosphere imagery) to Level 2 (geophysical variables) turbidity data. As a starting point we used Level 1 data pre-processed by the CoastColour project (Brockmann et al. 2012, Coastcolour 2011, Coastcolour 2014). These data were downloaded for the open-water season representing the years 2005, 2008 and 2011. Level 1 data were converted to turbidity using BEAM 5.0 software (Doerffer & Schiller 2007, Attila et al. 2013).

With regard to the applicability of remote sensing methods in coastal and archipelago waters, three challenges occur. First, coastal waters are optically complex, and the greater the number of optical components found in the water, the more difficult it is to distinguish them via remotely sensed absorption and scattering properties (e.g. Attila et al. 2013, Kratzer et al. 2008, Smith et al. 2013). Second, coastal areas in the study region are topographically fragmented, and errors caused by mixed pixels and adjacent land masses disturb studies of water quality (Kratzer & Vinterhav 2010, Santer & Zagolski 2009). The larger the spatial resolutions, the more a pixel may cover various coastal realms, such as water, land, littoral vegetation and shoals. The third challenge in using remote sensing in coastal waters is the non-regular alteration of water properties at different time scales. Polar-orbiting ocean color instruments like MERIS have temporal resolution of 1-2 days, but their data are in practice temporally incomplete due to atmospheric disturbance such as clouds and – especially at high and low latitudes – sun glint and a lack of daylight for part of the year.

Land areas were masked with fine-scale shoreline data 1:10 000. In Temporal Linear Averaging (TLA), previous and successive observed values are used to estimate a lacking diurnal value, i.e. to create artificial imagery for days when no remote sensing data are available. Diurnal turbidity values were validated against turbidity observations downloaded from the HERTTA database, and the artificial dataset was also cross-validated with the leave-one-out method. Eventually we made temporal compilations with the produced data sets, and sought spatial divergences in the temporal variation of turbidity.

4. RESULTS AND DISCUSSION

4.1 Generalizations in dynamic coastal environments have to be made with caution

4.1.1 New perspectives on the temporal characteristics of coastal water properties

In all the papers included in this thesis, I tried to develop new viewpoints to highlight the spatiotemporal characteristics of the variables studied. More specifically, three main themes were identified in papers I-V relating to the spatiotemporal characteristics of the study area: amplitude and variability, spatial and temporal persistence, and the effect of coastal topography (Table 3). In the following sections, the characteristics of waves, salinity and water transparency are described in terms of these three themes.

Table 3. Summary of spatiotemporal themes addressed in papers I-V

	Amplitude and variability	Spatial and temporal persistence	Effect of coastal topography
I Waves			
Fetch on shore	x		x
Seasonal wave power	x		x
II Persistence			
Seasonal persistence	x	x	
Interannual persistence	x	x	
III Salinity			
Isohalines 2007 and 2007/2008	x		x
Seasonal range 2007	x		
Seasonal developments in 1999-2008	x	x	
IV Euphotic seafloor			
Seasonal changes in illuminated area and patches			x
Long-term change in illuminated area			x
V Turbidity			
Monthly median/seasonal progression		x	
Variability	x		
Interannual autocorrelation	x	x	

4.1.2 Amplitude and variability

Exposure measures can be used as a surrogate that simulates the vulnerability of a shore to waves for example in an ecological context, and can be enhanced by data on wind conditions to provide more accurate estimations (Wijkmark & Isæus 2010). The impact of waves is spatially and temporally variable (Paper I), and the temporal aspects of exposure-related measures should be given prominence in the study of shore geomorphology and biota. Using the mean values of wind fields and consequent wave conditions may be problematic, as mean values ignore the influence of rare events; storms may prevent the attachment of perennial species on the seafloor (Bučas et al 2007) or alter sedimentary shore-forms. In paper I we calculated the accumulation of wave energy (Ekebom et al. 2003) to define actual wave power on a shoreline, and presented a graph indicating the cumulative wave power at two sites opening in different directions. We found considerable differences between the two sites and between years in both the intensity and the timing of storms, which are ultimately short-lived events. On an open shore, severe storms from a certain direction result in multiplied wave power compared to an average year. In sheltered parts of the archipelago, wave power distribution is limited by shorter fetches, and annual differences are less extreme than in the outer areas. It may thus make sense to incorporate the concept of probability of occurrence in shore studies.

The surface layer salinity range during 1999-2008 at the three intensively monitored sites located in the middle and outer archipelago was 0.6 PSU (Paper III). During the 2007 season from May to October, the lowest median within the sample of 22 sites occurred in June (5.4 PSU, range 5.2–5.7 PSU), the highest in September (5.9 PSU, range 5.7–6.1 PSU). The widest site-wise salinity range occurred in the inner bay near the mainland (0.8 PSU), where the variation may be due to terrestrial runoff. The lowest site-wise ranges (0.3 PSU) occurred in the southern archipelago, where circumstances were more uniform due to the vicinity of the larger water masses of the northern Baltic Proper (Paper II). Similar levels of salinity occurred in both middle and inner archipelago areas at different times of the year (Papers II and III). A causal connection between species distribution and salinity regime is commonly accepted, but is frequently based on the assumption of a relatively static salinity field. Considering the ecological relevance of salinity as a limiting factor in brackish water habitats (Bonsdorff 2005, Rinne et al. 2011), the spatially divergent seasonal amplitudes observed may be particularly significant from an ecological perspective (Papers II, III).

Secchi depth observations at the twenty sites from May to October 2007 were also distinctive. As a general seasonal trend, the relatively high Secchi depths of the early summer decline to lower values in the late summer, rising again gradually in the autumn. The highest range (1.3–7.5 m) was measured in early June, the lowest (1.3–3.4 m) in late July (Paper II). In paper V we studied variability in turbidity (related to Secchi depths) from May to September. The lowest variability was observed in the open Bothnian Sea and in the archipelago area east of Åland. Turbidity in the innermost archipelago was constantly high and showed little variability. Due to seasonal changes, the middle archipelago, i.e. the outer areas of river influence, is a varying environment. High variability was also detected in the open sea in the south, where short but intense algal blooms occur.

4.1.3 Spatial and temporal persistence

High persistence implies that the spatial patterns of surface waters properties will remain similar over times. Surface-layer salinity varies from the low levels at the river mouths of the inner archipelago to approximately 6.0-6.6 PSU at the southern edge of the Archipelago Sea and 5.6-6.2 PSU on the northern side (Paper III). The gradation from low-saline waters in the inner parts to higher salinity towards the open sea was persistent during the year studied (2007). Seasonal development was parallel at all twenty sites, i.e. waters were less saline in the early summer, with salinity increasing towards the autumn (paper II, III). Likewise the seasonal averages in a time series of ten years at three intensively monitored sites confirm that on average salinity peaks in the winter and is at its lowest in either early or late summer (see Fig. 3, sites A and B respectively). The increase in salinity during the open water season, however, did not recur annually; years of static or decreasing salinity also occurred. The site-wise timing of the high and low salinity periods was broadly similar over the ten-year monitoring period, and if the seasonal component was ignored, fluctuation emerged which was to a degree related to the overall salinity regime of the Baltic Proper. At the sites on the southern and northern side of the Archipelago Sea these fluctuations interacted with a lag, as waters flow from south to north via both sites (Paper III).

A gradual change in water transparency from the inner to the outer archipelago areas was spatially persistent throughout the open water season. Likewise inter-annual late summer data collected in 2002-2008 showed persistently lower/higher Secchi depths in the inner/outer areas, respectively; a zone in the middle showed more varied Secchi observations. Inter-annual variations in late-summer Secchi depths were found to be higher in the outer areas than in the middle or inner archipelago areas (Paper II). Spatially divergent seasonal development in water transparency was also obtained from remote sensing imagery, by calculating the deviations of the monthly medians from the median of the whole season, and by calculation of inter-annual similarity measures. In the middle archipelago the waters were at their clearest in May-June. In July, the waters became more turbid in the middle archipelago and in the pelagial, especially in the Baltic Proper, due to the presence of phytoplankton and cyanobacteria. In the innermost archipelago fluvial waters kept the base level of turbidity high through the season. Turbidity generally decreases towards the autumn, but not everywhere in the middle archipelago (Paper V). Near the coasts turbidity showed irregular seasonal changes. Annually repeated cycles were found further off from the coast, where the direct effect of coastal discharges leveled off. In the southern pelagic sea phytoplankton blooms were frequent but the annual cycle was still regular, as well as in the northern and eastern pelagic, where the circumstances were more pristine.

4.1.4 Effect of coastal topography

The third theme had to do with the effects of seasonal development, and whether they differ according to such geographical features as bathymetry and shoreline shape. The effect of waves is mainly determined by these features, but seasonal and annual differences in wind direction and magnitude define the actual temporal pattern of wave power distribution over time (Paper I). Isohalines in the region result from the area's overall flow pattern: the waters of the Baltic Proper flow northward through the middle parts of the archipelago at an average flow rate of approx. 0.5 cm s^{-1} (Paper III). Papers II and III describe the way in which the barrier formed by three large islands (Nauvo, Korppoo and Houtskari) restricts water diffusion and shapes the surface-layer isohalines.

In paper IV changes in water transparency were related to bathymetry in order to highlight the spatiotemporal dynamics of the euphotic seafloor. We concluded that about 25 % of seafloor is euphotic throughout the entire open water season, 25 % is euphotic part of the time, and 50 % is always dark. For the period from the 1930s to the present, the area of euphotic seafloor was estimated to decrease by one half. The outer archipelago is characterized by a steep topography, giving rise to a different euphotic seafloor dynamic from the inner areas, with their more gentle bathymetry (Paper IV). In consequence, the number and area of separated euphotic patches change; the patchiness of the euphotic seafloor may be another ecologically relevant question related to the temporal characteristics of the marine environment.

4.1.5 The Archipelago Sea as an open spatiotemporal system

Gradations of surface layer water properties in the Archipelago Sea are bi-directional (Paper III, Varsinais-Suomen ELY-keskus 2011). One gradation occurs between pelagic areas and the mainland (and, to a lesser extent, the Åland islands) and is driven by the diffusion of runoffs in an area where water movements are restricted by islands and thresholds. The other gradation, between south (the Baltic Proper) and north (the Bothnian Sea), is driven by the northward circulation pattern of the Baltic Sea basin (Paper III, Leppäranta & Myrberg 2009). On a broad scale, these gradations define water quality in the Archipelago Sea: less saline, more turbid and warmer waters prevail near the coast, while at the southern edges of the Archipelago Sea waters are more saline and clear. Accounting for the temporal characteristics of waters, however, expands and broadens the concept of spatially gradated waters (Fig. 4), evaluated here according to the turbidity dynamics.

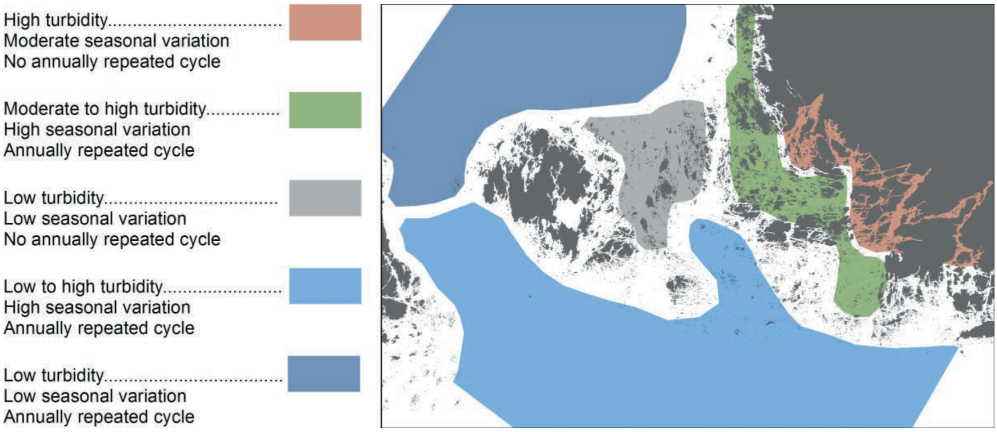

Fig. 4. Interpretation of areas with divergent temporal characteristics based on their surface layer turbidity, derived from satellite imagery (Paper V).

The factors affecting turbidity and subsequent light availability are doubled; rivers are bringing organic and inorganic materials to bays, and planktonic algae increase turbidity when circumstances are favorable for their growth. The different zones are affected by different contributing features; in the outer regions, the main driver to consider is phytoplankton, in the inner parts, the dispersion of turbid fluvial waters has a proportionally greater effect on transparency. Increased eutrophication, however, reduces water clarity in the inner archipelago as well (Kauppila 2007, Varsinais-Suomen ELY-keskus 2011), although in such turbid coastal waters the high fluvial loads of SPM and CDOM may depress primary production due to light limitation (Kauppila 2007, Wasmund et al. 2001).

Irregular seasonal cycles occur in near-shore areas and in the sea area east of Åland. In near-shore areas irregular seasonal cycles may be induced by natural variation in the intrusions of turbid fluvial waters, eutrophication-related processes and anisotropic water diffusion. In the middle parts of the archipelago, adjacent to near-shore areas, the seasonal cycles are still relatively regular. In these areas, developments eventually leading to decreased water transparency may still be controlled by seasonality; seasonal cycles indicate an equilibrium between seasonally highly varying climatic conditions and water properties. In the southern pelagic sea the waters are strongly characterized by relatively clear waters, a condition which is regularly interrupted by intensive algal blooms. On the eastern and northern sides of the Archipelago Sea, regular seasonal cycles prevail and the amplitudes are also at their most narrow.

Some variables, such as water transparency and underwater light, are more liable to spatially divergent seasonal developments, as they are influenced by multiple factors. Unlike water transparency, variables such as temperature and salinity have a more straightforward spatiotemporal pattern, since they do not interact for example with biological processes. Spatial divergences in the seasonal water transparency dynamic are, however, so high that this parameter, essential for water quality management and habitat modeling, would be spatially biased if temporally extensive data were not available. According to Papers II, IV and V, spatial divergences may seem reduced if only late-summer values are used in comparisons. And vice versa: spatial divergences would be emphasized if only early-summer measurements were used as waters in the outer areas are clearer while no significant change in turbidity occurs in the inner bays.

As long as direct observations and models of light attenuation are sparse, Secchi depth and turbidity are useful measures in monitoring water transparency (Luhtala et al. 2013, Fleming-Lehtinen & Laamanen 2012). Using them as a proxy for light availability, however, must be done with care, since light is attenuated in the water column in an exponential manner. The dynamics of the underwater light climate are further complicated because of the high seasonal variations of incident solar radiation and the effects of the optical characteristics of seawater on the composition of underwater wave lengths at different depths. Light attenuation in a water column regulates for example the vertical distribution of macroalgae (e.g. Dupont & Aksnes 2013, Rinne et al. 2011), but at present there is less information as to how seasonally varying light conditions affect different marine species. Some may tolerate turbid, darker periods better than others, and survive even when the early-summer period of frequent sunlight is short. The impact on habitats of the divergent development of transparency is further diversified under varying topographical regimes (Paper IV, Stock et al. 2010).

4.1.6 Measures of times series characteristics

Change in the temporal pattern is used to identify anomalous developments for example in the phenology of terrestrial primary production (e.g. Lhermitte et al. 2011, Verbesselt et al. 2010). Seasonal developments of remotely sensed vegetation indicators are relatively regular and predictable, and deviations may be identified almost in real time (Verbesselt 2012). Typical scaling and translation differences in the timings and amplitudes of temporal trajectories are illustrated in Fig. 5 (Lhermitte et al. 2011). Seasonal developments may be highly divergent but still difficult to distinguish with simple statistical measures. Areas whose amplitude is scaled or translated differently may be placed in different categories, even if the shape of their seasonal development indicates that their variability is dominated by a similar mechanism (Fig. 5 and Fig. 6).

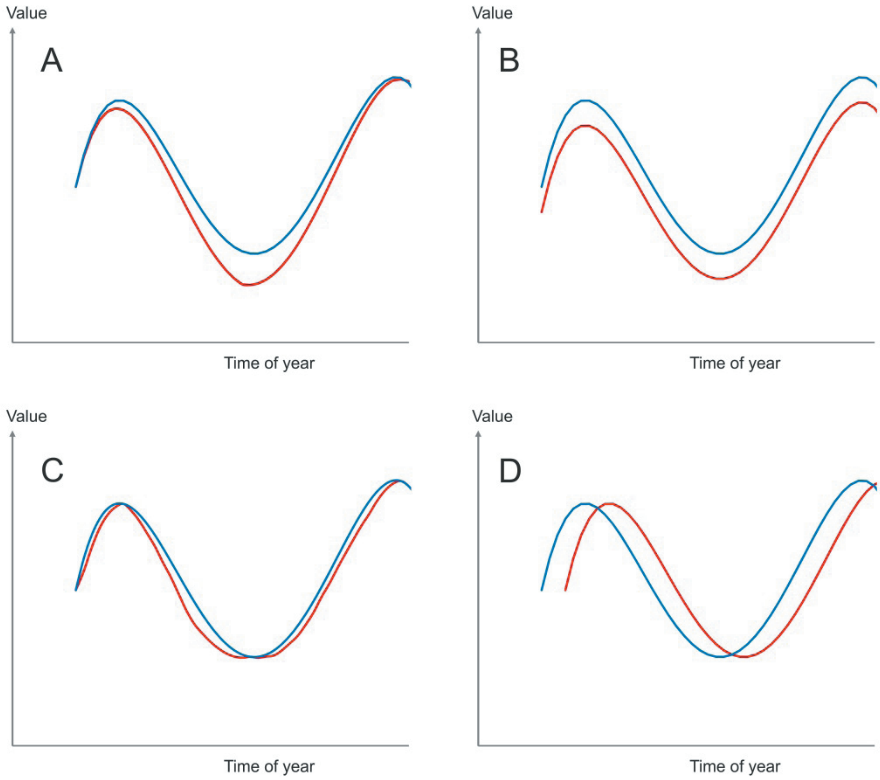

Fig. 5. Illustration of time series and phenology characteristics (modified from Lhermitte et al. 2011). Red and blue lines indicate two possible trajectories of annual developments. A) Amplitude scaling B) Amplitude translation C) Time scaling D) Time translation

Regular inter-annual developments in scaling or translations are more likely to occur in connection with variables regulated primarily by seasonally regular climatic factors (e.g. temperature). In coastal environments, however, anisotropy and temporal irregularity are common (Fig. 6). This may hinder the usability for example of remote sensing in acquiring real-time surveillance data of anomalous phenomena. Analysis of long-term imagery may nevertheless reveal the mechanisms regulating water properties, help to distinguish underlying causalities, and identify areas affected by these mechanisms. Notable changes in physico-chemical and/or biological time series may indicate regime shifts in ecosystems (Dippner et al. 2012, Mantua 2004). It is important to have sound knowledge of the seasonal variability of marine ecosystem components and inter-annual variations from the seasonal norm (Yoo et al. 2008). With regard to projections of the future impact of current global changes on the seas, such information will be increasingly relevant. Statistical analysis alone cannot replace an understanding of the underlying dynamic relations of the different variables (deYoung 2009).

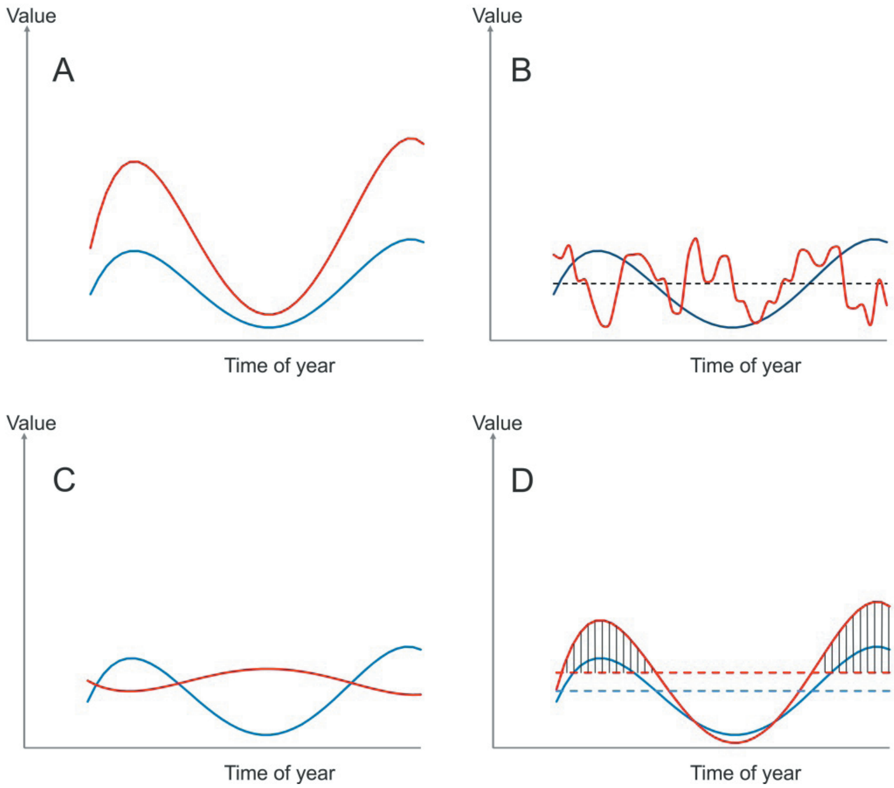

Fig. 6. Aspects of possible seasonal developments at two sites. The simplified graphs are based on the results of Papers I-V.

A) Two observation sites have different amplitude scaling, but a relatively similarly shaped annual cycle. Sampling is not time-dependent, as the proportions of the two sites are equal at all times.

B) Another site does not have a clear temporal shape, due e.g. to river discharges or local flow patterns. Means and/or ranges of the sites may still be the same. The distinctive feature of a highly varying area is its variability, which cannot be measured with sparse sampling or annual means.

C) Both sites have regular temporal shapes, but seasonal developments are not simultaneous. Areas are compared differently, depending on the time of sampling.

D) Sites have similar temporal shapes but different amplitudes. Peaks or lows may facilitate or prevent something occurring. Periods when the red curve is above the annual mean may for example enable the survival of a species which would not survive under the mean circumstances of red or blue (dotted lines).

Possible divergent seasonal developments at separate locations are shown in Fig. 6, based on Papers I-V. Sparse sampling may result in a biased image of spatial variability (B, C), or a given environment may require continuous sampling to enable comparisons with other areas (B). Even when the shapes of temporal trajectories are alike, i.e. sampling is less time-dependent in a spatial sense, diverging amplitudes may still enable (or exclude) physical or biological processes (A, D).

4.2 Integrated data and analysis contributes to evidence-based coastal management

4.2.1 Changing needs require multi-source data

Conventionally the long-term development of coastal sea water properties is monitored by *in situ* observations, i.e. repeated samplings during the same period(s) in consecutive years and at specific sites. Water sampling, combined with laboratory analysis, forms an essential basis for most coastal monitoring programs, because of its accuracy, the wide range of variables covered, and the ability to obtain data for the whole water column. It has on the other hand been reasonably questioned whether time-series data derived from *in situ* sampling provide the most cost-effective approach to the monitoring of coastal water dynamics (Ferreira et al. 2011). *In situ* sampling and laboratory analysis are expensive, and in a fragmental environment such as the Archipelago Sea they may offer only a general spatiotemporal view of the region. Resources are limited and need to be narrowly focused to produce information about long-term changes, rather than seasonality; much of the spatiotemporal variability of water properties may thus be missed.

Ship-based flow-through instruments, allowing water analysis in real-time along selected ship routes, have been mounted from the 1990s onward on a number of passenger and freight ships in the Baltic Sea (Petersen et al. 2008, Rantajärvi 2003, Wänstrand & Snoeijs 2006). The set of variables covered by these configurations, however, is limited by the availability of *in situ* sensors, usually covering temperature, salinity, pH, turbidity and the fluorescence of photosynthetic pigments. While the temporal resolution of the data transects might be just a few days, the spatial coverage of the transects is limited to the routes of their platforms; thus they are more applicable to monitoring than to the mapping of dynamic coastal waters. *In situ* sensors can also be mounted on moored buoys to collect continuous data, and in some instrumentations the sampling covers the whole water column. These data cannot be used in mapping either, but their continuous, comparable time-series data offer an insight into the seasonal processes of sea water and straightforward data for analysis. In remote-sensing–based monitoring, the number of variables assessed is limited and information is available only for a thin surface layer. The spatial and temporal coverage of satellite imagery is nevertheless superior to any other method, offering an illustrative and holistic view of the region (Gohin et al. 2008, Kratzer et al. 2014)

There is no single method which meets the challenge of collecting multi-temporal data in a topographically fragmental coastal sea with dynamic water properties (Gohin et al. 2008, Petersen et al 2008). A comparison of the different methods indicates that both *in situ* sampling and remote sensing are needed: the first (including both water sampling and *in situ* measurements) for its accuracy and range of variables, the second for its superior spatial and temporal coverage at relatively low cost. (See Table 4)

Table 4. Pros and cons of sampling methods in fragmental coastal waters.

	Spatial coverage	Vertical sampling	Temporal coverage	Accuracy	Number of variables	Costs
***In situ* sampling**	+	+++	+	+++	+++	+
Flow-through	++	+	++	++	++	++
Buoys	+	+ - +++	+++	++	++	++
Remote sensing	+++	+	+++	+	+	+++

New technologies enable the gathering of more accurate and spatially and/or temporally extensive information about a wide range of water properties, but data needs have changed as well. In the 1990s, neither remote sensing data nor *in situ* sensors were extensively used for monitoring and research purposes because of their high cost, their technical impracticality, and the lack of expertise. In the 2010s they provide alternatives for enhancing the spatiotemporal coverage of monitoring and research data (Paper V). New methods have also given rise to new data needs and questions, such as the operational use of *in situ* samples for error assessment of remote sensing data and *in situ* instruments. The application of GIS techniques and the inclusion of multiple data sources help to process increasingly tailored information products (Papers I, III, IV, V). The joint use of data, regular and standardized maintenance of *in situ* instruments, and integrated and robust data management would facilitate the use of accurate, reliable information for multiple purposes. Whatever the means of adapting monitoring to concurrent needs, it is crucial to maintain the integrity of long-term data while introducing new sampling and analytical techniques (Carstensen et al. 2011, Erkkilä & Kalliola 2007, Lindermayer & Likens 2009, Murtojärvi et al. 2008).

4.2.2 Integrated management of low processing level data facilitate efficient data mining

Data, its analysis and management should not answer only current threats and needs, but also the new ones that are constantly emerging. A wealth of data has sometimes led to disposable data sets; advanced end products, created to answer a particular current research question, may have limited applicability later on. To avoid this, the documentation of procedures of data preparation has to be transparent and comprehensive, thus enhancing possibilities of stratifying new information over older. Rather than collecting already processed, advanced but rapidly outdated digital material, there should be a pool of well organized and quality-assured low processing level data. The data in this pool should be hierarchically structured, so that new data can be logically attached to it when new data sources and needs emerge. This data pool would serve as a basis for a well-documented set of data analysis methods. Together these pools would form a flexible data mining process, meeting the requirements of varying information needs, including robust data storage and allowing for changing information needs and analysis methods.

Access to large digital data sets has improved significantly in the last decade, and scientific studies such as those reported in this thesis (Papers I to V) have become possible. A change in attitudes regarding public data has followed the implementation of the INSPIRE (EC European Commission 2007). This positive development has created new possibilities for example of environmental studies, as existing data sources can be taken into account in setting research questions and frames. This has also opened up new possibilities in physical geography, where the use of large spatial data sets concerning wide-ranging topics is typical. The coastal seas are unique environments, where the determination of causalities is hindered by the presence of multiple simultaneous processes. Thus coastal geography has become more visible among other areas of coastal research, and in this field the strength of geography lies in its versatility.

4.2.3 Data needs are constantly restructuring

The Water Framework Directive WFD (EC European Commission 2000) and the EU Marine Strategy Framework Directive MSFD (EC European Commission 2008) require the implementation of a holistic ecosystem approach to the management of European waters (e.g. Borja et al. 2010). Recognition of the centrality of the living environment for human wellbeing has also added certain new elements to the needs of coastal data and monitoring, and monitoring programs have been restructured accordingly. Indicators, sampling frequency and observation sites are required to be defined in a way that allows evaluation of the state of the marine environment in a holistic manner. The frequency and timing of sampling should be such that acceptable levels of reliability and accuracy are achieved, considering the diverse pressures affecting the coastal seas. All the pressures, however, have not yet been met, and specifying a monitoring scheme according to current requirements may be problematic. A set of observation sites, not connected to known pressures but justified in terms of purely spatial and temporal coverage, should be preserved.

The Finnish Inventory Programme for the Underwater Marine Environment (VELMU), aiming at the comprehensive mapping of underwater habitats and natural values, was launched in the early 2000s; the fieldwork is intended to be completed in 2014-2015. The results of VELMU will be based extensively on the modeling of habitats and species distribution, requiring information on the interactions of the physical, chemical and biological environment. Implementing the program has revealed shortcomings in the existing spatiotemporal knowledge concerning the coastal physical marine environment, calling for the development and standardization of methods related to the collecting of coherent data and to data management. The program has thus been beneficial for marine research in Finland outside the scope of the actual program; it has induced mapping of the underwater environment from multiple points of view, and has identified and partly resolved methodological challenges in contemporary marine research in Finland.

Reliable data are needed in Coastal Zone Management (CZM) and Marine Spatial Planning (MSP). In terrestrial environments, spatial planning relies on extensive information concerning environmental values and human activities, and planning definitions and tools are established. In marine environments, pressures for exploiting the seas have diversified, and interaction among the environmental, cultural and economic interests may be more controversial. Due to the transborder nature of the seas, the planning process should also involve an international perspective, but no established model for applying the MSP as yet exists (Douvere & Ehler 2009). Scientific knowledge concerning the marine environment has until recently remained fragmental and dispersed; thus with respect to many coastal systems no spatially and temporally comprehensive view could be formed. Due to the wide range of potentially applicable information, the data used in MSP should be based on a transparent and structured process, and the limitations of existing knowledge of the marine environment should be recognized (Shucksmith & Kelly 2014). Otherwise the lack of comprehensive and coherent information in well-organized form may result in a situation where planning is directed by the availability of information rather than by the actual public interest. Due to diversity of data needs, the demands of decision-making are hard to answer with ready-made maps and generalizations. Administration calls for robust and unambiguous information, but the oversimplification of dynamic and multidimensional phenomena such as coastal water properties merely shifts decision making responsibility from office-holders to researchers, because simplification requires making choices. With the papers included in this thesis, I thus wanted to emphasize the need for adaptable methods and work flows, allowing a process which can produce on-demand data concerning dynamic coastal regions.

5. CONCLUSIONS

Water properties in the Archipelago Sea are affected by multiple factors; the three adjacent main basins of the Baltic Sea, the inflows of fluvial waters from the mainland, the division into numerous sub-basins and the wide amplitudes of seasonal cycles. These result in spatially divergent seasonal developments in surface-layer water properties.

While variables such as salinity and water transparency have seasonal characteristics, over large areas water properties show no inter-annually repetitive cycle; it is obscured by local and short-term variation, or by temporally and spatially wider-scale fluctuations.

Under dynamic coastal conditions, spatial and temporal generalizations concerning the shore processes and water properties have to be made with caution. Seasonal observations enable exploring and distinguishing areas by their time-series characteristics and phenology, yielding new information as to the spatiotemporal regime of the Archipelago Sea.

The enhanced availability of quality-assured data facilitates focusing on environmental processes and helps to increase our understanding of the coastal seas. Low processing level data offer an applicable starting point for a variety of studies; together with well documented pools of geostatistical methods, they offer a flexible on-demand procedure for satisfying various information needs. Highly processed and static data and information cannot adequately describe dynamic coastal shore and water properties.

KIITOKSET

Maantieteen laitos on liittynyt elämääni pian 25 vuotta; ensin opiskelin maisteriksi, valmistumisen jälkeen olin joko töissä laitoksella tai muualla työskennellessäni tein yhteistyötä sen kanssa, ja viimeiset vuodet olen tehnyt siellä jatko-tutkintoa. Olen siis paljosta kiitollinen laitokselle, sen henkilökunnalle ja kanssaopiskelijoilleni vuosien varrella. Risto Kalliola on toiminut useassa roolissa opiskelu- ja työurani aikana, mm. tutkintojen ohjaajana ja esimiehenä. Kiitän häntä lämpimästi sekä ammatillisesta että henkilökohtaisesta kannustuksesta, jota sain niinäkin aikoina kun oma usko työn valmistumiseen oli koetuksella. Harri Tolvanen on toiminut väitöskirjan toisena ohjaajana, antaen usein varsin käytännöllisiä neuvoja. Olen iloinen ystävyydestämme, toivottavasti päädymme samaan veneeseen taas joskus. Maantieteen laitoksen väkeä kiitän hyvän työskentelyilmapiirin luomisesta, hymyilevistä kasvoista ja iloisista tervehdyksistä. Leena Laurilalle erityiskiitos lukuisista kerroista, joina olen saanut apua teknisiin ongelmiin nopeasti ja aina ystävällisesti.

Yliopiston rinnalla olen työskennellyt Lounais-Suomen ympäristökeskuksessa/Varsinais-Suomen ELY-keskuksessa. Vaikkei työni siellä olekaan liittynyt väitökseeni, tehtäväni ovat antaneet minulle käytännön tietoa vesiensuojelutyöstä. Kiitän kollegoja, joiden kanssa olen saanut työskennellä toimistolla ja maastossa. Janne Suomelan kanssa olen käynyt keskusteluja vesistöjen seurannasta, siitä kiitos hänelle. Saaristomeren tutkimuslaitoksella sain ensimmäisen käsityksen siitä, mitä vesi- ja rannikkotutkimus on, ja myöhemminkin se on tarjonnut puitteet kenttämatkoilla. Kiitän laitoksen henkilökuntaa, ja myös heitä, jotka ovat jo siirtyneet Seilistä pois.

Väitöskirjani esitarkastajat Thomas R. Allen ja Ülo Suursaar antoivat asiantuntevia kommentteja, jotka rohkaisivat ja auttoivat löytämään viilausta tarvitsevat kohdat tekstistä. *(I thank the pre-examiners of my thesis, Thomas R. Allen and Ülo Suursaar for their comments, which both encouraged and helped me to improve the text)*

Väitöskirjatyötäni ovat rahoittaneet Turun yliopistosäätiö, Suomen kulttuurirahaston Varsinais-Suomen rahasto, Suomen Akatemia, Turun yliopisto sekä Maantieteen ja geologian laitos.

Isäni vei perheemme saaristoon, kun olin lapsi. Vietimme kesämme luonnonsatamissa ja uimme nykyistä kirkkaamissa vesissä. Äitini työskenteli vuosikymmeniä yliopiston hallintorakennuksessa, ja muistan yhä painomusteen tuoksun sen ala-aulassa käydessäni hänen työpaikallaan. Myös näistä lapsuuden eväistä olen heille kiitollinen, ilman niitä väitöskirjani Saaristomereen liittyvästä aiheesta olisi tuskin toteutunut.

Vaimoani Annea kiitän sydämeni pohjasta rakkaudesta ja tuesta, väitöskirjan valmistelussa ja elämässä. Kiitos Ossi kannetuista kahvikupeista, ja siitä, että sait minut välillä leikkimään.

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