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SPATIOTEMPORAL ASPECTS OF ENVIRONMENTAL MONITORING IN THE COMPLEX COASTAL REGION OF SOUTHWEST FINLAND

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I Kirkkala T, H Helminen & A Erkkilä (1998). Variability of nutrient limitation in the Archipelago Sea, SW Finland. *Hydrobiologia* 363, 117–126.

II Ekebom J & A Erkkilä (2003). Using aerial photography for identification of marine and coastal habitats under the EU's Habitats Directive. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13, 287–304.

III Erkkilä A & R Kalliola (2004). Patterns and dynamics of coastal waters in multi-temporal satellite images: support to water quality monitoring in the Archipelago Sea, Finland. *Estuarine, Coastal and Shelf Science* 60, 165–177.

IV Erkkilä A & R Kalliola (2007). Spatial and temporal representativeness of water monitoring efforts in the Baltic Sea coast of SW Finland. *Fennia* 185: 2, 107–132.

ABSTRACT

The management and conservation of coastal waters in the Baltic is challenged by a number of complex environmental problems, including eutrophication and habitat degradation. Demands for a more holistic, integrated and adaptive framework of ecosystem-based management emphasize the importance of appropriate information on the status and changes of the aquatic ecosystems. The thesis focuses on the spatiotemporal aspects of environmental monitoring in the extensive and geomorphologically complex coastal region of SW Finland, where the acquisition of spatially and temporally representative monitoring data is inherently challenging. Furthermore, the region is subject to multiple human interests and uses. A holistic geographical approach is emphasized, as it is ultimately the physical conditions that set the frame for any human activity. Characteristics of the coastal environment were examined using water quality data from the database of the Finnish environmental administration and Landsat TM/ETM+ images. A basic feature of the complex aquatic environment in the Archipelago Sea is its high spatial and temporal variability; this foregrounds the importance of geographical information as a basis of environmental assessments. While evidence of a consistent water turbidity pattern was observed, the coastal hydrodynamic realm is also characterized by high spatial and temporal variability. It is therefore also crucial to consider the spatial and temporal representativeness of field monitoring data. Remote sensing may facilitate evaluation of hydrodynamic conditions in the coastal region and the spatial extrapolation of *in situ* data despite their restrictions. Additionally, remotely sensed images can be used in the mapping of many of those coastal habitats that need to be considered in environmental management. With regard to surface water monitoring, only a small fraction of the currently available data stored in the Hertta-PIVET register can be used effectively in scientific studies and environmental assessments. Long-term consistent data collection from established sampling stations should be emphasized but research-type seasonal assessments producing abundant data should also be encouraged. Thus a more comprehensive coordination of field work efforts is called for. The integration of remote sensing and various field measurement techniques would be especially useful in the complex coastal waters. The integration and development of monitoring system in Finnish coastal areas also requires further scientific assesement of monitoring practices. A holistic approach to the gathering and management of environmental monitoring data could be a cost-effective way of serving a multitude of information needs, and would fit the holistic, ecosystem-based management regimes that are currently being strongly promoted in Europe.

ACRONYMS

ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
BSPA	Baltic Sea Protected Areas
DG	Directorate General of European Commission
DPSIR	Driving forces-Pressures-State-Impacts-Responses
EEC	European Economic Community
ENVISAT/MERIS	ENVIronment SATellite / Medium Resolution Imaging Spectrometer Instrument
EC	Commission of the European Communities
EU	European Union
ESA	European Space Agency
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GMES	Global Monitoring for Environment and Security
GIS	Geographical information systems
HELCOM	The Helsinki Commission, i.e. the Baltic Marine Environment Protection Commission
Hertta-PIVET	The environmental information system of the Finnish Environmental Administration (Hertta) – the sub-system for State of Finland’s Surface Waters (PIVET)
ICES	The International Council for the Exploration of the Sea
ICZM	Integrated Coastal Zone Management
ISODATA	Iterative Self-Organizing Data Analysis Technique
Landsat TM	Landsat Thematic Mapper
Landsat ETM +	Landsat Enhanced Thematic Mapper Plus
MarCoast	Marine & Coastal Environmental Information Services
NE	notrheast
NOAA/AVHRR	National Oceanic and Atmospheric Administration / Advanced Very High Resolution Radiometer
NRC	The National Research Council (United States)
OECD	The Convention on the Organisation for Economic Co-operation and Development
SW	southwest
Terra/MODIS	Terra satellite / Moderate Resolution Imaging Spectroradiometer
U.S. EPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture
WFD	Water Framework Directive

1. INTRODUCTION

Coastal regions and shallow seas are among the most productive and diverse environments in the world. They are also highly important to humans, despite the relatively small area they cover (Costanza et al. 1997). Throughout the history of civilization, coastal ecosystems have been altered by multiple synergistic human activities (Jickells 1998; Jackson et al. 2001). During the past 150 to 300 years, near-shore marine systems have severely deteriorated due to rapid industrialization and technological progress, human population growth, and commercialization (Lotze et al. 2006). One of the most widespread environmental problems in coastal waters is eutrophication (e.g. Carpenter et al. 1998). Biodiversity losses caused by the deterioration of marine and coastal ecosystems, as well as the impending consequences of global climate change, indicate that substantial ecological and socioeconomic changes will continue to occur in coastal regions (e.g. Kennish 2002; Walther et al. 2002; Balmford & Bond 2005).

The management of marine ecosystems has often implied the assumption of a more or less linear response and smoothly changing state of the ecosystem (Scheffer et al. 2001). In practice, however, the unpredictability of multiple environmental agents and uncertainty about the ecosystem responses is common (e.g. Walters & Hilborn 1978; Costanza et al. 1998; Hulme 2005). Environmental management and protection measures are further challenged by the cumulative consequences of multilayered and multi-scaled environmental threats. A more holistic, integrated and adaptive framework of ecosystem-based management has therefore been called for in the pursuit of sustainability. In coastal areas the aim is to promote high ecosystem diversity and resilience, along with the sustainable use of marine resources (Ludwig et al. 1993; Botsford et al. 1997; Costanza et al. 1998; Costanza 1999; Scheffer et al. 2001; Folke et al. 2002; Elmqvist et al. 2003; Balmford et al. 2005; Hooper et al. 2005; Worm et al. 2006). Comprehensive information on changes in the status of ecosystems is thus becoming increasingly important for the management and decision-making processes affecting coastal areas (e.g. Holdgate 1994; Laskowski & Kutz 1998; Elmgren 2001; Kallis & Butler 2001; Hiscock et al. 2003; de Jonge et al. 2006).

Most of the available information supporting the management and protection of coastal and marine areas is produced by environmental monitoring. In its broadest sense, environmental monitoring helps to detect all environmental effects of both natural change and anthropogenic activities (e.g. Niemi 2006; NRC 1990; Vos et al. 2000). The different aspects of the monitoring regime can be represented using the DPSIR framework, which illustrates aspects of causality of multifaceted environmental and socio-economic processes (Table 1; e.g. Turner 2000; Elliot 2002). This thesis focuses primarily on the monitoring of the status and changes of the coastal environment (corresponding to “State” and “Environmental impacts” in Table 1), referred to below as “environmental monitoring”. These characteristics are primarily monitored by observing and measuring diverse quantitative aspects of the environment (e.g. Vos et al. 2000; Niemi 2006).

The monitoring process also involves conversion of the measured data into meaningful information through scientific data analysis, and the reporting of the results for the general public and for decision-makers (Fig. 1). As such, monitoring stands at the interface of society and science. Initiatives arise from the diverse information needs of societies, especially from statutory requirements (i.e. “Responses” in Table 1 and “Information needs of society” in Fig. 1). The practical implementation of monitoring efforts needs to be established on a sound scientific basis, in order for the information produced to have the necessary legitimacy and credibility. This demand has been highlighted in a number of articles concerning the practices and efficacy of environmental monitoring (e.g. Kwiatkowski 1991; Messer et al. 1991; Burt 1994; Elliot & de Jonge 1996; Ward 1996; de Jonge et al. 2006; Knowlton & Jones 2006; Håkanson 2007).

Scientific research pertaining to *in situ* aquatic monitoring has been relatively fragmented and disconnected, or has largely concerned inland waters (Dixon & Chiswell 1996). Methodologies and recommendations from related academic disciplines, such as statistics, have contributed to the development of efficient *in situ* data collection and methods of analysis (e.g. Green 1979). In recent years, methods based on remote sensing and automated measurement techniques have been developed to improve the spatial and temporal representativeness of coastal and marine monitoring (e.g. Glasgow et al. 2004; Dickey et al. 2006). In addition, geographical information systems (GIS) provide a powerful tool for the management and analysis of the data collected (e.g. Tolvanen & Kalliola, in press). The challenge of environmental monitoring is nevertheless the cost-effective production of accurate and appropriate data that adequately fulfil the foreseen information objectives (e.g. Ward 1996; Vos et al. 2000). In this regard, the spatial distribution and temporal frequency of data collection are highly important (e.g. Loftis & Ward 1980; Loftis et al. 1991; Strobel et al. 2000; Summers et al. 2000; Danielsson et al. 2004; Aplin 2006; Strobl et al. 2006). While demands for more effective and holistic environmental management and protection have been incorporated into legislation and international conventions, the role of monitoring as the primary source of basic information on the status of the environment is emphasised.

Table 1. DPSIR-framework regarding coastal water quality and habitats; potential and actual variables and indicators (based on Turner et al. 1998; Luiten 1999; Walmsley 2002; Bowen & Riley 2003; Lundberg 2005; Auvinen & Toivonen 2006; Niemi 2006; Auvinen et al. 2007). Arrows show major causal and feedback connections. State and environmental impacts are intertwined.

DPSIR framework	**D**riving forces	**P**ressures	**S**tate	**I**mpacts	**R**esponses
Examples of DPSIR factors	Socio-economic forces, e.g. population growth, transport, agricultural intensification, land-use changes, recreation demand, fisheries and aquaculture, industrial development Natural conditions, e.g. amount of rainfall	Agricultural runoff, industrial point source emissions, sewage, aquaculture Estuarine and coastline engineering, land reclamations, dredging	Status and changes (often increase) in nutrient concentrations and phytoplankton production; status and changes (often decrease) in oxygen in sediments and near-bottom water layer Status and chances in area of habitats, changes in biodiversity	Environmental impacts: Primary or secondary symptoms of eutrophication e.g. increase in occurrence of harmful algal blooms or decreased water transparency Loss of habitats and biological diversity Social impacts: e.g. decreased resources for cultural use Economic impacts: e.g. costs of abatement procedures	Measures of environmental policy e.g. statutory requirements, establishment of nature conservation and other protected areas
Examples of variables and indicators related to the quality of waters in the coastal areas	Resident coastal population Patterns of land use / Land cover Economic value / employment in coastal industry	Fertilizer use in coastal watershed (i.e. loading of phosphorus and nitrogen)	Concentrations of chlorophyll-*a* and nutrients	Incidences of harmful algal blooms	Environmental protection expenditure Number of water quality monitoring sites
Examples of variables and indicators related to the coastal habitats		Percentage of altered coastal land	Number and/or area of habitats and biotopes, species abundance and composition	Number of threatened species (also a state indicator)	Area of protected sea areas and shores

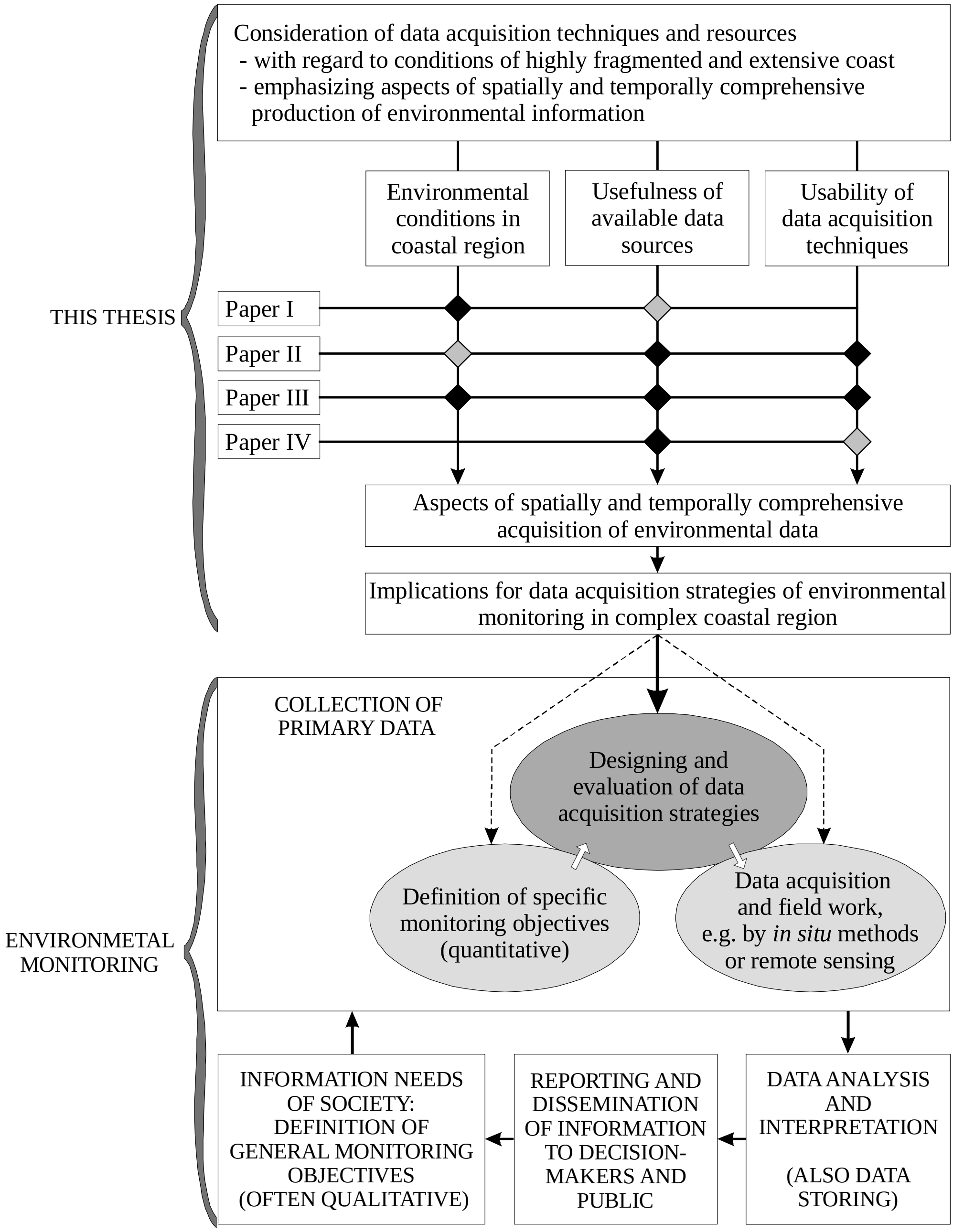

Figure 1. Role of the thesis with regard to the process of environmental monitoring (modified from NRC 1990; Dixon & Chiswell 1996; Vos et al. 2000). Topics which are at the focus of the papers of the thesis are marked by black diamonds; topics which are tangentially touched on are marked by grey diamonds.

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In physical and applied geography, aspects of the aquatic environment constitute an important research field (e.g. Yli-Jokipii 1994; Webb 1999; Lourie & Vincent 2004). The adoption of geographical information systems and remote sensing methods in the environmental sector has increasingly involved geography as a discipline in the mapping and monitoring of the aquatic environment (e.g. Liu et al. 2003; Aplin 2005; McDermid et al. 2005; Duro et al. 2007; Knudby et al. 2007; Longhurst 2007). GIS and remote sensing allow the characterization of the aquatic environment and human activities embracing diverse data sources and a multitude of different scales, thus contributing to the increased information needs of society. Geography also provides a comprehensive overview of spatial planning and environmental management issues, which is especially advantageous in coastal management (e.g. Ratinen 2005; Tolvanen 2006).

This thesis applies a holistic approach in considering data acquisition practices for the different needs of environmental decision-making. In this sense the thesis also extends to the very roots of geography, occupying as it does an intermediary position between science and society (c.f. Granö 1996). One special focus in the thesis is on the challenges of environmental monitoring in the geographically complex and extensive coastal areas of southwest Finland. This region is subject to multiple human interests and uses, which may in some cases be mutually conflicting (e.g. Granö et al. 1999; Leppäkoski et al. 1999). In such a setting environmental monitoring is challenged by contradictory requirements, such as cost-effectiveness versus adequate and regionally comprehensive data production. This reality foregrounds the need for a systematic examination of the methods and strategies applied in environmental data acquisition and the usefulness of the available data sources, particularly in terms of their spatial and temporal performance.

Although environmental monitoring has been performed in the southwest Finland coastal region for decades, monitoring methods and practices have not been comprehensively analysed from a scientific point of view. This thesis thus focuses on the validity of those methods and data sources that are readily available and/or have been collected in the region over a long period of time. Because of the considerable efforts required in environmental data acquisition, the usefulness of the present data sources is necessary to evaluate. The key point in my approach is that the framework for any human activity is ultimately established by physical conditions, and that this reality has to be taken into account in any practical monitoring activity. My approach to data acquisition practices and the corresponding field procedures is based on a spatial comprehension of the highly fragmented coastal areas and their dynamics (Fig. 1).

Paper I forms the basis for the investigation of the spatial and temporal characteristics of the quality of surface waters in the SW Finland archipelago. The study analyzes the factors behind coastal eutrophication, using data collected in environmental monitoring programmes. The paper also serves as an example of the possibilities offered by monitoring data as a sound scientific basis for decision-making. The paper examines the spatial and temporal development of water quality variables at three stations, located in different parts of the archipelago. The results provide an insight into the spatial and temporal development of surface water quality from the 1970s to the late 1990s; the discussion focuses mainly on nutrient ratios and nutrient load in the Archipelago Sea. As such, this paper also exemplifies the type of research that is needed for in-depth knowledge regarding the nutrient dynamics of these sea areas. Such studies, however, have been relatively rare (e.g. Lagus et al. 2004, 2007a,b; Suomela et al. 2005; Vuorio et al. 2005).

Paper II considers the usefulness of remote sensing data for the mapping of coastal and marine habitats as defined in the EU Habitats Directive (Council Directive 92/43/EEC, Anon. 1992). More specifically, the paper explores the usability of high altitude aerial images in the identification of coastal and marine habitats that are listed in its Annex I, as a potentially rapid and inexpensive survey method. The habitats under consideration vary in size and definition, as they may consist of variable geomorphologic features, vegetation or geographical areas (European Commission, DG Environment 2007). Thus a mere examination of their spectral or spatial properties may not reveal the full usefulness of such images. In order to better evaluate their operative potential in the identification of the targeted habitats, a number of respondents were asked to distinguish and visualise the habitats under consideration in a practical test. A group of 34 persons, consisting of environmental administrators, researchers and students in physical geography, participated in the test. Each respondent identified habitats from five aerial photographs from the Ekenäs archipelago and the Hanko peninsula. These consisted of 15 habitats, which were well known and had been in part mapped in the field by the first author. In general, this study thus examines the usability of existing data sources for the current practical information needs of the environmental authorities. An additional value of high altitude aerial images is that they are available for the entire coastal region since the 1960s, thus being the longest regularly acquired imagery with a high potential to contribute to the research and assessments of environmental change.

Paper III explores the dynamic spatial characteristics of surface water quality in the Archipelago Sea. By exploring satellite images, it approaches the aquatic environment of the coastal archipelago using a spatially more synoptic view than was the case in papers I and II. The reflectance patterns of surface waters were analysed from high resolution Landsat TM and ETM+ images that had been acquired during the summers of the late 1990s. The relatively extensive spatial coverage and the 30 meter spatial resolution of the optical bands allows the retrieval of detailed surface water patterns, particularly in the central and inner parts of the archipelago. The patterns were analysed by visual inspection, principal component analysis and unsupervised classification. These were compared to surface water patterns of the region that were derived from *in situ* water quality data collected in the monitoring programmes. The water quality data applied consisted of the mean transparency and phytoplankton chlorophyll-*a* values, as measured during 1995-1999. The study contributes to our understanding of the spatial characteristics and dynamism of the coastal waters; it also addresses spatial aspects of water sampling in the archipelago and considers the potential of remote sensing and its integration with *in situ* water quality monitoring.

Paper IV examines the spatial and temporal coherence of *in situ* water quality data sets in the Hertta-PIVET register. The SW Finnish coastal areas have been intensively monitored and studied during the second half of the 20th century, and the majority of the raw analytical results have been archived this register of the Finnish Environmental Administration. *In situ* sampling provides precise information on water bodies, which is valuable in quantitative studies and as ground truth data for remote sensing and modelling applications. In this paper, phytoplankton chlorophyll-*a* and primary productivity were studied as sample resources for environmental studies, using data collected at 733 sampling stations from 1971 to 2006. Water samplings were examined at annual and semi-monthly levels; temporal patterns of sampling are illustrated by frequency tables. Similarly to Papers II and III, this study too investigates the use potential of existing data sources for the current practical information needs of environmental monitoring.

2. METHODS OF MARINE AND COASTAL MONITORING

2.1. General framework and field sampling

The technical definition of environmental monitoring is given by Vos et al. (2000) as follows: “the repetitive measurement of a specified set of variables at one or more locations over an extended period of time according to prearranged schedules in space and time.” Definitions of environmental monitoring vary to some degree, but in general they are based on the same idea (e.g. NRC 1990; ANZECC & ARMCANZ 2000; Yoccoz et al. 2001; Niemi 2006; Taljaard et al. 2006). Regardless of their objectives and methods, the establishment and implementation of efficient monitoring programmes requires stable governance and institutional involvement. Thus environmental monitoring is usually well established in developed countries (e.g. NRC 1990; Ford et al. 1993; Kristensen & Bøgestrand 1996; ANZECC & ARMCANZ 2000; U.S. EPA 2003; Kennish 2004a,b; Niemi 2006). Coastal and marine monitoring programmes based on *in situ* sampling require considerable and consistent material and human resources because of the special expertise, equipment, and logistics needed in field sampling. Monitoring has developed from simple, restricted analyses into multivariate large-scale programmes, including interpretation and dissemination of information to end-users in an appropriate format (e.g. Ward 1996; Vos et al. 2000; de Jonge et al. 2006).

Environmental monitoring serves a wide range of societal information needs simultaneously (NRC 1990; Kristensen & Bøgestrand 1996; Boesch 2000; Niemelä 2000; U.S. EPA 2002; Rice et al. 2005). It is used to evaluate natural resources, anthropogenic impacts, natural changes and the state of the environment. It supports environmental management by providing feedback about e.g. the effectiveness of pollution abatement activities. Monitoring may further serve as an early warning system or provide background data in case of emergency. It should provide a scientific rationale for defining environmental quality standards and making decisions on protection priorities or environmental permits.

For scientific research, carefully designed monitoring programs may provide evidence of environmental change, reveal unexpected patterns, verify and calibrate models that describe and predict ecosystem functions and responses, and provide a context for research hypotheses (Elliot & de Jonge 1996; Boesch 2000; Burt 2003; Balmford et al. 2003). Effective monitoring systems thus make an important contribution to both research and decision-making while increasing our level of understanding concerning the issues being monitored. Monitoring itself should be based on scientific principles, it should be built on active links to research, and it should produce high-quality data (e.g. Maher & Norris 1990; U.S. EPA 2002; EC 2003). For instance, the definition of relationships and causality between biological stressors and effects requires experimental studies and basic research (Yoccoz et al. 2001; Adams 2003, 2005).

Sampling design is critical to ensure that the data collected as part of a monitoring programme are accurate and adequate to produce an appropriate and defensible basis for drawing conclusions. Thus the collection of data is the methodological core of monitoring programmes and a fundamental part of science-based decision-making (NRC 1990; Vos et al. 2000; Yoccoz et al. 2001; U.S. EPA 2002, 2003). Many of the practical information needs are of a qualitative nature. The important part of the planning and evaluation of a given monitoring programme is defining the concrete information goals and monitoring objectives (e.g. Dixon & Chiswell 1996; Vos et al. 2000). After the general objectives have been defined, the formulation of specific monitoring questions is crucial to the process (NRC 1990; Dixon & Chiswell 1996). Careful consideration of the variables or indicators to be monitored is required in order to avoid unnecessary and uncontrolled data collection and because of the limited resources available for data gathering (NRC 1990; Vos et al. 2000; Petts et al. 2006).

There are basically two different criteria for site selection: probability-based sampling and sampling based on expert judgment (U.S. EPA 2002). The former allows for the calculation of uncertainty and suits for making statistical inferences. It is a scientifically valid method that protects against the bias that may occur in the case of subjective design (e.g. Green 1989; NRC 1990; U.S. EPA 2002; Stevens & Olsen 2004; Legg & Nagy 2006). The cost of probability-based sampling schemes, however, may be high, because for instance of the difficulty of reaching the sampling sites or the considerable number of sites required to cover the target population adequately. A considerable proportion of monitoring costs is also associated with sampling frequency. Expert judgement and case-by-case decisions have therefore been applied in the monitoring programmes (e.g. Dixon & Chiswell 1996; Elliot & de Jonge 1996; Kristensen & Børgestrand 1996; Olsen et al. 1999; USDA 2003; EC 2003).

2.2. Remote sensing of water quality and coastal habitats

Remote sensing studies on water resources have been carried out since the 1970s, and their applications for marine monitoring have been developed since then (Kirk 1983; Muller-Karger 1992; Clark 1993; Dickey et al. 2006; Allan 2008). The development of geographical information systems has supported the introduction of remotely sensed data (Hinton 1996; Yang 2005). Passive space-borne remote sensing using optical and thermal bands is used to describe water quality, including turbidity, algal blooms, temperature and trophic level (Lindell et al. 1986; Esaias et al. 1998; Rast et al. 1999; Ritchie et al. 2003; Hellweger et al. 2004; Zhang 2005; Reinart & Kutser 2006).

Space-borne instruments such as Landsat TM, with fairly good ground resolution, are useful in coastal and lake studies over wider areas; although their spectral and/or radiometric resolution is not optimal for water quality detection (e.g. Zilioli & Brivio 1997; Lindell et al. 1999; Kutser et al. 2005; Doxaran et al. 2006; Hadjimitsis et al. 2006; Miyazaki & Nadaoka 2006; Tyler et al. 2006; Wang et al. 2006; Zhou et al. 2006; Duan et al. 2007; Rajawat et al. 2007; Teodoro et al. 2007). Hyper-spectral instruments, especially those with high ground resolution, have also been tested for coastal and lake applications (e.g. Kutser et al. 1998; Dekker et al. 2002; Brando & Dekker 2003; Kallio et al. 2001, 2003; Koponen et al. 2001; Giardino et al. 2007). The advantage of hyper-spectral applications is precisely their very high spectral resolution, producing numerous narrow spectral bands. They are thus able to extract the spectral characteristics of an object in a more detailed manner than instruments with a broad bandwidth such as those onboard in the Landsat satellites.

Data from *in situ* monitoring programmes are used as the ground truth data for the interpretation of satellite images and algorithm calibration and validation (e.g. Kallio 2000; Rantajärvi 2003; Niemi et al. 2006). The trend is to integrate different types of measurement and observation techniques in order to gain more comprehensive knowledge on the aquatic environment (e.g. Dekker et al. 1996; Pulliainen et al. 2001; Vos et al. 2003; Udy et al. 2005; Nezlin et al. 2007; Allan 2008). In the Baltic Sea, where optically active constituents of water column are abundant as well as spatially and temporally variable, the use of remote sensing methods for water quality assessment has been advancing especially in recent years. Nevertheless, the development of the atmospheric correction methods for the Baltic Sea and coastal waters is challenging (e.g. Koponen et al. 2007; Berthon et al. 2008; Kratzer et al. 2008). Methods and algorithms have been developed in particular for the retrieval of distinct water quality parameters, such as turbidity and chlorophyll-*a* (Kutser 1997; Kutser et al. 1998; Härmä et al. 2001; HELCOM 2004b; Zhang et al. 2003; Zhang 2005; Chen et al. 2007; Koponen et al. 2007; Krawczyk et al. 2007). Current remote sensing instruments are suitable for qualitative but not quantitative assessment or prediction of cyanobacterial blooms (Kutser et al. 2006a; Metsamaa et al. 2006). The integration and development of field sampling, remote sensing and modelling techniques further enhances our understanding of the coastal and marine environment in the Baltic Sea (e.g. Siegel et al. 2005; Edelvang et al. 2005; Vepsäläinen et al. 2005; Sipelgas et al. 2006; Kahru et al. 2007).

Remote sensing methods can potentially support the monitoring of water quality, but their use also requires long-term commitment to data production processes and systematic strategies for providing data and accumulating consistent archives for monitoring (Chen et al. 2004; Aplin 2006). For example, the European Water Framework Directive introduces a new, area-oriented approach instead of the traditional point sampling. This provides an opportunity for the development of integrated management and monitoring systems and thus the increased use of remote sensing techniques (Dworak et al. 2005).

Space-borne remote sensing methods have also been developed for the mapping of shallow water habitats and their features (Dekker et al. 2005; Phinn et. al 2005; Roelfsema et al. 2006; Vahtmäe et al. 2006; Cho 2007). Recently high and very high resolution multispectral satellite imagery has been used for habitat and vegetation surveys in coastal waters (e.g. Larsen et al. 2004; Mishra et al. 2005; Fornes et al. 2006). Airborne instruments are suitable for the study of water and littoral areas in relatively small-scaled environments and small areas (e.g. Liu et al. 2003; Gilvear et al. 2004; Valta-Hulkkonen et al. 2003, 2005). Hyperspectral remote sensing and the use of aerial photography are being continuously developed in order to detect fine-scale variability in benthos or small-scale changes in habitat boundaries (e.g. Dierssen et al. 2003, Kutser 2006b). Multisource methods have been developed that combine airborne images, high resolution satellite images and other cartographic data, since data from different sources complement each other (e.g. Valta-Hulkkonen et al. 2004; Guariglia et al. 2006). Recent studies on the applicability of remote sensing for Habitats Directive monitoring in coastal areas also emphasise terrestrial applications (Boresjö Bronge & Flodin 2006; Boyd et al. 2006; Sanchez-Hernandez et al. 2007).

3. DEVELOPMENT OF FINNISH MARINE AND COASTAL MONITORING

3.1. Environmental pressures and their effects on the Baltic Sea and Finnish coastal waters

The Baltic Sea catchment area, which is 4.3 times larger than the actual sea area, is currently inhabited by nearly 85 million people and about 15 million people live within 10 kilometres of the coastline (Ehlin 1981; HELCOM 2003). The extensive alteration of the Baltic waters started more than a century ago (Bonsdorff et al. 1991; Rheinheimer 1998; de Jonge et al. 2002; Österblom et al. 2007). This has reduced biodiversity and increased the discharge of harmful organic and inorganic substances into the sea (e.g. Larsson et al. 1985; HELCOM 2003, 2004a). Climate-driven changes, such as increases in temperature and precipitation, will arguably modify hydrographic and ecological conditions, and will affect the future composition, distribution and interactions of marine species (Elmgren 2001; HELCOM 2007a; Suikkanen et al. 2007).

The long residence time of the water and the shallowness of the sea have led to an undesired accumulation of some nutrients and harmful substances into the Baltic Sea ecosystems (HELCOM 2002, 2003). Across the entire Baltic Sea, the majority of nitrogen and phosphorus inputs originate from diffuse sources via riverine inputs, especially from intensively cultivated areas (Larsson et al. 1985; Stålnacke et al. 1999; HELCOM 2005a; Leivonen 2005; Wulff et al. 2007). Airborne nitrogen constitutes c. 25 % and phosphorus only c. 1-5 % of the total nutrient loading (HELCOM 2005a). Eutrophication has affected the Baltic aquatic communities: for instance occurrence of *Fucus vesiculosus* has decreased and the species composition of macroalgae communities has changed (Bäck 2004; Kraufvelin & Salovius 2004; Karlson et al. 2002; Lundberg 2005). The Baltic Sea sub-basins differ in their water exchange patterns and other hydrographic conditions, and thus also in ecosystem responses to eutrophication vary (e.g. Larsson & Hagström 1982; Wulff et al. 1990; Bonsdorff et al. 1991; Håkansson et al. 1996; Larsson et al. 2001; Rönnberg & Bonsdorff 2004). The Gulf of Finland is the most eutrophicated part of the Baltic Sea. The least eutrophicated part of the Baltic Sea is the Gulf of Bothnia; its shallow sills prevent the flow of nutrient-rich deep waters from the southern sea areas (Bonsdorff et al. 1997; Pitkänen et al. 2004; Lundberg et al. 2005; Alahuhta 2008).

Geomorphological complexity impairs water exchange on the archipelago coasts; thus nutrient inputs from land and adjacent sea areas accumulate in the coastal ecosystems and facilitate biological production in shallow areas (e.g. Bonsdorff et al. 1997; Helminen et al. 1998; Hänninen et al. 2000). The status of the environment in terms of eutrophication has been improved in the innermost parts of the Finnish coasts by the effective treatment of waste waters, but the opposite is true of the outer archipelago because of nutrient loading from diffuse sources. The eutrophication of the Gulf of Finland, for example, extends to the southeastern parts of the Archipelago Sea (Pitkänen et al. 2004; Lundberg et al. 2005). Nutrient loading from coastal fish farming and the impact of non-point source pollution from agriculture have increased the eutrophication of Finnish coastal waters, especially in the Archipelago Sea (Bonsdorff et al. 1997; Pitkänen et al. 2004). In recent years, however, nutrient loading from fish farming has decreased considerably, while discharges from agriculture have remained high (Pitkänen et al. 2004; Leivonen 2005; HELCOM 2006b). Also internal phosphorus loading from sediments has increased in the Archipelago Sea (Kauppila & Bäck 2001). Eutrophication thus persists as a major environmental problem in SW Finland coastal waters (e.g. Bonsdorff et al. 2002).

3.2. Development of the coastal water quality monitoring regime in Finland

The earliest oceanographic and biological research in the Baltic Sea area was conducted by individual scientists and research groups and by the International Council for the Exploration of the Sea (ICES) (e.g. Leegaard 1920, Dybern 1980; Fonselius & Valderrama 2003). The primary aim of the early research and management regarding coastal waters was often linked to the need to exploit the marine resources of the sea (e.g. Elmgren 2001). In Finland, the Water Act of 1902 initiated water conservation activities to protect water resources for purposes of further utilization (Sairinen 2000). In the 1930s, protection activities were still primarily focused on providing clean water for industrial processes, even though water pollution was already a local nuisance. After World War II, water pollution problems were exacerbated with the accelerated pace of industrialization, mainly due to insufficient knowledge concerning the aquatic ecosystems and inadequate surveillance of the provisions enacted under the Water Act (Heinonen 1972).

The report of the Water Protection Committee, released in 1958, can be seen as initiating a period of active water protection in Finland; it led to more stringent prohibitions on water contamination in the new Water Act of 1961 (Heinonen 1972; Sairinen 2000; Anon. 1961). The new Act also enacted implementation measures, such as emission monitoring, obligatory notification by polluters, and wastewater treatment. These principles were also adopted in the Environmental Protection Act and Decree of 2000, which currently regulates water pollution control and the issuing of environmental permits in the country (Ministry of the Environment, Finland 2000a,b).

As a consequence of the Water Act of 1961, a local pollution control monitoring network, based on the “polluter pays” principle, was established in inland and coastal waters from 1962 onwards (Sarvala 1992; Niemi & Heinonen 2003). Along with the existing governmental water protection authorities, Water Protection Associations were established in the 1960s. These are voluntary consortia of stakeholders with an interest in the use of water resources, many of them also being holders of environmental permits (Heinonen 1972). The associations aim at promoting water protection in their areas of jurisdiction; they also play an important role in pollution control monitoring (e.g. Jumppanen 1996). The local pollution control monitoring is based on environmental permit system. Holders of such permits are obliged to monitor the environmental impact of their operations, for instance to map environmental changes and the extent and intensity of environmental impacts (Anon. 1976; Vuoristo 1992). The results are used in the evaluation of possible damage and the need for compensation as well as in further permitting operations. The joint monitoring programmes by several environmental permit holders have been applied for decades (Anon. 1976; Vuoristo 1992).

In the 1970s, the continuous and expanding pollution of Finnish waters was acknowledged as an environmental problem requiring effective solutions. According to the National Board of Waters (1974), over half of the population in Finland lived close to moderately or severely polluted waters. With the aim of bringing about an effective and consistent decrease in the level of pollution, the board issued the first Decision-in-Principles on the Water Protection Targets in Finland in 1974 (National Board of Waters 1974). In 1986, the National Board of Waters was transferred to the new Ministry of the Environment and duties concerning water issues were concentrated in thirteen Water and Environmental Districts, currently known as Regional Environment Centres (Sairinen 2000).

Both regional centres and the national Finnish Environment Institute monitor the general status and change of the coastal and marine waters (e.g. Anon. 1990; Niemi & Heinonen 2000, 2003; Niemi et al. 2006). National monitoring programmes consist of physical and chemical monitoring of coastal waters, biological monitoring of macrozoobenthos and phytobenthos, and monitoring of material inputs into the Baltic Sea by rivers as well as harmful substances in biota (Kauppila & Bäck 2001). Physical and chemical water quality variables and chlorophyll-*a* are mapped at circa one hundred coastal stations twice a year and at some twelve intensive stations throughout the year (Niemi et al. 2006). The sampling sites chosen are either located outside areas affected by wastewaters or represent large coastal water bodies, and their sampling is possible with reasonable effort (Kauppila & Bäck 2001). The regional centres supervise local pollution control monitoring and conduct regional monitoring programmes within their jurisdictional areas in order to fill the gap between the coverage of the national and local pollution control monitoring programmes (Niemi & Heinonen 2003). In open sea areas, marine monitoring has been carried out by the Finnish Institute of Marine Research. The entire coastal and marine monitoring regime is planned to extend from water areas near pollution sources to the open sea (Kauppila & Bäck 2001).

Finland has also participated actively in multilateral conventions in the field of water policy and has integrated these into the national environmental policy and regulations

(Anon. 1998). These include the water protection policy outlines until 2015 and the Action Plan for the Protection of the Baltic Sea and Inland Watercourses published in 2005 (Anon. 2005a; Nyroos et al. 2006). The establishment of international cooperative bodies was especially intensive in the 1970s, mainly because of the general concern about the environmental impact of heavy anthropogenic stress (Dybern 1980; Rotkirch 1984; Sairinen 2000). One of these was the Committee for the Gulf of Bothnia, which was established in 1972 and which was monitoring the coastal and sea areas of southwest Finland (e.g. the Committee for the Gulf of Bothnia 1989; Johansson 1996).

The premises for Baltic-Sea-wide monitoring were established in the first half of the 1970s, in particular as a consequence of the Helsinki Convention and establishment of the Helsinki Commission (HELCOM). The Helsinki Convention is one of the most comprehensive environmental treaties worldwide, and was the first regional convention for marine protection (Hägerhall 1980; Rotkirch 1984). HELCOM monitoring started on a routine basis in 1979 (HELCOM 1981). The assessments of coastal water quality are based on the results of the national monitoring programmes (e.g. HELCOM 1993). In recent years, HELCOM has adopted the principles of ecosystem approach and adaptive management, in order to improve the status of the sea area and the basis for a more sustainable use of its natural resources (HELCOM 2005a,b, 2006a,b, 2007b). Efforts to maintain and restore water quality also form an important part of long-term biodiversity conservation and management (HELCOM 2006a).

The Finnish Environment Institute has used satellite imagery for operative monitoring since the beginning of the 2000s. It has developed broad-scale operational satellite observing systems for the Baltic Sea. NOAA/AVHRR, Terra/MODIS and ENVISAT/ MERIS images are used to monitor surface water temperatures, nuisance algal blooms, water turbidity and chlorophyll-*a* concentrations in the northern Baltic Sea. The results of remote sensing monitoring are available on the public in the website of the Finnish Environment Institute (Niemi et al. 2006; see Fig. 2). Finland also participates in the Group on Earth Observations (GEO) as well as the Global Monitoring for Environment and Security programme (GMES) and its sub-programme the MarCoast programme, which aims at developing remote sensing services for oil spills and water quality observation (Dworak et al. 2005; GEOSS 2005; Anon. 2006a). The Finnish Institute of Marine Research is responsible for the joint operational monitoring and information service in the Baltic Sea (Alg@line, The Baltic Sea Portal). The backbone of the system consists of an intensive automatic flow-through system that produces nearly real-time information about the algal situation and hydrographic conditions of the Baltic Proper (Rantajärvi et al. 1998a,b; Niemi et al. 2006).

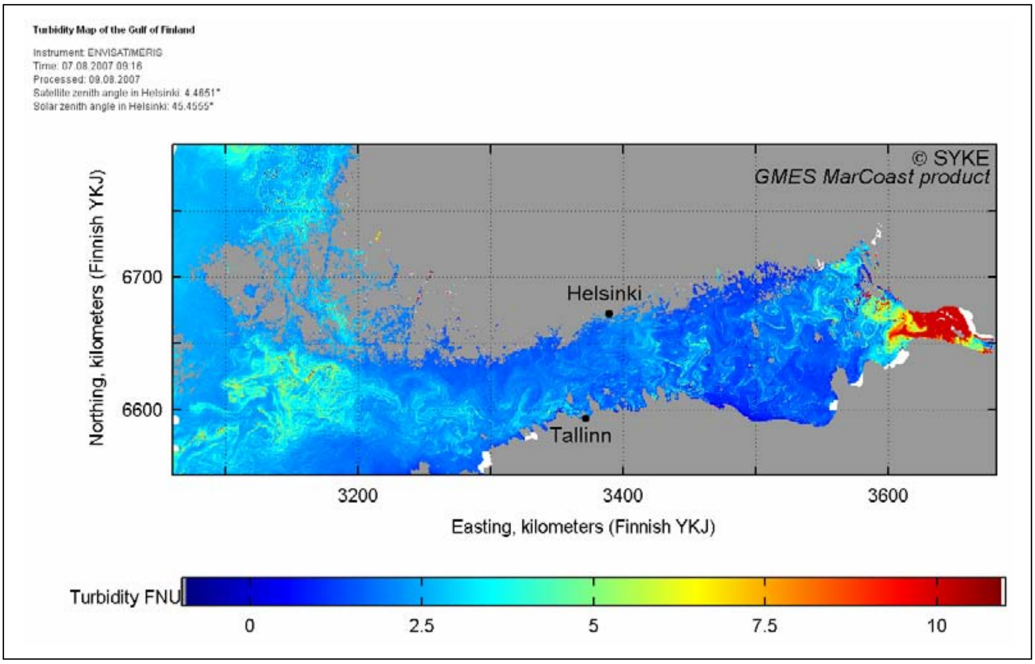

Figure 2. Turbidity of seawaters in NE Baltic as revealed by operative monitoring satellite images and presented on the Finnish Environment Institute website (www.ymparisto.fi, 7 August 2007).

3.3. Habitats mapping and monitoring

In addition to the negative effects of eutrophication and the potential threats of climate change, many types of coastal habitats are also threatened by other human activities, including the dredging of boat channels, the extraction of gravel and marine sand, boating and other leisure activities, human-induced erosion, littering, the building of holiday housing and other development projects (e.g. Bäck 2004; Auvinen et al. 2007; Numers & Korvenpää 2007). Varied shore activities also pose a threat to valuable habitats and nature types in the Archipelago Sea (e.g. Granö et al. 1999; Numminen 2002; Peippo 2003).

Finland has been involved in international conservation cooperation since the 1920s, and has integrated the respective aims and obligations into its national legislation (HELCOM 1996; Vuorisalo & Laihonen 2000). Membership in the European Union since 1995 has had a major impact on conservation policy. In 2002 the European Union recommended that member countries should adopt the Integrated Coastal Zone Management (ICZM) scheme, recommended by the OECD (Anon. 2002). The Finnish Coastal Zone Strategy was established according to this recommendation in 2006 (Hanhijärvi 2006), and together with the action plan for the conservation and sustainable use of biodiversity it aims at halting the decline in biodiversity in Finland among their other objectives (Heikkinen et al. 2007). The national ICZM strategy was preceded by a local strategy established by regional forces for southwest Finland (Peippo 2002, 2003).

The EU Habitats Directive together with the Birds Directive form the basis of the European Union's nature conservation policy (Council Directives 92/43/EEC and 79/409/EEC). These are also the Union's major contributions to halting the loss of biodiversity by 2010 (EC 2006). Both directives have been incorporated into the revised Nature Conservation Act of 1996 (Anon. 1996). The Habitats Directive aims at conserving the most endangered European species and habitats. Natura 2000 is a network of nature protection areas established in the 1990s under the Habitats Directive. The aim of the Baltic Sea Protected Areas (BSPAs) is also to restore certain marine habitats or species from degradation. In Finland, coastal BSPAs have been integrated in the Natura 2000 network (Vuori et al. 2006a). In an international context, coastal archipelago areas and post-glacial uplift zones in the Gulf of Bothnia are among unique habitats in Finland (Vuorisalo & Laihonen 2000). For this reason the coastal areas of SW Finland have a dense network of Natura 2000 sites.

In Finland, the entire system for monitoring biodiversity and the definition of suitable indicators has been evaluated in recent years (Muurman & Lehvo 1997; Toivonen & Liukko 2005; Auvinen & Toivonen 2006; Liukko et al. 2006). Current activities include monitoring programmes for economically important fish stocks and coastal phytobenthos as well as phytoplankton, zooplankton and macrozoobenthos in the Baltic Sea. However, modifications and additions are needed in order to monitor biodiversity at all levels and produce information for the adaptive management of biodiversity (Liukko et al. 2006; Auvinen et al. 2007). The endangered species and habitats listed in Annex I of the Habitats Directive are among prioritised targets in developing the biodiversity monitoring system (Ympäristöministeriö 2003).

Finland has twenty-one of the coastal and marine habitats listed in Annex I of the Habitats Directive, of which eight habitats are partly or entirely submerged (see Paper II; also European Commission, DG Environment 2007). The geographical location, number and area of the underwater habitats is inadequately known, which impairs the development of an effective monitoring system (Toivonen & Liukko 2005; Auvinen et al. 2007). The information is therefore collected from existing data and new surveys are implemented to fill the gaps (Vuori et al. 2006a; Anon. 2005a; Toivonen & Liukko 2005). The development of a monitoring system for protected areas is important, but monitoring of non-protected areas is also necessary in order to safeguard the overall maintenance of total biodiversity (Auvinen et al. 2007).

3.4. Need to revisit the scientific basis

The above review reveals the evolutionary development of the current environmental monitoring on Finnish coasts. The outcome of these developments is the compendium of present monitoring activities and thus far completed efforts to bring the separate activities together. As an example of such efforts, the Finnish environmental administration has created combined data registers to accommodate all data produced, such as the Hertta-PIVET register (see Manni & Nurmio 2006). Similarly, the chain of quality assurance measures is continuously developed nationally and as part of international obligations in covering the entire process of monitoring (e.g. Lääne & Heinonen 2005; Bäck et al. 2002). The laboratories that take part in monitoring are certified and use standardized analytical methods. In recent years the personnel engaged in field sampling have also been certified (e.g. Lääne & Heinonen 2005).

The monitoring of habitats is a new component of the monitoring system and creates pressures for a renewed monitoring regime (Toivonen & Liukko 2005). Remote sensing is also considered promising for the mapping and monitoring of coastal habitats. The usefulness of remote sensing technology in water habitat conservation, however, rests on its ability to map relevant environmental variables based on sound scientific principles (Knudby et al. 2007). Underwater *in situ* methods are necessary for the detailed mapping of species and habitats in a deeper phytobenthic zone, along with calibration reference for spaceborne or airborne remote sensing data. Mapping also serves the delineation of conservation areas and the selection of appropriate areas for monitoring, since habitat monitoring presumes that the occurrence and spatial distribution of habitats is known (Bäck et al. 1996). Automatic underwater vehicles and underwater videography and photography improve the efficacy of on-site marine habitat monitoring (e.g. Vahteri et al. 2000; Kutser et al. 2007; Moline et al. 2007).

In an overall evaluation of the entire Finnish environmental monitoring regime (Ympäristöministeriö 2003, p. 11), weaknesses were found in the form of poor coordination, low prestige, underutilization of information and inadequate spatial coverage of monitoring. Strengths, however, were also observed, including highly developed GIS, effective regional sampling and analysis, long-term monitoring activities and an established expertise as well as close connections between research and monitoring. The development of cooperation and the introduction of new methods were seen as opportunities, while deficiencies in resources and communication and an overemphasis on international obligations were seen as problems. These notions, however, were based merely on the internal evaluation of environmental monitoring system for its own sake. Similarly, the recent internal evaluation of the Finnish Environmental Administration proposes that regional and national monitoring programmes should be integrated into a single comprehensive monitoring programme in order to increase the administrative cost-effectiveness of monitoring efforts (Malm 2007). In the recent international evaluation of

Finnish water research, the importance of long-term data sets and continued monitoring as well as the public availability of such data via the Internet were recommended (Moss et al. 2008). The scientific use and applicability of marine and coastal monitoring efforts have not been systematically assessed.

In recent years national water quality monitoring programmes have been updated for the implementation of the EU's Water Framework Directive (WFD, Council Directive 2000/60/EC) and Habitats Directive (Ympäristöministeriö 2003). The WFD has been the main instrument of EU water policies in the 2000s, with the aim of restoring the good status of natural waters by 2015 (Anon. 2000). There are also other treaties, legislative texts and directives which include requirements for water quality monitoring (Mitikka et al. 2005; HELCOM 2006b). HELCOM too stresses the importance of monitoring in contributing to scientific understanding of the marine environment and as a tool for determining further management measures (HELCOM 2007b). The fact that the WFD embraces all inland and coastal water resources reflects the ecosystem approach adopted by the EU (EC 2004; Gipperth & Elmgren 2005). The EU's Marine Strategy Directive seeks to apply the ecosystem approach to open sea areas (Laffoley et al. 2004; Anon. 2006b).

4. STUDY AREA

This study is mainly concerned with the southwestern coasts of Finland, with an emphasis on the Archipelago Sea. Prevalent in these middle latitudes is a boreal forest climate, with frequently passing depressions and cyclones from the Atlantic Ocean. The mean temperature is c. + 15 °C in July and below 0 °C in winter, causing the formation of an ice cover in coastal areas. The strong seasonality affects the coastal waters; in spring and autumn vertical mixing takes place, while summers are characterised by thermal stratification and winters by inverse stratification (Mälkki 1986). Salinity varies approximately from 5-7 ‰, but density stratification due to salinity in shallow coastal waters is rarely observed (Kirkkala 1998; Kauppila & Bäck 2001). Tidal variation is nearly non-existent. This is due to the fact that the basin is semi-enclosed, shallow and small in terms of water volume (Kullenberg 1981). Variation in water level is more affected by meteorological conditions, such as wind.

The high geodiversity of the SW Finland coastal area is due to the gently sloping but uneven land surface (Granö et al. 1999). The coastal region is continually altered by isostatic land uplift which has prevailed since the last deglaciation. The rate of annual land uplift ranges from circa 3 mm/year in the southern Archipelago Sea to 6-7 mm/year in the Bothnian Sea (Winterhalter et al. 1981, p. 21; Ristaniemi et al. 1997). The anticipated rise in sea level due to climate change may offset the effect of land uplift in the Gulf of Finland, but in the Gulf of Bothnia the fall in the mean relative sea level will probably continue (Johansson et al. 2004). The complex topography increases the length of the shoreline and affects its exposure, leading to a variety of biogeographical and geomorphological conditions in the littoral zone (Fig. 3; Granö et al. 1999; Ekebom et al. 2003; Tolvanen et al. 2004; Gyllenhammar & Gumbricht 2005; Tolvanen & Suominen 2005; Suominen et al. 2007).

On a regional scale, environmental conditions in coastal areas are affected by the interaction of marine and terrestrial factors, leading to gradients of climate and hydrography (e.g. Bonsdorff et al. 2002; Kauppila & Bäck 2001). Coastal zones have been defined according to geographical and biological factors as well as human activities (Häyrén 1900, 1948; Jaatinen 1960; Granö 1981; Granö et al. 1999). While the delineations differ to some degree depending on their focus, they are all fundamentally affected by variations in the land-sea ratio. In general, the most sheltered mainland zone is followed by zones where the proportion of land decreases towards the open sea (Granö et al. 1999). In SW Finland the concepts of the inner, middle and outer zone are relatively well established expressions describing different parts of the archipelago relative to the coastal area as a whole. In the inner archipelago the land area is greater than the water area, in the middle archipelago they are approximately equal, and in the outer archipelago the sea area predominates (Figs. 4–7). Spatial disparities have also been observed between the communities of aquatic biota, e.g. benthos, in different parts of the coastal region. These are mostly due to differences in abiotic environmental factors and conditions as well as human activities (Mattila & Räisänen 1998; Hänninen & Vuorinen 2001; Kraufvelin et al. 2001; Bonsdorff et al. 2003; O'Brien et al. 2003; Perus & Bonsdorff 2004; Virtasalo et al. 2005).

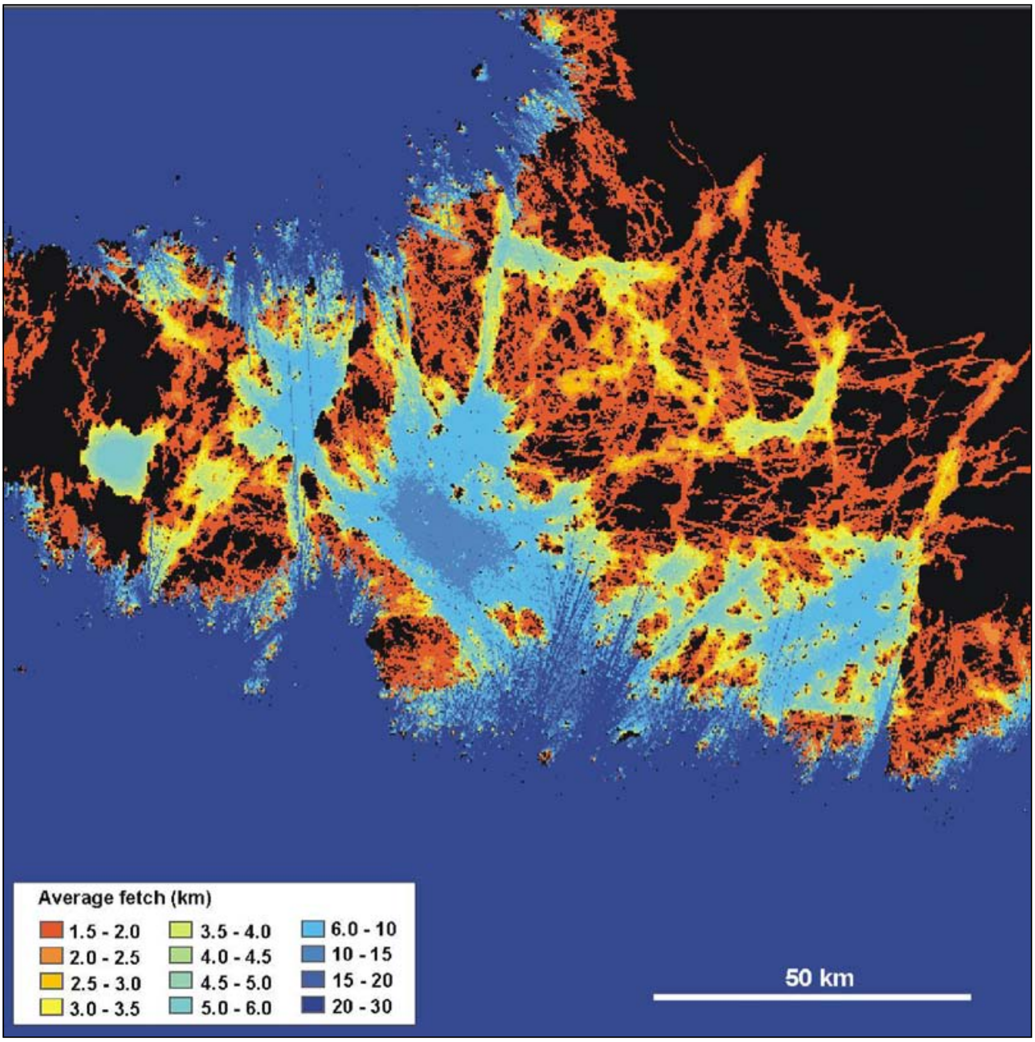

Figure 3. Exposure (average fetch length) of the SW Finland archipelago waters (from Suominen et al. 2007, see also www.lounaispaikka.fi).

Figure 4. Inner archipelago near port and city of Turku (Pukinsalmi Strait, bordered by Hirvensalo and Ruissalo islands, 3 July 2005). © Hannu Vallas / Lentokuva Vallas Oy.

Figure 5. Inner archipelago in the northern Archipelago Sea (Velkua, yellow Palva-Velkuanmaa ferry in upper right corner, 4 September 2005). © Hannu Vallas / Lentokuva Vallas Oy.

Figure 6. Middle archipelago in the NE Archipelago Sea (Dragsfjärd, Rosala village, 21 July 2007). © Hannu Vallas / Lentokuva Vallas Oy.

Figure 7. Outer archipelago in the southern Archipelago Sea (in center of picture: Lake Insjö formed by postglacial land uplift, Björkö island, Archipelago National Park, 13 July 2007). © Hannu Vallas / Lentokuva Vallas Oy.

5. MATERIAL AND METHODS

5.1. Water quality data

The water quality data used in Papers I, III and IV were obtained from the environmental information system of the Finnish Environmental Administration. Monitoring data are stored in this system, and data on water quality were retrieved from a subsystem of surface waters, referred to as Hertta-PIVET register (see Manni & Nurmio 2006). Since eutrophication is a major concern in the SW Finland archipelago, physical, chemical and biological variables related to trophic status and turbidity were examined in particular (Table 2). In Paper IV, the sampling of chlorophyll-*a* and primary productivity were examined.

In Paper I, trend analyses were computed for observation periods of 15 to 25 years in length using linear regression. The paper also considers spatiality of the variables studied and the evaluation of limiting nutrients. Calculations of nutrient limitation were carried out using three ratios, obtained from the literature (see Paper I).

In the spatial examination of averaged water quality parameters in Paper III, the values of the variables acquired from sampling stations were classified and plotted at their corresponding locations on maps using GIS. The classes were defined in such a way as to reveal spatial variation in detail. Thus the classification was different from approaches that aim at quantifying environmental change for management purposes (e.g. Anon. 1985; Bricker et al. 2003; Nygaard 2004; Rönnberg & Bonsdorff 2004; Vuori et al. 2006b). Visual analysis of spatial data is commonly used in water quality assessments of the Archipelago Sea, because it is easy to implement and it gives rapid insight into the spatial characteristics of different variables, even though the weak spatial representativeness of *in situ* sampling is recognised (e.g. Kirkkala 1998; Erkkilä & Kirkkala 2000; Suomela 2001, 2003; Suomela & Sydänoja 2006).

5.2. Remote sensing data

The primary reason for using remote sensing data in Papers II and III was their ability to provide a synoptic view over extensive coastal areas with adequate spatial resolution. In Paper II, high-altitude panchromatic aerial images were selected due to their extensive coverage of the Finnish coastal region, which is required for the mapping and monitoring of habitats addressed in the EU Habitats Directive. In Paper III, Landsat TM and ETM+ images covered the Archipelago Sea and adjacent sea areas with high spatial resolution. Adequately cloud-free images from the SW Finland coast are poorly available due to the relatively weak temporal resolution of Landsat images and the frequent cloudiness of the Baltic Sea region.

In Paper II the identification of shore habitats from remote sensing data was carried out using a selection of panchromatic images. The test was based on the visual inspection of photographs, which were also field-checked by the first author of the study. When printed and scanned photographs were compared, printed photographs were found to provide sharper contrast and a wider range of greyscale tones than scanned ones; this favoured the selection of hardcopy prints for the test. The focus was on the usability of "raw" photographs; image analysis was supported only by printed topographic maps and nautical charts.

Table 2. Water quality data used in Papers I and III.

	Paper I	**Paper III**
Study Period	• 1970 – 1996	• 1995 – 1999
Season/months	• Winter (data collected during February/March) • Open water seasons from May to October	• Open water seasons from May to September
Number of sampling stations	• 3 stations for time series analysis • 50-60 for spatial analysis of nutrient limitation	• 84 (45 located within extent of satellite image and 39 from adjacent sea areas)
Variables	• Total phosphorus, phosphate-phosphorus, total nitrogen, ammonium-nitrogen, nitrate- and nitrite-nitrogen • Phytoplankton chlorophyll-*a* and primary productivity	• Phytoplankton chlorophyll-*a* • Secchi depth
Sampling depth	• Nutrients from discrete unfiltered samples (1–2 m above bottom). • Phytoplankton pigment and production from composite samples (discrete water samples mixed, taken from different water layers until the depth of twice the Secchi Disk depth)	• Composite samples (discrete water samples mixed, taken from different water layers until the depth of twice the Secchi Disk depth)
Analysis Methods	• Time series analysis and linear regression • Calculation of nutrient ratios • Visual analysis of spatial distribution using GIS	• Average values of variables from each individual station • Visual analysis of spatial distribution using GIS and narrow class limits to aid the analysis

Our harvest in the ESA/Eurimage data archive included most of the cloud-free images from the summers of 1996-1999. The digital image processing in Paper III used geographically rectified images that had not passed through any spectral processing steps.

Principal component analysis was used to reduce the dimensionality of Landsat optical bands 1-3 in a two-dimensional plane (e.g. Jollife 2002), thus facilitating the detection of spatial patterns in individual images. The unsupervised ISODATA classification was applied in order to objectively examine spatial patterns in multitemporal images. The focus was on relative spatial variations in reflectance. Thus some typical problems of unsupervised classification, such as mixed pixels or overlapping clusters, were not of special concern (Tran et al. 2005).

5.3. Evaluating data usability

Papers II and IV examined the usability of water quality data, i.e. sampling station records from the Hertta-PIVET register and aerial photographs, for purposes of monitoring, research and mapping. Both data types were readily available for mapping and monitoring purposes. Since both of these databases have been accumulating for several decades, they provide a potential opportunity to assess trends in environmental change. The usefulness of these data types was explored, emphasising the practical needs of data usability for current and future assessments and research.

In Paper III, a usability test was arranged in order to investigate the ability of experts to identify the habitats defined in Annex I of the EU Habitats Directive from aerial photographs. This was required because allowing easy identification of key habitats is a crucial property of aerial photographs with regard to their usability. The identification of spatial patterns requires the analyst to have a good ability to discern geometry, tones, contrast and association of habitats. The photographs were presented to the respondents with specific instructions before each test (Ekebom & Erkkilä 2000). The time available for completing a set of tasks was rather short, and the use of supporting data sources such as nautical maps was limited.

Paper IV investigates the usability of the extensive data collections of coastal monitoring programmes available in the Hertta-PIVET register. The usability of water quality data depends on the sampling design and performance according to different criteria. The approach in this paper was to examine the usability of archived data, regardless of the different initial aims and designs of the various monitoring programmes concerned. The spatial and temporal representativeness of the different sampling stations were evaluated by frequency tables and distribution maps.

6. RESULTS AND DISCUSSION

6.1. The coastal environment in SW Finland contains highly variable habitats

The complex geomorphology of the coastal archipelago in SW Finland has created a mosaic of land and water with variable exposition and openness. This condition entails a multitude of habitats that differ in size and shape as well as in their abundance in both littoral areas and shallow waters (Papers I, II & III). The partly or entirely sublittoral habitats considered in the EU Habitats Directive represent one part of this variability (Paper II; European Commission, DG Environment 2007). The size of diverse water-associated habitat patches ranges from a few square meters of a sandbank to a few square kilometres of an estuary or a large bay. Furthermore, some marine habitats are complex biotope mosaics, demonstrating for example a clear local depth zonation of fauna and flora (HELCOM 1998; Bäck & Ruuskanen 2000; European Commission, DG Environment 2007). The benthic biodiversity found in the SW Finland archipelago and Åland islands is the highest of any Finnish coastal waters (Perus et al. 2004).

In shallow and semi-enclosed water basins, local environmental conditions and sources of nutrient loading may have a considerable effect on biotic communities and water quality. This increases the spatial heterogeneity of coastal waters (Papers I, II & III; Norkko & Bonsdorff 1996; Mattila & Räisänen 1998; Kraufvelin et al. 2001; Nordvarg & Johansson 2002; Weckström et al. 2002; Kauppila et al. 2003; Perus & Bonsdorff 2004; Appelgren & Mattila 2005). The small-scale spatial variability of surface waters is also evident in more open water areas, especially in the middle and outer archipelago. Complex meteorological and hydrographical conditions have an impact on the water realm, causing rapidly changing and irregularly varying patterns of surface waters. These indicate mixing of water bodies, occasional upwelling events and water exchange between adjacent water basins (Paper III; Virtaustutkimuksen neuvottelukunta 1979; Helminen et al. 1998). Wind-induced mixing also affects internal or background load and nutrient ratios, and may thus cause rapid spatial and temporal changes in phytoplankton abundance (Papers I & III, see also Blomqvist & Larsson 1994; Suomela et al. 2005; Lagus et al. 2007b).

6.2. Evidence of dynamic zonation and subregional differences in water quality

Evidence of a consistent water turbidity pattern is here documented, despite the high spatial and temporal variability of the coastal hydrodynamic realm in detailed level (Papers I & III; Erkkilä & Kirkkala 1999, 2000). In general the pattern is expressed in the form of zones running parallel to the mainland coast, with decreasing turbidity towards the open sea. A turbidity pattern also emerges around the large island groups in the middle archipelago areas. The general turbidity pattern has features similar to coastal zoning, which is based mainly on the land-sea ratio and its effects on the physical environment and biota (Paper III; Häyrén 1948; Granö 1981; Granö et al. 1999). The coastal water types of the WFD have been delineated based on very similar criteria (Paper IV; Perus et al. 2004; Vuori et al. 2006b). These similarities indicate that the summertime turbidity pattern is fundamentally connected to the geomorphology of the archipelago, especially in the inner and middle parts (Papers III & IV). The effect is arguably enhanced by the spatial distribution of point-source and riverine nutrient loading (Papers I & III; Hänninen et al. 2000; Kauppila & Bäck 2001; Suomela 2001). In summer, decreased riverine nutrient fluxes mainly affect the inner archipelago. In the middle and outer archipelago, on the other hand, local point-sources such as fish farming may have a major effect on biological production, for example increasing the turbidity of waters near groups of large islands (Hänninen et al. 2000; Kauppila & Bäck 2001).

Some disparities are visible in the water quality patterns when *in situ* data are compared to satellite images of the same region (Papers I & III; see also e.g. Kirkkala 1998; Erkkilä & Kirkkala 1999, 2000; Hänninen et al. 2000; Kauppila & Bäck 2001; Suomela 2003, 2001; Suomela & Sydänoja 2006). These differences are partly due to the fundamental differences in the acquisition of these data types. The spectral reflectance values recorded at the water surface are affected by a number of factors and variables that indicate features of the water column. For this reason, hardly ever individual variables of water chemistry or biology correlate directly with the reflectance values observed (i.e. general water turbidity).

The inner archipelago is clearly distinct from the other sea areas due to its turbid and clearly eutrophicated waters. In the middle and outer archipelagos, the spatial and temporal patterns of water quality are more variable; the middle archipelago, however, is more eutrophicated and appears to harbour smaller-scale hydrodynamic conditions than the outer archipelago (Papers I & III; Erkkilä & Kirkkala 1999, 2000; Hänninen et al. 2000; Vahteri et al. 2000; Suomela 2001, 2003; Suomela & Sydänoja 2006).

Coastal regions are also affected by large-scale environmental changes. Progressing eutrophication is observed in the middle and outer archipelago areas, reflecting the general trend of the Baltic Sea proper (Papers I & III; Bonsdorff et al. 1997, 2002; Rönnberg & Bonsdorff 2004; Pitkänen et al. 2004; HELCOM 2006b). Similarly, based on nutrient ratios, the phytoplankton production have been shifting during the 1990s towards nitrogen limitation in the entire archipelago (Paper I), and the eutrophicated coastal waters seem to be nitrogen limited (e.g. Vuorio et al. 2005; Lagus et al. 2007a; Tamminen & Andersen 2007). However, aspects of nutrient limitation in the Baltic are complex, e.g. because of species-specific responses to changing nutrient levels and variable seasonal and spatial patterns (e.g. Paper I; Granéli et al. 1990; Hänninen et al. 2000; Moisander et al. 2003; Savage et al. 2002; Vuorio et al. 2005; Carstensen &

Heiskanen 2007; Håkanson et al. 2007; Lagus et al. 2007a; Tamminen & Andersen 2007). The general water quality classifications of the Finnish coastal zone, produced every several years by the environmental authorities, also reflect large-scale temporal changes (Nygaard 2004; Anon. 2005b). In addition to addressing these trends, future research should also focus on the high dynamism and small-scale variability of the coastal sea areas. This work requires extensive fieldwork and good sampling design.

6.3. Spatial and temporal representativeness of data is crucial in the complex coastal region

In situ sampling is necessary in order to survey the physical, chemical and biological properties of the aquatic ecosystem. The considerable extent and high variability of the coastal environment emphasises the need to carefully consider the spatial representativeness of the data sources and *in situ* sampling designs. In SW Finland, water quality sampling is mostly conducted at established sampling stations which are repeatedly visited (Papers I, III & IV). These sites are often located in open waters, assuming that they represent the average water quality in a given sub-area (Suomela 2001). These locations are also easy to access. This system supports the long-term monitoring of a given water area, but also reflects the importance of practical aspects of fieldwork in such an area.

While a considerable number of sampling stations has been established especially in the Archipelago Sea, the most representative stations in terms of sampling frequency and consistency are located in the inner archipelago, mainly covering only the innermost turbid waters (Papers I, III & IV). Examinations of other aspects of water quality, such as the vertical profile of a water column are performed at an even lesser number of stations (e.g. Suomela 2001, 2003). The high dynamism of the Archipelago Sea coastal waters also challenges the definition of the impact areas of any particular human activity in these waters (e.g. Paper III; see also Virtaustutkimuksen neuvottelukunta 1979; Helminen et al. 1998; Kraufvelin et al. 2001).

The inherently weak spatial representativeness of *in situ* sampling hardly captures the variability of the middle and outer archipelago waters (Paper III; Erkkilä & Kirkkala 1999, 2000). This reality emphasises the importance of local hydrodynamic conditions in the interpretation of water quality results. These conditions should be assessed each time as part of the data gathering procedure, in order to evaluate the spatial representativeness of the samples. In general, the information value of any single measurement is low if it is not spatially and/or temporally connected to the status of the ambient environment and other measurements (Papers III & IV; also Vuoristo 1992; Erkkilä & Kalliola 2003). In the middle and outer archipelago, for example, some coherently sampled sites are located in areas where water bodies appear to be actively mixed or exchanged (Papers III

& IV). These aspects highlight the need to assess the spatial representativeness of *in situ* sampling and the need for a regionally comprehensive data acquisition regime.

While most environmental data are gained through monitoring activities, the scarcity of resources as well as demands for cost-effective monitoring exert pressure to reduce and optimise sampling efforts (Paper III & IV; also e.g. Danielsen et al. 2005; Axe & Håkansson 2006). In SW Finland, the water quality sampling regime has already been reduced since the peak years of the early 1990s (Paper IV). In a topographically complex aquatic environment, the local variability in environmental conditions means that the spatial correlation of data gathered at sampling stations is not necessarily a function of distance (c.f. U.S. EPA 2002). Instead, small-scale diversity within a heterogeneous environment should be taken as the basis in evaluating representativeness. Investigation of the spatial correlations between data from different sampling stations is thus required in order to make sampling more efficient and eliminate unnecessary stations.

Although judgemental sampling does not allow the derivation of quantitative statements about the level of confidence, it may be more cost-efficient than random sampling. This is especially the case when reliable historical and physical knowledge is available about the site or the condition under investigation (U.S. EPA 2002). Spatially balanced sampling covering the monitored area as a whole may be more efficient than random sampling (Stevens & Olsen 2004). If the analyses do not require an unbiased sample population, restrictions on statistical analyses may not be harmful (Overton et al. 1993). Furthermore, the results of a deterministic sampling grid and probability-based sampling efforts may not differ significantly (Warren & Horvatin 2003). However, an important part of the quality assurance of monitoring is to assess the feasibility of the data collected for their targeted use (e.g. Peterson & Urqhuart 2000; U.S. EPA 2002; EC 2003; Legg & Nagy 2006; Carstensen 2007).

6.4. Remote sensing data complement the spatial representativeness of coastal monitoring

Remote sensing methods are useful in the mapping and monitoring of marine habitats and coastal waters (Papers II & III). In habitat monitoring the frequency of data gathering can be relatively sparse, for instance every several years (e.g. Bäck et al. 2002). Spatial coverage is more of an issue on the fragmented coast if adequate coverage of the different sub-areas in the region is to be ensured. Remote sensing methods are particularly efficacious in this context, as they provide fast and reliable means for the mapping and monitoring of many coastal habitat types (e.g. Bäck et al. 1996). A very high spatial resolution, however, is required for the mapping of small habitat patches (Paper II; see also Dåverhög & Lindström 2001). In addition, the delineation of underwater habitats especially in the turbid Baltic waters is impaired by the strong light attenuation (Papers

II & III; Vahtmäe et al. 2006; Kutser et al. 2006c). Remote sensing methods for habitat mapping and monitoring thus need to be complemented with field methods (Paper II).

Papers II and III highlight the significance of visual qualitative examination of spatial data, especially in relation to such practical applications as the planning of field monitoring activities. Geographic features such as littoral forms and contrasting tones in shallow waters are relatively easily identifiable. The visual inspection of data is especially powerful when implemented by individuals trained for or involved in environmental issues, since even a few clues observed in geographical context provided by the images may assist the interpretation of the environmental issues in focus (Paper II). In water quality studies, high resolution satellite images with large spatial coverage, such as Landsat TM and ETM+ products, reveal relative surface water patterns in detail. Even if the spectral resolution of such images and/or thus far developed correction and analysis methods are not adequate for further quantitative analyses, the images may facilitate the evaluation of hydrodynamic conditions in the coastal region at a given time, which also contributes to the spatial extrapolation of *in situ* monitoring data (Paper III; c.f. Kallio 2000; Kallio et al. 2003).

The spatial or temporal resolutions of space-borne instruments currently used in water quality applications are mostly too coarse for detailed observations regarding surface water dynamics in coastal areas or other phenomena pertaining to the aquatic realm (Papers II & III; Erkkilä & Kalliola 2003; Dickey et al. 2006). In particular environmental analyses based on satellite images and covering parts of the inner and middle zones of the archipelago require high-resolution imagery; the shallow waters and multitude of islands and skerries that characterise these regions cannot otherwise be taken fully into account (e.g. Tolvanen et al. 2004; Tolvanen & Suominen 2005). Yet even coarser-grained images may facilitate water quality studies, especially with regard to the connection between coastal water quality and conditions in adjacent water basins and sea areas. In this sense, recent MERIS and MODIS data types appear highly valuable for regular, frequent and near real-time monitoring. They are especially beneficial in assessing water quality in the outer archipelago and adjacent open sea areas, where on-site data gathering is rarely performed (Papers III & IV; Fig. 2; c.f. Koponen et al. 2007; Kratzer et al. 2008). In open water areas they may also be used to assess the spatial representativeness of *in situ* sampling if they are available from the same day as the sampling. Space-borne remote sensing thus seems to be particularly usable as a complementary data source in water quality studies (Paper III).

6.5. Inconsistency of current data resources reduces their re-usability

The past and current water quality sampling regime in the SW Finland coastal waters is both spatially and temporally inconsistent and irregular. While the total number of stations is high, sparsely and minutely sampled stations abound (Paper IV). These types of spatiotemporal incoherencies reduce the possibility of using these data for the assessment of the region's seasonal dynamics as a whole or their long-term trends (Paper IV, see also Papers I & III). The *in situ* sampling of water quality implemented thus far takes place in the months of July and August, and provides snapshots only of the spatial characteristics of surface waters (Papers I, III & IV). In providing information about the sea waters since the 1980s, however, these data are irreplaceable; they provide the most extensive spatial data resource for assessing trends in the spatial and temporal patterns of eutrophication in the Archipelago Sea (Papers III & IV; Kirkkala 1998; Erkkilä & Kirkkala 1999, 2000; Suomela 2001, 2003; Suomela & Sydänoja 2006).

Consistency of sampling is also important in the Baltic Sea, where sampling frequencies have generally been rather sparse (Raateoja et al. 2005). Distinguishing between natural year-to-year variation and genuine temporal trends will arguably require more coordinated efforts in the future, for example in regard to the predicted climate change (Jickells 1998, Carstensen et al. 2002; HELCOM 2007a). In order to identify the ecological changes induced by gradual trends, long-term consistent monitoring is increasingly important (Elmgren 2001). It is noteworthy that many long-term trends in water quality parameters vary considerably between different sampling stations, even those located at relatively short distances from each other (Paper I; see also Hänninen et al. 2000; Suomela 2001; Suomela & Sydänoja 2006). Furthermore, understanding the cumulative effects of local anthropogenic impacts, atmospheric or background loading and natural variations requires further examination of ecosystem functioning (e.g. Helminen et al. 1998; Honkanen & Helminen 2000; Kraufvelin et al. 2001; Vuorio et al. 2005; Lagus et al. 2007b). In such situations irregular or sparse sampling is ineffective; it provides only snapshots of momentary conditions, and overlooks seasonal and short-term variations in water quality (Paper IV; c.f. Carstensen et al. 2002; Knowlton & Jones 2006). Long-term data gathering, with adequate frequency and spatial representativeness, is necessary to detect changes, their consequences and their spatial interactions in different parts of the coastal region (Paper IV; c.f. Papers I & III; also Håkanson 2007).

For the assessment of trends in habitat and water qualities, the availability of long-term data archives is critical (Papers II, III & IV). Synoptic and even panchromatic series of high-altitude aerial photographs facilitate the monitoring of coastal habitats and the interpretation of sea water patterns. Collections of high-resolution space-borne images can be valuable as well, but due to their low temporal resolution so far and the frequent cloudiness in the Baltic Sea and its coastal areas, they consist of temporally irregular and scattered snapshots (Paper III; e.g. Kutser et al. 1998). The application of remote sensing in coastal monitoring also requires spatially and temporally representative ground-truth data, particularly in the case of the highly variable Baltic Sea waters (Rantajärvi 2003; Erkkilä & Kalliola 2003; Niemi et al. 2006). Due to this, regional data archives containing *in situ* measurements from a number of sampling stations are indispensable (Paper IV).

The sampling design should consider the spatial and temporal scales of natural variability (Papers I & III). In detecting long-term changes, monitoring programmes should allow distinguishing between random variation (“noise”) and a directional trend (the “signal”) (e.g. NRC 1990; Parr et al. 2002). Another important factor that affects the scientific value of environmental monitoring is the re-usability of the results. Inconsistent and unharmonised methods may reduce the usability of archived monitoring data (Ringold et al. 1996). Monitoring regimes should not be changed too frequently to ensure the long-term consistency and comparability of the data produced. Excessive adaptative changes may lead to incoherent data resources (Ringold et al. 1996). Multiple uses should be considered in designing any new monitoring endeavour (Paper IV; Boesch 2000). It should also be acknowledged that monitoring is not a single, once-off form of research but a continuous activity, designed to answer an array of current and future questions (Vos et al. 2000). Only long-term monitoring data supports reliable detection, understanding and predicting of changes, trends and relationships in the physical environment, habitats and populations (Burt 1994, 2003; Parr et al. 2002, 2003; Balmford et al. 2003; Kratz et al. 2003; Raateoja et al. 2005). Thus it is also highly valuable for any society (Goldberg 1995; Kates et al. 2001). The continuance of long-term monitoring, however, is often questioned because of its seemingly low cost-effectiveness (e.g. Burt 1994). To optimize the sampling design, statistical methods have been developed for the determination of minimum sample size and optimal distance between sites (e.g. Laberge et al. 2000; Danielsson et al. 2004; Strobel et al. 2000; U.S. EPA 2002; Axe & Håkansson 2005).

6.6. Integration of monitoring efforts should be set as a goal

In a coastal environment, no single method of data gathering is able to produce information giving a spatially and temporally comprehensive description of environmental status and changes from a local to a regional scale (Papers I, II, III & IV). Still, monitoring programmes are expected to provide useful data for multiple purposes, thus increasing the cost-effectiveness of investments allocated to data-gathering efforts (Papers I & IV). Multisource approaches and integration of data gathering activities are thus beneficial on the SW Finland coast in increasing the spatial and temporal resolution and coverage of environmental data (c.f. Kutser et al. 1998; Kratzer et al. 2003; Vos et al. 2003; Knudby et al. 2007). However, the high spatial resolution of data sources is important in this region, as coarse data are of limited use especially in fragmented parts of the coast where the need for high-resolution sampling is also pressing. Water quality in sheltered water areas, for example, may differ naturally from that of more open water areas, and should thus be evaluated by different criteria in water quality assessments (Suomela 2001; Dolah et al. 2003). Sheltered areas are often excluded from monitoring programmes, even though their condition substantially affects the public opinion, since recreational and other coast-bound human activities are concentrated in these areas (Papers III & IV; Granö et al. 1999; Weckström et al. 2002; Tett et al. 2003).

Similarly, the considerable number and variability of small-scaled coastal and marine habitats in the coastal region requires high spatial resolution and extensive coverage of data (Paper II; Perus et al. 2004; Auvinen et al. 2007). Compared to traditional biomonitoring, which focuses primarily on individual species or small-scale biotic communities, the special feature of the Habitats Directive is that the habitats are geographical entities more than anything else. Thus remote sensing data are particularly suitable for the mapping and monitoring of coastal habitats, since they allow the perception and in some cases the delineation of these habitats. Even coarse-scale panchromatic aerial photographs show geographical characteristics adequately, and may serve as a practical and rapid tool providing the environmental authorities and researchers with a synoptic view of the coasts.

The integration of diverse monitoring methods and practices provides great potential to increase the cost-effectiveness and information value of environmental monitoring and the data gathered. Integration should be implemented at different levels and stages of the environmental monitoring process, from primary data gathering to the dissemination of data and processed information via the Internet (e.g. EC 2003; Laihonen et al. 2003, 2004; Rantajärvi 2003, HELCOM 2006b; Tolvanen & Kalliola, in press). In Finland the implementation of modern ecosystem-based management schemes is already facilitated by the longstanding tradition of national and international cooperation in water resources management and protection. This applies especially to the archiving and dissemination of environmental data in national and international data systems, as well as regionally in SW Finland (Paper IV; Niemi 2006; Kalliola & Toivonen 2004). As the implementation of the WFD and the Habitats Directive also demand a holistic approach to monitoring systems, integrative actions are increasingly required (Paper IV; Niemi 2006; EC 2003; HELCOM 2005b, 2006b). In practice, this requires increasing coordination of sampling design, field work efforts, the use of remote sensing, spatio-temporal modelling and other means to improve the use value of the environmental monitoring data gathered.

7. CONCLUSIONS AND RECOMMENDATIONS

The gathering of primary field data is at the heart of environmental monitoring. The planning of field sampling and the use of different data sources require careful consideration of monitoring objectives and a suitable sampling design to achieve them. Global and regional environmental problems have increased the need for more comprehensive information on the status of the environment and its changes on a large scale. In coastal areas and especially in the Baltic Sea, eutrophication is one of the worst and most extensive environmental problems damaging water quality and aquatic habitats. At the same time, the growing public and political awareness of environmental issues has increased the need for local and small-scaled information about the environment. The greater part of primary field data are produced by environmental monitoring, which should be able to respond to the diverse information needs of society by producing spatially and temporally representative but cost-effective data. This emphasises the importance of appropriate monitoring and sampling designs. In a complex and extensive coastal environment, however, the production of spatially and temporally comprehensive environmental information is a challenging task.

These conditions considered, the thesis puts forward the following notions:

- **A geographical approach is indispensable in coastal environmental monitoring.**

  The natural variability of habitats and water quality is high throughout the entire coastal region. Abiotic and biotic processes interact and thus patterns of aquatic phenomena occur on variable spatial and temporal scales. The zonation of waters, the disparities between different parts of the archipelago and the large-scale patterns of some environmental phenomena, such as eutrophication, all add to the intricateness of the coastal system. The need for holistic management and monitoring requires comprehensive consideration of the diverse components of coastal systems and their spatial and temporal interaction within the coastal region. All these needs can be effectively facilitated by an approach that considers the coastal region as a geographical entity, with diverse interacting processes occurring on a multitude of spatial scales. As part of this approach, it is important to choose the topics to monitor and their indicators in a way that yields a good cost-benefit ratio considering their short and long-term uses.

- **The consideration of spatial representativeness is crucial in the monitoring of complex coastal areas.**

  The contradictions between the needs of local, regional and large-scale environmental assessments constitute a considerable challenge to environmental data acquisition on a complex coast. The spatial representativeness of *in situ* sampling is important to consider in the planning of monitoring and sampling regimes, but also in the interpretation of the data collected. The patterns of coastal water bodies cannot be assumed to be static anywhere, but they are particularly dynamic in those areas where frequent water mixing occurs, such as the middle archipelago. The following aspects should therefore be considered as part of future data gathering activities:

- The information value of any single *in situ* measurement is relatively low, unless it can be connected spatially to ambient environmental conditions and past measurements performed in the same location.
- An assessment of the concurrent hydrodynamic conditions for each sampling event would help to evaluate the spatial representativeness of data sampled.
- The retrieval of spatial correlations between data collected at different sampling stations is not straightforward, but requires consideration of the local and subregional geographical factors that influence water movements.

- **Remote sensing methods should be applied in complex and extensive coastal regions despite their restrictions.**

  Remote sensing imagery provides a spatially synoptic view, which is especially valuable under the conditions of a highly fragmented coastal archipelago. High and very high spatial resolution images are most useful for the assessment of water quality and habitats, albeit spectrally or temporally limited, because they allow the display of detailed spatial patterns. Despite current restrictions in terms of availability, their use should be increased whenever possible. Coarse-resolution images from operative Baltic monitoring efforts may also be useful in the assessment of large-scale hydrodynamic situations and changes in surface water quality. In future monitoring in the region, remotely sensed data should be considered as a routine source of information, since they contribute to the interpretation of field data.

- **Long-term consistent sampling from established stations should be increased, but research-type seasonal assessments producing abundant data should also be encouraged.**

  The higher the frequency of sampling and the more long-term the efforts, the better the temporal representativeness of the data and their applicability to environmental monitoring. This applies especially with respect to water quality and phytoplankton dynamics. In practice monitoring frequency is seriously constrained by resource limitations. However, while sampling has already decreased in recent years, the temporal frequency and consistency of the sampling efforts could still be be increased in the middle and outer archipelago in order to provide more comprehensive information on the temporal dynamics of this dynamic part of the archipelago. Frequent sampling should be concentrated at sites that are spatially representative of their surroundings and useful in regional scale assessments.

Monitoring and research would benefit in particular from further use of high-frequency automated sampling devices (e.g. buoys) on a number of sites (c.f. Tedesco et al. 2003). This would increase our understanding of seasonal site-specific dynamics, even if the accuracy of the observations were less high that that of laboratory measurements (e.g. Glasgow et al. 2004; Johnson et al. 2007). The traditional *in situ* sampling regime could also be made more cost-effective by employing new sampling devices, such as sondes and on-board flow-through systems, which allow more rapid sampling in a number of stations; this is valuable for spatial modelling even though the potential problems on vertical and spatial representativeness need to be considered (e.g. Suominen 2003; Kutser 2004; Wenner et al. 2004; Lindfors et al. 2005).

- **Environmental monitoring in the Finnish coast should be further integrated and assessed scientifically**

  This notion is highlighted from many different aspects within this thesis. The comprehensive regional coordination of monitoring activities would increase the spatial and temporal consistency and coherence of data gathering and the cost-effectiveness of information production. This condition should be put forward as a societal objective. Future monitoring would then be more cost-efficient, multi-purpose and scientifically robust than past and current systems. National level efforts with this goal in mind should be implemented as a joint action between a number of specialist and interest groups, and the corresponding financing bodies. A holistic approach to the gathering and management of environmental monitoring data would fit the holistic, ecosystem-based management regimes that are currently being strongly promoted in Europe.

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