Water Quality Monitoring Using Remote Sensing in Support of the EU Water Framework Directive (WFD): A Case Study in the Gulf of Finland

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ORIGINAL ARTICLE

Water quality monitoring using remote sensing in support of the EU water framework directive (WFD): A case study in the Gulf of Finland

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Abstract Water quality monitoring using remote sensing has been studied in Finland for many years. But there are still few discussions on water quality monitoring using remote sensing technology in support of water policy and legislation in Finland under the WFD. In this study, we present water quality monitoring using remote sensing in the Gulf of Finland, and focus on the spatial distribution of water quality information from satellite-based observations in support of water policy by a case study of nitrate concentrations in surface waters. In addition, we briefly describe instruments using a system of river basin districts (RBD), highlighting the importance of integrated water resources and river-basin management in the WFD, and discuss the role of water quality monitoring using remote sensing in the implementation of water policy in Finland under the WFD.

Keywords Water quality monitoring · Remote sensing · Water policy · WFD · Water quality standards

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1. Introduction

Water quality monitoring in Europe is intended to control water pollution and enforce water protection legislation (Nazarov *et al*., 2000; Kallis and Butler, 2001). Modern water legislation in Europe pursues the target of balancing the requirements of human needs and nature conversation by sustainable planning and public participation, which is virtually the cornerstone of the European Union (EU) Water Framework Directive (WFD) (2000/60/EC). The European regional working group studies show that the different systems and mechanisms developed by European countries meet this target (Kroiss, 1999; Dirksen, 2002; Maia, 2003). With a view to unifying of Europe, national regulations have to be harmonized and transformed into water policy in compliance with the WFD.

In Finland, the use and protection of waters have been regulated by the Water Act, which dates back to 1961. The Act contains rules on water management, public use and all kinds of water-related constructions, such as hydropower regulation, flood control, and water pollution control (Kuusiniemi, 1993; Vihervuori, 1998; Kuusiniemi, 2000; Kumpula, 2002). The use of surface water in Finland is governed by public use rights and stipulations based on this law. The Water Act involves a permit system for water abstraction and wastewater discharge. Although groundwater is not owned by anyone, the landowner has the right of priority to use it as water supply (Varjopuro, 2000). Especially after Finland joined the EU in 1995, water legislation was modified to comply with the WFD. For instance, Finland chose to adopt some stricter requirements than those set out in the WFD concerning urban wastewater treatment and drinking water, as well as groundwater (Vihervuori, 1998). The water protection targets for 2005 set by the Finnish Council of State (MoE, 1998) pointed out that the quality and quantity of all waters must be maintained at least at the present level and improved in locations where the quality has been degraded by human activities. In consequence of the enforcement of water policy and legislation, the water quality in Finland assessed by United Nations (UN) agencies was ranked the highest among 122 countries (Esty and Cornelius, 2002; WWAP, 2003).

Remote sensing technology is a valuable tool in obtaining information on the processes taking place in the surface of waters. The monitoring of water quality using remote sensing technology started in the 1970s. Since then, the digital evaluation of remotely sensed data onboard both airborne and space-borne platforms has been used to estimate water quality characteristics of rivers, lakes and coastal waters. One major advantage of remote sensing observations over traditional measurements for water quality monitoring provides both spatial and temporal information of surface water characteristics (Lindell *et al.*, 1999). With present advanced satellite sensors, a large number of water quality information about chlorophyll-a, suspended sediment, yellow substance, turbidity, Secchi disk depth, wave height, colour index and surface water temperature can be observed on a regular basis (Zhang *et al.*, 2002a-d).

Water quality monitoring using remote sensing in Finland has been studied for many years (Pulliainen *et al.,* 2001; Koponen *et al.,* 2001 and 2002). The output of water quality monitoring from satellite-based observations is to present the spatial distribution of water quality in all surface waters. But there are only a few studies to discuss water quality monitoring using remote sensing in support of water policy and legislation in Finland in compliance with the WFD. In this study, we present water quality monitoring using remote sensing in the Gulf of Finland, and focus on the spatial distribution of water quality information from satellite-based observations to support water policy by a case study of nitrate concentrations in surface waters. We also briefly describe instruments using a system of river basin districts (RBD), which emphasizes the importance of integrated water resources and river-basin management in the WFD, and discuss the role of water quality monitoring using remote sensing in the implementation of water policy in Finland under the WFD.

2. Methodology

The methodology of this research consists of three main parts. The first one is water quality monitoring using remote sensing for all surface waters (e.g., lakes, rivers and coastal waters). The spatial distribution of water quality information is produced using empirical algorithms from satellite-based observations and also verified by *in situ* measurements. These empirical methods provide site-specific predictions of water quality with reasonable accuracy. The second one briefly describes instruments using a system of river basin districts (RBD), which highlight the importance of integrated water resources and river-basin management under the WFD. The last one outlines the role of water quality monitoring using remote sensing in the implementation of water policy in the WFD. To detect and monitor whether it reaches or exceeds emission limit or critical values of water quality standards in water policy, a linkage table is needed to establish with the spatial distribution of water quality information from remotely sensed data.

2.1. Water quality monitoring

Water quality monitoring using remote sensing regularly provides and updates both spatial and temporal information of water quality. Such spatial distribution of water quality is used to monitor the change of water quality information.

Regression analysis algorithms (RAA) of water quality information from remotely sensed data (Zhang *et al.,* 2003b) are expressed as

$$RAA = A_0 + A_k \left(\frac{OpticB_i}{OpticB_j} \right)^k \tag{1}$$

Or

$$RAA = A_0 + \sum A_i (OpticB_i) + \sum A_j ComB_j \tag{2}$$

where $OpticB_i$ and $OpticB_j$ are the digital number (DN) values of optical bands data and $ComB_j$ is the combination of optical bands employed in the retrieval (usually used as band ratios or differences). A_0, A_k, A_i, A_j and *k* are the derived parameters, which can be simulated by using *in situ* measurements of ground truth points with the coefficient of determination in the optimization routine.

2.2. Instruments using the RBD plan

The WFD sets new objectives for the condition of Europe's water and introduces new means and processes. The overall objective is a good and non-deteriorating status for all waters. The means contains organization and planning at the hydrological (i.e., river basin) level and the implementation of a number of pollution-control measures. The measures to achieve these goals are based on a system of River Basin Districts (RBD). RBD refers to the area of land and sea, comprising one or more neighbouring river basins together with their associated groundwater and coastal waters, which is identified as the main unit for management of river basins. For each RBD an analysis of its characteristics, a review of the impact of human activity on the status of surface waters and on groundwater, and an economic analysis of water use shall be completed within five years. A programme of measures will be established for each RBD, taking into account of the above-mentioned analysis. This aims to move progressively towards achieving the environmental objectives of the Directive. Basic measures are the minimum requirements to be complied with and shall contain measures required to implement European Community (EC) legislation for the protection of waters.

For each RBD, there will be a river-basin management plan. This plan could be based on a geographical information system (GIS) simulation (Luijten *et al.,* 2003). The plan shall include (Kallis and Butler, 2001): a summary of significant pressures and the impact of human activities on the status of surface waters (and groundwater); identification and mapping of protected areas; a map of monitoring networks; a list of environmental objectives; a summary of economic analysis of water use; a summary of the programme of measures; and finally, a summary of the public information and consultation measures taken.

Based on the Dangerous Substance Directive (76/464/EEC), the implementation of the WFD presupposes adoption of future daughter Directives and review of present daughter Directives. EU Council shall adopt specific measures against pollution of water by individual pollutants and groups of pollutants presenting an unacceptable risk to or via the aquatic environment. EU Commission will submit a proposal setting out a first priority list of substances. After its adoption, the list becomes Annex X to the Directive. The Commission shall submit proposals for controlling the principal sources of the emissions of listed substances, taking into account of both point and diffuse sources and identifying the cost-effective and proportionate level and combination of product controls and emission limit values for process controls (Kroiss, 1999; Maia, 2003). In addition, The Commission will submit proposals for water quality standards applicable to the concentrations of the priority substances in surface waters, emission controls, sediments or bioa (Bloch, 2001). One additional component is that an economic analysis of water use within the river basin must be carried out. This enables there to be a rational discussion on the cost-effectiveness of the various possible measures. It is essential that all interested parties are fully involved in this discussion, and indeed in the preparation of the river-basin management plan as a whole (Neal and Heathwaite, 2005).

2.3. The role of water quality monitoring in the WFD

The role of water quality monitoring, especially using remote sensing technology, is outlined in the implementation of water policy required by the WFD in this section. With the spatial distribution of water quality information (Marjanovic and Miloradov, 1998) obtained from satellite-based observations, a linkage table is output to detect if it reaches or exceeds the emission limit or critical values of pollution in the WFD.

The objective of the WFD is to establish a framework for the protection of inland surface water, transitional waters, coastal waters and groundwater. This legislative framework should prevent further deterioration, protect and enhance the status of aquatic ecosystems and wetlands, and promote sustainable water use on a long-term protection of available water resources. Three general environmental goals are:

1) good surface water status in all surface waters;
2) good groundwater status in all groundwaters;

3) compliance with all standards and objectives relating to protected areas, including water used for the abstraction of drinking water.

The WFD also contains a standstill principle demanding that the deterioration of ecological status and pollution of surface waters and deterioration of the quantitative and qualitative status of groundwater will be prevented (Bloch, 1999 and 2001).

As a Member of EU States, Finland adopted the WFD for water policy into force in 2000, which sets the framework and objectives for water protection in Finland. A major objective is to reach a good quality and chemical status of all waters within 15 years from the entry into force of the WFD (Katko *et al.,* 2006). To better meet the requirements of the WFD, a monitoring network of water quality and quantity is developed in the Finnish environmental administration for the area of surface waters over 0.01 km^2, which can be effectively detected by some current satellite sensors.

Regarding water pollutants and priority substance, remote sensing is at present one of the best methods for providing both spatial and temporal information on such water quality and also for monitoring changes in these water characteristics, particularly in relation to river discharge, river discharge changes, and agricultural and industrial activities. One major benefit of using remote sensing data to support the monitoring of water quality status is that systematic observation systems and their associated historical archives of data already exist; the latter can be continually expanded through current and future data acquisition. As such, remote sensing technology can meet the requirements of Article 8 and Article 16 in the WFD, which highlight the importance of developing such systems and archives for monitoring and assessing water status and trends regarding the substances of surface waters. In addition, remote sensing technology can play an important role in the establishment of water status information datasets concerning point and diffuse sources of pollution and the assessment of changes in their spatial distribution (Chen *et al.,* 2004; Backhaus and Beule, 2005; Dworak *et al.,* 2005). Such datasets are implicit requirements under Article 10 of the WFD, which has to quantify the relevant emission limit or critical values of pollution. This really requires the integration of scientific and technological progress into the policy-making and the implementation of the WFD (Quevauviller *et al.,* 2005).

Fig. 1 A map of the study area

3. A case study in the Gulf of Finland

3.1. Study area

The study area is the Gulf of Finland (see Fig. 1). It is relatively shallow with a mean depth of 38 m and a maximum depth of 123 m. The total water volume is about 1,130 km^3. The surface area (29,600 km^2) is small compared with the catchment area (421,000 km^2). The incoming river discharge is about 110 km^3/year. In the easternmost part of the Gulf the salinity is very low because of the fresh water of the River Neva. The average salinity on the surface is close to 0.6% in December and 0.3–0.6% in June. The Gulf is also saline stratified and in summer temperature stratified. In general, most of the Gulf is nitrogen (N) limited, but the inner Neva estuary is phosphorus (P) limited (Kuusisto *et al.,* 1998). Algal growth season is generally from the early May to the late August. Therefore, factors causing increased light attenuation (e.g., organic, inorganic matter, and yellow substance) vary both spatially and temporally in the study area.

3.2. Remotely sensed data

Satellite-based optical observations are affected by the atmosphere and the radiation from the direct reflectance due to the water surface. These effects should be removed before data analysis. One scene of Landsat TM data was acquired on 16 August 1997. The resolution of TM data is 30 meters (except band 6 with 120 meters).

Since the TM data only consisted of one scene of the study area, the atmospheric correction of TM data was ignored for the purpose of correlation analyses. However, the TM image was geometrically corrected using a land use map, and then the land area of the image was masked off. In order to extract the TM band data from those ground truth points (water quality sampling stations), the mean and standard deviation of TM digital number (DN) values were calculated using the defined windows of 300 by 300 meters for each ground truth point (Zhang *et al.,* 2002a–c).

AVHRR data were received and also examined from April to August 2000. *In situ* measurements of water quality by ship-borne over the study area were daily available from April to May 2000. Only a few AVHRR data were completely cloud-free, a majority however was cloudy or partly cloudy during the period over the Gulf of Finland. These data have previously been used to detect chlorophyll-a, turbidity and water surface temperature (Zhang *et al.,* 2002d and 2003b). The AVHRR data were atmospherically corrected using a simplified method for the atmospheric correction (SMAC) of satellite measurements in the solar spectrum, which is an approximation of 5S (simulation of satellite signal in the solar spectrum). The geometric corrections of AVHRR were performed in two steps. The first step is the approximate rectification using the pre-calculated grid. The second step generates automatic set of control points used for adjusting the gird points to correct locations within one pixel. For the chlorophyll-a estimation, the DN values of AVHRR bands were extracted using the X and Y coordinates corresponding to each point of water quality ship-borne sampling. The spatial size of each grid of AVHRR data is 1*1 km. 11 samples of *in situ* measurements were available daily over the study area corresponding to each AVHRR image, and thus 11 grid points at the most of each AVHRR data were extracted for the purpose of chlorophyll-a estimation.

MODIS data were obtained from GES DAAC archive. For chlorophyll-a estimation in coastal waters of the Gulf of Finland, the bands of 250-m were used to identify cloud-covered areas and nine bands of 1000-m were used to estimate chlorophyll-a in the area. *In situ* measurements of chlorophyll-a were also available in April and May 2000. A few of MODIS images were cloud-free (or partly free) during April and May 2000 in the study area. In the similar way with AVHRR data extraction, MODIS data were extracted corresponding to those ground truth points by using square-shaped regions of 1000 by 1000 m for each ground truth point (Zhang *et al.,* 2003b).

3.3. Water quality monitoring in support of the WFD

The implementation of the WFD and the achievement of its water quality objectives largely depend on scientific knowledge about the status of water resources and the effects of mitigative measures taken. Coastal waters will be of central interest, since the river-basin management may be affected if coastal water status is not satisfactory (Gipperth and Elmgren, 2005). Satellite sensors are able to regularly provide the spatial information of water quality for coastal waters in the Gulf of Finland. This spatial distribution of water quality derived from remotely sensed data would be practically output into a linkage table to detect and monitor if it reaches or exceeds the critical values of water quality standards in water policy for coastal waters in the study area. In order to establish this linkage from water quality monitoring, the following five steps will be needed in general.

Step 1: Identification of appropriate measures of water quality and indicators of water quality. These measures and indicators may vary between river basin districts (RBD), which are mainly dependent on the actual concerns, problems, and landscape characteristics in a GIS-based management plan. Local stakeholders should indicate what issues are important to them (Luijten *et al.,* 2003). In the GIS-based plan, they should include: the impact of human activities on surface waters; mapping of protected areas; monitoring networks; environmental objectives; an economic analysis of water use; the programme of measures; public information and consultation measures; and the seasonal variation in all these measures.

Step 2: Water quality monitoring using remotely sensed data. Satellite-based observations are used to provide the spatial distribution of water quality information such as chlorophyll-a, total suspended mater, yellow substance, turbidity, Secchi disk depth, and water surface temperature in the study area. A summer average of chlorophyll-a information is defined as the average of its values in June, July and August. This chlorophyll-a summer average is used to analyse changes of important indicators of water quality information in the spatial domain. Furthermore, the concentrations of nitrogen (N) and phosphorus (P) with their spatial distribution in water bodies could be correlated and then determined from the summer average.

Step 3: The spatial distribution of water quality information in relation to aquatic ecosystems and environmental changes. This analysis is mainly based on a number of changes in the biophysical and/or socio-economic environment that may impact on hydrological processes, the overall water balance and sustainable water use within the watershed during at least part of the year. The spatial distribution of water quality information is directly related to its aquatic ecosystems, wetlands and environmental changes. Such examples include land cover (and/or use) changes (e.g., deforestation), demographic changes, industrial development, and the amount of water use.

Step 4: A linkage table between water quality monitoring and water policy. A linkage table can connect the spatial distribution of water quality information derived from remotely sensed data to water quality standards in water policy. In the linkage, the summer average is used to indicate any changes of water quality information, especially, the changes of nitrogen (N) and/or total phosphorus (P) in the water body. The results of water quality monitoring using remote sensing show the present situation of aquatic environment that can be compared to the actual measurements and problems in surface waters. This comparison can help identify under what conditions or indicators of water quality may reach or exceed critical values in water policy.

Step 5: Evaluation of the role of water quality monitoring using remote sensing in the WFD. Evaluation is important to determine how water quality monitoring using remote sensing contributes to water policy in the WFD. The evaluation includes:

1) to ensure that the findings are plausibly and potentially useful to the critical values of water quality standards;
2) to refine the analysis by such as using different measures of water availability and adjusting indicators or thresholds of water security;
3) to assess the efficiency of water quality monitoring using remote sensing in support of water policy.

These could help develop appropriate rules and norms for water use, initiate specific water conservation activities, identify better water allocation techniques, formulate specific needs for community participation and external needs, and design water use monitoring schemes that work under a wide range of conditions.

This multi-steps process does not stop after a single iteration. As time passes so new scenarios have to be explored to see how the watershed system is progressing (Luijten *et al.,* 2003). Goals and desired future conditions would need to be re-defined as needs, environmental conditions, personal desires and institutional missions may change.

Table 1 A summary of the results of water quality variables derived from different optical remote sensors in Finland

R^2	Chl-a	Turbidity	SSC	SDD	WST
Landsat TM	0.90	0.94	0.89	0.92	0.86
AVHRR	0.97	0.98	NA	NA	0.97
MODIS	0.98	0.96	NA	NA	NA

Note: R^2 means the regression determination coefficient; Chl-a means chlorophyll-a; SSC means suspended sediment concentration; SDD means Secchi disk depth; WST means water surface temperature; NA means not available yet.

4. Results and discussion

The previous studies of water quality monitoring using remote sensing indicated that major water quality variables like chlorophyll-a, suspended mater, yellow substance, turbidity, Secchi disk depth, water colour and water surface temperature can be derived with reasonable accuracy (Pulliainen *et al.,* 2001; Koponen *et al.,* 2001 and 2002; Zhang *et al.,* 2002a–d and 2003a–c). Table 1 shows a summary of the results of water quality variables derived from different optical remote sensors in the Gulf of Finland. These results also indicate that the spatial distribution of water quality information can be regularly provided and updated using remote observations. Figure 2 gives an example map of the spatial distribution of water quality information estimated from MODIS data using empirical algorithms in the Gulf of Finland.

With the spatial distribution of water quality information, the summer average of chlorophyll-a information can be created into a linkage table that could be used to detect the critical values of water quality standards in water policy. Table 2 presents the summary of water quality elements for rivers and lakes in EU water policy, and Table 3 shows an example of all surface waters (and groundwater) with nitrates pollution (Bloch, 2001; Heinz *et al.,* 2002). In Table 3, the nitrates

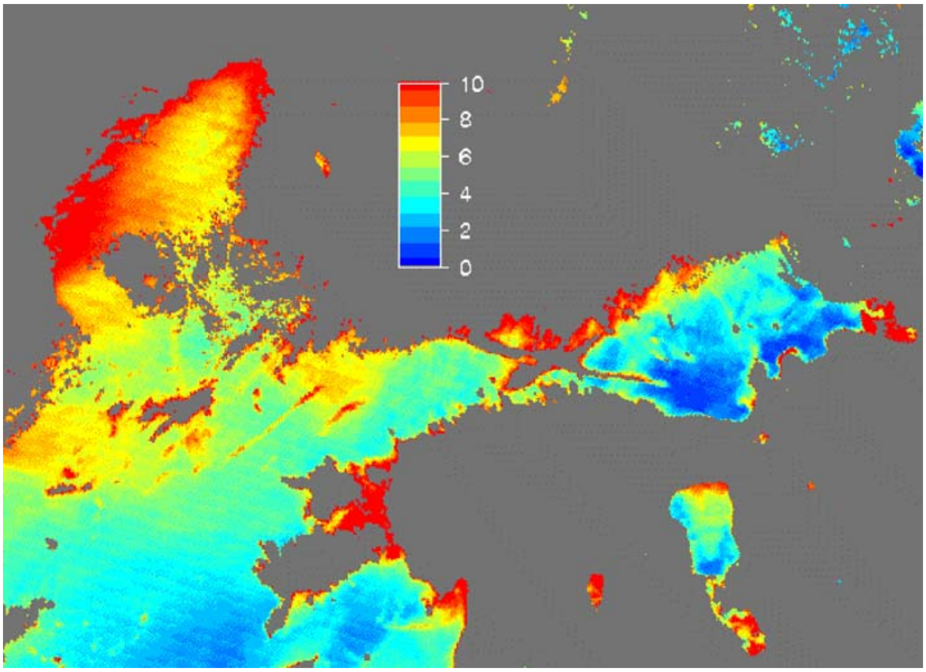

Fig. 2 An example map of water quality information estimated from MODIS data

Table 2 The summary of water quality elements for rivers and lakes in a new EU water policy

Rivers:
• Biological elements: 1) aquatic flora; 2) invertebrate fauna; 3) age structure of fish fauna.
• Hydromorphological elements: 1) hydrological regime (quantity and dynamics of water flow; connection to ground water bodies); 2) river continuity; 3) morphological conditions (river depth and width variations; structure and substrate of the river bed; 4) structure of the riparian zone).
• Chemical and physico-chemical elements: 1) general elements (thermal conditions; oxygenation conditions; salinity; acidification status; nutrient conditions); 2) specific pollutants (pollution by all priority substances discharged into the water body; pollution by other substances into the water body).
Lakes
• Biological elements: 1) Phytoplankton (slight changes of planktonic taxa compared to the type-specific communities; no accelerated growth of algal in the water body or sediment; slight increase in the frequency and intensity of the type-specific planktonic blooms; macrophytes and phytobenthos etc.; benthic invertrebrate fauna etc.).
• Physico-chemical quality elements: 1) General conditions (nutrient concentrations within the levels to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements).

directive (91/676/EEC) describes the critical values for the nitrates pollution from agricultural resources in EU. Within vulnerable zones affected by nitrates pollution, mandatory measures have to be taken as follows:

1) restriction to land application of livestock manure in terms of time and location as well as maximum amounts to be applied to land every year;
2) minimum storage capacities for livestock manure;
3) measures based on a balance between the nitrogen requirements of the crops and the nitrogen supply to the crops from the soil and from fertilization.

Since Finnish water policy has to be harmonized and transformed into the WFD, we consider the level of Finnish water pollution same as the EU level in our case study, although Finland usually adopted the stricter water standards.

Table 3 An example of surface waters and groundwaters with nitrates pollution

• Freshwaters contain 50 mg/l nitrates.
• Groundwaters contain 50 mg/l nitrates.
• Natural freshwater lakes, other freshwater bodies, estuaries, coastal waters and marine waters found to be eutrophic or may become eutrophic.

Water quality standards for surface waters and groundwater under the WFD exist only for nitrates. According to the WFD, the critical value of nitrate concentrations for all surface waters is 50 mg/l. The results we obtained indicate that the value of nitrate-content in the study area is below 25 mg/l (see Fig. 2). This value implies that there is a significantly less affected quality compared to those of most European countries except for a few ones such as Iceland, Norway and Sweden. This clearly reflects the higher level of nitrogen pollution in surface waters (and also groundwater) particularly in the European continent. In any case, all freshwater and groundwater bodies will be brought to a good state in terms of quality and quantity, except for a few cases involving severe contamination. Criticism has been shown that the WFD would not improve water protection and might even lead to weakening of existing water quality standards (Katko *et al.,* 2006). The main reason is its broad definition of the 'good' water status in terms of quality for all waters except those that are severely polluted (Kallis and Butler, 2001).

In the future, we will demonstrate the further results with the spatial distribution of water quality information retrieved from remotely sensed data that has linked to water quality standards in Finnish water policy in compliance with the WFD. More studies are still required to evaluate the contribution of water quality monitoring using remote sensing to water policy and legislation in Finland under the WFD.

5. Conclusions

In this study, we present water quality monitoring using remote sensing in support of the EU WFD by a case study in the Gulf of Finland. Water quality monitoring in EU aims at controlling water pollution and enforcing water protection legislation. The EU water legislation seeks balancing requirements between human needs and nature conservation via public participation and sustainable planning; this is the cornerstone of the WFD. It is also evident that there is an increasing demand by citizens and environmental organizations for cleaner rivers and lakes, groundwater and coastal beaches. This demand is the main reason why EU Commission made water protection its priority. As a Member of EU States, Finland had to comply with water policy and legislation into the WFD from 2000. In order to meet the requirements of the WFD, a monitoring network of water quality is developed in the Finnish environmental administration for all surface waters.

Water quality monitoring using remote sensing technology has been studies for many years in Finland. This expertise provides the technique support to extract the spatial distribution of water quality information for all surface waters. The change of water quality information can be effectively detected and monitored from satellite-based observations. In addition, the importance of integrated water resources and river-basin management under the WFD is briefly described in the study, by which RBD is used to manage appropriate measures and indicators of water quality changes via a GIS-based plan.

In the study, we only gave an example of nitrate concentrations for surface waters in the WFD. When the spatial distribution of water quality information is regularly provided and updated from satellite-based observations, the summer average of chlorophyll-a should be first used to determine the level of nitrate concentrations in surface waters. With its spatial distribution of nitrate-content, a linkage table is established to detect and monitor if it reaches or exceeds the critical values. In the future, more studies are still needed to evaluate the role of water quality monitoring using remote sensing technology in the implementation of water policy in Finland in compliance with the WFD.

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References

Backhaus, R., & Beule, B. (2005). Effective evaluation of satellite data products in environmental policy. *Space Policy*, *21*(3), 173–183.

Bloch, H. (1999). The European Union Water Framework Directive, taking European water policy into the next millennium. *Water Science and Technology*, *40*(10), 67–71.

Bloch, H. (2001). EU policy on nutrients emissions: legislation and implementation. *Water Science and Technology*, *44*(1), 1–6.

Chen, Q., Zhang, Y., Ekroos, A., & Hallikainen, M. (2004). The role of remote sensing technology in the EU water framework directive (WFD). *Environmental Science and Policy*, *7*(4), 267–276.

Dirksen, W. (2002). Water management structure in Europe. *Irrgation and Drainage*, *51*(3), 199–211.

Dworak, T., Laaser, C., Kuntz, S., & Seifert, F.M. (2005). Possible contributions of ESA global monitoring for environment and security initiative for the WFD implementation. *Environmental Science and Policy*, *8*(3), 321–326.

Esty, D.C., & Cornelius, P.K. (2002). *Environmental Performance Measurement: Global Report 2001–2002*, Oxford University Press, New York.

Gipperth, L., & Elmgren, R. (2005). Adaptive coastal planning and the European Union's water framework directive: A Swedish perspective. *AMBIO*, *34*(2), 157–162.

Heinz, I., Andrews, K., Brouwer, F., & Zabel, T. (2002). Voluntary arrangements to cope with diffuse pollution from agriculture and their role in European water policy. *Water Science and Technology*, *46*(6–7), 27–34.

Kallis, G., & Butler, D.(2001). The EU water framework directive: measures and implications. *Water Policy*, *3*(2), 125–142.

Katko, T.S., Lipponen, M.A., & Ronka, E.K.(2006), Groundwater use and policy in community water supply in Finland. *Hydrogeology Journal*, *14*(1), 69–78.

Koponen, S., Pulliainen, J., Servomaa, H., Zhang, Y., Hallikainen, M., Kallio, K., Vepsäläinen, J., Pyhälahti, T. & Hannonen, T.: 2001, Analysis on the feasibility of multisource remote sensing observations for chl-a monitoring in Finnish lakes. *The Science of the Total Environment*, *268*(1–3), 95–106.

Koponen, S., Pulliainen, J., Kallio, K., & Hallikainen, M. (2002). Lake water quality classification with airborne hyperspectral spectrometer and simulated MERIS data. *Remote Sens. Environ.*, *79*(1), 51–59.

Kroiss, H. (1999). Water protection strategies – Critical discussion in regard to the Danube river basin. *Water Science and Technology*, *39*(8), 185–192.

Kumpula, A. (2002). Environmental Law. In J. Poyhonen (2nd eds.). *An Introduction to Finnish Law*, Finnish Lawyers' Publishing, pp. 500–555.

Kuusiniemi, K. (1993). Environmental Law. In J. Poyhonen (1st eds.). *An Introduction to Finnish Law*, Finnish Lawyers Publishing, pp. 345–386.

Kuusiniemi, K. (2000). Water policy and legislation in the EU-the call for an integradted approach, Lecture Note of Nordic Research Course on Water Resources-Legal Protection and Regulation, 19–24 August, Ebeltoft, Denmark.

Kuusisto, M., Koponen, J., & Sarkkula, J. (1998). Modelled phytoplankton dynamics in the Gulf of Finland, *Enviorn. Modelling and Software*, *13*(5–6), 461–470.

Lindell, T., Pierson, D., Premazzi, G., & Zilioli, E. (1999). *Manual for Monitoring European Lakes Using Remote Sensing Techniques*, (EUR 18665 EN, Official Publications of the European Communities, 161 p. Luxembourg.

Luijten, J.C., Knapp, E.B., Sanz, S.I., & Jones, J.W.(2003). A role GIS-based simulation for empowering local stakeholders in water resources negotiations in developing countries: case studies for two rural hillside watersheds in Honduras and Colombia. *Water Policy*, *5*(3), 213–236.

Maia, R. (2003). The Iberian Peninsula's shared rivers harmonization of use: A Portuguese perspective. *Water International 28*(3), 389–397.

Marjanovic, P., & Miloradov, M. (1998). Systems view of integrated water quality monitoring within the requirements of the new national water policy in South Africa. *Water Science and Technology*, *38*(11), 141–148.

MoE (Ministry of the Environment): (1998). Water protection targets to 2005 (Abstract in English). *The Finnish Environment*, *226*, FEI.

Nazarov, N., Cook, H.F., & Woodgate G. (2000). Water pollution control in an independent Ukraine. *Journal of the Chartered Institution of Water and Environmental Management*, *14*(2), 117–123.

Neal, C., & Heathwaite A.L. (2005). Nutrient mobility within river basins: a European perspective. *Journal of Hydrology*, *304*(1–4), 477–490.

Pulliainen, J., Kallio, K., Eloheimo, K., Koponen, S., Servomaa, H., Hannonen, T., Tauriainen, S. & Hallikainen, M. (2001). A semi-operational approach to water quality retrival from remote sensing data. *The Science of the Total Environment*, *268*(1–3), 79–93.

Quevauviller, P., Balabanis, P., Fragakis, C., Weydert, M., Oliver, M., Kaschl, A., Arnold, G., Kroll, A., Galbiati, L., Zaldivar, J.M., & Bidoglio, G. (2005). Science-policy integration needs in support of the implementation of the EU Water Framework Directive. *Environmental Science and Policy*, *8*(3), 203–211.

Varjopuro, R., Sahivirta, E., Makinen, T., & Helminen, H. (2000). Regulation and monitoring of marine aquaculture in Finland. *Journal of Applied Ichtyology*, 16(1), 148–156.

Vihervuori, P. (1998). Environmental Law – Finland. *International Encyclopaedia of Laws*, Kluwer Law International, The Hague, London, Boston.

WWAP (2003). Water for people, water for life', United Nations World Water Development Report, UNESCO-WWAP.

Zhang, Y., Pulliainen, J., Koponen, S., & Hallikainen, M. (2002a). Application of an empirical neural network to surface water quality estimation in the Gulf of Finland using combined optical data and microwave data. *Remote Sensing of Environment*, *81*(2–3), 327–336.

Zhang, Y., Pulliainen, J., Koponen, S., & Hallikainen, M. (2002b). Water quality studies of combined optical, thermal infrared, and microwave remote sensing. *Microwave and Optical Technology Letters*, *34*(4), 281–285.

Zhang, Y., Pulliainen, J., Koponen, S., & Hallikainen, M. (2002c). Applicability of combined microwave and optical data for surface water quality retrievals. *Journal of Electromagnetic Waves and Applications*, *16*(2), 249–251.

Zhang, Y., Pulliainen, J., Koponen, S., & Hallikainen, M. (2002d). Detection of sea surface temperature (SST) using infrared band data of advanced very high resolution radiometer (AVHRR) in the Gulf of Finland. *International Journal of Infrared and Millimeter Waves*, *23*(10), 1407–1412.

Zhang, Y., Pulliainen, J., Koponen, S., & Hallikainen, M. (2003a). Water quality retrievals from combined Landsat TM data and ERS-2 SAR data in the Gulf of Finland. *IEEE Transactions on Geoscience and Remote Sensing*, *41*(3), 622–629.

Zhang, Y., Koponen, S., Pulliainen, J., & Hallikainen, M. (2003b). Application of empirical neural networks to chlorophyll-a estimation in coastal waters using optosensors. *IEEE Sensors Journal*, *3*(4), 376–382.

Zhang, Y., Pulliainen, J., Koponen, S. & Hallikainen, M. (2003c). Empirical algorithms for Secchi disk depth using optical and microwave remote sensing data from the Gulf of Finland and the Archipelago. *Boreal Environment Research*, *8*(3), 251–261.