MAKING WATER INFORMATION RELEVANT ON LOCAL TO GLOBAL SCALE – THE ROLE OF INFORMATION SYSTEMS FOR INTEGRATED WATER MANAGEMENT

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**ABSTRACT**

Relevant information is essential for finding solutions in Integrated Water Management (IWM). Complex water systems and a need for increasing integration of sectors, actors and scales in IWM require new methods for developing and managing such information. This thesis investigates the role of information within the IWM process, as well as the main challenges for development of representative, accessible and harmonized information. Results show how information needs and the information production process for IWM may be systematized, and indicate a large potential for information system development for IWM. However, in order to reach the full potential, today’s limited and heterogeneous water information needs to become more comprehensive, transparent, interoperable, dynamic, scalable and openly accessible. Large pressures on water systems are found in coastal catchment areas that are unmonitored across the local to the global scale, indicating a large importance of these areas for nutrient and pollutant loading. The globally accessible runoff data from catchment areas that are rich in pressures from population, agriculture and general economic activity further exhibit a rapidly declining trend during recent years. Major water system changes may therefore pass unnoticed if analyzed on the basis of openly accessible runoff global data. Furthermore, large discrepancies are found between land cover databases, which may result in major uncertainties in quantification of water and evapotranspiration flows. Identified information challenges may be relatively easily overcome by making better use of available information, while other challenges such as development of consistent baselines of core data and a possible re-prioritization of water-environmental monitoring programs may be both difficult and costly.

**Keywords:** Integrated water management, hydrology, environmental information systems, environmental monitoring, land cover, GIS, Sweden, Baltic Sea, European Union, global water, global change, Water Framework Directive.
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LIST OF APPENDED PAPERS

This doctoral thesis summarizes and interweaves the following appended papers, which are referred to by roman numerals in the text:


The co-authorship of these papers reflects the collaborative research conducted for their development.

- Paper I was based on a series of discussions on Integrated Water Resources Management between all co-authors. I took the lead on the paper writing, based on an idea from G. Destouni who also made major contributions to the paper formulation.
- For Paper II I had the main responsibility for analysis, interpretations and writing the paper. The idea of the paper and methods used sprung from a discussion between S. Langaas and myself.
- For Paper III and IV and V I had the main responsibility for methodology, analysis and writing the paper. G. Destouni (Paper III) and A. Lotsch (Paper IV) contributed to methodologies, interpretations and writing of the paper. For Paper V G. Destouni and L. Gordon contributed to the interpretation and paper formulation. L. Gordon further contributed to the evapotranspiration modeling methodology.
OTHER PUBLICATIONS BY THE AUTHOR

Other publications by the author from 2004 and onwards:


ABBREVIATIONS

The following abbreviations are used in several places throughout the text:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BSDB</td>
<td>Baltic Sea Drainage Basin</td>
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<tr>
<td>GIS</td>
<td>Geographical Information Systems</td>
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<td>GRDC</td>
<td>Global Runoff Data Center</td>
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<td>GTN-R</td>
<td>Global Terrestrial Network for River Discharge</td>
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<td>IWIS</td>
<td>Integrated Water Information Systems</td>
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<td>IWM</td>
<td>Integrated Water Management</td>
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<td>WFD</td>
<td>EU Water Framework Directive</td>
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<td>WIS</td>
<td>Water Information Systems</td>
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<td>WISE</td>
<td>Water Information System for Europe</td>
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INTRODUCTION

Water of adequate quantity and quality is a prerequisite for life. However, it is neither always plentiful nor necessarily of high quality. It is unevenly distributed and always in a state of flux as it constantly moves and changes phases. In liquid form it has a unique capability of transporting large masses of dissolved and suspended substances, affecting its quality. Flows of water and waterborne substances are further difficult to predict as flow paths are both complex and variable in surface and sub-surface catchments (Chow, 1964; Bouwer, 1978). In addition to this complexity, global change processes such as climate change (Milly et al., 2005; de Wit and Stankiewicz, 2006), population and water demand increases (Vörösmarty et al., 2000), land use changes (Gordon et al., 2005) and infrastructure development (Nilsson et al., 2005) may all have considerable effects on flows of water and waterborne substances. Ultimately, these changes have an impact on human societies, ecosystems and ecosystem services (Kurukulasuriya and Mendelsohn, 2006; Perry et al., 1997; Millennium Ecosystem Assessment, 2005). The complexity of the water system combined with the necessity of managing water resources results in water management situations where facts are often uncertain, stakes high and values sometimes in dispute. In order to achieve good solutions to complex water management problems securing relevant information that resolves uncertainties is therefore of critical importance.

Present systems for monitoring and processing environmental information, however, commonly fail to deliver timely and relevant information for policy and assessment needs (Pentreath, 1998). Nilsson and Langaas (2003) propose that one reason may be that traditionally information has been supply-driven, i.e. driven by water science and technology rather than by needs. Another reason may also be the data and information management per se. Large quantities of data are being produced, however much is poorly used, and some critical data remain non-communicated (Lopez, 1998). A third possible reason is related to difficulties of harmonization of monitoring and information systems between different administrative units, such as municipalities, counties, states and countries (Bishr, 1998, Harvey et al., 1999, Annoni and Smits, 2003, Vanderhaegen and Muro, 2005). Within water management, the shift to a drainage basin perspective necessitates a difficult process of harmonization of priorities, data management and analysis methodologies across such administrative boundaries. The shift from water management to integrated water management (IWM) further challenges data and information management as it extends the scope of relevant information from the purely technical to a wide range of different information, from water quality samples to water use behavioral studies and water economics. IWM also challenges old methods for information sharing and stakeholder involvement.

Simply collecting more data does not necessarily constitute an improvement, if the data collected is not relevant, or is not systemized, analyzed and interpreted by relevant methods. Today, monitoring and regulation, as well as relevant research and education, are fragmented between various actors within society. None of the actors, such as governmental authorities, may have the overall responsibility for coordinating the fragmented parts and aspects of IWM for the benefit of long-term sustainability of available water resources. In Sweden alone, even the single responsibility for monitoring the water environment is divided between municipalities, county administrative boards, national authorities, such as the Swedish Environmental Protection Agency, the Geological Survey of Sweden and the Swedish Meteorological and Hydrological Institute, as well as municipal and private companies and river basin associations. On any international scale there exists additional complexity of actors and priorities. Without a relevant system solution for organizing data collection, processing and interpretation, as well as for disseminating information, there is considerable risk that ineffective water management options will be promoted.

One possible component of the solution analyzed in this thesis is to move from restricted

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1 Thus indicating that science about integrated water management is post-normal science according to the definition by Funtowicz and Ravetz (1993).
and narrow Water Information Systems (WIS) for traditional water management, towards open, non‐restricted, comprehensive and multi‐purpose Integrated Water Information Systems (IWIS) for IWM. These should provide the necessary basis for transparent and independent control of water‐environment investigation methods, results and conclusions (see also Haklay, 2003; Carver, 2003) as well as constituting a data and information communication platform for all stakeholders and the general public. While WIS are generally limited to technical data and comprise data and a technical function for the purpose of distribution, a move towards IWIS involves extending the definition of the information system to a broader set of base data and metadata, to include numerical models of relevance, as well as aggregated information and the necessary institutional and technical capacities to satisfy stakeholder information demands and needs for transparency and open communication.

Geographical Information Systems (GIS) and the Internet in combination (Haklay, 2003; Langaas et al., 2004; Schreier and Brown, 2002) are two available tools for meeting some of the information challenges arising in developing IWIS. It is, however, by no means obvious how the large potential of these tools should be brought into effect in IWM. Learning from early attempts made in establishing today’s WIS is therefore important. WIS based partly on GIS and the Internet are being developed for a range of geographical scales, from the individual and national drainage basin scale, to national, international river basins scale and also for continental and global scale. In Europe, the aims and requirements in the EU Water Framework Directive (WFD; Council of the European Communities, 2000) have certainly pushed actors in this direction (Langaas et al., 2004). WIS are under way for some of the transboundary river basins in Europe (e.g. Elbe, Rhine, Danube, Odra, Narva/Peipsi, Daugava and Nemunas), initiated by existing international river basin commissions, bi‐ or multilateral cooperations or by scientific projects dependent on spatial water‐environmental data (e.g. Schreiber et al., 2003, 2005; Hannerz et al., 2002). At the European scale, the European Environment Agency is responsible for the European Environment Information and Observation Network and the Waterbase while the European Commission is currently trying to develop a more comprehensive Water Information System for Europe (WISE), building largely upon required WFD reporting data. While more limited in thematic scope and spatial detail, global WIS are also developed in order to support global water science and policy. Examples, among others, are AQUASTAT (FAO, 2008), GEMStat (UNEP, 2008) and the online atlases and databases at the Oregon State University (2008), including e.g. the Transboundary Freshwater Dispute Database (Wolf et al., 2003). Such WIS are today generally (with exceptions) rather static and limited as they are most often dependent on manual reporting of data from a specific national institution to a centralized institution. Integration of these different WIS at national, transboundary, continental and global scale is very limited.

An information system is never better than its component parts, and information for integrated water management is therefore intrinsically limited by the qualities of underlying data and tools for analysis. Numerical models are e.g. always imperfect because they abstract and simplify processes that are themselves not perfectly understood (Brown and Heuvelink, 2005). As a result, false assumptions about main processes may be validated rather than falsified if relevant data for model validation are unavailable. In order to quantify the uncertainties in water system assessments (e.g. Beven and Binley, 1992; Zhang et al., 1993; Christensen and Cooley, 1999) and corresponding uncertainty costs for a specific water‐environmental management situation (Gren et al., 2002; Baresel et al., 2006; Mysiak and Sigel, 2005) it is important to understand the qualities and limitations of IWIS relevant information. While the total set of IWIS relevant information is broad, some information is more critical than other. Of particular interest are water‐environmental monitoring programs, usually established on local to national scale, that provide a large base of data for studying trends in water quality and flow development over time. These data are critical for development and validation of estimates of water and waterborne substance fluxes. Large public resources are spent on sustaining monitoring programs worldwide and it is therefore important to
ensure their benefits by capturing the relevant pressures on the water system. In this respect an understanding of the general characteristics of monitoring networks and the water systems they are covering is of particular significance. In the absence of contradictory evidence, unmonitored catchment areas are often assumed to have analogous water and waterborne substance transport behavior as monitored river basins. The validity of such assumptions is naturally difficult to assess in unmonitored areas, but may be especially important since these are, in general, near-costal areas with short transport paths from inland sources of nutrient and pollutant inputs to coastal ecosystem recipients.

Land information is another critical component of an IWIS as land use and land cover as well as their changes largely affect the size and quality of water flows across the world (Feddema et al 2005; Foley et al, 2005). Remotely sensed categorical land cover data is increasingly used in hydrological (e.g. Gordon et al., 2005; Vörösmarty et al., 2000; Döll, 2003; Arnell, 1999) and climate (Hagemann and Gates, 2003) models for evapotranspiration and runoff estimates. Such estimates may be sensitive to uncertainties in input data, as exemplified by Fekete et al. (2004), showing highly variable runoff estimates by use of gridded precipitation data sets from different sources. Discrepancies in other core input data may also correspond to similar uncertainties, but so far such discrepancies have not been extensively analyzed and reported. Specifically the sensitivity of evapotranspiration and runoff estimates to uncertainties in remotely sensed land cover data has, to the best of my knowledge, so far not been quantified. The African continent is particularly interesting in this context for several reasons. The availability of core hydrological data is low (Brown, 2002) while at the same time the continent is particularly vulnerable to water and climate system changes (IPCC, 2007; Rockström et al., 2007, de Wit and Stankiewicz, 2006). The economy is driven by agricultural production (IFAD, 2001), but land use statistics have been reported to be inconsistent over time and across countries (Young, 1998; Wood et al., 2000; Ramankutty, 2004; George and Nachtergaele, 2002). This implies that other sources of land information, e.g. remotely sensed land cover data, are critical for understating interactions between the water system, agriculture and economy. To date only limited information is available regarding the uncertainties of such data on a continental scale and the implication of such uncertainties on water system studies.

Objectives

The general objective of this thesis is to contribute to deepened understanding of the role of information in development of information systems for Integrated Water Management across scales, from local measurement to regional, continental and global scale assessments. More specifically the objective has been to find answers to the following main questions relating to core challenges in the development of such information systems:

i) What role does information, and in particular spatial information, play as an integrator in IWM; how can the potential benefits of spatial analysis and information technology be exploited maximally for development of an IWIS that provides integration of information and multipurpose use across traditional scale and stakeholder boundaries? (Papers I and II)

ii) Representative monitoring and modeling of fluxes at the land-sea and land-atmosphere interfaces is critical for establishing reliable information about large-scale water and substance flows in an IWIS. Are water flux and quality monitoring data available at the local to national level as well as openly accessible data on the continental to global level, really representative? Do they capture the main pressures on water systems across scales, and does monitoring data generally provide a representative basis for extrapolation to unmonitored catchment areas? Considering the large impact of land use on water flows, does available land information provide a reliable basis for assessing land-to-sea and land-to-atmosphere water and moisture fluxes on large regional and continental scales? (Papers III, IV and V)

The term available data refers throughout the text to the entire set of data that is available, regardless of constraints for its use. The term accessible data on the other hand refers to the subset of all available data that is made openly
accessible and distributed through shared information systems.

METHODS

Development of IWIS

The integrating role of information in IWM and the development of a IWIS is the focus of Paper I. In order to clarify the most important information and information process components the paper presents a systematization of general information needs for IWM. The WFD is taken as the starting point and a conceptual flowchart, focusing on information needs and the information process, is presented for operational implementation of the WFD. Necessary components for the systematization are identified as well as suitable scientific quantification tools for its implementation. Characteristics of a IWIS are identified for facilitating the process and aiming to provide transparency for all stakeholders and the general public. Paper I is based on a series of open-ended and in-depth discussions on integrated water management in Europe between the authors, all having experiences from different topical water research and policy areas. Discussions are combined with an analysis of main water management issues at the local scale, the requirements and aims of WFD, the process and state of WFD implementation in EU member states, and specific results from an EU research project focused on WFD-based management of water pollution from mining activities and wastes (ERMITE Consortium, 2004).

Paper II continues the analysis from Paper I but focuses on actual information systems under development, and in particular on the Water Information System for Europe (WISE; European Commission, 2003; Usländer, 2005). The process of the WISE development is analyzed, as well as the spatial water-environmental data constraints for this development. First, the possibilities and process of establishing a shared WISE is analyzed based on published material regarding WISE, selected national WIS initiatives and an analysis of the initial WFD implementation and reporting process. Second, spatial data

Figure 1. Geographical areas in focus for the Papers I–V. Paper I does not have a precise geographical boundary, but focuses mainly on the European Union through is analysis partially based on EU legislation. Paper II makes a comparative analysis between southwestern England and southern Sweden and an analysis of the Baltic Sea Drainage Basin (BSDB). Paper III focuses on Sweden and the BSDB. Paper IV focuses on the African continent and eleven example countries (indicated in map) across climate and agro-ecological zones within Africa (aridity zones based on Arnold (1992) and as indicated on map). Paper V presents analyses for the different continents, especially Africa, as well as globally.
components of initial WFD reporting, required from all EU member states to be sent to the European Commission, is analyzed for Sweden and England with regard to possibilities, within a future WISE, to develop a harmonized set of water information based on such national reporting data. The WFD required analysis of the risk of failing to achieve the environmental objectives for water, a core component of the WFD (Art. 5 of the WFD), is used for the comparison between England and Sweden. Third, small scale spatial hydrological base data sets in already available pan-European data, identified by the European Commission as potential core data for a centralized WISE base map, are analyzed with regard to transboundary heterogeneity. For this third analysis the Baltic Sea Drainage Basin (BSDB; Figure 1) is taken as an example case. Results from these analyses may give advice on future priorities in development of a harmonised WIS and ultimately an IWIS.

Representativeness, gaps and gap implications of core monitoring data

Paper III and V analyse the characteristics of traditional water-environmental monitoring and reporting systems, mainly focusing on monitoring systems for river runoff and nutrient and fluxes. They characterize in particular detail unmonitored catchment areas on different geographical scales, from the national (Sweden, paper III) to the regional (BSDB, paper III) and the continental to global (paper V) scale. Figure 1 shows the different characterization locations. Paper III presents spatial core WIS data for the BSDB, based on meta-analysis, integration and further processing of relevant spatial and non-spatial data (mainly from Defence Mapping Agency, 1992; Dobson et al., 2000; EEA, 2005a; Joint Research Centre, 2003; Hannerz, 2002; HELCOM, 2003; Hiederer and de Roo, 2003; Nilsson et al., 2004; Oak Ridge National Laboratory, 2004; SMHI, 2005; Sweitzer et al., 1996). Main catchments are here delineated at a level of detail previously not presented, followed by characterization of these catchments at a detailed scale for the whole BSDB. Using a distributed hydrological routing model based on topography, in combination with the developed catchment delineations, the catchment areas upstream of the 165 most near-coastal nutrient concentration monitoring locations within the BSDB are identified and mapped. Indicators of major drivers for hydrological, pollutant and nutrient transport in catchments are developed, calculated and compared between unmonitored and monitored catchment areas.

Paper V includes a similar but much larger-scale runoff monitoring analysis, addressing the spatial distribution and temporal development of our ability to detect continental-global water system change based on globally accessible hydrological monitoring data from 1940 – 2000. The first step in this analysis is based on data from 377 major near-ocean gauging stations, identified by the Global Runoff Data Centre (GRDC) as the most important for quantifying global river discharges into the world’s oceans. These stations are included in the Global Terrestrial Network for River Discharge (GTN-R; GTN-R, 2005; Maurer, 2005). The spatial distribution of areas covered by actually reported runoff data for these 377 globally prioritized, near-ocean discharge monitoring stations (GTN-R) are for the period 1940 – 2000 mapped, analyzed and compared to areas not covered by this reporting, with particular regard to population, area, evapotranspiration, cropland extent and economic gross area product in the covered and uncovered areas. In a second step of the analysis, all 7317 runoff stations in the GRDC data holdings are used in conjunction with the development of a global drainage direction map of 10 minute resolution, based on a 10 minute digital elevation model (USGS, 2005) as well as automated and manual correction of flow pathways by use of a digital global drainage network. The drainage direction map was used for calculating the catchment areas upstream of the 7317 stations and their characteristics. On a continent by continent basis the temporal development of catchment area, mean annual runoff generation, cropland extent, mean annual evapotranspiration, irrigated cropland extent and population in areas upstream of monitoring locations is calculated for the considered period 1940 – 2000 (for data references, see paper V).

Both Paper IV and Paper V analyze further the robustness and spatial agreement of major continental-global scale inventories of remotely sensed land cover data, which are frequently used independently and for large-scale modeling of hydrological and water resource conditions.
(e.g. in hydrological models by Fekete et al., 2002; Arnell, 1999; Döll et al., 2003). In paper IV, remotely sensed and statistical inventories are studied particularly for African croplands. First, the extent of croplands in 48 African countries is studied using both remote sensing and statistical data. Second, spatial patterns of agreement and disagreement between remotely sensed land cover data are analyzed on a pixel-by-pixel basis and evaluated using pair-wise categorical agreement (Lillesand and Kiefer, 1994) at scales of 1km, by development of cross-tabulations of land cover category. For eleven countries, selected to represent the range of different climate and agro-ecosystems on the African continent (see locations and climatic zoning in Figure 1), the data is examined in further detail, and particularly so for Burkina Faso, where local cropping patterns and their representation in remotely sensed land cover data is analyzed. The following six sources of remotely sensed data were analyzed in Paper IV: 1) Global Land Cover 2000 assessment (Mayaux et al., 2003); 2) the moderate imaging spectroradiometer (MODIS) land cover data (Friedl et al., 2002); 3) the Global Land Cover Facility data (Hansen et al., 2000); 4) the Landsat land cover data (Dobson et al., 2000); 5) the International Food Policy Research Institute (IFPRI) Agricultural Extent data (Wood et al., 2000); and 6) the Center for Sustainability and Global Environment (SAGE) Cropland Distribution data (Ramankutty and Foley, 1998). These sources were also compared to available local and regional agricultural statistics (AgroMAPS initiative, 2005; FAO, 2005).

Paper V includes a similar land cover data base analysis for the global scale and examines how discrepancies between alternative data bases may affect continental-global scale estimates of moisture flux from land to atmosphere through evapotranspiration. As examples of evapotranspiration calculations, Paper V uses a GIS based calculation model proposed and used by Gordon et al. (2005), as well a calculation method reported and used by Rockström et al. (1999). The identified extent and distribution of land cover and the potential impacts of resulting discrepancies on evapotranspiration were analyzed based on the following four categorical global land cover inventories: 1) Global Land Cover 2000 assessment (Fritz et al., 2003); 2) the moderate imaging spectroradiometer (MODIS) land cover data (Friedl et al. 2002); 3) the Global Land Cover Facility data (Hansen et al., 2000); and 4) the Global Land Cover Characterization (GLCC) data (Loveland et al., 1991). In addition the results from Paper IV, based on seven land cover data bases for the African continent, are also used for calculating the potential impacts on evapotranspiration estimates from land cover identification and labelling discrepancies for a single land cover category and geographical region. Evapotranspiration from agricultural fields in Africa are calculated using the crop specific values of actual evapotranspiration presented by Wahaj et al. (2007) on district level for major locally produced crops.

**Results**

**Development of IWIS (Papers I and II)**

Paper I shows the possible role of information as an integrator in IWM. It systematizes information needs and the information production process for IWM, focusing on operational implementation of the WFD in a conceptual flowchart (Figure 2). Based on openly shared, harmonized and dynamic information in the IWIS (denoted EIS in Figure 2 and Paper I), reoccurring main water management tasks are integrated into one common information-based process. These three identified main tasks are: 1) development of water management plans and action programs; 2) environmental evaluation of permit applications for various development projects; and 3) remediation decisions for contaminated land. Figure 2 shows how these main tasks are processed through a flowchart based on three main management questions: i) Does/will the given water environment comply with relevant water environment standards now as well as in the future without need for further measures? ii) Are there any technologically and/or socio-economically feasible and sustainable measures that can be taken for achieving environmental compliance in the considered water environment? and iii) Which particular measure allocations or methods identified with regard to Question ii, among several feasible possibilities, should be chosen for compliance with environmental standards, or at least for non-deterioration of the water environment?
Important information components to address these questions have been identified and are also indicated in Figure 2. These components are dynamic and distributed hydrological characterization (de Wit, 2001; Darraç et al., 2005), abatement optimization for economic efficiency (ERMITE Consortium, 2004; Gren et al., 2002) and a decision-making process building on ideas of participation and legitimacy (Lahdelma et al., 2000; Carver, 2003; GWP, 2000). A common need for all these components is the IWIS (EIS in Paper I), building upon recent developments of spatial data infrastructure (Bernard et al., 2005; Vanderhaegen and Muro, 2005) and spatial data technologies for the Internet (Tait, 2005; Langaa et al., 2004), and including a technical and institutional solution for storage, updating and dissemination of all available information. The entire set of available information is referred to here, crossing administrative borders and institutional structures. Openly shared information (free and easily accessible) in the IWIS, in line with Haklay (2003), the Århus Convention (UNECE, 1998) and EU legislation regarding public access to environmental information (Council of the European Communities, 2003), forms a basis for necessary open review of methodologies, interpretations and results. The openly shared information also forms a necessary basis for negotiations and agreements. It is proposed that uncertainties and value differences may be accounted for by using existing decision support systems (Collentine et al., 2002) and multicriteria methods, such as those presented by Lahdelma et al. (2000) and Giupponi (2007). Many of these account requirements are indeed quite different from today’s limited WIS.

Paper I also addresses the openness and transparency of the proposed IWIS. While public accessibility to environmental information is often limited to aggregated information, such as Environmental Impact Assessments or final management and action plans, paper I points out the need to increase the legitimacy of the IWM process and also to embrace open accessibility to underlying information and data in the IWIS. Access constraints may lead to different data and

Figure 2. The general flowchart presented in paper I considers water management decisions for three main tasks: 1) development of water management and action plans; 2) environmental evaluation of individual permit applications; and 3) remediation decisions for contaminated land. These main tasks require answers to three questions (see Paper I) through a process that is continuously fed with information from designated analyses (dynamic characterization and optimization analyses) and dialogues at the “Stakeholder Interplay Arena” and the “Negotiation Table”. The IWIS stores all relevant information and serves as a communication center to facilitate the necessary analyses and dialogues.
information being used by different stakeholders and consequently to different water system identification and characterization results, and to different answers to the main above-stated Questions i)-iii). In addition, data analysis and aggregation into processed new information, produced by models and model interpretations, is by no means straightforward or standardized. Resulting quantifications and proposed solutions to specific water-environmental problems from this process will largely depend on who is doing the interpretation and with what kind of modeling and interpretation tools. Independent open review, based on open access to all underlying data, is therefore a critical component for trust building among stakeholders and enables independent analysis of developed management plans and action programs.

The WISE, developed by the European Commission, is intended to build on spatial data, submitted from EU member states to the European Commission as part of the WFD reporting requirements and should result in an envisioned harmonized overview of European waters. While the WFD in itself is unclear regarding how the reporting should be carried out, the European Commission has requested EU member states to use the established electronic submission facilities for reporting data via WISE. Electronic submission of data, e.g. GIS formatted data, in contrast to traditional hardcopy reporting, is a prerequisite for inclusion of national data into a shared WISE. Results in paper II show a slow response from EU member states in the use of the WISE electronic reporting facilities. Even 16 months after the reporting deadline of the WFD article 3, less than half of the member states had used the reporting facilities in the WISE prototype. Paper II indicates that main hindrances to an effective process of WISE development are: 1) the heterogeneous and fragmented water-environmental information priorities within and between EU member states already steering the development of WIS at national and sub-national scale (e.g. in Germany – Wasserblick, 2006; Sweden – WISS, 2006; and the UK – Environment Agency, 2006); and 2) the widely different usage of water-environmental information between those developing WIS in EU member states and within the European Commission. While on national and sub-national scales the aim of WIS information is to find solutions for main management tasks (paper I), the European Commission uses the information reported from EU Member States primarily for checking legal transposition, compliance, and practical implementation of the various water-related directives. These very different purposes of water-environmental information cause conflict on the aim and purpose of a shared WISE.

Figure 3. Comparison of spatial data and analysis methods for the Water Framework Directive article 5 risk assessment for southern Sweden (left) and southwestern England (right). The figure shows that the basic analysis and mapping unit in Sweden is the river basin, while in England it is the individual water body. Legends show the different risk classification schemes used in the two countries. The methodologies for risk classification are also different - areas which risk falling the WFD objectives are identified in Sweden based on eutrophication (displayed), acidification and metal loading, while risk identification in England is based on macroinvertebrates, point source emissions, diffuse emissions, water abstraction and regulation, morphological factors and the sum of all analyzed risk categories (displayed).
Paper II further analyses spatial data and information heterogeneity challenges when developing a WISE, either by concatenation of information from national WIS (as e.g. Wasserblick, 2006), as proposed by some member states, or by using a more small-scale and centralized solution as proposed by the European Commission. Results from the comparison of initial WFD reporting (Risk analysis, WFD article 5) between Sweden and the United Kingdom reveal substantial differences between the two countries in how required information about the water-environment is developed and analyzed. Results, partly visualized in Figure 3, show that analyses were developed for completely different spatial base-units in the two countries (UK - water bodies; Sweden – drainage basins) and that analysis methodologies and main assumptions for water quality development over time are non-comparable. Also the risk classification scheme varies between the two countries with no reference made to the concept of risk in the WFD. Paper II does not analyze whether these different approaches are in line with the regulations within the WFD, but concludes that a harmonized and seamless WISE, based on concatenation of such pieces of information, seems quite distant. Results further show that existing small-scale data sets, proposed to form the basis for a small-scale and centralized WISE, as proposed by the European Commission, are cross-country border heterogeneous. Heterogeneity is in certain cases large enough to affect the basic quantification of European waters, if analyzed small-scale data sets are adopted as base maps in a centralized WISE. One of the main aims with the WFD is to enable cross-country comparisons of water status. Results in paper II suggest that spatial water environmental data heterogeneity alone may constrain the possibilities for such international comparison.

Representativeness, gaps and gap implications of core monitoring data (Papers III, IV and V)

Paper III initially presents a short overview of environmental spatial data initiatives and a compilation of nutrient monitoring data targeting the BSDB. It is shown that in contrast to the political agreement on the severity of the water-environmental problems of the Baltic Sea and its drainage basins, no long-term efforts, supported by national authorities, have so far targeted the development of a comprehensive water-environmental information system in support of science, education and policy. Furthermore, openly shared nutrient concentration monitoring data (Stålnacke et al., 1999; Baltic Environment Database, 2005) are surprisingly limited within the BSDB compared to the political attention given to the problem of eutrophication. Instead, efforts have all been initiated and funded on a project-by-project basis, mainly by general research funds, and resulting research products are therefore seldom or never updated.

Although the freely accessible spatial environmental data for the DBSB is limited, it is widely used. This is shown in Paper III by a study of usage statistics of the spatial data and statistics in the Baltic Sea Region GIS, Maps and Statistical Database (Sweitzer et al., 1996), published on the Internet in 1995. Between March 2000 and August 2004, spatial data alone were downloaded 36 000 times from this database, containing eight thematic layers of GIS-formatted data. The small-scale (about 1:5 000 000) drainage basin delineation layer constituted about one tenth of the total downloads. Paper III develops and proposes a better geographically distributed characterization of the BSDB and its nutrient-pollutant drivers, especially for the 553 relatively small coastal catchment areas that have previously not been identified as separate catchments in earlier spatial data for the BSDB (Langaas, 1992; Sweitzer et al., 1996; Ursin, 2001).

While population distribution is one important driver for nutrient pollution in the BSDB, as shown by Smith et al. (2005), the only previously available scientific assessment (Sweitzer et al., 1996) of population distribution within the BSDB was based on data and interpretation from 1990. Results in paper III show major changes in population estimates of individual drainage basins, areas draining to the major marine areas of the Baltic Sea, as well as for shares of countries within the BSDB and for all the small unmonitored coastal catchments compared to the estimate based on 1990 data. It is also shown that the population in unmonitored catchment areas, with regard to nutrient fluxes, is relatively
high. Out of a total of 84 239 000 people living in the BSDB, 24% live in unmonitored catchment areas corresponding to 13% of the total BSDB area. Sweden, see Figure 4, stands out with a particularly large proportion of its total area (20%) and population (55%) being unmonitored within the national environmental monitoring program. The population density in Sweden is thus five times higher (for the BSDB two) in unmonitored catchment areas than in the monitored (see Figure 4), which indicates the possibility of large unmonitored substance flows originating from these coastal and highly populated catchment areas. Results further show a high variability between catchment areas in regard of other important parameters for nutrient release and transport (land cover, terrain gradients and drainage density) as well as systematic differences between monitored and unmonitored catchment areas for these parameters. The generally short nutrient and pollutant transport pathways from sources in unmonitored coastal catchments to the Baltic Sea further underscore the potential importance of these areas for nutrient and pollutant loading.

Pollutant, climate and other pressures on the global water system have been increasing dramatically in recent times as component parts of the overall global change. Timely and high-quality data are needed not only on the local but also on continental and global scales in order for the water science and policy community to detect and predict changes to the water system and suggest relevant policy measures. In contrast to these needs, Paper V shows that globally accessible and prioritized runoff data are made continuously less accessible and accessible data are continuously less representative for a changing global water system. This is exemplified in Figure 5, showing the geographical coverage of areas upstream of reported runoff-data to GRDC from the 377 near-coastal gauging stations, identified as the most important for monitoring global runoff oceans (GTN-R, 2005). Paper V provides the full dynamics of this development and Figure 5 summarizes the situation for the years 1975 and 2000. Between 1975 and 2000, the area upstream of accessible monitoring data declined from 45% to 10% of the global area (excluding Antarctica). The upstream population declined from 46% to

![Figure 4. Catchment areas monitored (light gray) and non-monitored (dark gray) by the Swedish national environmental network for nutrient mass flow monitoring, along with monitoring locations (black dots) for monitoring of a) nutrient concentration; b) river runoff; and c) combined nutrient concentration and runoff. The non-monitored areas in c) correspond to 20% of the Swedish area but to 55% of the population. Panel d) shows by color the population density in unmonitored catchment areas, with regard to nutrient mass flows, compared to nearest monitored catchment. The chart relates to panel d) and shows the total population within the different categories used for population density comparison.](image-url)
only 6% of the total global population. The corresponding global share of croplands dropped from 55% to 10% and the share of global economic production from 45% to 25%.

Figure 6 summarizes the coverage-dynamics of reported data of river runoff, associated upstream catchment area and population within that catchment area on the global scale during 1940 – 2000. The development is compared with the development of global mean temperature (Folland et al., 2001) and total human water withdrawals (Shiklomanov, 2000) over the same time period. Figure 6 shows that the present global temperature is considerably higher than at the peaks of reported runoff, catchment area and population coverage (1955-1975). The global human water withdrawal has also increased by 140% compared to 1955 and by 40% compared to 1975. Figure 6 and detailed figures in Paper V further show that the upstream areas covered by global monitoring reports since 1970 are generally runoff-rich but poor in pressures from population distribution, overall economic activity and specifically agricultural production. This shows a systematic tendency that globally accessible runoff data primarily represent areas with relatively low human pressures (and demands) on water. Global change effects of human pressures in uncovered areas, where pressures are higher than in covered areas, are therefore increasingly uncertain. This development stands in contrast to society’s requirement for reduced water system uncertainty in order to better plan strategies for coping with and adapting to climate and other global change.

Figure 7 is based on the complete set of 7317 GRDC runoff monitoring stations spread around the whole world. It shows, relative to 1940, the development of the total number of stations for which data has been reported (right axis) and average covered sub-catchment area, runoff from that area and population, evapotranspiration, cropland extent and extent of areas equipped for irrigation within the area. Figure 7 shows that the characteristics of sub-catchment areas have changed over time. The average covered sub-catchment area has decreased substantially for Africa, Asia, South America and, with exception for the year 2000, also for North America. With the exception of Europe, the presence of main pressures has also decreased in covered sub-catchments. Results for Africa and Asia are especially worrying in a global change context as although there was an initial increase from 1940, the relative change effects of human pressures in uncovered areas, where pressures are higher than in covered areas, are therefore increasingly uncertain. This development stands in contrast to society’s requirement for reduced water system uncertainty in order to better plan strategies for coping with and adapting to climate and other global change.

Figure 7 also shows, for the purpose of comparison, the development of global mean temperature as an anomaly relative to the 1961–1990 mean temperature (Folland et al., 2001) and total human water withdrawals (Shiklomanov, 2000) over the same time period.
data commenced with coverage of a few large drainage basins, to 1975-1980 when many more stations were covered, the period between 1990 and 2000 witnessed a considerable decrease in coverage whereby only monitoring data from a small number of sub-catchments with relatively small human pressures was reported.

As relevant hydrological records and their human pressure coverage decrease, it becomes increasingly important to use and include other types of data in addition to hydrological information in predictive models and IWIS. Paper IV examines the coverage and reliability of a number of other such data examples for the African continent. Specifically, it investigates cropping patterns and cropland extent in six sources of remotely sensed data and two sources of agricultural statistics. Results reveal discrepancies across alternative sources for land cover and land use baselines in both the extent estimates in one third of the 48 African countries exceeded 25% of total country area. Based on all these sources, new base lines of national cropland fractions are presented. It is further found that the spatial agreement between different land cover data sources is low, as visualized in Figure 8.

A quantitative pixel-by-pixel comparison and derived error matrices reveal that much of the disagreement between different data sources is in areas of low cropping density. Large areas of agreement are in regions with relatively homogeneous land use patterns, and featuring a high cropland ratio. For the eleven countries studied in detail, Egypt is the only country characterized by an overall high agreement, while semi-arid countries show a high variability in agreement and relatively low overall agreement between data sources. These results show that even where relevant land information and location of croplands to a degree that is likely to affect any water flow and water use analysis using these types of data. Differences between lowest and highest cropland extent is most pertinent for formulation of future water and agricultural policy, it may also be very uncertain, not only with regard to traditional sources of agricultural statistics (as previously

![Figure 7. Development of catchment area characteristics upstream of the 7317 river runoff monitoring stations included in the Global Runoff Data Centre. Development is shown by continent and relative to the 1940 values of average covered sub-catchment area (green curves), runoff generation (red curves), population (yellow curves), ET (black curves), agricultural field extent (light blue curves) and area extent equipped for irrigation (gray curves) within the covered sub-catchment area. The total number of stations with reported runoff data (purple curves; secondary y-axis) is also shown relative to the 1940 quantity.](image-url)
Making water information relevant on local to global scale

reported by George and Nachtergaele, 2002; Ramankutty, 2004; Young, 1998; Wood et al., 2000) but also for remotely sensed land information. Gaps and gap implications of this type of information for continental-global water system assessments are further analyzed in Paper V.

Also on the global scale, discrepancies between land cover information may be large. Figure 9 shows a pixel-by-pixel agreement/disagreement map that identifies the geographic areas where main categorical global land cover databases disagree in the identification and labeling of forested land. Considerable uncertainty is indicated on all continents, but in particular in northeastern and southeastern Asia, in eastern and northern Europe, and in Central and South America (Amazonas and the forests west of the Andes excepted). The difference between the largest and smallest forested area estimate from these databases amounts to as much as 17.5 million km², roughly equal to the size of South America. These discrepancies support the result from paper IV for the African continent, and show the need for precaution in the use of medium resolution categorical land cover data for water resources assessment.

Calculations in Paper V show that, on the global scale, the use of different categorical land cover data for calculation of global evapotranspiration

![Figure 8. Spatial agreement (pixel-by-pixel) across Africa between the agricultural field categories in four remotely sensed categorical land cover datasets (MODIS, GLCF, GLC2000 and GLCC Landscan). Colors indicate the number of maps identifying croplands at a given location (1 km² pixel): white = none, green = one of four, blue = two of four, yellow = three of four, red = all four. Zoom-ins show regional spatial agreement patterns in areas of particular interest.](image)

Number of LC data identifying cropland: [1] [2] [3] [4]

Africa (with the exception of central African evergreen broadleaf forests), in northern,
Gordon et al. (2005) calculation method for evapotranspiration and 3800 km$^3$/yr (for the Rockström et al. (1999) calculation method for evapotranspiration). These maximum deviations correspond to about 6% of the mid-range evapotranspiration value obtained by each calculation method. The differences between the different calculation methods for evapotranspiration were considerably larger, around 10 000 km$^3$/yr, based on the same land cover data. The data base differences in the range of 3200–3800 km$^3$/yr are comparable to the additional transpiration needed for global food production to meet the Millennium Development Goals by 2030 (Rockström et al., 2007). Nevertheless, these differences are still small compared to the differences resulting from use of different evapotranspiration calculation methods.

However, corresponding results of evapotranspiration from African agricultural fields show that for some geographical regions and land cover categories, the database discrepancies may yield much larger evapotranspiration result differences. This is also indicated by the forest land cover discrepancies in Figure 9 (should be quantified) for forested land cover classes. For the African continent as a whole, estimates of evapotranspiration from agricultural fields, based on the seven different sources of land cover data, range from 160 to 820 km$^3$/yr. In this case, the estimated evapotranspiration value varies by as much as 67% depending on the different land cover identification and labeling, relative to the mid-range value of all different estimates of 490 km$^3$/yr. Discrepancies of such magnitudes are particularly serious for the African continent, where major hydrological changes may be expected due to climate change, putting food security and livelihoods at risk (Kurukulasuriya and Mendelsohn, 2006; de Wit and Stakiewicz, 2006). In such situations, it is particularly important to have ready access to relevant and timely information in an IWIS.

**General Discussion**

**Development of IWIS**

The complexity of water systems combined with the necessity of managing water resources leads to water management situations where facts are often uncertain, stakes high and values sometimes in dispute. In such situations, the available information basis and its accessibility are essential, as are also the use of extended peer review and explicit accounts and transparency of uncertainties, methodologies, debates and values (Funtowicz and Ravetz 1993; Marchi and Ravetz, 1999). Paper I indicates how an IWIS could be used to address these information challenges. It is argued that such an IWIS should be comprehensive yet transparent and cover a broad range of temporal and spatial scales, methods and tools that enable inclusion of extended information. An extension of water information is proposed, beyond today’s often
static information limited to the water system itself, toward further including comprehensive dynamic characterization and water resource management optimization data, modeling and model results. An open IWIS allows for new types of inputs from stakeholder groups and increases the possibilities for public participation and extended peering. Open structures further enable traditional administrative and sector boundaries to be crossed, and harmonized information for any topic based on shared standards to be made accessible through the IWIS for any particular scale. Paper I shows that an IWIS may be a centerpiece for integration of main water management tasks into a common process, based upon openly shared information.

Paper I argues that a development from WIS to more comprehensive and open IWIS may be necessary. Paper II on the other hand shows that, even with today’s limited information systems, the integration of water information into shared information systems is complicated. The analysis of the ongoing development of a shared WIS for Europe, partly based on WFD requirements for data reporting, shows that the practical implementation of harmonized approaches by water administrations is difficult. Cross-border spatial data heterogeneity, different aims of WIS development and use among stakeholders, different water-system analysis methodologies and different water-environmental priorities are large potential pitfalls for maximizing the benefits of a WIS. As the scope shifts from a WIS to an IWIS, such problems are likely to increase if issues of standardization and harmonization are not dealt with early on.

Two thirds of the area of River Basin Districts established under the WFD is international (Nilsson et al., 2004). This implies a need for IWIS development focus on the international aspects of information IWIS and information accessibility across Europe. In international basins, the international compatibility of information is particularly important as countries are requested, by provisions of the WFD, to develop joint river basin management plans. Biases or incompatibility of information may in these cases result in sub-optimal or unsustainable water resource management. On the European scale, compatible information is important for development of a European overview of the status of European waters, and not least for WFD compliance verification. The overview and cross-border compatibility have been among the main identified benefits with the WFD. Results from Paper II, however, show significant heterogeneity between data and methods used for water-environmental analysis and WFD reporting purposes. This heterogeneity may hinder a European comparison of water status information. It is also shown that this is not only a spatial data problem, but also a problem of differences in methods and main assumptions used for the WFD-required analyses in different EU member states. An information system building upon such heterogeneous information may result in a patchwork of incompatible and inconsistent information characteristics. This emphasizes the need for standardization of analysis and mapping of European waters, from local to continental scale, for successful implementation of WFD and development of WISE, towards an even more comprehensive IWIS development.

Information technology to facilitate better harmonization and communication of water-environmental data already exists, but needs to be used. The major challenges are rather the inter-operability difficulties, due to differences in thematic and semantic content of data, which can partly be explained by different aims and methods for primary data collection (Denzler, 2001; Bishr, 1998; Harvey et al., 1999; Annoni and Smiths, 2003) and differing data analysis methods. Differing water-environmental problems across Europe (EEA, 2005b; Furberg et al., 2006), as well as public estimation of these problems (European Commission, 2005), affect the possibilities and willingness of politicians and water managers to spend considerable resources on harmonization of water-environmental information, as a means to fulfill the aims of the WFD. The harmonization issue therefore has to be managed in a broader context, as part of the development of an effective environmental spatial data infrastructure for Europe. Such development must be supported by both water managers and national spatial data infrastructure experts alike.

A new feature in the WFD, compared to earlier water related directives, is the requirement of reporting actual spatial data to the European Commission and not only in hard copy reports. One reason that EU member states have been
reluctant to report such data may be that, once data has been reported to the European Commission, it is, at least in theory, publicly available. Each individual EU member state therefore to some degree loses control over the use of reported data. The cost-recovery principle applied to many European authorities that handle water-environmental spatial data will be undermined if these data are made accessible via the WISE. Further, a primary purpose for the European Commission to collect data from EU member states as part of WFD-reporting is compliance checking. If countries are not found to comply, the check leads to an infringement procedure that may result in a penalty. The reporting of spatial data and attribute information itself, and not only aggregated measures of such data, gives the European Commission hard facts, and extended possibilities for independent analysis of such data. This may not necessarily be in the interests of individual EU Member States, and may therefore in itself result in the slow progress of WISE development.

Representativeness, gaps and gap implications of core monitoring data

For a range of geographical scales, form local to global, the present results show systematic gaps of water-environmental information, in particular for coastal catchments areas with possible large nutrient and pollutant load contributions to the sea. In the BSDB about 24% and in Sweden about 55% of the population lives in near-coastal areas that are unmonitored with regard to land-to-sea nutrient loading. These unmonitored areas were also found to differ significantly from the monitored areas with regard to main drivers for nutrient and pollutant discharges. These areas may therefore contribute unexpectedly to nutrient and pollutant loads to the sea, due to the combined effect of high human pressures and short nutrient and pollutant transport pathways to the sea.

In contrast to what may be expected, present findings also show serious and growing access constraints to global runoff-data, even in the case of a monitoring network that is considered to include the most important data for quantification of global land-to-ocean water fluxes. The general trend over the last 30 years is that accessible runoff data are increasingly reported from only catchment areas with relatively small human pressures, while climate change and increase in human-induced pressures on water systems are rapidly increasing. Land cover inventories of critical data for water and vapor flow quantification are further shown to be inconsistent between different data sources, which implies large uncertainties in the quantification and spatial attribution of water fluxes. In combination, these results imply a great need to quantify all the uncertainties and corresponding uncertainty costs that are associated with water system analysis and water resource management across a wide range of different scales in space and time.

While unavailability of and inaccessibility to environmental data have the same implications for those in need of such data, the causes are not the same. Unavailability of data results from physical monitoring gaps, while inaccessibility is caused by the lack of open reporting, sharing and/or communicating of the available data. The availability of data is comparatively expensive to increase, since it requires further monitoring to be established. The accessibility of data may on the other hand be comparatively inexpensive to increase, at least technically with a suitable combination of Internet and database technology. However, heterogeneity problems related to the general quality of the data, including thematic and semantic contents, make data integration across administrative and institutional borders difficult, even if all the technology is in place. The lack of meta-data and the use of different standards, procedures and processing are some factors that often make data incompatible. These problems are accentuated on the continental-global scale, since different countries feature different water environmental challenges, preferred solutions and priorities.

Commitment is needed to drive an increase of data accessibility. Paper III focuses on the BSDB, an area where water-environmental data availability is relatively high. But even though it is a relatively rich region of the world, where major water-environmental problems exist and are relatively well-acknowledged, surprisingly few steps have been taken to develop openly shared water-environmental information. The steps taken have been on research project basis with short-term research funding. In addition to
such research based and discontinuous pieces of information, it seems logical that large public spending on e.g. abatement of nutrient loading from land to the Baltic Sea should also include an organized development of comprehensive and project-independent WIS, which can be used to follow water-environmental development trends and the effects of public spending for changing negative trends.

Legal obligations are also important for driving increased data accessibility (e.g. Harris and Browning 2003). Looking only at the EU, member states are legally forced to report to the European Commission on 12 water-related EU Directives. In addition to such legally required reporting, information should be prepared for dissemination to the public, to the European Environment Agency, to various international conventions and institutions and also to other countries following bi- or multilateral agreements. Information sent to all these different information users is different in scope and format. Public authorities may spend considerable time on reporting, and there is naturally a conflict between spending time on reporting and on the actual tasks that the reports are about. It is thus understandable if authorities prioritize legally required reporting over reporting that is just wished and hoped for by information users but not backed by any forcing legislation.

With a more comprehensive data infrastructure in place, however, the information production could be streamlined so that information producers need only establish one set of useful and accessible information for information users to draw from. This would require a higher level of standardization, or alternatively more intelligent data mining methods. While this is certainly both an institutional and a technical challenge, such a development may free

and dissemination to information users. The EU WFD intercalibration exercise (Heiskanen et al., 2004), aiming to develop common ecological quality criteria for surface waters, is a good example of how legal requirements may initiate steps to move from today’s heterogeneous situation towards necessary water-environmental data harmonization (paper II; Buffagni and Furse, 2006; Birk and Herning 2006).

Lack of relevant infrastructure may also have other effects than those discussed in Papers II and V. Systematic biases in the available set of data may be amplified in accessible data at larger scales due to subjective rules for data reporting to global databases. Further, selected data may need to be aggregated e.g. to long-term averages or by reduction of spatial resolution, and reported only after long time delays. Such aggregation in itself limits the possibility of detecting variability and change in water system data. In regard of the technological possibilities for automation and today’s cheap data storage and fast communication possibilities, such aggregation and draining of information in available data seem unnecessary.

On the global scale, resolutions reached by the World Metrological Organization (WMO, 1999; WMO, 1995) are apparently not sufficient to ensure continuous comprehensive reporting from national runoff data archives. Downsizing of national water flow monitoring is also noted for many countries (Vörösmarty, 2002; Shiklomanov et al., 2002; Lanfear and Hirsch 1999), but this does not explain why apparently available data are not made accessible to global archives. Several possible reasons may exist in this regard. As water issues have become more political in many areas around the world (Postel, 1993; Postel and Wolf, 2001), the politicization of hydrological data and information may also be increasing, and sharing of water-environmental information may become more politically sensitive. Further, an increasing commercialization of environmental data, including hydrological data, can be noted in parts of the world where governments and governmental agencies are trying to recover costs for environmental monitoring programs (National Research Council, 2001; WMO, 1999). However, little research that analyses the costs and benefits for the public of such cost-recovery principles is to be found. A recent study from the US (Joffe,

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2005) and another from Austria (Austrian Federal Ministry of Economics and Labour, 2003) point in the same direction and indicate that governments that sell environmental data often lose rather than gain revenues.

To the best of my knowledge, the reasons behind the increasing inaccessibility to water-environmental monitoring data on the global scale has not been systematically analyzed. While the reasons given above may all partly explain the current situation, the current considerable need for relevant water data for studies of global change effects indicates the need for research to analyze the true reasons, and the need for policy to remove potential hindrances to accessibility.

**CONCLUSIONS**

This thesis has addressed the role of and core challenges in development and use of information in support of IWM. The geographical scale of studies included ranges from local to continental and global, with the purpose of finding the possible scale-dependence of challenges in establishing harmonized and transparent IWIS. The role of openly shared information systems has also been analyzed, as well as specific critical characteristics of IWIS, in particular with regard to representativeness, timeliness, spatial data harmonization, interoperability, comparability and accessibility of water system data. Novel analyses of the characteristics of areas that are not covered by reports of water-environmental monitoring, due either to the lack of monitoring or to unreported monitoring data, are further presented along with quality assessments of continental to global land information and their links to large-scale water flux estimates. Main findings may be summarized in terms of the following main conclusions.

- A comprehensive IWIS may facilitate integration between actors and sectors in the IWM process. In order to realize the full potential of such an IWIS, results show that the included information must be extended and have other characteristics than those specific to current limited water information systems. Information must be openly accessible, transparent, interoperable, dynamic (covering past times and future scenarios) and scalable, as well as include necessary data for different critical aspects of IWM. It would thus need to include the water system itself and linked systems (such as land use) and processes (such as flux interactions with the atmosphere and coastal-marine systems). Presented examples based on limited information systems like the WISE - Water Information System for Europe, however, show that there are today large differences in water-environmental spatial data, data analysis and interpretations even between EU member states that share common water-environmental legislation. Such differences hinder the development of seamless and harmonized information systems at any scale, and specifically for the EU it is the existence of such incompatibilities that hampers the possibility of developing a harmonized overview of European waters, which is one of the main aims of the EU Water Framework Directive. Water managers at all levels, and especially those responsible for national water information priorities, need therefore to push for new, and support existing, data infrastructure and harmonization initiatives. The current information patchwork is otherwise likely to persist and hamper the prospects of developing relevant IWIS for integrated water resource management.

- Limited access to as well as low quality and poor representativeness of critical water system information may further obscure our understanding of the state, variability and change of water resources worldwide. It is here shown that unmonitored catchment areas may differ largely from the monitored areas with respect to main human pressures on the water system, as displayed here for a range of scales, from national (Sweden) and regional (Baltic Sea Drainage Basin) to continental and global. In the case example of Sweden, where the majority of the population is shown to live in catchment areas outside the national environmental monitoring network for nutrient loading to the sea, serious uncertainties may exist with regard to actual impacts on Baltic Sea ecosystems. Globally, accessible runoff data is shown to have similar large gaps and problems of representativeness. In addition, the globally accessible runoff data show a rapid decline trend of data from catchment areas that are rich in human pressures from population, agriculture
and general economic activity. Large discrepancies are furthermore also found between moderate resolution land cover data that may be used for large-scale water flux estimates. Present quantification examples show substantial differences in the identification and labeling of global forest cover, and very large differences for the specific case of African agricultural fields. While many of these differences can be explained by difficulties of, and differences in, methods for land cover classification and labeling, the use of these data for water system studies may be associated with large uncertainties. Converging land cover baselines are critical parts of an IWIS, especially for areas such as African agricultural fields, where the need to analyze the effects of global change, including climate and land use changes and their effects on the water system, is urgent.

- The increasing monitoring and reporting gaps for near-coastal catchment areas found here for globally accessible databases may further yield misleading estimates of water and waterborne pollutant fluxes from land to sea. The magnitude of gaps identified in this thesis indicate a possible inability to detect major water system changes in large areas around the world. Even for well-monitored areas of the world, the relatively low human pressures prevailing in monitored areas compared to the unmonitored areas may lead to underestimated pollutant loads and load impacts.

- A development from today’s insufficient WIS to more comprehensive IWIS necessary for integrated water resource management should be beneficial. However, many hindrances of both a technical and institutional nature remain to be overcome on the way there. From an information quality point of view, accessibility restrictions, lack of timeliness and representativeness as well as low quality of core data are here identified as important constrains to comprehensive IWIS development. Many of these constraints to making better use of available information could be evaded by relatively inexpensive means, e.g., by increased use of international data standards and spatial data infrastructure that could readily facilitate extended and effective use of available data at large geographical scales. Other constraints are more difficult and costly to overcome, such as necessary increases of physically declining water-environmental monitoring programs all over the world.

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