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A Decision Support System for the Assessment and Management of Surface Waters.

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: INF/01
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Glossary

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CIS	=	Center of gravity
COG	=	Common Implementation Strategy
CSV	=	Comma-Separated Values
DBMS	=	Database management system
DGMS	=	Dialog generation and management system
DM	=	Decision Maker
DPCER	=	Driving forces, Pressures, Chemical state, Ecological state, Responses
DPSIR	=	Driving forces, Pressures, States, Impacts, Responses
DSS	=	Decision support system
EEA	=	European Environment Agency
EQR	=	Ecological Quality Ratio
EQS	=	Ecological Quality Standard
ES	=	Ecological Status
EU	=	European Union
FIS	=	Fuzzy Inference System
GIS	=	Geographical Information System
GUI	=	Graphical user interface
GW	=	Groundwater
HH	=	Human Health

IDE	=	Integrated Development Environment
IDSS	=	Intelligent Decision Support System
IETU	=	Polish Institute for Ecology of Industrial Areas
IRI	=	Integrated Risk Index
IWRM	=	Integrated Water Resource Management
JRE	=	Java Runtime Environment
LoE	=	Line of Evidence
MBMS	=	Model-based management system
MCDA	=	Multi-Criteria Decision Analysis
MoOM	=	Mean of maxima
MPC	=	Management Planning Cycle
NSIS	=	Nullsoft Scriptable Install System
NUT	=	Nomenclature of Territorial Units for Statistics
OGC	=	Open Geospatial Consortium
OWA	=	Ordered Weighted Averaging
PA	=	Protected Areas
PGI	=	Polish Geological Institute
PI	=	Prioritization Index
PP	=	Priority pollutant
QE	=	Quality Element
QSI	=	Quality Status Index
RBMP	=	River Basin Management Plan
SEI	=	Socio-Economic Index
SRID	=	Spatial Reference System Identifier
SSD	=	Species Sensitivity Distribution
SW	=	Surface Water
TSO	=	Targets' Spatial Objects
TSK	=	Takagi-Sugeno and Kang inference method
WA	=	Weighted Average
WFD	=	Water framework directive
WoE	=	Weight of Evidence
WSO	=	Watersheds Strahler Order

Chapter 1

Introduction

1.1 Context

Water protection is one of the priorities in the preservation of human health and environmental sustainable conditions. All over the world, and especially inside the European Union (EU), there is an increasing awareness and demand from citizens for cleaner waters and in general for a better management of ecological resources.

Environmental scientists are constantly engaged in the research for effective assessment and management methodologies and procedures. The most important aspects of environmental and human health assessment are related to the evaluation of risk. Risk may be defined as "the combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence" [NRC, 1983], [Royal Society, 1992]. It should be differentiated from hazard, which is commonly defined as "a property or situation that in particular circumstances could lead to harm" [Royal Society, 1992]. In fact the distinction between hazard and risk is that hazard represents just a possible source of harm and risk evaluates the probability that an hazard may lead to harm and the related consequences.

In order to evaluate the remedial strategies which can largely increase the environmental and human health status, first the likelihood of adverse effects on these two targets must be assessed. This is typically obtained by applying two consecutive strategies. First, the risks associated with the baseline conditions are evaluated to determine whether risks from the unremediated sites (e.g. polluting factories or waste areas) are acceptable. Second, if baseline risks are unacceptable, the risks associated with alternative remedial actions (e.g., capping of the hazard source, removal, or land use restrictions) are compared. These remedial assessments consider whether sufficient risk reduction would be achieved and whether significant risks are associated with the remedial process itself.

Accordingly, *Risk Assessment* is the procedure in which the risks posed by hazards associated with processes or situations are estimated either quantitatively or qualitatively. Specifically, Environmental Risk Assessment is the estimation of risks resulting from hazards in the environment that threaten ecosystems, plants, animals and people. It includes *human health* risk assessment and *ecological* risk assessment. Within environmental risk assessment, Ecological Risk Assessment is a process for organizing and analyzing data, information, assumptions, and uncertainties to evaluate the likelihood of adverse ecological effects [US-EPA, 1998]. This definition emphasizes the role and benefit of risk analysis as a methodology for systematically gathering, structuring and analyzing relatively large amounts of complex information.

Risk Management is the decision-making process for identifying, evaluating, selecting and implementing actions to prevent, reduce or control risks to human health and to the environment [CRARM, 1997]. The Risk Management process involves the comparison of the risks related to taking no action with those associated with each remedial alternative, while taking into account social, cultural, ethical, economic, political, and legal considerations. It is often performed informally and subjectively by the decision-maker, but it may be informed by a formal management assessment employing cost-benefit analysis, net benefit analysis, decision analysis, or other techniques. It should result in risks being reduced to an "acceptable" level within the constraints of the available resources.

Environmental risk assessment has become a fundamental tool for the environmental decision making process, especially for chemical risk control. Several complementary factors led to the definition of this fundamental role, for example the increased public concern about pollution and environmental risks was the most important. This concern has raised the demand for prevention and protection and, as a consequence, has led to the development of environmental regulations and policies in order to define stringent environmental benchmarks (i.e., environmental quality standards) and innovative assessment approaches to support environmental management processes.

As a result, decision-making tools for risk assessment and management are used more and more [Fairman *et al.*, 1998] for: *a*) designing regulations (e.g., the EU legislation regarding new and existing hazardous substances); *b*) providing a basis for site-specific decisions (contaminated land sites are an example where risk-based regulation is being used in Europe); *c*) ranking environmental risks (e.g., prioritization of chemicals); and *d*) comparing risks.

Environmental risk assessment has become useful for planning and managing land use and for defining environmental monitoring plans. The fact that environmental risk assessment has been used by regulators has led the industries to increasingly adopt it. In fact, companies use environmental risk assessment to determine the levels of risk associated with certain processes or plants and for industrial financial planning [Salgueiro *et al.*, 2001]. Risk assessment and management can also be useful in the decision-making process related to evaluation and prioritization of industrial risk reduction measures by supplying reliable and comprehensive tools able to evaluate different what-if scenarios.

1.1.1 The Water Framework Directive

The main piece of legislation for the management of river basins and water quality in Europe is the European Directive 2000/60/CE [EC, 2000], also known as Water Framework Directive (WFD), which establishes a framework for community action in the field of water policy. It entered into force in 2000 and its timetable for implementation extends over 15 years.

The WFD represents a milestone in European water legislation since the concept of Integrated Water Resource Management (IWRM) has been introduced providing a common and coherent framework within which the previous European directives regarding water policy can be reformulated or coordinated [EC, 2003b]. Moreover, for the first time water management is: (i) based mainly upon biological and ecological elements with ecosystems at the center of the management decisions; (ii) applied to all European water bodies, including inland surface waters (rivers and lakes), transitional and coastal waters and groundwater; and (iii) based upon the whole river basin including adjacent coastal area.

The WFD sets new goals for the European water management and introduces innovative means and processes for achieving them [Kallis & Butler, 2001]. The main environmental objectives related to surface waters are (Art. 4):

- to prevent further deterioration of the surface water body's conditions;
- to protect, enhance and restore all surface water bodies with the ultimate aim of achieving at least the "good ecological status" and the "good chemical status" by 2015;
- to protect and enhance all artificial and heavily modified water bodies with the aim of achieving the "good ecological potential" and the "good chemical status" by 2015;
- to reduce, cease or phase out emissions, discharges and losses of "priority pollutants";
- to promote sustainable use of water.

The management measures to achieve the WFD environmental objectives should be coordinated at the geographical/administrative level of the "river basin district" which is identified under Art. 3(1) as the basic management unit of river basins while individual "water bodies" represent the assessment units to which the environmental objectives established by WFD must apply. For each river basin district a "competent authority" (Art. 3) should be designated, which is responsible for preparing and implementing a River Basin Management Plan (RBMP) (Art.13), reporting a summary of the river basin environmental and economic characterizations (Art. 5), and providing a description of the "programme of measures" (Art. 9) to be implemented to achieve the environmental goals and bridge the gap between actual conditions and expected good ecological and chemical status. The RBMP relies heavily on monitoring (Art. 8) to provide information for classifying water quality status and to address additional measures in response to non compliance with the environmental objectives [Dworak *et al.*, 2005]. In particular, the Directive describes (Annex V, paragraph 1.3) three different designs of monitoring programs (i.e. surveillance, operational and investigative monitoring) and specifies in which cases they are requested.

In order to achieve the main environmental objectives (i.e. good status and no-deterioration) by 2015, a planning process (Management Planning Cycle, MPC), reported in Figure 1.1, was established that includes a series of tasks to be accomplished by prescribed deadlines. First is the identification of river basin districts, based on hydrological catchment, and of related competent public authorities, then the process continues with:(i) water bodies typologies and reference conditions identification; (ii) pressures and impacts analysis; (iii) economic valuation of water uses; (iv) setting up of monitoring programs; (v) status classification; and (vi) selection and application of management measures. In 2015 a first evaluation of management results have to be performed, after which the cycle can be started again (see [EC, 2003b]). After the first MPC ended in 2009, information and results will be refined and updated during the further 6-years management cycles. Stakeholders participation (i.e. all the private, public and non governative associations that are involved in the management of water bodies and whose interests can be conflicting) as well as public consultation should be assured throughout the whole process [EC, 2003b].

From a water quality management point of view, the Directive promotes a combined approach based on environmental quality standards and emission limit values; it requires authorizations for all groundwater extractions (unless minimal) in order to guarantee the conservation of water quantity; it incorporates the "polluter pays principle" through a set of measures for the charging of water use in order to identify pollution responsibilities. The WFD (Art. 2.17) defines the "surface water status" as the general expression of the status of a body of surface water, determined by the poorer of its ecological status and its chemical status (1.2). Both terms are equally required to reach the good status.

The "ecological status" is one of the main innovative concept introduced by WFD in order to assure the holistic[1] protection of water resources. As explained by

[1] Holism is the idea that all the properties of a given system cannot be determined or explained by its component parts alone. Instead, the system as a whole determines in an important way how the parts behave.

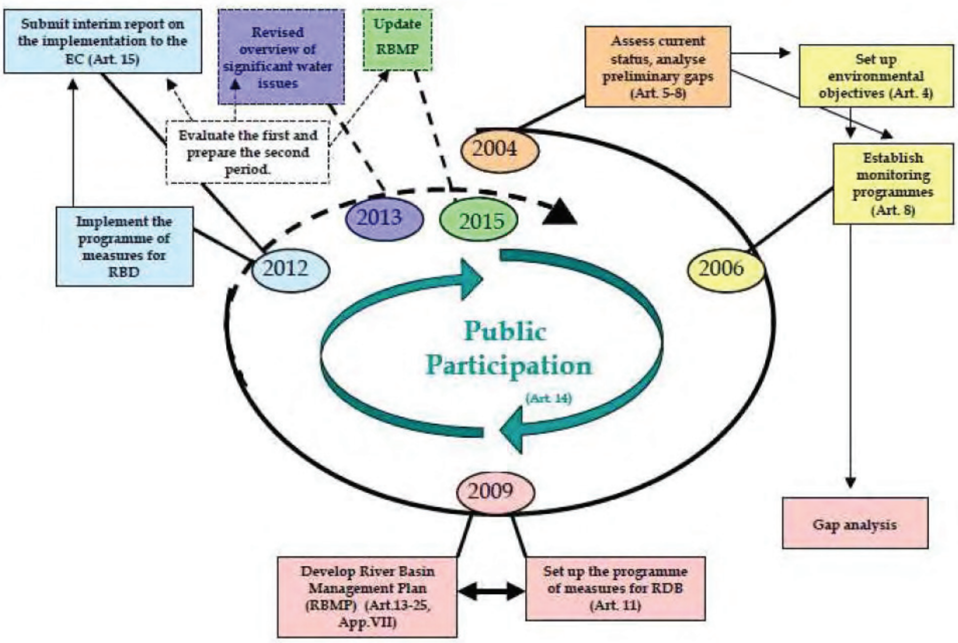

Figure 1.1: WFD Management Planning Cycle (source:[EC, 2003b])

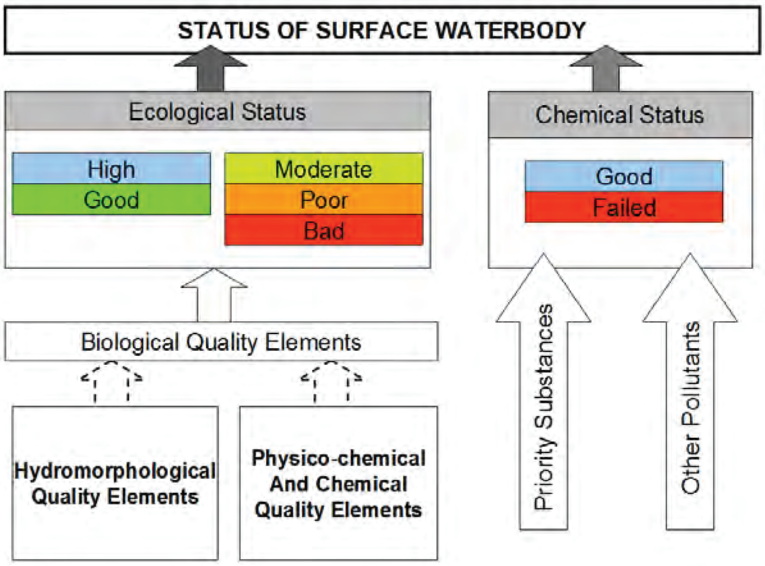

Figure 1.2: Procedure for classification of water bodies' overall status according to WFD provisions (source: [Achleitner *et al.*, 2005]). Dotted arrows are for supportive QEs.

[Vighi *et al.*, 2006] the WFD overcomes the use of traditional chemically-based water quality criteria, based on fixed values for chemical and physical parameters considered as safe for the aquatic ecosystem, by emphasizing the site-specific evaluation of ecological effects. This means that classification systems for the ecological status should evaluate how the structure of the biological communities and the overall ecosystem functions are altered by multiple anthropogenic stressors [Heiskanen *et al.*, 2004].

The ecological status shall be considered as an expression of the quality and the functioning of aquatic ecosystem associated with surface water (Art. 2.21). For heavily modified water bodies, resulting from a human physical modification and serving economic activities, the concept of ecological status is translated into that of "ecological potential" (Art. 2.23).

WFD Annex V (Table 1.1) explicitly defines which Quality Elements (QE) must be evaluated in order to assess the ecological status, with separate lists for rivers, lakes, transitional waters, coastal waters and heavily modified water bodies. As shown in Figure 1.2 the QE for each surface water category are subdivided into three groups:

– biological QE;

– hydromorphological QE;

– physico-chemical and chemical QE.

The ecological status of water bodies has to be classified as *high*, *good*, *moderate*, *poor* or *bad* using biological QE as key components and physico-chemical, chemical and hydromorphological QE as supportive components, i.e. they are used to check the values obtained by the biological QE. Each QE can be described by means of one or more indicative parameters: some parameters are explicitly required but Member States can decide to monitor additional parameters if considered locally significant. Figure 1.3 shows QE and related indicative parameters recommended by WFD for rivers.

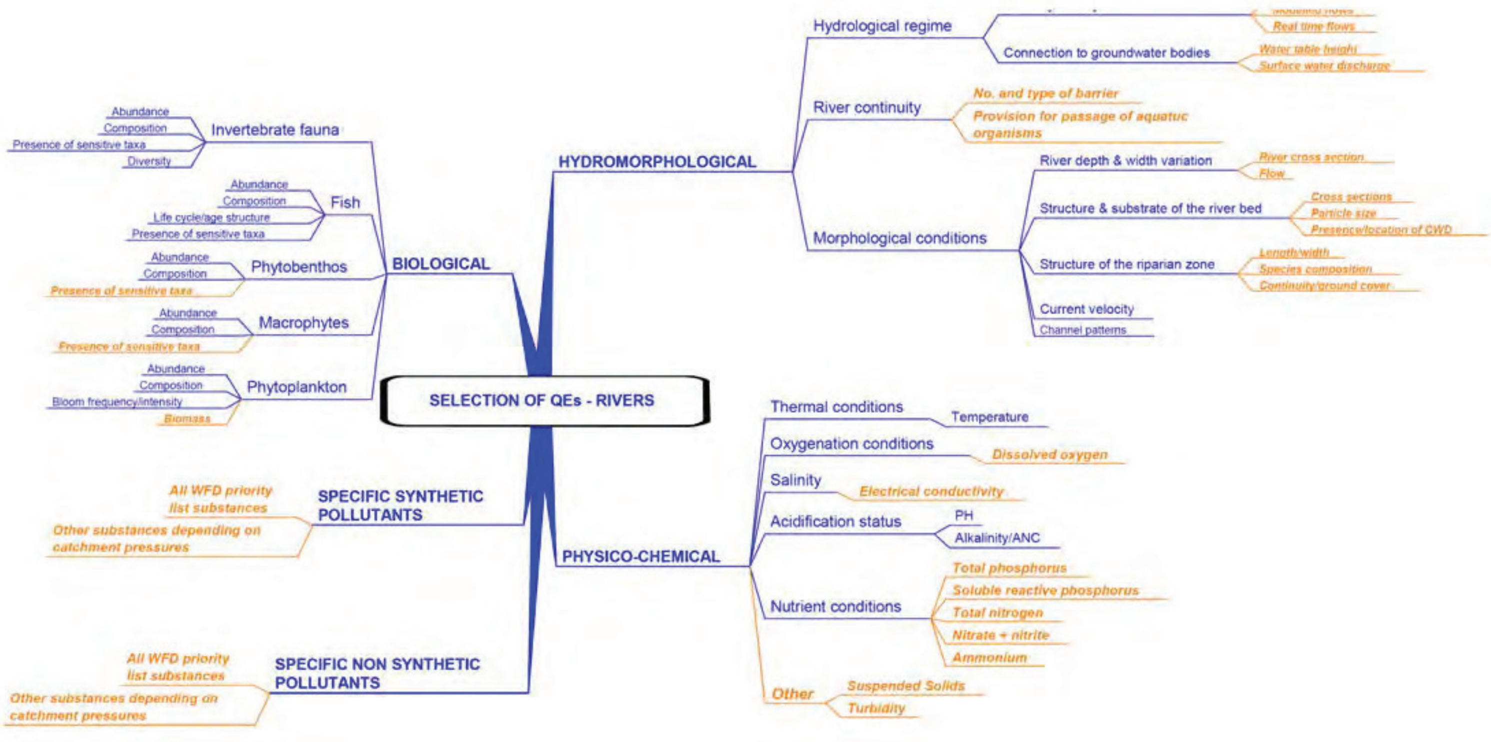

Figure 1.3: Scheme for the selection of Quality Elements (QE) for rivers proposed by WFD (source: [EC, 2005b]). The blue lines indicate mandatory QE, specified in Annex V.1.2. The red lines indicate recommended QE.

For each biological QE a descriptive definition of high, good, moderate, poor and bad status is given. In order to assign each QE to a class, type-specific reference conditions are needed. Reference conditions represent the value of a certain QE for that surface water body at high status: they do not correspond necessarily to total undisturbed, pristine conditions but include water bodies characterized by very minor disturbance which means that human pressure is allowed as long as there are no or only minor ecological effects [EC, 2003a]. These references cannot be defined at European level due to the wide variety of water bodies types determined by climatic, geographic and geological differences. The WFD requires that Member States first assign surface water bodies to a category (river, lake, transitional water, coastal water, artificial or heavily modified water bodies) and then differentiate water bodies within each category into different types based on two approaches named System A and System B (Annex II, paragraph 1.1). For each typology, finally, reference conditions have to be established by properly identifying sites, based on predictive modeling, using either historical data or paleoreconstruction, or by means of expert judgment (Annex II, paragraph 1.3). However, this last approach deals with a number of weaknesses, because it can be characterized by high subjectivity, low degree of transparency and inability to arrive at quantitative and standardized procedures [Economou, 2002]. Thus, it has to be applied with caution and explaining all possible bias and limitations.

The results of the monitoring shall be expressed as Ecological Quality Ratio (EQR), defined as the ratio between observed values and reference conditions for the relevant biological QE. The comparison to reference conditions represents a normalization of the measured value for each parameter on a common scale ranging from 0 (worst class) to 1 (best class) that ensures comparability among different water bodies. This interval shall be divided into five equal ranges coinciding with the WFD quality classes.

The ECOSTAT CIS working group published a general guidance [EC, 2005a] where the relative roles of various groups of QE are indicated and recommendations on how to combine them are included. As it is shown in Figure 1.4 the "one-out, all-out" principle drives the ecological status classification that is determined by the worst relevant QE. It means that the status of the biological quality element estimated to be the most affected by anthropogenic pressures will initially determine the class of the water body, but its ecological status could decrease if a lower class is assigned to physico-chemical or hydromorphological quality elements [EC, 2005a].

No prescriptions exist on how to combine available indicative parameters within each QE. As far as biological QE are concerned the authors suggest to aggregate (e.g. by using the average) parameters reflecting generic deterioration or that are sensitive to the same pressure while the worst parameter or group of parameters able to detect impacts caused by different pressures should guide the assignation of the QE of concern to the correct class. It was stated that in the "one-out, all-out" scheme the risk of misclassification due to different sources of errors (e.g. sampling

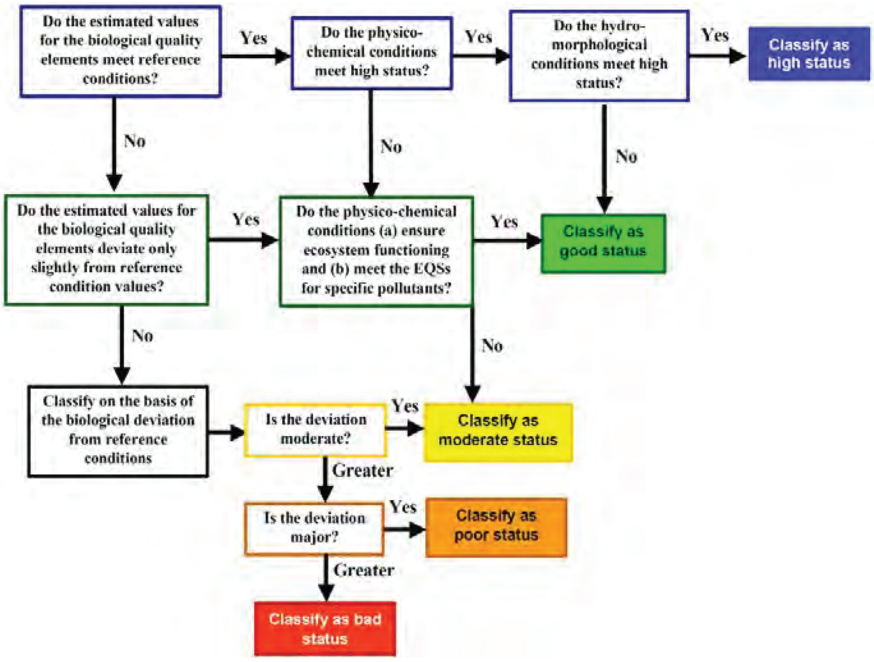

Figure 1.4: Scheme illustrating the relative roles of biological, hydromorphological and physico-chemical quality elements in ecological status classification (source: [EC, 2005a]).

and monitoring systems, laboratory activity, establishment of reference conditions, EQR derivation, metrics aggregation) is amplified by the number of QE that are considered [EC, 2005a], [Irvine, 2004]. For this reason combining metrics or focusing exclusively on relevant QE could enhance confidence in ecological status classification [EC, 2005a].

The ecological status classification is matched with the "chemical status" that has to be evaluated by comparison of measured concentrations of "priority substances" and "priority hazardous substances" in water, sediment and biota compartments with Environmental Quality Standards (EQS) to be set at EU-wide level (Art. 16). In particular, Art 16.7 refers to priority substances as *chemicals presenting a significant risk to or via aquatic environment, including such risks to waters used for the abstraction for drinking waters.* When there is full compliance with EQS established for priority substances the chemical status of the water body of concern is classified as good while one individual exceedance is enough to consider it as failing achieving good.

The procedure for setting of EQS is reported in Annex V (par. 1.2.6) where the "base set" of ecotoxicological data and uncertainty factors are specified according to the European Technical Guidance Document of risk assessment [ECB, 2003]. In addition Annex VIII of the WFD requires Member States to derive EQS for "specific pollutants" that are discharged to water in "significant quantities". These pollutants represent one of the chemical QE to be considered in the ecological status classification (Figure 1.4). It should be noted that once EQS have been adopted at Community level for priority substances, these chemicals shall no longer be considered as chemical QE in the ecological status classification but only in the evaluation of chemical status [EC, 2005a].

The application of the water framework directive, as well as any kind of risk assessment and risk management activity, requires suitable instruments possibly related to a common framework. Such widely adopted framework is the DPSIR framework developed by the European Environment Agency (EEA, 2003). In the next section an introduction to the DPSIR framework is reported.

1.1.2 The DPSIR framework

DPSIR is an acronym for Driving forces, Pressures, States, Impacts, Responses; its framework, reported in Figure 1.5, is used in order to describe the components of environmental problems and exploit the relations occurring between them taking into account all the factors which can concur in the creation of an impact in the environment.

In the DPSIR socio-economic developments are considered base factors or driving forces (D) that perform pressures (P) respect to the environment (e.g. with waste, emissions, wastewater, etc.), so that the environment conditions, i.e. the state (S),

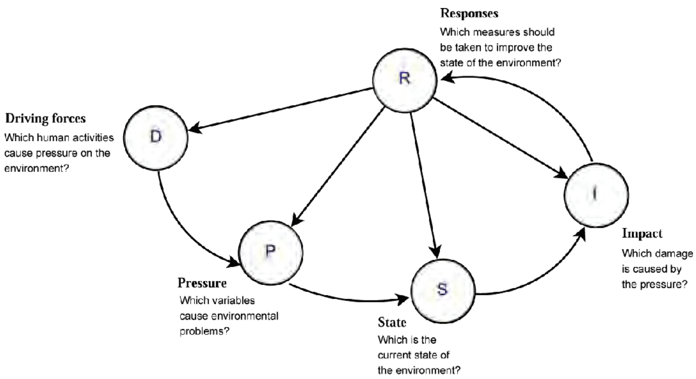

Figure 1.5: DPSIR framework (source: [EEA, 2003])

change in resources availability, biodiversity, air quality and many other aspects. The change generates impacts (I) on ecosystems and socio-economic conditions so that responses (R) of intervention are required by the society. Responses may concern any of the different actors of the DPSIR framework for example by just effecting the environment or modifying the driving forces and their impacts by changing the way socio-economic activities are performed.

In order to fully understand the DPSIR a deepened explanation is needed which can be found in section 4 where is also presented a WFD compliant modified version of the framework called DPCER (introduced by Rekolainen et al. [Rekolainen *et al.*, 2003]). To briefly introduce DPCER it is important to note that its main difference from the original DPSIR is that the state (S) and impact (I) factors are replaced respectively by the chemical (C) and ecological (E) status analysis. This because the state of the superficial water (coherently with the WFD) is completely defined by its chemical and ecological status. In Figure 1.6 the scheme of the DPCER framework is reported.

1.2 Motivations

As it has been presented, risk assessment and the consequent choice of remediation strategies is an emerging problem in environmental management, this implies that precise and reliable tools are needed by decision makers in order to be able to take informed decisions. These tools can be suited for different tasks such as water pollution status analysis, driving forces identification or the choice of remediation strategies but nevertheless some common procedural aspects can still be identified. They are always related to the application of some predefined assessment frameworks which take into

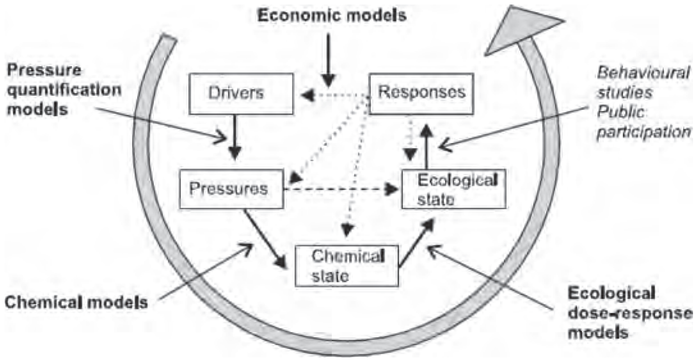

Figure 1.6: DPCER framework [Rekolainen *et al.*, 2003]

account decision makers' preferences. In order for the assessment frameworks to be able to deal with these preferences, specific mathematical tools must be embedded in the frameworks. Another important aspect which is nowadays increasingly present in environmental tools is the spatial aspect of the assessment. It is not anymore possible to develop environmental assessment tools without taking into account spatial relations between the elements being studied. For example elicitation of polluting sources for a determined site along a river network is impossible without taking into account distance from the river and direction of water flaw in the network.

In particular, as far as the WFD is concerned, it does not provide exact definitions of the good ecological status that has to be achieved while the development of needed monitoring and assessment systems for surface waters quality classification is left to the Member States. As a consequence, successful transposition and implementation of the WFD represent a challenge to the governments and competent authorities but also to the research organizations providing the scientific support for the different steps of the implementation process [Rekolainen *et al.*, 2003]. In fact, there is the need for a more specific definition of targets (e.g. formal definition of "good" ecological status) and also for tools covering the cause-effect relationships between chemical, physico-chemical, hydromorphological and biological conditions in order to predict ecological effects in watercourses and adjacent coastal-marine areas.

1.3 Main contribution of the thesis

As reported before there is an emerging demand on environment related decision aid. The most suitable software tools in decision aiding are Decision Support Systems (DSSs). Such systems are computer-based tools designed to support management decisions [Eom, 2001].

My work in the last years was devoted to the study and application, through the creation of environmental DSSs, of novel approaches to environmental assessment and management based on the need to be aware of decision makers preferences and spatial relations between assessed entities as well as the more classical sampled data. I've been studying mathematical methodologies related to Multi-criteria Decision Analysis (MCDA) as well as specific spatial based techniques which has proved to be useful in the ecological field.

The objective of this thesis is to explain my studies so far in the development of reliable and novel MCDA approaches to environmental risk assessment and their implementation in Decision Support System (DSS) software tools which are aware of geographical relations between the different entities of concern. As this is a multidisciplinary issue all of the different aforementioned aspects toke part in the thesis.

An important research assumption shared among our group is that environmental issues, where involved criteria are always belonging to continuous domains, it is more suitable to obtain informed solutions by the application of value functions followed by aggregation and ranking as can be achieved by the Multi-Attribute Value Theory filed of MCDA.

During my PhD period I've been involved in the realization of an important European projects related to environmental assessment and based on the application of MCDA methodologies to spatially distributed information. This project which was accompanying me throughout all my PhD experience is the Modelkey project, a European FP6 project which aims at supporting the implementation of the Water Framework Directive (WFD). I've been responsible of the project and development of the environmental DSS which was one the final outcomes of the project. In particular I've been studying the different MCDA methodologies which could be applied in this situation in order to discover the most suitable one. The Modelkey DSS is a risk assessment tool devoted at the evaluation of the current status of water bodies, of the economic value of water use and at the hot-spots prioritization. The Modelkey DSS is one of the most advanced tools in decision making related to the WFD because of its novel assessment methodology and GIS interface. It is based on a particular Multi-Criteria Decision Analysis (MCDA) framework and provides useful evaluations both at river basin scale and site specific scale.

The contribution of my studies to environmental assessment is primarily related to the creation and development of a novel MCDA methodology related to the application of the WFD. Also the DSS I've developed inside the Modelkey project take part in the fulfillment of the lack of specific tools for the application of the WFD. The project is based on innovative solutions in the decision analysis part and also for the way they take into account spatial relations. The presented work can be a starting base in order to build more powerful and compliant tools in the future which can take advantage of the introduction of this novel approach.

The objectives of this thesis are to introduce the diverse disciplines involved in my interdisciplinary studies and to explain the MCDA methodology which I've been studying and the way it has been implemented inside a practical project, Modelkey. For this reason the Modelkey project is presented as it was the "real life" case study application of my theoretical efforts.

1.3.1 Modelkey project

The main work presented in this thesis has been developed within the MODELKEY project, an European Integrated Project (SSPI-CT-2003-511237-2; www.modelkey.org) involving 26 partners from 14 European countries.

It started in 2005 and it was funded by the European Commission within the Sixth Framework Programme. MODELKEY is the acronym for *Models for Assessing and Forecasting the Impact of Environmental Key Pollutant on Marine and Freshwater Ecosystem and Biodiversity.* The project was inspired by the demands of the EU Water Framework Directive 2000/60/CE (WFD) [EC, 2000] for a good ecological status of European surface waters by 2015 and by the actual lack of tools for the assessment of the causes of impaired aquatic ecosystems.

MODELKEY is based on a multidisciplinary approach and aims at developing diagnostic and predictive modeling tools to improve the understanding of the cause-effect relationships between environmental pollution and changes in the ecological state at river basin scale, and also to assess the risk originated by key toxicants on freshwater and marine ecosystems [Brack *et al.*, 2005], [Gottardo *et al.*, 2008], [Gottardo *et al.*, 2009a], [Gottardo *et al.*, 2009b], [Gottardo *et al.*, 2009c], [Semenzin *et al.*, 2010a], [Semenzin *et al.*, 2010b], [Zabeo, 2007], [Zabeo *et al.*, 2009] and [Zabeo *et al.*, 2010].

The main objectives of the project were:

- to assess, forecast and mitigate the risks of traditional and recently evolving pollutants on freshwater and marine ecosystems and their biodiversity at a river basin and coastal environment scale;
- to provide early warning strategies on the basis of sub-lethal effects in vitro and in vivo;
- to provide a better understanding of the cause-effect relationships between changes in biodiversity and the ecological status, as addressed by the Water Framework Directive;
- to provide methods for risk assessment and a Decision Support System (DSS) for the management of river basins in order to prevent adverse effects on biodiversity and to prioritize contamination sources and contaminated sites;

– to strengthen the scientific knowledge on an European level in the field of impact assessment of environmental pollution in aquatic ecosystems and biodiversity by extensive training activities and knowledge dissemination to stakeholders and to the scientific community.

The project included the application of the developed tools to three case studies representing European key areas: the river *Llobregat* (Spain) as a typical Mediterranean river basin, the river *Elbe* (Czech Republic, Germany) and the river *Scheldt* (France, Belgium and The Netherlands), both representing highly impacted central European river basins with a strong interaction with the coastal zone.

As state before one of the aims of the Modelkey project was the development of a DSS. My work during the PhD was devoted to the study and implementation of the mathematical structure of the DSS as well as of its software architecture and development. The main issue was to find what could be the most suitable MCDA tool to be applied in the evaluation of the environmental status of sampling sites along the river basin. I actively participated in meetings with the environmental experts involved in the project in order to understand the underlying model which they usually adopt in environmental analyses and the best software implementation which could be preformed. I proposed a mathematical approach based on MCDA and specifically a slightly modified version of the Takagi-Sugeno-Kang (TSK) method [Takagi & Sugeno, 1985] which can appropriately take into account relations between criteria and users' preferences, I also developed the DSS prototype software. This tool has been created in order to simplify the application of the methodology designed along the project to perform the ecological and chemical status assessment at river basin scale and the ranking of sites considered at risk, in order to select hot spots which need further investigations. To this end the integration of environmental information with socio-economic indicators has been considered, as it is useful for management goals.

1.4 Thesis structure

The thesis is composed by a first introductory part presenting the theoretical background useful to seamlessly proceed with the following sections. Then is the presentation of the project which involved my PhD work along with the achieved results and finally the results of my PhD studies which are strictly related to the projects.

In chapter *2 Decision Support Systems, page 20* we introduce Decision Support Systems and their role in environmental assessments and decision making along with, in *2.3 Survey of EDSSs for River Basins and Coastal Waters, page 29* , a survey and comparison among the most widely used environmental DSSs. We also present, in *2.2 Geographic Information Systems, page 24* , Geographical Information Systems and their role in environmental assessment tools.

After introducing the required technologies, in *3 Theoretical foundations, page 38* , we describe the theoretical foundations. Initially, in *3.1 Multi-Criteria Decision Analysis, page 38* , an explanation of Multi/Criteria Decision Analysis theory and application especially focusing on value functions is reported. Then, in *3.2 Aggregation operators, page 42* , a review of the most important aggregation operators which are usually applied in environmental MCDA is presented followed in *3.3 Fuzzy logic, page 45* by an introduction to Fuzzy Logic and Fuzzy Inference Systems.

Chapter *4 Modelkey, page 60* reports how the presented technologies and theoretical aspects are used in environmental risk assessment and management. In this chapter we discuss the objectives, methodologies, DSS tools and obtained results concerning the Modelkey project.

Finally chapter *5 Conclusions and future work, page 118* draws some conclusions and suggests some improvements.

Chapter 2

Decision Support Systems

In this chapter Decision Support Systems are briefly introduced, then a more specific dissertation is made upon Environmental DSSs and Geographical Information Systems which are more specifically related to my studies.

Decision Support Systems (DSSs) are a class of computerized information systems or knowledge based systems that support decision making activities. The concept of a decision support system is extremely broad and its definitions vary depending upon the author's point of view. A DSS can take many different forms and the term can be used in many different ways.

DSSs are broadly defined as computer-based systems that aid the process of decision making. In a more precise way, a DSS is an interactive, flexible, and adaptable computer-based information system, especially developed for supporting the solution of a non-structured management problem for improving decision making [Sol *et al.*, 1987]. It utilizes data, provides an easy-to-use interface, and allows for the decision maker's own insights. DSSs couple the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions in fact they are a computer-based support for management decision makers who are dealing with semi-structured problems. Another way to look at a DSS is interactive computer-based systems that help decision makers in using data and models to solve unstructured problems. In many cases DSSs are specific Software applications that help to analyze data contained within a customer database. This approach to customers is used when deciding on target markets as well as customer habits.

Although many definitions of DSS have been produced it is impossible to give a precise one including all the facets of the problem. Nevertheless the term Decision Support System remains a useful and inclusive term for many types of information systems that support decision making. As there is no omni-comprehensive DSS definition, so there are no omni-comprehensive DSS types.

We can differentiate *passive*, *active*, and *cooperative* DSS [Haettenschwiler, 1999] A *passive* DSS is a system that aids the process of decision making, but that cannot bring out explicit decision suggestions or solutions. An *active* DSS can bring out such decision suggestions or solutions. A *cooperative* DSS allows the decision maker (or its advisor) to modify, complete, or refine the decision suggestions provided by the system, before sending them back to the system for validation. The system again improves, completes, and refines the suggestions of the decision maker and sends them back to her for validation. The whole process then starts again, until a consolidated solution is generated.

From the conceptual level point of view DSS can be very different. In fact, based on the underlying decision process technique the DSS can be conceptually divided in five classes: *communication-driven DSS*, *data-driven DSS*, *document-driven DSS*, *knowledge-driven DSS*, and *model-driven DSS* [Power, 2002]. These classes are not mutually exclusive, therefore one single DSS can be (and usually is) member of more than one class.

A *Communication-driven DSS* is based on collaborative tasks, it supports more than one person working on a shared goal; examples include integrated tools like Microsoft's NetMeeting, Skype and many others. *Data-driven DSSs* emphasize access to and manipulation of time series of internal company data and, sometimes, external data. This type of DSSs relies on huge databases whose data are examined through data mining techniques in order to derive the correct decisions. *Document-driven DSSs* manage, retrieve and manipulate unstructured information in a variety of electronic formats. This is a borderline type of DSS in the sense that it can be seen just as a smart document manager, nevertheless this type of systems still provides useful information in order to take correct decisions and is therefore included in the DSS's set. A *knowledge-driven DSS* provides specialized problem solving expertise stored as facts, rules, procedures, or in similar structures. This type of system is usually composed by a predefined set of rules that the Decision Maker (DM) can explore by answering to subsequential questions. Finally, *model-driven DSSs* emphasize access to and manipulation of a statistical, financial, optimization, or simulation models. Model-driven DSSs use data and parameters provided by DSS users to aid decision makers in analyzing a situation, but they are not necessarily relying on huge databases.

From a technical structure point of view there are many ways of obtaining a DSS but more or less all DSSs encompass the same basic technical structure made by a *database management system (DBMS)*, a *model-base management system (MBMS)* and a *dialog generation and management system (DGMS)* [Sprague & Carlson, 1982], as reported in Figure 2.1.

More precisely, the *DBMS* stores information (which can be further subdivided into that derived from an organization's traditional data repositories, from external sources such as the Internet, or from the personal insights and experiences of individual

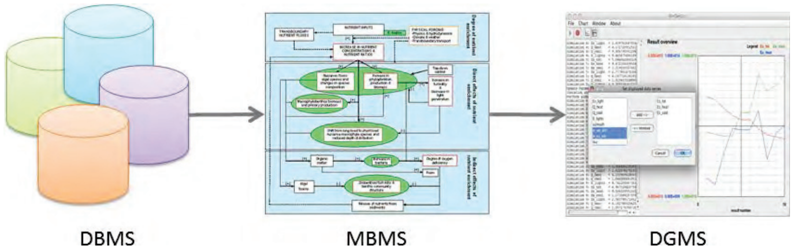

Figure 2.1: Technical structure of a DSS

users); the *MBMS* handles representations of events, facts, or situations (using various kinds of models, two examples being optimization models and goal-seeking models); and the *DGMS* is of course the component that allows a user to interact with the system.

When developing a DSS, a critical part of the process, which also determines the actual use of the system for policy and management purposes, is the planning phase when definition of key issues, referred frameworks and objectives are set up. Even if planned to respond to a very specific management question, the efficiency and consistency of a system increases if the application is based on commonly used management frameworks. The re-use of such well known and reliable frameworks allows an homogeneity of systems characteristics, the ability to be applied in the light of already existing policy and legislative requirements, and also the possibility of seamless integration with other systems.

It is a general issue in decision making (and therefore in DSSs) the need to take into account many different aspects and criteria during the decision process. The decision maker insights and valuations about these criteria can be multifaceted and some time conflicting. In order to manage all this information and end up with a set of feasible decisions, complex mathematical tools are usually adopted. Many mathematical tools can be used to build the decision model inside a DSSs ranging from probabilistic methods (e.g. Bayesian networks, Hidden Markov models, etc.) to Neural networks and other Artificial Intelligence and optimization tools ending to Multi-Criteria Decision Analysis (MCDA).

In this thesis the Modelkey DSS is presented which is a *model-driven DSSs*. The model embedded in the Modelkey DSS is based on a hierarchical mathematical MCDA structure who demonstrated to be particularly adapt in solving such complex structured problems. This because MCDA simplifies the treatment of interrelated criteria and allows to take into account users' preferences. MCDA includes a large variety of methods for the evaluation and ranking, or selection, of different alternatives that consider all the aspects of a decision problem involving many actors [Giove *et al.*, 2009].

2.1 Environmental DSSs

Although there are many types of environmental problems that need solutions, it is possible to find common patterns in their decision strategies. For example, watershed management is similar in watersheds or stream systems around the World, land revitalization is similar from site to site, or environmental restoration at Superfund [1] sites in the U.S. follows the same regulations and guidance. DSSs devoted to environmental problems are called Environmental DSSs (EDSS).

Developing EDSSs based on common frameworks which share the same approach for different types of problems, allows the achievement of advantages related to the consistency of approach. At another level, all environmental problems are similar in that they require considerations of the same basic economic, environmental, and sociopolitical factors. Consequently, a common EDSSs framework that address different types of environmental problems can also share functionalities and approaches to problem solving. EDSSs can be based on different structures from information-based DSS to model-based DSS.

Environmental-related decisions are inherently holistic problems. EDSSs' frameworks should be constructed in a way which facilitates this holistic decision analysis by integrating all the aspects related to environmental problems' solving while facilitating communication and discussion among all stakeholders through presentation and document production capabilities.

The output from a DSS often must be shared broadly. Therefore, when designing a DSS it is important to consider how to communicate and share the results. Transparency and reproducibility of the process build trust in the output. This proper behavior should begin from the very start of the process by the involvement of end users and stakeholders already from the EDSS designing and planning phase. End users and stakeholders opinions should be assessed throughout the whole developing process, moreover the production of open source software allows a high level of transparency.

As noted above, to complete a proper EDSS, it is critical that uncertainty and cost/value cover the full range of environmental, economic, and socio-political components of environmental decision support.

EDSSs are always concerned with environment related aspects and therefore with problems which encompass spatial aspects like proximity, intersections, etc. A Geographical Information System (GIS) is a computer-based information system aimed at manipulating geographically referenced data (i.e. geospatial data) which are otherwise cumbersome to deal with. GISs are mainly related to storage, retrieval and

[1] Superfund is the common name for the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), a United States federal law designed to clean up sites contaminated with hazardous substances.

presentation of geospatial data, more advanced features are also supplied in some cases which encompass a wide variety of spatial statistical and analytical functionalities. A more precise and complete explanation of GISs is reported in section *2.2 Geographic Information Systems, page 24* .

MCDA is perfectly suitable to be used inside Geographical DSSs, in fact geographical relations can be take into account inside the MCDA model in order, for example, to establish the magnitude of relevance of a relation between to entities basing on their distance.

Usually EDSSs are *model driven DSS* and therefore rely on complex mathematical tools. The most widely used mathematical techniques in environmental-related problem solving are those encompassed in MCDA. This technique is used because it is able to deal with the endemic presence of uncertainty in environmental related problems and also because of the need to keep track of decision makers' preferences about many different aspects.

2.2 Geographic Information Systems

A GIS is a computer-based information system that enables capture, modeling, storage, retrieval, sharing, manipulation, analysis and presentation of geographically referenced data [Worboys & M.Duckham, 2004]. Such complex systems are needed in order to deal with the various problems arising when working with geographically referenced data (referred to as geospatial data). In Figure 2.2 is reported the typical software architecture of a GIS, in figure 2.3 is an example of a GIS's GUI (ESRI ArcMap).

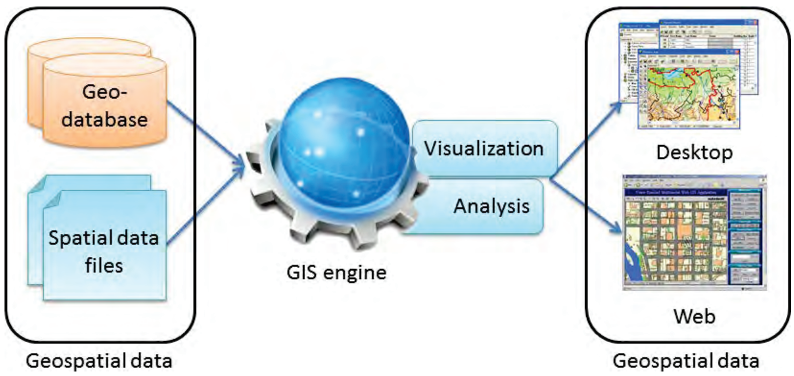

Figure 2.2: Typical software architecture of a GIS.

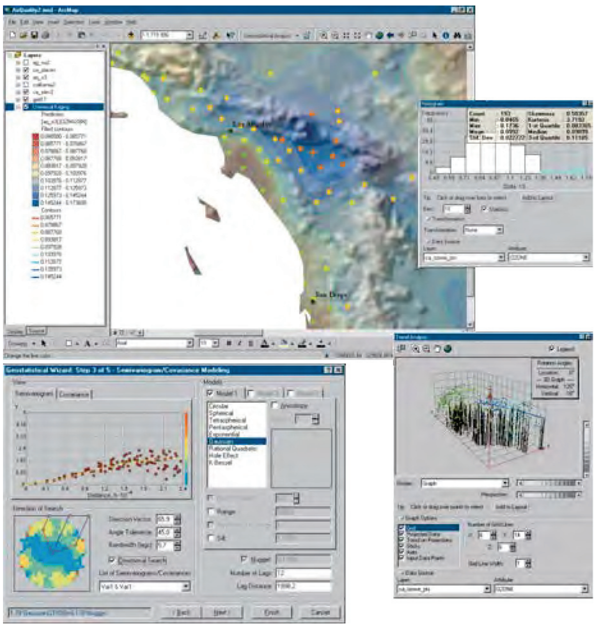

Figure 2.3: Example of a GIS GUI: ESRI ArcMap.

Components of a GIS are database elements, data storage and retrieval elements, data sharing elements, data presentation elements and spatiotemporal elements. Databases in GIS applications are not trivial. In fact, information relied to geographic elements is not only formed by ordinary data types but also it includes special characteristics such as images, shapes, topological and network relations. The storing and handling of images in databases is a well known problem and GISs use the standard techniques to accomplish this task. On the other hand, the storing of shapes is more complex since it required the definition of techniques to capture the essence of planar or three dimensional shapes. To describe shapes, *geometries* are required; various kinds of geometries can be used to deal with objects representing space. The most used geometries are *Euclidean space geometry* and *set based geometry*. Before defining these geometries it is useful to focus on the definition of space, more precisely due to our GIS interest, geographical space. A space can be defined as *a relation defined on a set of objects* [Gatrell, 1991]. This definition is very generic, moving to geographical spaces, we can say space is a relation defined on a set of *geographical objects* usually referring to earth's surface. A geometry provides a formal representation of the abstract properties and structures within a space.

In *Euclidean space geometry*, space is measured by the use of coordinates. Such coordinates allow the transformation of spatial properties, like distances between points, into properties of tuples of real numbers. In this geometry objects of concern are points, lines, polygons and also arcs and polylines, moreover coordinates may induce a metric. In *set based geometry*, no metric is requested, geographical objects are modeled as elements and sets. This kind of geometry is especially useful when dealing with relations between objects and for the application of functions.

Another important aspect in geographical spaces is *topology*. Topology is a branch of geometry concerning geometrical properties invariants under topological transformations. Topological transformations are involved when space is bent, twisted, stretched, or deformed in any way; the only exceptions are that tearing the space is not allowed, and distinct points in the space cannot be made to coincide.

The last important geographical space aspect concerns the treatment of *networks*. Networks, usually abstracted as graphs, are perfect to capture connection relations between objects and for path problems.

Operating with GIS involves (even if not directly) dealing with problems derived from the modeling process of the different aspects presented before. Many ways of storing data have been developed in order to manipulate such particular objects in reliable and effective ways. The most important distinction concerns *raster* and *vectors*. In raster data structures, the land is tessellated [2], usually with regular shapes, each tassel has an identifying label (e.g. the coordinates in a square based tessellation structure) and at least one associated value (e.g. elevation). More generally, each

[2] A tessellation or tiling of the plane is a collection of plane figures that fills the plane with no overlaps and no gaps.

tassel is associated with an attribute table containing various information about it. Vector data structures model land by identifying objects in it and representing them as vector shapes composed by basic vector structures (points, lines and polygons). As in the raster model each object has an associated attribute table.

Finally, functionalities of GISs can be subdivided in three categories:

- Geodatabase,
- Geovisualization,
- Geoprocessing.

Geodatabase functionality is required to be able to gain data from different types of sources. As stated before, geographical data can be viewed and therefore stored in many different ways and formats, according to characteristics to be preserved. Formats present in the GIS world are for example rasters, shapefiles, geodatabases, etc. A GIS is not useful if it is not able to deal with a large number of different data formats.

Geovisualization functionality is very important when dealing with geospatial data, this is because land maps need to be viewed by users to understand their content and also to recognize data relations that may be hidden inside geodatabases data organization.

Geoprocessing functionality concerns the creation of new derived data from previously possessed data by the use of specialized tools. Usual operations are union, intersection, bufferization, etc. of shapes of concern.

2.2.1 GIS Software

ESRI ArcGis [ESRI, n.d.] is an integrated collection of GIS software products for building and deploying a complete GIS. It is the mostly used GIS software, it is not free and it is able to read almost every type of geo-data, visualize them in a consistent and powerful graphical user interface and it contains lots of geoprocessing tools to make many types of geographical, topological and network related evaluations. Moreover users can create their own processing tools by using different programming languages (e.g. python, java, VBA) and the ESRI's geoprocessing object model library inside the ArcGis environment.

In the last decades, many open source free GISs have been developed. The most notable are:

- MapServer [MapServer, n.d.]
- GRASS GIS [GRASS, n.d.]

– Qgis [Qgis, n.d.]

– uDig [uDig, n.d.]

– MapWindow [MapWindow, n.d.]

MapServer is an Open Source development environment for building spatially-enabled internet applications. However, it is not a full-featured GIS, it is especially suited at rendering spatial data (maps, images, and vector data) for the web.

GRASS (Geographic Resources Analysis Support System) is a raster/vector GIS, image processing system, and graphics production system. GRASS contains a large number of programs and tools to render maps and images on monitor and paper; it manipulates raster, vector, and sites data; it processes multi spectral image data; and creates, manages, and stores spatial data. In GRASS there is not a standardized plug-in system development and it is developed only for linux operative systems.

The last three applications, namely *Qgis*, *uDig*, and *MapWindow* are all complete GIS frameworks with also standardized plug-in development procedure. These open source solutions are the GIS applications closer to ArcGis which represents the most effective and used GIS solution nowadays. *Quantum GIS* (Qgis) is a user friendly Open Source GIS that runs on Linux, Unix, Mac OSX, and Windows. Qgis supports vector, raster, and database formats and is able to perform various processing on data. It also supports the creation and application of C++ and python plug-ins. The *User-friendly Desktop Internet GIS* (uDig) is both a GeoSpatial application and a platform through which developers can create new, derived applications. uDig is a core element in an internet aware Geographic Information System. The uDig application is built upon Eclipse environment and it supports the creation of plug-ins via the usual java Eclipse plug-in standard. *MapWindow* is an open source "Programmable Geographic Information System" that supports manipulation, analysis, and viewing of geospatial data and associated attribute data in several standard GIS data formats. MapWindow is a mapping tool, a GIS modeling system, and a GIS application programming interface (API) all in one convenient redistributable open source form. Plug-ins may be created by using visual basic .NET or C#.

2.2.2 GIS in environmental risk assessments

GISs tools are becoming more and more essential in every modern environmental risk assessment software. As a matter of fact territorial aspects are strictly related to environment, this implies that the relations between spatial objects and also the shape of the land under assessment are factors which must be accounted when assessing environmental and ecological problems.

Nowadays thinking of an environmental risk assessment tool which is not making use of GIS features is not professional. Not only GISs are needed every time spatial relations must be elicited but they are also the most effective and useful instruments to present the obtained results to the users.

Most of the EDSSs that will be presented in section *2.3 Survey of EDSSs for River Basins and Coastal Waters, page 29* make use of GIS tools to present results and in many cases also to perform spatial enabled assessments. The trend of using GISs inside EDSSs is constantly growing. This is due to the constant improvements in GIS software usability and also to the growth of free GIS softwares available.

2.3 Survey of EDSSs for River Basins and Coastal Waters

Many different EDSSs have been created throughout the years, related to almost all the different environmental decision making issues. These systems vary from very simple *document* and *knowledge* driven systems to complex systems integrating *database*, *model* and *communications* paradigms.

Making comparisons between EDSSs in general is therefore not possible due to the wide variety of fields of application (e.g. water, soil, protected areas, etc.). This thesis is based on the development of an EDSS related to water management (i.e. *Modelkey*) therefore the survey and comparisons proposed in the next sections have been focused on EDSSs for river basins and coastal waters.

Many Decision Support Systems are currently available to tackle decision making problems for river basins and coastal waters in Europe. Since the European legislation requires integration of policies and management actions, the different DSSs do not address only problems of contamination of rivers, sediments and coastal waters, but rather they frame them in the context of the general assessment and management process for water resources.

The selected EDSSs encompass tools for river basins, coastal waters and lagoons. They are examples of how the management needs of decision makers with respect to water resources are translated into developed tools and software. The selected EDSSs are briefly described in the next section.

2.3.1 Main types

The **DITTY** Decision Support System was developed within the European project DITTY and its main objective is to support the sustainable management of southern European coastal lagoons affected by the river-basin runoff, taking into account relevant impacts caused by agricultural, urban, and economic (e.g. fish/shellfish farming/fishing, tourism) pressures. In order to achieve this goal, DITTY follows the principles of the Integrated Water Resource Management (IWRM) as a part of the

Water Framework Directive (WFD), as well as the DPSIR (Driving forces-Pressures-State-Impact-Responses, [EEA, 1999]) framework.

The DITTY conceptual framework includes three main steps: (i) the decision problem definition, in terms of management options (i.e. policies, strategies, alternative actions) affecting the system behavior; (ii) the alternatives generation, quantified by means of indicators, simulated by applying ecological, biogeochemical, hydrodynamic, and socio-economic models, taking also into account external factors which can not be manipulated by the decision maker (e.g. climate change); and (iii) the alternatives evaluation and ranking by Multi-Criteria Decision Analysis (MCDA), applied to evaluate the system performance under different scenarios taking into account economist, decision makers, and stakeholders. The DITTY DSS has been applied in five different sites: Ria Formosa (Portugal), Mar Menor (Spain), Etang de Thau (France), Sacca di Goro (Italy), and Gera (Greece). ([Agnetis *et al.*, 2006]; [Casini *et al.*, 2005]).

The **Elbe river DSS** has been developed within the study "Towards a generic tool for river basin management" supported by the German Bundesanstalt fur Gewasserkunde (BfG). The principal function of this GIS-based DSS is to address different river problems, such as the improvement of socio-economic use of the river basin and the definition of sustainable level of flood protection. The DSS has a modular structure, from a catchment's scale to more detailed river sections, and the different scales are linked through analysis results. At the highest level of analysis (Catchment) there are models describing the impact of land use and hydrology on diffuse runoff as well as impact of point discharges. At the second level of analysis (River) there are models describing among others navigation conditions, flood risk and water quality. At the third level (River section) there are detailed models describing the impacts of river engineering measures such as dike shifting and the habitat conditions for different species in the river. The system includes a spatial overview model of the Elbe catchment, a network of models that fulfils analysis and communication functions, and 2D or 3D process models ([Verbeek *et al.*, 2000]; [de Kok *et al.*, 2001]; [Hahn *et al.*, 2002]).

The **MULINO DSS** (MULti-sectoral, Integrated and Operational Decision Support System for Sustainable Use of Water Resources at the Catchment Scale) was developed within the EU FP6, to be an operational tool which meets the needs of European water management authorities and which facilitates the implementation of the EU WFD. The MULINO DSS aims at contributing to the quality and transparency of decision making by achieving a truly integrated approach suitable for the development of River Basin Management Plans. The decision process considers alternative options for the use of water resources and integrates multi-disciplinary approaches based on criteria and preferences that are elicited from decision maker and stakeholders, by Multi-criteria Decision Analysis (MCDA) tools. The DSS guides the user to consider the most important social, economic and environmental parameters/indicators that determine changes in water uses and in the state of water resources, organized in the structure of the DPSIR framework. Some of the used criteria concern nutrients concentrations, water quality, energy consumption, land use, recreation. The system is divided into three main phases: the Conceptual phase, with the identification of issues and problem exploration; the Design phase, where possible management options are defined and modeled for the evaluation of their performances; the Choice phase, where all options are judged according to the value functions and the preferences expressed by decision makers, who give weights to the evaluation criteria, through the MCDA methodologies ([Fassio *et al.*, 2005]; [Mysiak *et al.*, 2005]).

The **RiverLife DSS** was developed within a project of Finnish institutes. It is an interactive computer-based decision support system, used via Internet, which helps to integrate environmental considerations into land use planning and management practices in river basins. The system contains information on river biota and their habitats, on the effects of land-derived loading on water systems and on the water pollution control measures against non-point pollution. The included methods support the evaluation of the hydrological and ecological status of the rivers and the control of non-point source pollution originating from different forms of land use.

RiverLife is characterized by a hydrological watershed model VMOD, which assists in estimating the effects of diffuse and point-source loading on the river flow and water quality; by a GIS tool, for obtaining data on the characteristics of the drainage basin, and examining hydrology and loading in the drainage basin; by a tool focused on the analysis of the ecological status of the river basin area and the river beds, through Ecological Risk Analysis (ERA) ([Karjalainen Satu & Heikkinen, 2005]).

The **TRANSCAT DSS** was developed, within the EU funded project with the same name, for the Integrated Water Management of transboundary catchments. The system, built on a GIS platform, should provide the basis for the water management in the borderland regions in the contexts of the EU WFD. Therefore the DSS is built upon modules that allow simulation of the different climatic, topographic, environmental and socio-economic conditions of various transboundary catchments. The system is basically an aggregator of different already existent systems which simplify their application. It is subdivided in four main subsystems: the mapping subsystem with the manipulation and visualization of geographic information; the modeling subsystem which encapsulates various models, including runoff models, precipitation models, river system analysis and groundwater flow models and solute transport models; the data management subsystem which concentrates on editing and management of data needed in other subsystem; and the DSS subsystem which specifies decision alternatives, by means of one of the Multi-Criteria Decision Analysis (MCDA) methodologies available or via group decision devices, and helps in choosing between them.

A TRANSCAT prototype, based on Open Source solutions, which are freely available, is available and has been applied to 5 selected pilot areas in Central-Eastern EU countries ([Horak & Owsinski, 2004]).

The **WadBOS DSS** was developed in the Netherlands specifically for the integrated management and policy preparation in the Dutch part of the Wadden sea, an important estuarine system in the north of the Netherlands. In fact, it links ecological and economic knowledge and information about the Wadden Sea in order to facilitate the planning and decision making process. Its main purpose is therefore to design and analyze potential policy measures and to be useful for all those involved in the management of the system. Accordingly, the system provides different functions covering all phases in a typical decision making process.

First of all, WadBOS allows to gather, order and link knowledge about issues and problems; then, it allows to deepen the understanding about particular topics and linkages, providing a holistic representation of the Wadden system; and finally, it allows to evaluate the effects of different policy interventions onto the system and facilitates the discussions among policy makers, stakeholders and the public. The core element of WadBOS is an integrated dynamic model of the Wadden system representing strongly coupled social, economic, ecological, biological, physical and chemical processes. The output of the DSS includes summarized information and policy indicators required to evaluate the success of scenarios and policy options tried out on the system [Engelen, 2000], [van Buuren *et al.*, 2002].

2.3.2 Comparison Evaluation

The selected Decision Support Systems have been reviewed in consideration of methodological as well as structural issues. DSSs can be characterized by two main elements: *framework* and *structure*. The former refers to the assessment and management issues to which the DSS responds and for which it offers specific functions. The latter instead describes the main components of the system in terms of databases, models and graphical interface.

In consideration of these general characteristics and other relevant aspects the following criteria have been identified in order to present the different DSSs and propose their preliminary review:

- Framework
  - *Legislative framework*. It specifies to which legislation the DSS refers to and to which phase of the decision process it provides support.
  - *Scale of analysis*. It specifies if the system is applicable to watershed, river basin, or coastal waters and to local, regional or global scale.
  - *Functions*. Relevant functions of the systems are here reported. They include, according to the decision process: status evaluation, relevant pressures identification, scenarios generation and analysis, measures identification, measures evaluation, indicators production, monitoring programs definition.

  - *Included methodologies*. It refers to the methodologies included in the system and used in the elaborations, such as risk assessment, the DPSIR framework, the Multi-criteria Decision Analysis (MCDA), scenario analysis, socio-economic analysis.
  - *Case-studies*. The European river basins or coastal areas where the DSS has been tested and applied are listed.

- Structure

  - *Structural elements*. The three main elements of the DSS are detailed: models, such as economic, morphological, hydrological or ecological; database with specification of its nature; interface, addressing if the system is user-friendly and what kind of visual aids are provided to the user.
  - *GIS-based*. This aspect specifies if the system is built within the Geographical Information System environment.
  - *Web-based*. This feature assesses if the system is partly or totally accessible and usable via Web, and not in the form of a downloadable software to be installed in the user PC.
  - *Flexibility*. This characteristic refers to the fact whether the system is adaptable, in terms of change of input parameters or addition of new models and functions. It is also linked to the possibility to be adaptable to different coasts or basins than those of the case-studies.

The results of the comparisons are reported in Table 2.1 for a better understanding. As general observations it has to be noted that all of the examined DSSs could be used toward the application of the WFD but only a few were strictly developed for that purpose (DITTY, MULINO and RiverLife). By examining the selected DSSs two basic typologies are present, on the one hand there are DSSs which by the use of collected data and model results generate results useful in the decision making process by the use of decisional frameworks (usually based on MCDA) (DITTY and MULINO). On the other hand there are model based DSSs which allows different models to communicate and cooperate toward the creation of different scenarios (Elbe river DSS, Riverlife, TRANSCAT and WadBOS). One last important remark is that DSSs created for specific case studies (Elbe river DSS and WadBOS) are much less flexible than others and tend to adopt case specific techniques which are difficult to transpose in other situations.

	FRAMEWORK					STRUCTURE			
Name	Related to WFD	Methodologies	Functionalities	Scale	Case studies	Structural elements	GIS	WEB	Flexibility
DITTY	Y	MCDA DPSIR	Scenarios Assessment Uncertainty	Lagoons	Ria Formosa (Portugal) Mar Menor (Spain) Etang de Thau (France) Sacca di Goro (Italy) Gera (Greece)	Models Database Interface	Y		poor
Elbe river DSS			Assessment Remediation scen.	Catchments Rivers	Elbe (Germany)	Models Database Interfaces	Y		poor
MULINO	Y	MCDA DPSIR	Scenarios Assessment Sensitivity Group decision	Catchments Rivers	Bahlui (Romania) Caia (Portugal) Yure and Bare (UK) Nethan (Belgium) Vela, Cavallino, Arborea (Italy)	Database Interfaces			good
RiverLife	Y		Assessment	Rivers	Simojoki, Kyronjoki, Siuruanjoki (Finland)	Models Database Interfaces	Y	Y	poor
TRANSCAT			Assessment	Transboundary_ catchments	Bela/Biala (Czech/Polish) Pasvik (Norwegian/Russian) Guadiana (Spanish/Portuguese) Mesta/Nestos (Bulgarian/Greek) Sumava (Czech/German)	Database Interface	Y	Y	good
WadBOS			Scenarios Assessment Remediation scen.	Catchments	Dutch Wadden Sea	Models Database Interface	Y		poor

Table 2.1: Comparison of DSSs related to water quality assessment. The factors taken into account are subdivided in *framework* related and *structure* related

Considerations about framework

As far as the river basins are concerned, all the reviewed DSSs reflect assessment and management aspects required or proposed in the decision making process for the *implementation of the WFD*. Most of them has been developed within EU funded projects, thus with the clear objective of supporting implementation of EU regulatory frameworks. This common objective may justify the inclusion in the reviewed systems of similar functions and approaches to tackle general problems. With respect to the WFD objective of a more comprehensive approach to water management, all the tools provide useful models for socio-economic analysis of the impacts of human activities and use of water. In this context, with RiverLife is possible to analyze in detail problems such as those related to ditching (i.e. water landing). MULINO and DITTY allow to clearly study the causal chain between the human activities and impacts on water resources through the DPSIR approach.

As stated before, in the general observations, not all of the presented DSSs contain a decisional *methodology* framework allowing the use of decision makers insights and the comparisons between the possible alternatives. The only two DSSs specifically designed toward this capability are DITTY and MULINO, TRANSCAT can perform the same analysis but just because it utilizes MULINO himself.

As far as *functions* are concerned the assessment phase of the decision process is supported by all of the DSSs by providing tools for analysis of characteristics of river basins, including definition of the water quality and analysis of human interactions. Most of them (DITTY, Elbe river DSS, WadBOS and MULINO) has a built in scenarios creation and evaluation tool but not all are able to also manage remediation scenarios. Scenarios are generated by algorithms which allow to make hypothesis about external influences not under the control of the policy maker (e.g. climate variability, economic prosperity and decline, population growth). A particular mention must be done for DITTY and MULINO which are the only DSSs which embed tools for the analysis of uncertainty and sensitivity respectively, MULINO is also the only DSS which is particularly structured to allow group decision theory techniques for multiple stakeholders.

The *scale* of the analysis can also be an important factor. In fact instruments able to deal with objects of different scales in a coherent way are preferable. To this end only DITTY and MULINO are enough generic to be used at river as well as catchment scale. Other DSSs are mostly related to a specific situation.

Case studies are someway related to scales and also to the purposes of the DSSs. Two of the examined tools were directly related to their case studies (Elbe river DSS and WadBOS), also RiverLife was only tested among Finnish rivers while the others have been more widely adopted (even if TRANSCAT is strictly related to transboundary catchments). If a generic tool may be preferable due to its adaptability to other contexts, it must be recognized that the development of generic tools is a difficult task and brings the disadvantage of providing a comprehensive but also very complex and often unpractical tool, which may be discarded by decision makers. On the other hand, a tool developed for a specific geographical context may be more appealing to local authorities, which may feel more comfortable in its application. Most of the DSSs support the implementation of EU directives, but they are not compulsory instruments, and they are not routinely used in water systems management. Except for cases where the DSS is specifically devoted to the management of a river system, e.g. the Elbe River DSS, the presented DSSs still lack of a wider applicability in regular management practices.

Considerations about structure

Numerical *models* often represent the operative nucleus of these systems. While some DSSs employ mostly analytical models aimed at the characterization of the state and main processes of the examined system others use simulation models to predict future environmental and socio-economic situations (e.g. DITTY and WadBOS). In the same way, while some DSSs are based on models mostly representing natural processes (e.g. RiverLife and TRANSCAT), many DSS (e.g. MULINO, DITTY and WadBOS) make use of both environmental models and socio-economic ones, in order to achieve the integrated management of inland and coastal aquatic resources. Accordingly, they do not consider only key environmental aspects of the analyzed problem, but also allow the generation and evaluation of alternative management options, thus supporting the assessment and management phases of the decision-making processes. Several DSS (e.g. WadBOS, Elbe river DSS) also utilize more complex integrated models in order to represent the interrelations among different categories of processes (e.g. physical, morphological, ecological, chemical and socio-economic), and provide more comprehensive information about linked environmental and socio-economic phenomena.

Many of the analyzed DSSs are *GIS-based*. In fact, in addition to automatic map production, GIS tools allow a better information management and a higher quality analysis and visualization of the study area. Moreover, GIS functions facilitate the storing, checking, manipulating, and displaying of data and allow the integration of environmental, economic and social factors into a shared platform. Finally, the use of geographically referenced data and the concise communication of complex spatial patterns are required by legislative frameworks and useful for environmental reporting.

Only RiverLife, and partly TRANSCAT, are developed on a *web-based* technology supporting a large group of users in a networked system. This is probably due to the additional effort required to develop this complex systems and to the necessity of updating and handling continuously a computer server. On the other hand such systems are largely less performing than the other desktop based solutions as the application of complex models to large databases is not a “web oriented” issue.

The *flexibility* of the systems should be taken into high consideration, since the possibility to use a tool in other contexts allows a common approach to decision making process and also the possibility to obtain more comparable results. In general, the most flexible and adaptable systems are TRANSCAT and MULINO, which are generic systems applicable to different water systems. Nevertheless, the fact that some of the reviewed systems, as the majority of worldwide available DSSs, have been developed specifically to address assessment and management issues in well-defined river basins or coastal areas must be kept in mind. Therefore, the tools usually include models and functions that respond to common legislative requirements, but at the same time they are narrowed to specific contexts, for which they provide suitable parameters or problem solving instruments.

In conclusion there is not a definitive way to rank environmental DSSs as the field of application is really wide and also the possible technical solutions to adopt are very different and often non comparable. Also almost every DSS faces the same problem by a different point of view and therefore supplies different instruments related to the solution of different issues (e.g. group decision mechanisms, web based framework, socio/economic aspects, etc.). The Modelkey DSS which will be deeply presented in the next sections brings novelty as it encompass many different positive aspects which can never be found within a single DSS in the ones presented. Modelkey is based on a specific own model aimed at the application of the WFD, its based on a GIS framework and is completely flexible allowing it to be used in many different situations.

Chapter 3

Theoretical foundations

In the following sections the theoretical foundations needed in order to proceed seamlessly with the subsequent chapters are reported. First is an introduction to Multi-Criteria Decision Analysis (MCDA) where the basics of this field of mathematics are explained, then is an explanation of the many different aggregation operators which can be used inside MCDA. In the last part Fuzzy logic and Fuzzy Inference Systems (FIS) are presented which are powerful tools that can also be utilized in MCDA.

3.1 Multi-Criteria Decision Analysis

Multi Criteria Decision Analysis (MCDA) includes a wide variety of methods for the evaluation and ranking, or selection, of different alternatives that consider all the aspects of a decision problem involving many actors ([Giove *et al.*, 2009]).

Features common to almost all the decision processes include the following items:

- the decision maker (DM). A single person, a group of persons or an entity in charge of finding the best solution for the problem under examination;
- a set A of alternatives, in the finite case: $A = (a_1, \ldots, a_m)$, out of which the DM must choose the best solution;
- a countable group of criteria $K = (k_1, \ldots, k_n)$. Criteria define the alternatives, they are aspects of the problem that the DM considers crucial. Criteria can be organized into a hierarchical structure, i.e. a decision tree where the root is the objective function whose branches are the first-level criteria, each of them splits again into second-level criteria (sub-criteria), and so on till the last level, whose terminal leaves are the indicators calculated on the basis of the available information (data or judgments);

– the decision maker's preferences for the different evaluations of the criteria.

In case of an infinite set of alternatives the final solution of a MCDA problem is also related to:

– an objective or target function (to be optimized) used to score alternatives, usually an aggregation function;

– an algorithmic tool designed to optimize the objective function, considering all the above information.

The infinite-alternatives based field of MCDA is called Multi Objective Decision Making (MODM), and is the counterpart of the finite-alternatives based branch called Multi Attribute Decision Making (MADM). Typically MADM can be subdivided into three main categories ([Vincke, 1992]): Multi-Attribute Utility/Value Theory (MAUT/MAVT), Outranking and Interactive methods.

In Multi-Attribute Utility/Value Theory (MAUT/MAVT) criterion values are first normalized into a common numerical scale by means of a suitable transformation function (or Utility/Value Function). Then criteria are aggregated by a suitable aggregation operator, a function which satisfies a set of rationality axioms. Using a bottom up approach, this operation is repeated for all the nodes in the decision tree (if the problem is hierarchically structured) for all the alternatives. Each branch or level of the tree may be aggregated to its root by using different aggregation functions on the basis of the relations between the criteria of concern. At the tree root (the objective) a single numerical value is finally computed, which is the score of the proposed alternatives. The alternatives can then be rated and ranked, since MAUT/MAVT produces a total ordering, and so the best one can be selected.

Outranking methods are based on "outranking relationship" between alternatives stating that one alternative may be dominant, with a certain degree, over another one. These outranking relationships are neither complete nor transitive generating therefore only partial orders. This is due to the fact that outranking methods comprise the existence of non comparable alternatives.

Interactive methods obviously consist of the iteration of certain procedure steps. At first, a rough solution is proposed to the DM, which can accept or reject it. In the latter case new data are acquired and/or more information is supplied (e.g. extra information concerning a DM's preferences) to the system. Then a new solution based on new data and information is presented to the decision maker. This extraction of preferences and re-computation steps are repeated, creating successive compromise solutions, until the satisfaction of the DM is reached.

Throughout the rest of this thesis only the MAVT filed of MCDA will be considered as is the one used in both the presented DSSs.

3.1.1 Value functions

As stated in the previous section multiple attribute value theory (MAVT) consists in the creation of a value function (normalization function) for each criterion, used to normalize all criteria values in a common numerical closed interval. Then normalized criteria are aggregated toward the obtainment of a final alternative score value.

Normalization functions are usually monotonic and their co-domain is included in the closed interval $[0, 1]$. Given that the assignment of such functions is subjective (even if guided by a suitable software interface) and depends on the user's preference structure or perception about the criterion impact, the normalization problem must be solved without resorting to any type of data-driven formulas (e.g. subdivision by maximum). This because any data-driven normalization algorithm is quite sensitive to outliers and may therefore induce distortion in the final scoring, distortion is also present if the data which have to be normalized are dense around an average value. As a consequence the most feasible solution for normalization is performing re-scaling of all the available criteria's data into a common closed numerical scale. This solution, not only is simpler but also solves the normalization problem in a better way.

Normalizing functions can be divided in two main categories: continuous and discrete. Continuous normalization functions are continuous, usually monotonic, functions mapping the domain into any value in the co-domain e.g. piecewise linear functions (figure 3.1 b). Discrete normalization functions instead map the domain into a finite number of alternatives (which may be expressed as fixed numerical values like in Figure 3.1 a but also as lexical labels e.g. "BAD" or "GOOD").

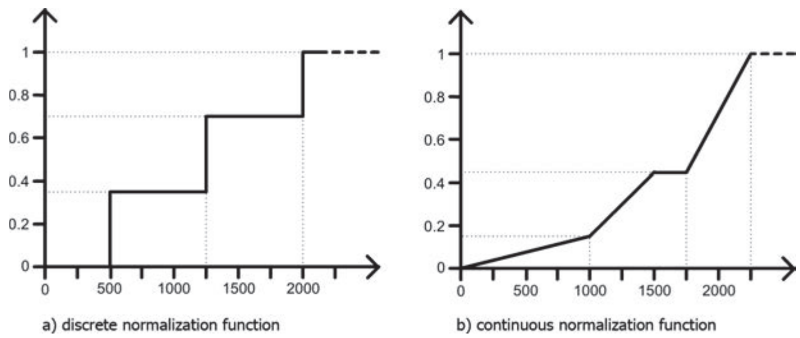

Figure 3.1: Examples of discrete $a)$ and continuous $b)$ normalization functions

Normalized data must then be aggregated into a single numerical output representing the score of the alternative, or of an intermediate level node in the decision tree if a hierarchical structure is defined.

To this purpose, an Aggregation Operator needs to be defined, [Klement *et al.*, 2000], that is a multi-dimensional function A defined as

$$A : \bigcup_{n \in N} [0,1]^n \rightarrow [0,1] \tag{3.1}$$

such that:

(i) $A(x_1, \ldots, x_n) \leq A(y_1, \ldots, y_n)$ whenever $x_i \leq y_i$ for all $i \in 1, \ldots, n$;

(ii) $A(x) = x$ for all $x \in [0,1]$; and

(iii) $A(0, \ldots, 0) = 0$ and $A(1, \ldots, 1) = 1$.

The most popular aggregation operators are: Pythagorean means (arithmetic mean, geometric mean and harmonic mean), median, Weighted mean, minimum and maximum. All these operators are widely adopted, well known and can be helpful in many, but not all, occasions. The drawback related to such basic aggregation methods is their poorness of expressivity. Other generalized operators are used as the aggregation problem complexity increases.

The *Ordered Weighted Averaging (OWA)* [Yager, 1988], [Yager & Kacprzyk, 1997] is a generalization of the weighted average, minimum and maximum aggregation functions which can be used to generate the necessary "in between" evaluations. Finer grained aggregations can be obtained by the use of the *discrete fuzzy integrals* based on *fuzzy measures*. The two most widely used discrete fuzzy integrals are the *Choquet integral* [Choquet, 1954] and the *Sugeno integral* [Sugeno, 1974]. These are two aggregation operators related to coalitions of criteria more than to single criteria. Aggregation in Fuzzy environments is mostly related to fuzzy sets conjunction and disjunction. These two concepts are mathematically represented by two families of operators: *T-norms* and *T-conorms* [Menger, 1942], [Schweizer & Sklar, 1983], [Schweizer & Sklar, 1960]. The drawback of these operators is their lack of compensation [1] behavior. In order to overcome this issue the *Compensatory operators* [Zimmermann & Zysno, 1980] have been introduced which are particular T-norms/T-conorms based operators taking into account compensation. Other compensative T-norms/T-conorms based operators are the *Uninorms* [Fodor *et al.*, 1997]. These operators not only have a compensation behavior but also supply *full reinforcement* which, like compensation, is not present in T-norms/T-conorms. In Figure 3.2 a graphical representation of the relations between the presented aggregation operators is reported.

All the above mentioned aggregation operators will be investigated more in depth in the next sections as they are useful tools in MCDA applied to environmental risk assessment.

[1] Compensation, for an aggregation operator, states that the aggregation result must always be bounded by the minimum and the maximum of its operands

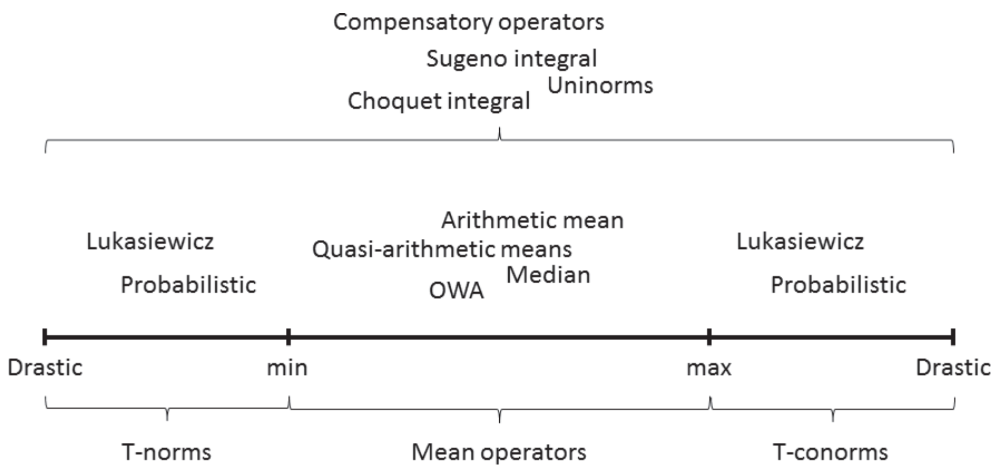

Figure 3.2: Relations between the aggregation operators

3.2 Aggregation operators

Aggregation operators correspond to particular mathematical functions used for information fusion. Generally, we consider mathematical functions that combine n values in a given domain D and return a value in the same domain. Denoting these functions by C (from *Consensus*), aggregation operators are functions of the form:

$$C : D^n \to D \tag{3.2}$$

Usually, operators fuse input values taking into account some information about the sources (data suppliers). That is, operators are parametric so that additional knowledge on the sources can be considered in the fusion process. Ew express this by C_P where P represents the parameters of C.

3.2.1 Simple aggregations

The simplest and most common way to aggregate is to use a simple **Arithmetic mean** (also know as the average). Mathematically we have:

$$M(x_1, \ldots, x_n) = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{3.3}$$

The typical extension of the simple arithmetic mean is the **Weighted mean** (the parametric version of *Arithmetic mean*):

$$M(x_1, \ldots, x_n) = \frac{1}{n} \sum_{i=1}^{n} w_i \cdot x_i \qquad \text{where } \sum_{i=1}^{n} w_i = 1 \tag{3.4}$$

These two aggregations are the first type of formulas which come into mind when thinking of finding a value representing a group of values. A slightly different idea of mean is given by the **Median** which consists in ordering the arguments from the smallest to the biggest and then taking the element in the middle. If the cardinality of the set of arguments is even then the mean of the middle pair is used, or in cases where the result must be one of the set elements then one of the two is selected. A generalization of the Median is the **k-order statistic**, with which the k^{th} position on the ordered list can be set.

Minimum and **Maximum** are also widely used basic aggregation operators. The minimum gives the smallest value of a set, while the maximum gives the greatest one. They do not give a representative "middle value", but they can be very meaningful in different contexts.

Like for the arithmetic mean, also minimum and maximum can have a weighted version. Introducing weights in these formulas is not as straightforward as for the arithmetic mean, this causes the presence of different solutions for this issue. The most widely used **weighted maximum and minimum** formulas are those proposed by Yager [Yager, 1981], where weights are $\in [0, 1]$:

$$\min^{\oplus}_{w_1,\ldots,w_n}(x_1, \ldots, x_n) = \min_{i=1}^{n}[\max(1 - w_i, x_i)] \tag{3.5}$$

$$\max^{\oplus}_{w_1,\ldots,w_n}(x_1, \ldots, x_n) = \max_{i=1}^{n}[\min(w_i, x_i)] \tag{3.6}$$

From the weighting point of view, these two operators have interesting properties. For instance, if a weight w_i equals zero then the argument x_i will not be taken into account in the aggregation. Also, by setting all weights to the same value, the usual minimum and maximum can be obtained.

3.2.2 Generalized mean

More than the simple means and aggregations seen in the previous chapter, other "classical" means can be introduced by explaining the set of **Pythagorean means** (or quasi-arithmetic means) which is composed by the Arithmetic mean (which was already introduced in the previous section), the **Geometric mean**, and the **Harmonic mean** reported below:

$$M_G(x_1, \ldots, x_n) = \sqrt[n]{\prod_{i=1}^{n} x_i} \tag{3.7}$$

$$M_H(x_1, \ldots, x_n) = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}} \tag{3.8}$$

The presented Pythagorean means altogether with all other possible quasi-arithmetic means are generalized by the Generalized mean which has been studied in detail by Kolmogorov [Kolmogorov, 1930] and by Aczel [Aczel, 1948], [Aczel, 1966] and is defined as follows :

$$M_p(x_1, \ldots, x_n) = \left(\frac{1}{n} \sum_{i=1}^{n} x_i^p \right)^{\frac{1}{p}} \tag{3.9}$$

Where p is is a non-zero real number. The geometric mean (3.7) is the particular case where $p \to 0$ while the harmonic mean (3.8) is the particular case where $p = -1$.

3.2.3 Ordered Weighted Average

Another interesting generalizing operator is the **Ordered Weighted Averaging** (OWA), originally introduced by Yager in [Yager, 1988] to provide a way for aggregating scores associated with the satisfaction of multiple criteria, which unifies in one operator the *conjunctive* (i.e. all criteria are important) and *disjunctive* (i.e. only some, or at least one, criteria are important) behaviors.

$$\text{OWA}(x_1, \ldots, x_n) = \sum_{i=1}^{n} w_i \cdot x_{\sigma(i)} \tag{3.10}$$

Where σ is a permutation that orders the elements $x_{\sigma(1)} \leq \ldots \leq x_{\sigma(n)}$ and all the weights w_i are non negative summing up to one.

The OWA operator provides a parameterized family of aggregation operators, which include many of the well-known operators such as the maximum (last weight set to 1 all others 0), the minimum (first weight set to 1 all others 0), the k-order statistics (k^{th} weight set to 1 all others 0) and the arithmetic mean (all weights set to $\frac{1}{n}$). All of these operators can be achieved by simply using the correct set of weights.

The OWA operator is commutative, monotone, idempotent and it has a compensatory behavior meaning that the obtained value is always between maximum and minimum. Since this operator generalizes the minimum and the maximum, it can be seen as a parameterized formula which can slide from the min to the max. In this context Yager introduced in [Yager, 1988] a degree of *maxness* (initially called *orness*) which is used to assess a particular set of weights and determine its proximity to the maximum operator:

$$\text{maxness}(w_1, \ldots, w_n) = \frac{1}{n-1} \sum_{i=1}^{n} w_i \cdot (n-i) \tag{3.11}$$

Noting that, the *maxness* of $(1, 0, \ldots, 0)$, representing the maximum, is 1 and the *maxness* of $(0, \ldots, 0, 1)$, representing the minimum, is 0.

Another operator, also introduced by Yager in [Yager, 1988], which can be used as an assessment indicator for the set of weights, is the *dispersion* which describes the degree of dispersion of the weights based on the idea of entropy. This operator evaluates the degree with which all factors are equally taken into account.

$$\text{dispersion}(w_1, \ldots, w_n) = -\sum_{i=1}^{n} w_i \cdot ln(w_i) \tag{3.12}$$

3.3 Fuzzy logic

The notion of *fuzzy logic* and *fuzzy sets* were introduced by Lotfi Zadeh in [Zadeh, 1965] as a formalization of vagueness. The basic idea concerns the fact that a predicate may apply to an object in a not absolute way, but rather to a certain degree, e.g. who can say if a person is part of the set of tall persons or if a movie is part of the interesting movies? These inclusion problems are very likely to happen in real life but are almost not treatable with classical bivariate *crisp* logic. Fuzzy logic is in fact a multi-valued logic (i.e. a logic which admits truth values different from "true" and "false") characterized by a continuous truth degree space usually corresponding to the whole interval $[0, 1]$. Furthermore, when linguistic variables are used, the membership degrees may be managed by specific functions called *membership functions* and usually denoted by the μ symbol. In Figure 3.3 membership functions for the crisp and fuzzy interpretations of the "tall persons" example are reported.

Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. Formally, given a set U (i.e. Universe) whose generic elements are denoted by x, a fuzzy set A in U is characterized by a membership function $\mu_A(x)$ which associates with each element in U a real number in $[0, 1]$. Then the fuzzy set A is usually denoted by the set of pairs:

$$A = \{x, \mu_A(x), x \in U\} \tag{3.13}$$

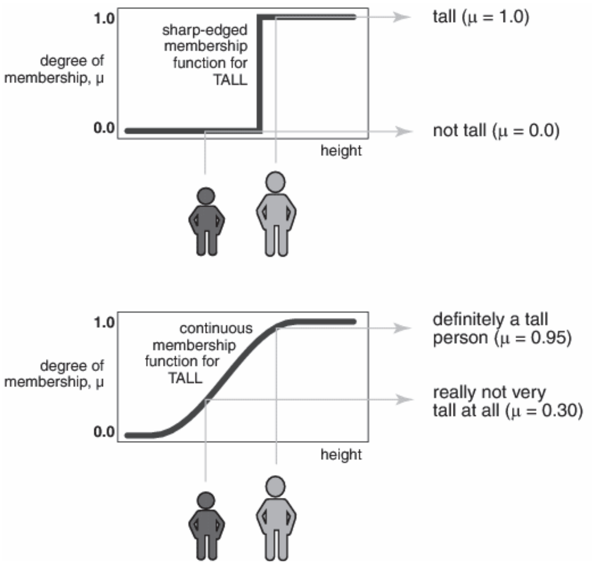

Figure 3.3: Crisp and fuzzy membership functions for the set of "tall persons"

For a classical crisp set:

$$\mu_A(x) = \begin{cases} 1 & \text{iff } x \in A \\ 0 & \text{iff } x \notin A \end{cases} \tag{3.14}$$

Other characterizations of classical crisp sets can be translated in the fuzzy environment. For example the formalizations of the concepts of *complement* and *cardinality* of the fuzzy set A are reported below:

$$\mu_{\overline{A}}(x) = 1 - \mu_A(x), x \in U \tag{3.15}$$

$$|A| = \sum_{x \in U} \mu_A(x) \tag{3.16}$$

It s important to note that membership degrees are not probabilities. This can be perceived by noting that the probabilities related to a finite set must sum up to one which is absolutely not true in fuzzy sets theory.

An important role in fuzzy logic is played by set-theoretic operations related to fuzzy sets. The notions of intersection and union can be translated into fuzzy sets as explained by Zadeh in [Zadeh, 1965]. In his work Zadeh utilizes the minimum and maximum aggregation operators to mimic respectively intersection and union. In a later publication Bellman and Giertz [Bellman & Giertz, 1973] pointed out that intersection and union can be logically interpreted as "AND" and "OR" and gave a formal justification for the use of minimum and maximum. Many other successive papers (e.g. [Dubois & Prade, 1984], [Dubois & Prade, 1985], [Zimmermann, 1985] and [Zimmermann, 1987]) treated the argument and explains that minimum and maximum, representing conjunction and disjunction, can be substituted respectively by any *T-norm* and any *T-conorm* which will be further investigated in the next section.

3.3.1 T-norms and T-conorms

The concept of *Triangular norm* was first introduced by Menger [Menger, 1942] in order to generalize the triangular inequality of a metric. The concept of a triangular norm was introduced by Menger [40] in order to generalize the triangular inequality of a metric. The current notion of a *t-norm* and its dual operator (*t-conorm*) is due to Schweizer and Sklar [Schweizer & Sklar, 1960], [Schweizer & Sklar, 1983]. Both of these operations are widely used as a generalization of the Boolean logic connectives to multi-valued logic. The *t-norms* generalize the conjunctive "AND" operator and the *t-conorms* generalize the disjunctive "OR" operator. This situation allows them to be used to define the intersection and union operations in fuzzy logic. Bonissone [Bonissone, 1985] investigated the properties of these operators with the goal of using them in the development of intelligent systems. T-norms and t-conorms have been well-studied and very good overviews and classifications of these operators can be found in the literature, see [Klir & Folger, 1988], [Dubois & Prade, 1985]. A particular complete work is presented in a book [Klement *et al.*, 2000] explicitly dedicated to these operators.

From a formal point of view the definition of a **T-norm** is as follows:

A *t-norm* is a function $T : [0,1]X[0,1] \rightarrow [0,1]$, having the following properties:

$$T(x,y) = T(y,x) \qquad \text{Commutativity} \tag{3.17}$$

$$T(x,y) \leq T(u,v), \text{ if } x \leq u \text{ and } y \leq v \qquad \text{Monotonicity (increasing)} \tag{3.18}$$

$$T(x,T(y,x)) = T(T(x,y),z) \qquad \text{Associativity} \tag{3.19}$$

$$T(x,1) = x \qquad \text{One as neutral element} \tag{3.20}$$

The formal definition of the dual **T-conorm** is:

A *t-conorm* is a function $S : [0,1]X[0,1] \rightarrow [0,1]$, having the following properties:

$$S(x,y) = S(y,x) \qquad \text{Commutativity} \tag{3.21}$$

$$S(x,y) \leq S(u,v), \text{ if } x \leq u \text{ and } y \leq v \qquad \text{Monotonicity (increasing)} \qquad (3.22)$$
$$S(x,S(y,x)) = S(S(x,y),z) \qquad \text{Associativity} \qquad (3.23)$$
$$S(x,0) = x \qquad \text{Zero as neutral element} \qquad (3.24)$$

It has to be noted that the properties of t-norms and t-conorms are almost identical, the only difference resides in the neutral element. Two important remarks regarding these functions are the following:

$$T(x,y) \leq \min(x,y) \qquad (3.25)$$
$$S(x,y) \geq \max(x,y) \qquad (3.26)$$

The first (3.25) can be proved by using monotonicity $T(x,y) \leq T(x,1)$, then by the neutral element $T(x,1) = x$ and finally commutativity says that $T(x,y) \leq T(1,y) = y$ and therefore $T(x,y) \leq \min(x,y)$. The second (3.26) can be proved in the same way by noting that $S(x,y) \geq S(x,0) = x$ and $S(x,y) \geq S(0,y) = y$ and therefore $S(x,y) \geq \max(x,y)$. These remarks are important as they demonstrate that t-norms and t-conorms cannot have any compensation behavior. *compensation* for an aggregation operator states that the aggregation result must always be bounded by the minimum and the maximum of its operands:

$$\min_{i=1}^{n}(x_i) \leq \text{Agg}(x_1,\ldots,x_n) \leq \max_{i=1}^{n}(x_i) \qquad (3.27)$$

One t-norm is said to be *associated* or *dual* with a t-conorm if they satisfy the DeMorgan law:

$$\overline{T(x,y)} = S(\overline{x},\overline{y}) \qquad (3.28)$$

Where negation is represented by the complement-to-one formula: $\overline{x} = 1 - x$.

In Table 3.1 the most widely used t-norms and the corresponding dual t-conorms are reported.

As shown in Figure 3.2 the minimum is the biggest t-norm (i.e. when using the min, we obtain a higher value than when using any other t-norm). It is also the only idempotent t-norm. Its dual, the maximum, is also idempotent and it is the smallest t-conorm. Also it is worth noting that the Drastic t-norm is the smallest t-norm and the Drastic t-conorm is the biggest t-conorm. The probabilistic case has the nice property to be "smooth", i.e. it has a continuous derivative. The Lukasiewicz t-norm satisfies the classical logical law of "non-contradiction" (i.e. $T(x,\overline{x}) = 0$). And its dual, the Lukasiewicz t-conorm, satisfies the classical logical law of the "excluded middle" (i.e. $S(x,\overline{x}) = 1$).

	t-norm	t-conorm
Min-Max	$\min(x, y)$	$\max(x, y)$
Probabilistic	$x \cdot y$	$x + y - x \cdot y$
Lukasiewicz	$\max(x + y - 1, 0)$	$\min(x + y, 1)$
Drastic	$\begin{cases} x & \text{if } y = 1 \\ y & \text{if } x = 1 \\ 0 & \text{else} \end{cases}$	$\begin{cases} x & \text{if } y = 0 \\ y & \text{if } x = 0 \\ 1 & \text{else} \end{cases}$

Table 3.1: most widely used t-norms and the corresponding dual t-conorms

3.3.2 Fuzzy integrals

As can be noted by examining Figure 3.2 on page 42, the presented aggregation operators, T-norms and T-conorms, where bounded respectively by the minimum and maximum of their operands, i.e. they all have no compensation behavior. Other operators, presented on top of figure 3.2, are instead spanning the whole gamut of possible values from 0 to 1, these aggregation operators are instead compensative operators.

The first compensative operators that will be introduced are *Sugeno* and *Choquet* integrals. Before being able to formally define these integrals some other theoretical foundations are needed as they are both based on the concept of Fuzzy measure.

3.3.2.1 Fuzzy measures

A measure μ on the set W is defined as a mapping between all the elements of the power set of W and a set of numbers. An example of a simple measure is the size of the subset. In this sense, a measure is a generalization of the concepts of length, area, volume, etc. When the measure is related to the elements of the subset by the sum (like in all of the examples above) we speak of an *additive measure*. A function $\mu(\mathcal{P}(W)) \to \mathbb{R}$ is formally an additive measure if:

$$\mu(X) \geq 0 \text{ for all } X \in \mathcal{P}(W) \qquad \text{non negativity} \tag{3.29}$$

$$\mu(\emptyset) = 0 \qquad \text{null empty set} \tag{3.30}$$

$$\mu\left(\bigcup_{i \in I} X_i\right) = \sum_{i \in I} \mu(X_i) \qquad \text{countable additivity} \tag{3.31}$$

A measure is said to be *non-additive* if it violates the last rule (countable additivity), i.e. if the value related to set under estimation is different from the sum of the measures of its components. A non -additive measure can be sub-additive if its value is less than the sum of the values of its elements and super-additive if its value is grater than the sum of the values of its elements. More than this, a measure can be defined as *monotone* if:

$$\forall X, Y \subseteq W : X \subseteq Y \Rightarrow \mu(X) \leq \mu(Y) \tag{3.32}$$

Non monotonicity can be present only when huge adversative or synergic phenomena are present between elements.

A *Fuzzy measure* is a monotone non-additive measure whose codomain is $[0, 1]$. Fuzzy measures are perfectly suitable in MCDA to deal with the issue of dependencies between criteria, this advantage comes with the complexity of defining the corresponding measure's $2^n - 1$ scores.

The discrete Sugeno and Choquet integral

The formal definition of the *discrete Sugeno integral* of scores $x_1, \ldots, x_n$ for the criteria $c_1, \ldots, c_n$ with respect to a fuzzy measure μ is defined as:

$$\mathrm{Sug}_\mu(x_1, \ldots, x_n) = \max_{i=1}^{n}(\min(x_{\sigma(i)}, \mu(C_{\sigma(i)}))) \tag{3.33}$$

Where σ is a permutation that organizes elements in ascending order (i.e. $x_{\sigma(1)} \leq \ldots \leq x_{\sigma(n)}$) and $C_{\sigma(i)} = \{c_{\sigma(i)}, \ldots, c_{\sigma(n)}\}$.

Under the same prerequisites the *discrete Choquet integral* is defined as:

$$\mathrm{Cho}_\mu(x_1, \ldots, x_n) = \sum_{i=1}^{n}(x_{\sigma(i)} - x_{\sigma(i-1)}) \cdot \mu(C_{\sigma(i)}) \tag{3.34}$$

With the same notation as before and $x_{\sigma(0)} = 0$.

Both *Sugeno* and *Choquet* integrals are monotone, continuous, idempotent operators, with a compensation behavior. The *Choquet* integral is stable under positive linear transformation ($f'(x) = af(x) + b$ with $a > 0$), while the *Sugeno* integral is stable under a similar transformation with minimum and maximum replacing the product and the sum respectively ($f'(x)$ =max(min$(a, f(x)), b)$ with $a > 0$). This last property points out that the *Sugeno* integral is more suitable for ordinal aggregation (where only the order of the elements is important) while the *Choquet* integral is suitable for cardinal aggregation (where the distance between the numbers has a meaning). The commutativity is only obtained when the fuzzy measure strictly depends on the cardinality of the sets, i.e. $\mu(A) = \mu(B)$ if $|A| = |B|$. The associativity is usually not satisfied.

The generalization capability of the *Choquet* and *Sugeno* integrals is remarkable. Both contain the k-order statistics and in particular the minimum and the maximum. The *Choquet* integral generalizes the weighted means and the OWA operator, while the *Sugeno* integral generalizes the weighted minimum and maximum.

3.3.3 Compensatory operators

Another class of aggregation operators which are also compensative are the so called *compensatory operators*. They were first introduced by Zimmerman and Zysno in [Zimmermann & Zysno, 1980], then Tursken in [Turksen, 1992] generalized the first formalization proposed by Zimmerman and Zysno. Below are the original Zimmerman and Zysno definition of *compensatory operator* followed by the generalized *exponential compensatory operator* refined by Tursken:

$$Z_\lambda(x_1, \ldots, x_n) = \left(\prod_{i=1}^{n} x_i\right)^{1-\lambda} \cdot \left(1 - \prod_{i=1}^{n}(1 - x_i)\right)^{\lambda} \quad (3.35)$$

$$E_\lambda^{T,S}(x_1, \ldots, x_n) = (T(x_1, \ldots, x_n))^{1-\lambda} \cdot (S(x_1, \ldots, x_n))^{\lambda} \quad (3.36)$$

Where T and S are respectively a t-norm and t-conorm.

Tursken also proposed another type of compensatory operator, the *convex-linear compensatory operator*:

$$L_\lambda^{T,S}(x_1, \ldots, x_n) = (1 - \lambda) \cdot T(x_1, \ldots, x_n) + \lambda \cdot S(x_1, \ldots, x_n) \quad (3.37)$$

In both cases the parameter λ indicates the degree of compensation. It is always not simple to set the correct value for λ, in [Yager & Rybalov, 1988] Yager and Rybalov proposed a method based on fuzzy modeling techniques to compute it by defining $T(x_1, \ldots, x_n)$ as highness and $T(1 - x_1, \ldots, 1 - x_n)$ as lowness:

$$\lambda = \frac{T(x_1, \ldots, x_n)}{T(x_1, \ldots, x_n) + T(1 - x_1, \ldots, 1 - x_n)} \quad (3.38)$$

3.3.4 Uninorms

The last compensatory operator presented is the *uniform aggregation operators* (uninorm). It was introduced by Fodor, Yager and Rybalov in [Fodor *et al.*, 1997] as a generalization of both t-norms and t-conorms. This operator has a neutral element laying anywhere in the unit interval rather than at one or zero as for the t-norms and t-conorms respectively. The formal definition of the *uninorm* function U is as follows:

$$U(x, y) = U(y, x) \quad \text{Commutativity} \tag{3.39}$$

$$U(x, y) \leq U(u, v), \text{ if } x \leq u \text{ and } y \leq v \quad \text{Monotonicity (increasing)} \tag{3.40}$$

$$U(x, U(y, x)) = U(U(x, y), z) \quad \text{Associativity} \tag{3.41}$$

$$\exists e \in [0, 1] \text{ s.t. } \forall x \in [0, 1]\ U(x, e) = x \quad e \text{ as neutral element} \tag{3.42}$$

The first three properties are identical to those from t-norms and t-conorms, but the fourth condition is more general in the case of uninorms, in fact it allows any value to be the neutral element. The interesting quality of *uninorms* (a part from those related to commutativity, monotonicity and associativity) is related to its neutral element as it can be considered as the score that we would give to an argument which should not have any influence in the aggregation, it is somehow a "null vote".

3.3.5 Fuzzy inference systems

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. A *Fuzzy Inference System* (FIS) is a system aided at applying a fuzzy inference process. A FIS is composed by three basic steps: *fuzzification*, *inference*, *defuzzification* as reported in Figure 3.4.

Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. Because of their multidisciplinary nature, fuzzy inference systems are associated with a number of names, such as fuzzy-rule-based systems, fuzzy expert systems, fuzzy modeling, fuzzy associative memory, fuzzy logic controllers, and simply (and ambiguously) fuzzy systems.

Fuzzification

As stated in section 3.3 every fuzzy set has an associated membership function which determines whether an element should be part of the set and the degree of its membership. Membership functions can be very different one from each other, ranging from simple piecewise linear functions to more complex curves. Figure 3.5 reports examples of the most widely used linear and continuous membership functions.

A single variable may belong to different fuzzy sets, this is the case for example for the height of a person, one person can in fact be part of the "small persons", "medium persons" or "tall persons". In FISs the fuzzy sets which are used to evaluate the originally crisp variables are represented by lexical labels. By putting together in a single graph the membership functions of all the fuzzy sets which are part of the

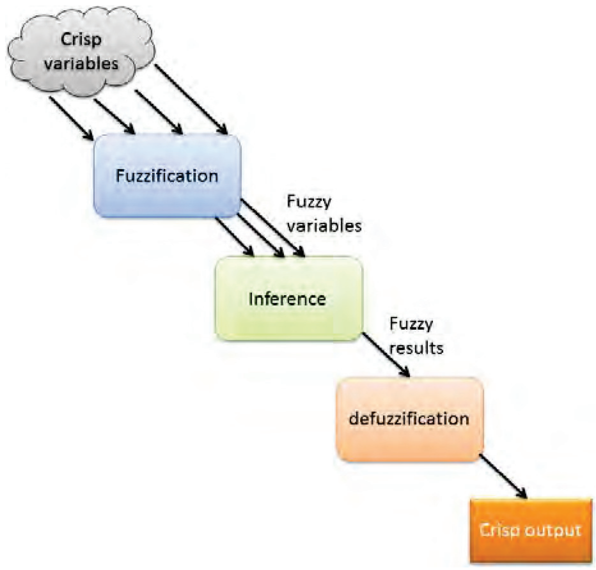

Figure 3.4: Architecture of a *Fuzzy Inference System*

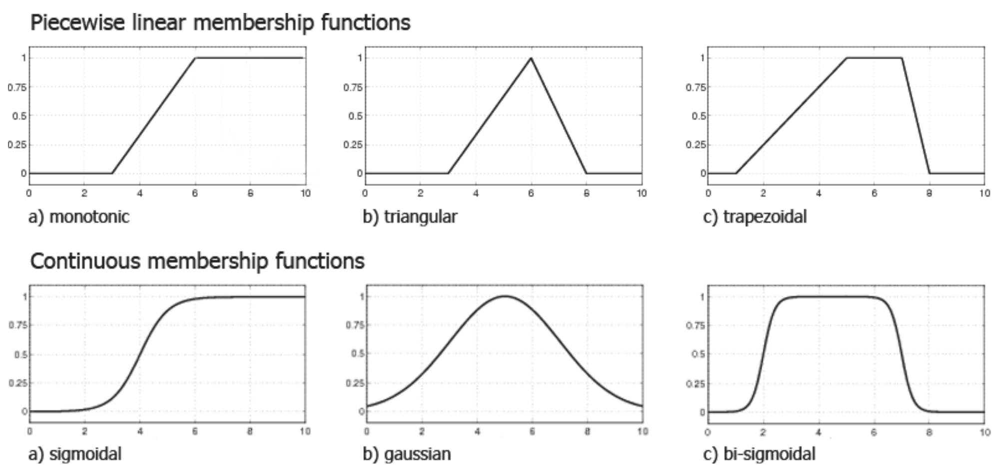

Figure 3.5: Examples of the most widely used linear and continuous membership functions

same concept (e.g. level of tallness), like in Figure 3.6, we obtain a single way to assign one or more (usually two) lexical labels to the variable of concern, this is what is called *fuzzification*.

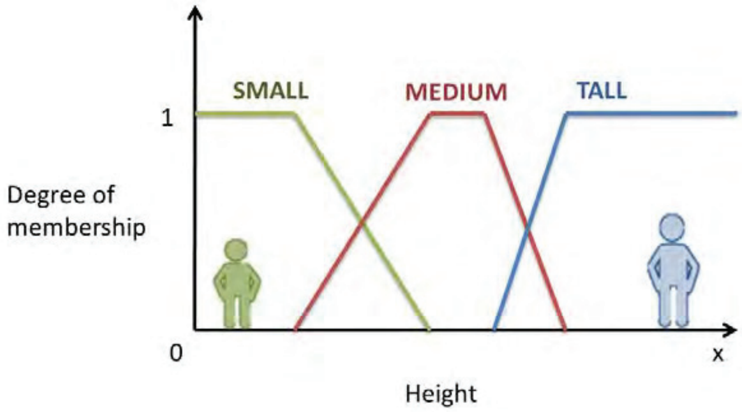

Figure 3.6: Fuzzification graph for the variable height

Inference

Once all the input variables have been fuzzified the inference part of the FIS must be applied. This step of the procedure is related to the logic which has to be modeled by the system. The inference is obtained by the application of a set of *inference rules* to the fuzzified inputs. An inference rule is a logical proposition of the form:

IF <*antecedent*>THEN <*consequent*> (3.43)

where *antecedent* and *consequent* are both linguistic variables (i.e. statements like "Alex is tall"). In the most general case antecedents are composed by many linguistic variables (propositions) connected by the basic logical connectives NOT ($\neg$), AND ($\wedge$) and OR ($\vee$). By using the membership degrees evaluated in the previous step, a degree of truth γ can be assigned to each proposition contained in the antecedent of each inference rule. By aggregating these many degree of truth the degree of truth of the consequent (or equivalently the degree of truth of the rule) is evaluated. In order to aggregate the antecedents the logical connectives are replaced by the corresponding t-norms and t-conorms originating from the set-theoretic operations on fuzzy sets implementing AND and OR, which are respectively *intersection* and *union*. For a general fuzzy inference set of m rules for n input variables $(x_1, \ldots, x_n)$, an output variable y, $(m \cdot n)$ input fuzzy sets $(A_{1,1}, \ldots, A_{m,n})$ and m output fuzzy sets $(B_1, \ldots, B_m)$ like the one reported below:

$$R_1 \quad : \quad \text{IF } (x_1 \text{ is } A_{1,1}) \ldots [\ \{\text{AND}|\text{OR}\}[\text{NOT}]\ (x_n \text{ is } A_{1,n})\ ] \text{ THEN } (y \text{ is } B_1) \tag{3.44}$$

$$\vdots$$

$$R_m \quad : \quad \text{IF } (x_1 \text{ is } A_{m,1}) \ldots [\ \{\text{AND}|\text{OR}\}[\text{NOT}]\ (x_n \text{ is } A_{m,n})\ ] \text{ THEN } (y \text{ is } B_m) \tag{3.45}$$

the corresponding evaluation formulae for the logical connectives of the generic i^{th} inference rule are reported in Table 3.2 below where T and S represent a t-norm and a t-conorm respectively.

NOT	$\overline{\gamma_i} = 1 - \gamma_i$
AND	$\gamma_i = T(\mu_{A_{i,j}}(x_j))\ \forall j = 1, \ldots, n$
OR	$\gamma_i = S(\mu_{A_{i,j}}(x_j))\ \forall j = 1, \ldots, n$

Table 3.2: Evaluation formulae corresponding to logical connectives in inference rules

Once suitable t-norms and t-conorms (usually min and max respectively) have been selected, degrees of truth for the antecedents of each inference rule can be evaluated. A graphical representation of this process, in the case of deciding the amount of a tip for a restaurant, is reported in Figure 3.7.

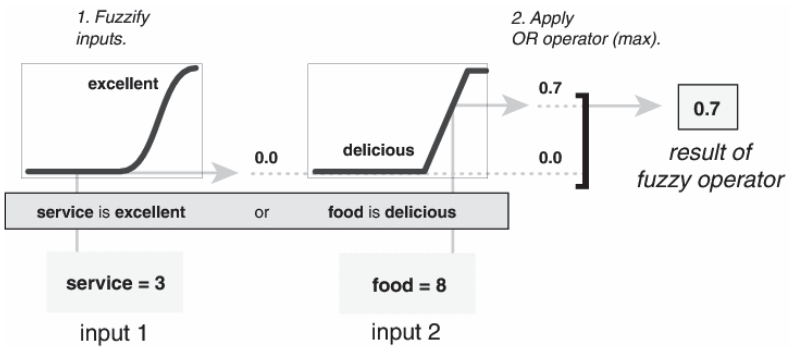

Figure 3.7: OR connective applied to antecedents in the case of deciding the amount of tip for a restaurant. The degree of truth of the proposition "service is excellent" evaluates to 0.0, the one of "food is excellent" to 0.7, the OR connective is performed by the use of the maximum operator and therefore the result for the amount of a tip is 0.7

If the inference system is composed by more than one rule then a single degree of truth for the consequent y must be evaluated by aggregating the consequents' degrees of truth from all rules. Many aggregation methods can be used, the most widely used and famous methods are: *Mamdani* [Mamdani & Gaines, 1981], *Takagi-Sugeno* also known as *Takagi-Sugeno and Kang (TSK)* [Takagi & Sugeno, 1985], [Sugeno & Kang, 1988] and *Tsukamoto* [Tsukamoto, 1979]. These methods have the same basic structure for the definition and evaluation of the degree of truth of the antecedents but differ in the definition and evaluation of degree of truth of the consequent.

Mamdani's fuzzy inference method is the most commonly used fuzzy methodology. In this case the consequents of the inference rules are membership functions of the output variable y. In order to evaluate the overall output membership function a two steps procedure is applied: 1) consequents' membership functions are upper bounded to the level derived from the degree of truth of the antecedents; and 2) all the obtained consequents' membership functions are aggregated into one single overall output membership function. One single crisp output can be obtained from the overall output membership degree function by means of *defuzzification*, this procedure will be explained in the next section. The first step simply concerns a cut-off of the membership function of the consequent, as far as the second step is concerned, there are many ways to aggregate such functions, the most widely used is simply to keep the maximum value as depicted in figure 3.8 where for each row, the consequents, whose membership degree function is reported in column 2, are upper bounded by the maximum of the antecedents' degrees of truth. Then, in column 3, all of the consequents' cut-off membership degree functions are aggregated by taking their maximum values.

The *Takagi-Sugeno and Kang (TSK)* method is completely different from the precedent *Mamdani*'s one. In fact its consequents are not structured as membership functions but rather they are functions of the inputs $f(x_1, \ldots, x_n)$; very often these functions are just constants, in other cases are linear or polynomial functions as in the example below:

$$\text{IF } (x_1 \text{ is } A_1) \text{ AND } (x_2 \text{ is } A_2) \;\; \text{THEN } (y = p\, x_1 + q\, x_2 + r) \tag{3.46}$$

The overall output of the system is obtained by just performing a weighted average of the consequents (which can be calculated regardless of the antecedents) by using the degree of truth γ of their antecedents as weights as reported in the following equation:

$$y = \frac{\sum_{i=1}^{m} (\gamma_i \cdot f_i(x_1, \ldots, x_n))}{\sum_{i=1}^{m} \gamma_i} \tag{3.47}$$

As obvious, the result of a *TSK* inference rules aggregation is already in the form of a crisp value, this means that no *defuzzification* is necessary.

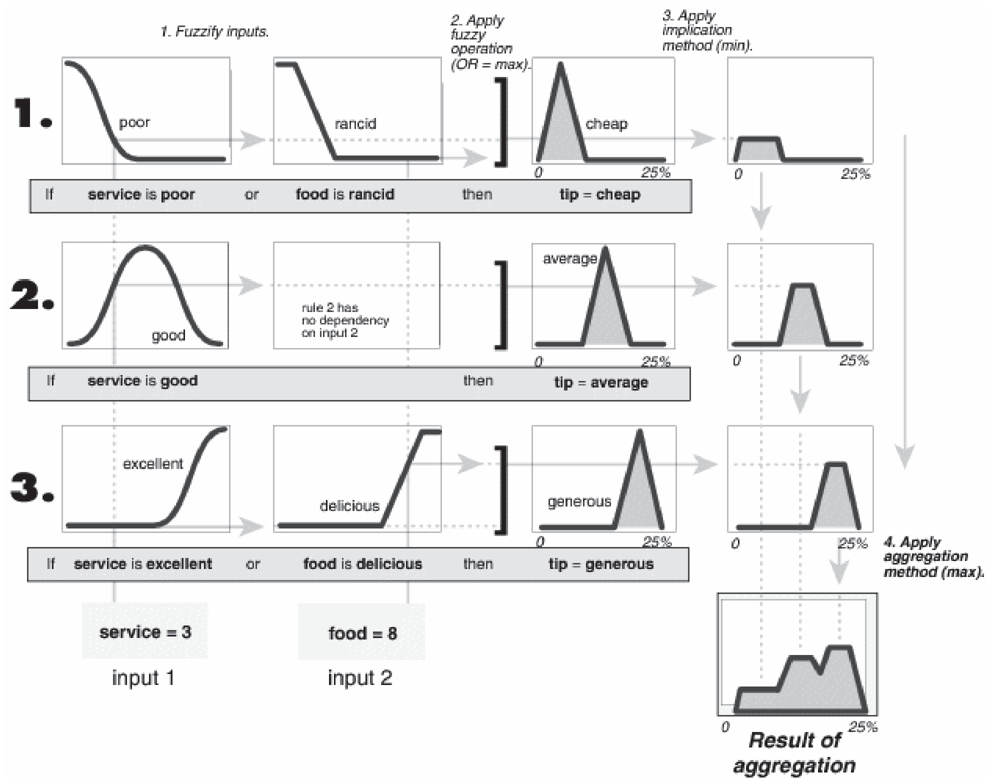

Figure 3.8: Example of the Mamdani aggregation of inference rules applied to the selection of the correct amount of tip in a restaurant. For each row, the consequents, whose membership degree function is reported in column 2, are upper bounded by the maximum of the antecedents' degrees of truth. Then, in column 3, all of the consequents' cut-off membership degree functions are aggregated by taking their maximum values.

The last presented method is the *Tsukamoto* method. This method is a kind of mesh-up between *Mamdani*'s and *TSK*'s methods. In this case the consequents are again in the form of membership functions, as in the *Mamdani*'s method, but, more than this, they must be monotonic functions (e.g. piecewise linear monotonic functions or sigmodal functions, see Figure 3.5). In this way, for each degree of truth of the antecedents there is only one corresponding value in the consequent. The last step of the process concerns the calculation of the output value which is obtained, as in the *TSK* method, by the weighted sum of the consequents (see Equation (3.47)). Again like in the *TSK* case, *Tsukamoto* method does not need a *defuzzification* step.

Defuzzification

The last step of a FIS is called *defuzzification* and its aim is to obtain a single crisp value from a membership function. This step is basically related to *Mamdani*'s inference rules aggregation method but it can be applied in every situation which concerns the same issue.

The most widely adopted *defuzzification* techniques are: *Center of gravity (COG)* (also known as *centroid* method) and the *Mean of maxima (MeOM)*. *COG* is probably the best known defuzzification operator. It is a basic general defuzziffication method that computes the center of gravity of the area under the membership function. Formally, given a fuzzy set B and its corresponding membership function μ_B the *COG* fot the universe $Y = \{y_1, \ldots, y_n\}$ is defined as:

$$\mathrm{COG}(\mu_B) = \frac{\sum_{y_{min}}^{y_{max}} y \cdot \mu_B(y)}{\sum_{y_{min}}^{y_{max}} \mu_B(y)} \tag{3.48}$$

The *MeOM* method is derived from *COG*. In order to better understand the *MeOM* method, first, the concept of *core* of a fuzzy set must be defined. The set of elements having the largest degree of membership in B is called the *core* of B. Formally:

$$\mathrm{core}(B) = \{y | y \in Y, \neg(\exists x \in Y) \text{ s.t. } (\mu_B(x) > \mu_B(y))\} \tag{3.49}$$

The *MeOM* simply calculates the mean of all elements of the *core* of a fuzzy set, which in fact equals the *COG* of the *core*:

$$\mathrm{MeOM}(\mu_B) = \frac{\sum_{y \in \mathrm{core}(\mu_B)} y}{|\mathrm{core}(\mu_B)|} \tag{3.50}$$

3.3.6 Probabilistic interpretation

Since the introduction of fuzzy logic by Zadeh in [Zadeh, 1965] an underlying dispute is ongoing on whether or not fuzzy logic can be just "probability theory in disguise". Zadeh himself claimed that probability is inadequate to capture what is usually treated by fuzzy theory since his first definition of fuzzy logic and still he supports this idea in [Zadeh, 2002]. Although this can be accepted for standard probability theory, Coletti and Scozzafava argued in many works [Coletti & Scozzafava, 2004], [Scozzafava, 2004], [Coletti & Scozzafava, 2005] that by relaxing the standard probability theory the unification of fuzzy logic and probability can be achieved basing on subjective probability theory proposed by de Finetti in [de Finetti, 1974]. They suggest that many traditional aspects of probability theory are not so essential as they are usually considered. For example, the requirement that the set of all possible "outcomes" should be endowed with a beforehand given algebraic structure, such as a Boolean algebra or σ algebra, or the aim at getting, for these outcomes, uniqueness of their probability values.

According to Coletti and Scozzafava probability is rather seen as a *measure of belief in a given proposition.* Basically, relevant events should always be contemplated (or, similarly, assumed) but not treated as asserted propositions as clearly expressed by de Finetti [de Finetti, 1974]: "it [the meaning] is simply that of 'not known' (for You), and consequently 'uncertain' (for You), but well determined in itself.... Its true value is unique, but if You call it random this means that You do not know this true value". Coletti and Scozzafava have chosen as their proper probabilistic framework, a framework based on the concept of *conditional* event and on the ensuing concept of *coherent conditional probability.* Basically, in such context, fuzzy logic membership functions can be interpreted as coherent conditional probabilities. Formally, a coherent conditional probability $P(E_\phi|A_x)$ measures how much You, given the event $A_x = \{X = x\}$, are willing to claim the property ϕ, which perfectly describes a membership function for the fuzzy set E_ϕ.

Chapter 4

Modelkey

In this chapter is reported a presentation of the Modelkey project and its related DSS. This because my PhD studies has been strictly related to this project, in fact my objective of finding the most suitable MCDA based algorithms in order to perform risk assessment and improve environmental DSSs has been put into practice through the development of this project. The project was inspired by the demands of the EU Water Framework Directive 2000/60/CE (WFD) [EC, 2000] for a good ecological status of European surface waters by 2015 and by the actual lack of tools for the assessment of the causes of impaired aquatic ecosystems. I've been involved in this project since its early stages. I participated to the initial meetings concerning the study of feasibility and the functional requirements; the conception of the software architecture has started during those meetings. After this first stage I've been studying MCDA techniques in order to discover which one should best fit in the situation of concern. The issues encountered during this phase were related to the multiplicity of heterogeneous information and the most suitable way to aggregate them into a single status evaluation. The mathematical algorithm adopted in the end, seemed to be the most adequate with regard to the environmental expert's modus operandi. Finally I've been working in the development of the DSS software prototype which has been released in early 2010 and has been downloaded and used by several users. As far as my PhD studies are concerned the development of the software prototype has been useful in order to discover the real issues related to the development of a GIS based DSS.

4.1 The Modelkey DSS

In the light of the WFD requirements illustrated in Section 1.1.1, a series of consecutive tasks has to be accomplished by water managers starting from reference conditions identification, pressures and impacts analysis, environmental monitoring, chemical and ecological status classification, setting of environmental objectives, selection of management measures, and leading to the production of the River Basin Management Plan (RBMP) in 2009. In this context, the DPSIR (Driving forces, Pressures, State, Impacts, Responses) framework developed by the European Environment Agency [EEA, 2003] (refer to Appendix B) has been identified as suitable in the implementation of the WFD since many of the tasks required by the Directive refer directly to the elements of the DPSIR framework. In particular, Rekolainen et al. [Rekolainen *et al.*, 2003] have proposed a modified scheme for the implementation of the WFD, called DPCER, where the State and Impacts indicators are substituted with the Chemical state and the Ecological state, respectively.

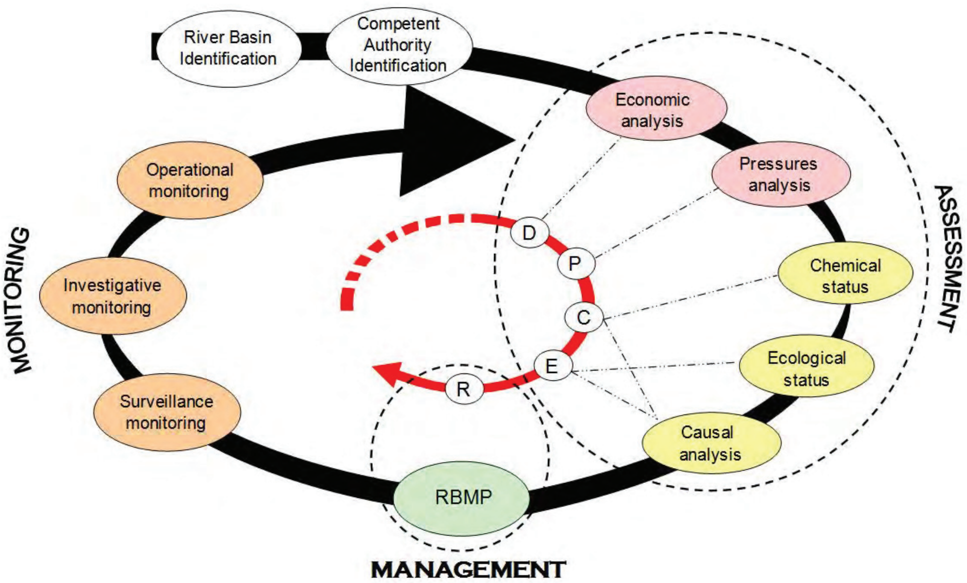

Figure 4.1: Integration of WFD Management Planning Cycle and DPCER scheme [Rekolainen *et al.*, 2003]. D = Driving forces; P = Pressures; C = Chemical state; E = Ecological state; R = Responses; RBMP = River Basin Management Plan.

As shown in Figure 4.1, such a scheme specifically addresses the assessment phase of the Management Planning Cycle by identifying Driving forces, Pressures, Chemical state and Ecological state, while the production of the RBMP required in the management phase corresponds to the identification of the Responses. Considering both the DPSIR framework adopted by the EEA (2003) and the DPCER scheme outlined by Rekolainen et al. (2003) for supporting the WFD implementation, a risk-based

DPSIR framework is proposed by the MODELKEY project, as reported in [Gottardo, 2008], for river basins assessment and management. fulfilling each element by means of risk-based methodologies and tools. The subsequent framework, is the one adopted inside the Modelkey DSS.

The first phase of the risk-based DPSIR framework aims at identifying significant Driving forces (D), pressures (P) and related potential impacts (hazard) on river basins with the ultimate goal of estimating the risk that water bodies will fail to achieve the good ecological status required by 2015. To this end, both socio-economic information on trends in key economic drivers and environmental data on current quality status and vulnerability of water bodies are needed. In order to achieve this objective the Regional Risk Assessment (RRA) approach [Landis, 2005] is suggested since it is able to provide a relative ranking of areas, stressors and receptors along river basins by integrating two components, i.e. sources and stressors spatial distributions with vulnerability assessments.

The second phase of the framework focuses on evaluating the Status (S) of water bodies in order to detect potential risk situations along river basins caused by priority substances or other pollutants measured in water column, sediment or biota tissues on aquatic organisms. This sort of screening assessment at basin scale needs ecotoxicological data quantifying toxic or carcinogenic effects caused by chemicals on generic aquatic species. In this framework it is proposed to aggregate ecotoxicological data referred to different organisms by applying the probabilistic approach of Species Sensitivity Distributions (SSD) [Posthuma *et al.*, 2002] in order to derive risk-based Environmental Quality Standards (EQS). Consequently, by comparing measured or predicted chemical concentrations with appropriate EQS it will be possible to identify substances potentially causing ecological risks.

In the third phase aiming at analyzing Impacts (I) two main objectives are identified: to evaluate the ecological status for each water body identified along river basins as required by WFD as well as to investigate causal relationships at hot-spot scale, i.e. on those areas resulting of major concerns. In both cases, a number of different quality information (i.e biological, physico-chemical, chemical and hydromorphological data) have to be integrated and evaluated in order to achieve comprehensive and confident results. To this end, in the risk-based DPSIR framework the Weight of Evidence (WoE) approach [Burton *et al.*, 2002] is suggested as it allows to evaluate environmental impacts by integrating multiple Lines of Evidence (LoE), so that the likelihood of ecosystem impairment is higher if more assessment results suggest it.

The last phase of the DPSIR risk-based framework aims at identifying and selecting adequate Responses (R), i.e. technical measures, mitigation measures or policy instruments for protecting or improving water quality of river basins in order to maintain or restore the good ecological status by 2015. This management phase needs decision-support tools guiding water managers in taking decisions on intervention alternatives, in assuring stakeholders involvement and participation, in communicating results in a transparent and simple way. To this end the development and application of a risk-based Decision Support Systems (DSS) is proposed: it is able to interlink different assessment methodologies and support tools in a comprehensive structure making the decision process flexible, repeatable, changeable, traceable and transparent. The DPSIR framework offers a structured solution to the complex assessment required by the WFD on water quality and it is implemented in the MODELKEY DSS conceptual framework as explained in the subsequent sections.

4.2 Decisional and Conceptual frameworks

When developing a DSS, a critical part of the process is the planning phase when definition of key issues, reference frameworks and objectives are set up. The *decisional* and *conceptual* frameworks illustrated in this section form the reference setting for the MODELKEY DSS software system development [Gottardo *et al.*, 2008], [Gottardo *et al.*, 2009a], [Gottardo *et al.*, 2009b], [Gottardo *et al.*, 2009c], [Semenzin *et al.*, 2010a] and [Semenzin *et al.*, 2010b]. I've been involved in the creation of such frameworks by participating actively in periodical meeting with the environmental experts involved in the project. This was crucial in my PhD experience because all of the fundamental information related to the MCDA methodology to be applied arose during these meetings. The decisional framework outlines the decisional process that allows assessing and managing river basins according to WFD regulations. In fact the decisional framework facilitates identifying and framing the problem of interest that includes the legislative context and related implementation tasks in order to tune the DSS development to management purposes. The need for the definition of a conceptual framework is two-fold. First, the conceptual framework is supportive in showing the areas of assessment covered by the final DSS and therefore it shows the usefulness and efficiency of the system to decision-makers in their assessment and management activities. Secondly, the conceptual framework gives a rationale for the internal integration of models and tools that need to be causally linked to each other, and also to the possibility of establishing positive interactions with external models and tools.

The MODELKEY DSS decisional framework outlining general phases and objectives of the river basins assessment and management process in the frame of WFD has been defined by taking into account and partially fulfilling regulations and goals of the Directive. The resulting decisional framework is visualized in Figure 4.2 which shows the different phases of the whole decisional process specifying assessment and management objectives of each phase. Moreover, it illustrates how the objectives are directly linked to the WFD articles. The phases of the MODELKEY decisional framework are: Problem Formulation, Preliminary Assessment, Integrated Assessment, Management, and Monitoring.

The Problem Formulation includes all the activities concerning the initial identification and organization of the river basin required by WFD that are preparatory

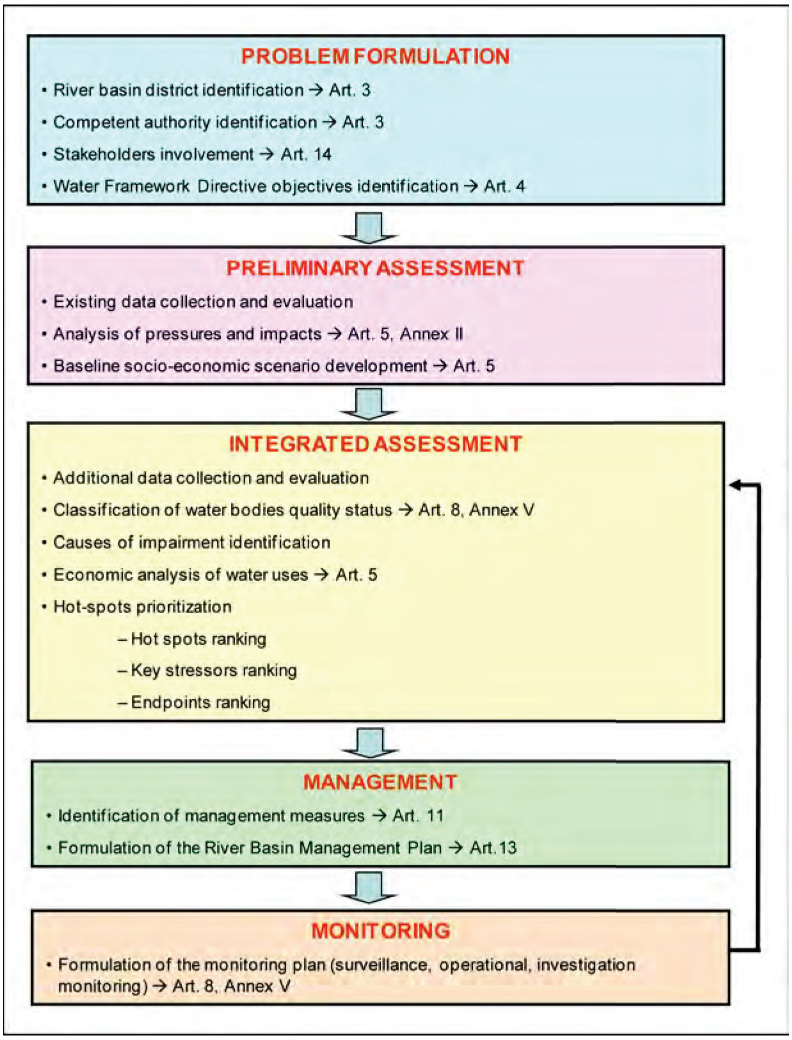

Figure 4.2: The MODELKEY decisional framework for assessment and management of European river basins in the frame of the WFD.

for the actual river basin assessment process. The main purpose of the Preliminary Assessment is to perform a first evaluation of the river basin environmental and socio-economic conditions by using only existing monitoring data and information. This way, involved decision makers will be able to identify gaps in data or knowledge as well as driving forces and pressures acting over their river basin to be focused during the next assessment activities. Moreover, based on pressures and impacts analysis results, potential reference sites for status classification can be identified and, if needed, a further sub-division of water bodies can be performed. The Integrated Assessment provides a more comprehensive and complex evaluation of the river basin conditions that could include the collection and integration of new environmental and socio-economic information. The ultimate aim is to identify and prioritize hot spots throughout river basins, i.e. sites or water bodies actually in need of immediate and consistent management interventions, thus targeting costs and efforts in an effective way. All the information collected during the Integrated Assessment is necessary for the selection and planning of the most effective solutions in the subsequent Management phase. The last phase of the MODELKEY decisional framework is the Monitoring, which is required by the WFD to accomplish two goals. On the one hand, monitoring programs support the previous assessment phases by providing new and targeted data (i.e. surveillance and investigative monitoring). On the other hand, appropriate monitoring activities can verify the effectiveness of management actions by detecting improvement or deterioration trends in the water body's status (i.e. operational monitoring).

The risk-based DPSIR conceptual framework proposed for the MODELKEY DSS is illustrated in Figure 4.3 and aims at describing in detail functions (i.e. squares), tools (i.e. parallelograms) and outputs (i.e. circles) provided by the DSS. The MODELKEY DSS specifically encompasses the whole assessment process, including both the Preliminary Assessment and the Integrated Assessment phases. The ultimate goal of the assessment process supported by the MODELKEY DSS is to assist decision makers in targeting future management actions on river basins by providing three main outputs: (i) evaluation and classification of the overall quality of sites and water bodies (both ecological and chemical status as required by WFD); (ii) evaluation and identification of the most responsible causes of impairment (i.e. key stressors and toxicants) as well as the most affected biological communities (i.e. key ecological endpoints); and (iii) identification and selection of the most critical hot spots that urgently need management measures.

In order to accomplish this task, a tiered risk-based procedure composed of the two assessment phases outlined in the decisional framework (i.e. Preliminary and Integrated Assessment) was implemented allowing end-users to make an effective use of available data at site-specific and basin scales and to refine evaluations by improving the dataset when a lack of knowledge or low confidence are highlighted. For each assessment phase one or more Integrated Risk Indices (IRI) are calculated through a risk-based integration of heterogeneous information coming from different areas of

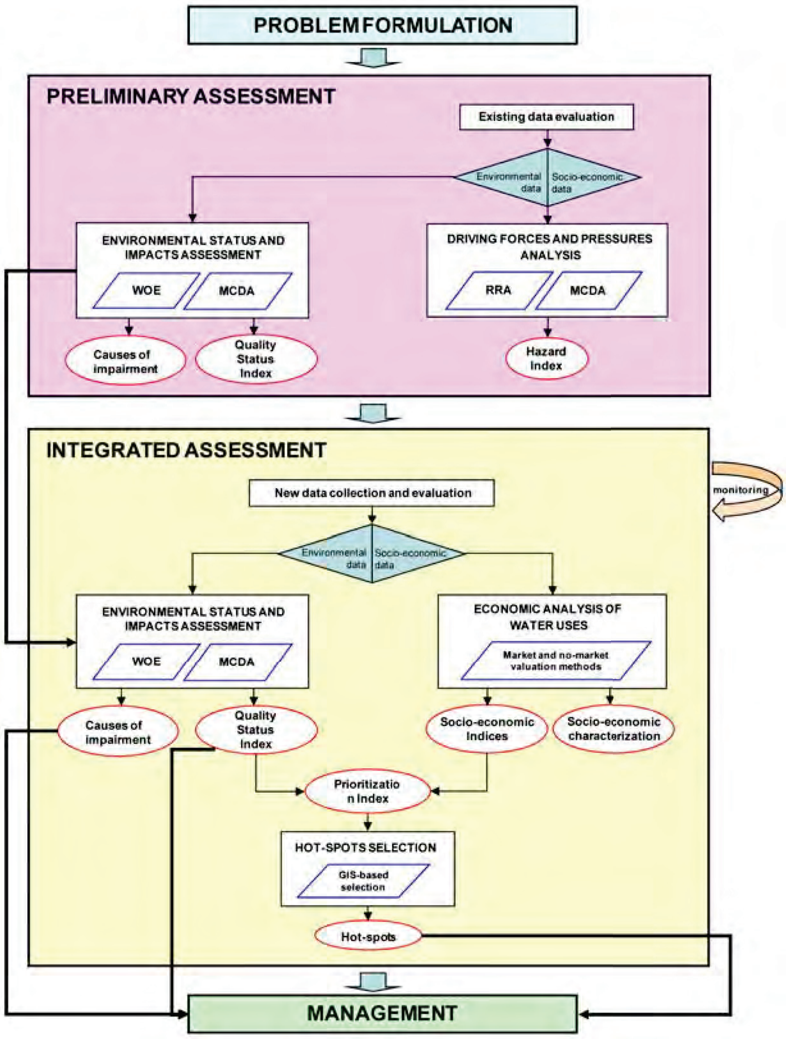

Figure 4.3: The MODELKEY DSS conceptual framework: functions (i.e. squares), tools (i.e. parallelograms) and outputs (i.e. circles) of Preliminary and the Integrated Assessment phases

investigation (i.e. ecology, ecotoxicology, chemistry, physico-chemistry, hydromorphology, economy).

Each Member State has over time carried out different monitoring programs and partly developed its own tools for fulfilling WFD requirements. In order to properly manage such diversity, the MODELKEY DSS is characterized by an "open configuration" which can use any type of relevant data, parameters and models. It provides end-users with default options, but also allows them to include their own specific tools. For this purpose, the MODELKEY DSS assessment process is based on a set of flexible IRI allowing applications on every river basin to take into account specific environmental characteristics and existing data and tools availability. The final outcome is an easy-to-use DSS supporting decision makers in assessing and managing river basins in compliance with the WFD regulations and including a procedure to normalize and integrate all the computational and experimental data.

The Driving forces (D) and Pressures (P) elements of the risk-based DPSIR framework are addressed in the Preliminary Assessment of the conceptual framework by using only existing data on the basin of interest. Practically, in the Preliminary Assessment the system first helps end-users to organize and explore existing environmental and socio-economic datasets in terms of typology, richness, spatial and temporal distribution in order to reveal needs for additional data. Subsequently, in order to identify significant driving forces and related pressures causing potential impacts (hazard) on river basins, socio-economic information on key economic drivers and sources as well as environmental data on vulnerability of water bodies are integrated according to a Regional Risk Assessment approach (RRA) [Landis, 2005] and by means of Multi Criteria Decision Analysis methods (MCDA). RRA is applied since it is able to provide a relative ranking of areas, stressors and receptors at regional scale (e.g. a river basin) by integrating the magnitude and spatial distributions of pollution sources and stressors with vulnerability assessments of receptors. The main output of this stage is the Hazard Index (HI) which highlights the most relevant pressures, the water bodies that are of greatest concern and those water bodies that might be considered as references sites.

Status (S) and Impacts (I) elements of the risk-based DPSIR framework are tackled by both phases. In the Preliminary Assessment by relying only on existing data and by using sites (i.e. sampling stations) as assessment units, in the Integrated Assessment by enlarging the datasets as needed and by considering both sites and water bodies as assessment units.

Both phases of the MODELKEY DSS conceptual framework support decision makers in evaluating and classifying the overall quality status of sites and water bodies according to the five quality classes proposed by the WFD: high, good, moderate, poor and bad. The main output is the Quality Status Index (QSI). All available environmental data and indicators are grouped into five Lines of Evidence, i.e. biology, chemistry, toxicology, physico-chemistry and hydromorphology, and aggregated in the

QSI by means of MCDA methods.

The ultimate aim of the Integrated Assessment and of the overall assessment procedure supported by the MODELKEY DSS is the prioritization of hot spots in need of immediate and consistent management interventions by using both environmental and socio-economic information. The system carries out the economic analysis of water uses by providing a socio-economic characterization of the basin of interest and by calculating a set of Socio-Economic Indices (SEI) related to different water uses (e.g. agricultural, industrial, residential, recreational, fish-farming). The SEI are developed by applying appropriate market and non-market valuation methods to purposely estimate the socio-economic importance of the water resources usage across different administrative regions. Finally, hot spots on the basin of interest are ranked by means of the Prioritization Index (PI) integrating the QSI results with the SEI results. The hot spots are visualized by means of GIS-generated maps. The last element of the DPSIR risk-based framework (R) is directly linked to the Management phase of the decisional process, as it aims to identify and select adequate responses. An adequate response would be a technical measure, mitigation measure or policy instrument that would protect or improve water quality of a river basin, so as to maintain or restore the good ecological status by 2015. This Management phase needs decision support tools to guide water managers in making decisions on intervention alternatives, to assure stakeholders' involvement and participation, and to communicate results in a transparent and simple way. The risk-based MODELKEY DSS interlinking different assessment methodologies and tools in a comprehensive structure is able to provide useful information to decision makers and to guide them in selecting the most appropriate management actions. Moreover the DSS makes the overall decisional process flexible, repeatable, changeable, traceable and transparent. The assessment process implemented by the MODELKEY DSS can be used not only for analyzing existing conditions of surface waters, but also for developing scenarios to evaluate different management alternatives. For example, some input parameters values (e.g. chemicals concentrations) could be modified according to the abatement efficiency of a set of restoration measures, to determine whether the final results will change, i.e. if the quality status of the water body of concern will actually improve. The management process recommended by WFD is cyclic: after defining the RBMP and applying the program of measures, the overall assessment procedure begins again. The purpose of iterating the process is to determine whether goals are being met after the prior round of assessment and management and, if not, to guide additional management actions. In this case all derived outputs and collected data will become new input for the first assessment phase of the MODELKEY DSS conceptual framework.

4.3 Models used by the Modelkey DSS

In this section the mathematical model adopted in the MODELKEY DSS is described. The MODELKEY DSS's model is a MAVT MCDA model based on a hierarchical structure of criteria. As shown in Figure 4.4 the hierarchy can be subdivided in three basic models: environmental, socio-economic and prioritization. Each model has a different typology of aggregation procedure based on fuzzy operators. The environmental and socio-economic models are both hierarchically structured inside, they both generate a top level status result separately starting from the basic level of indicators. The prioritization model aggregates in a last single level step values from the environmental and socio-economic modules which are not the top level status evaluation but rather lower levels results (more details will be given in section *4.3.3 Prioritization model, page 79*).

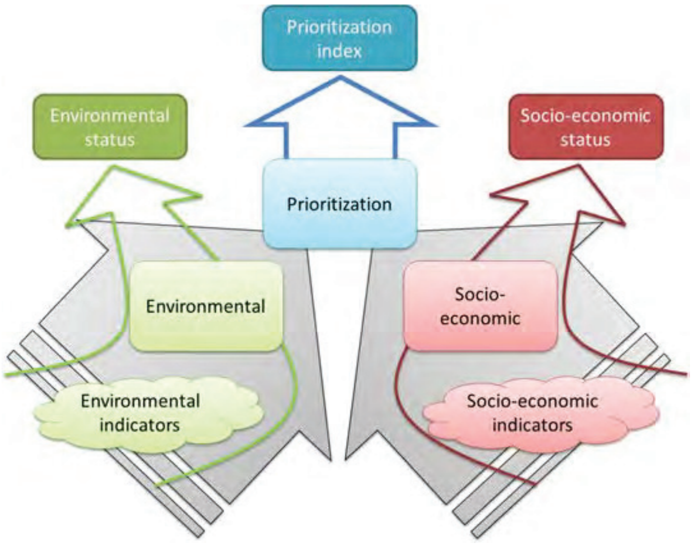

Figure 4.4: Basic models of the MODELKEY DSS' MCDA hierarchical structure

4.3.1 Environmental model

The environmental model is aimed at evaluating the Quality Status Index (QSI). QSI, also called *ecological status*, resides on the top of the assessment hierarchy reported in Table 4.1, the other levels in descending order are: 1) Lines Of Evidence (LOEs), 2) categories, 3) sub-categories 1, 4) sub-categories 2 and 5) indicators. LOEs represent the different types of environmental related aspects which could be assessed (e.g.

biology, chemistry, ecotoxicology, etc.), categories are used to elicit basic subdivisions inside the LOEs, these subdivisions are LOE specific (e.g. for the biology LOE communities are used as categories). Sub categories are used to further divide elements of the categories by taking into account their typology (subcategories are also different basing on the LOE they belong to) and finally indicators are the basic low level data which is generated by monitoring stations. For a detailed presentation of the contents of each level pleas refer to [Gottardo, 2008]. Each level of the aggregation hierarchy aggregates its elements by means of a specific aggregation operator as reported in Figure 4.5.

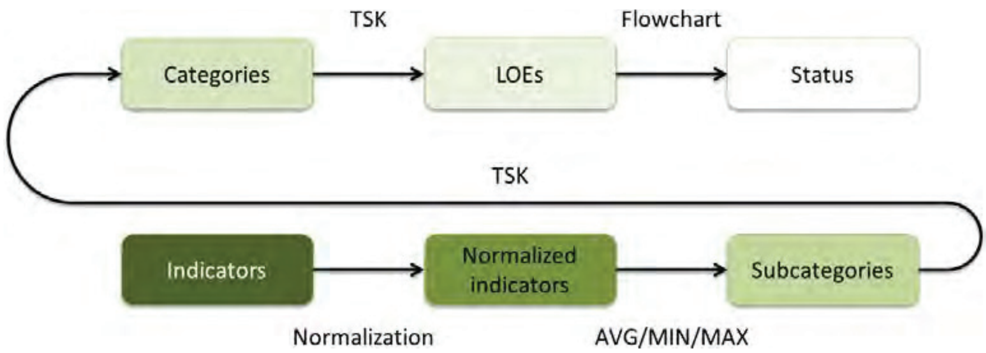

Figure 4.5: Aggregation sequence for environmental data. TSK: Takagi-Sugeno and Kang method

In the next paragraphs the aggregation procedure is examined following the natural flow of information from indicators to ecological status. My PhD work was strongly involved in this phase as I was depicted to the specification of the mathematical methodology used in the aggregation of indicators [Zabeo, 2007], [Zabeo *et al.*, 2010] and [Zabeo *et al.*, 2010]. Indicators are particular mathematical formulae which, starting from row sampled data, give as a result a numerical value emphasizing the status of the examined information from a particular point of view. Many environmental indicators exist in literature, moreover it is usual to find particular indicators perfectly suited only for their originating country (these type of indicators are created in the light of local laws). Indicators' codomains are different from each other ranging from discrete to continuous spaces and having different scales, e.g. percentages, values in $[0, 1]$ or even in $]-\infty, +\infty[$.

Normalization

The first step in the aggregation procedure is the normalization of indicators to the common $[0, 1]$ scale (see section 3.1.1). The applied normalization procedure contains interesting peculiarities which differs between indicators related to the Biology

Table 4.1: Environmental model hierarchical structure

STATUS TYPE	LINE OF EVIDENCE	CATEGORIES OF ENVIRONMENTAL INDICATORS	SUB-CATEGORIES OF ENVIRONMENTAL INDICATORS	
ENVIRONMENTAL STATUS	BIOLOGY	**Biological communities based on water body type (e.g. river)**	**Typology of impact (generic or pressure-specific)**	
		Invertebrate fauna	General degradation, eutrophication, acidification, organic pollution, hydromorphological pressure, toxic pressure	
		Fish	General degradation, eutrophication, acidification, organic pollution, hydromorphological pressure, toxic pressure	
		Phytobenthos	General degradation, eutrophication, acidification, organic pollution, hydromorphological pressure, toxic pressure	
		Phytoplankton	General degradation, eutrophication, acidification, organic pollution, hydromorphological pressure, toxic pressure	
		Macrophytes	General degradation, eutrophication, acidification, organic pollution, hydromorphological pressure, toxic pressure	
	TOXICOLOGY	**Biological communities based on water body type (e.g. river)**	**Toxicity endpoint**	**Ecological level**
		Invertebrate fauna	Acute	Cellular, individual, population
			Chronic	Cellular, individual, population
		Fish	Acute	Cellular, individual, population
			Chronic	Cellular, individual, population
		Phytobenthos	Acute	Cellular, individual, population
			Chronic	Cellular, individual, population
		Phytoplankton	Acute	Cellular, individual, population
			Chronic	Cellular, individual, population
		Macrophytes	Acute	Cellular, individual, population
			Chronic	Cellular, individual, population
	CHEMISTRY	**Nature of pollutants**	**Human pressure**	**Environmental matrix**
		Synthetic compounds	Agricolture	Water, sediment, biota
			Industry	Water, sediment, biota
			Population	Water, sediment, biota
			Transport	Water, sediment, biota
			Energy production	Water, sediment, biota
		Not synthetic compounds (e.g.metals)	Agricolture	Water, sediment, biota
			Industry	Water, sediment, biota
			Population	Water, sediment, biota
			Transport	Water, sediment, biota
			Energy production	Water, sediment, biota
	PHYSICO-CHEMISTRY	Thermal conditions		
		Oxygenation conditions		
		Nutrients conditions		
		Salinity		
		Acidification		
		Turbidity		
	HYDRO MORPHOLOGY	Hydrological regime		
		River continuity		
		Morphological conditions		

LOE and the other LOEs. This distinction can be frequently found throughout the MODELKEY DSS because, as will be further explained in the LOEs aggregation step, the Biology LOE is the most important LOE which establishes the initial outcome of the procedure which can be confirmed or not by the other LOEs, which are therefore used as checking parameters.

The normalization of the Biology's indicators is based on the concept of *reference site*. A reference site is a particular sampling site which is a priori considered in the highest possible Biological quality status for its river branch typology (different water bodies inside a single river may belong to different typologies based on their surrounding environment). Biological indicators can be either ascending or descending, meaning that the ecological quality increases as the indicator's value increases in the former case and the opposite in the latter case. For a particular indicator I and typology T, there can be multiple reference sites with their corresponding reference values $r_1, \ldots, r_n$, a single reference value r is obtained by average. By using the indicator's type (ascending or descending) the corresponding normalization function is evaluated, although in either case the function has a staircase shape, the difference resides in the way its segmentation points are evaluated. There are five ordinate values $(l_1, \ldots, l_5)$ for the staircase function, corresponding to the five quality classless identified by the WFD (i.e. BAD, POOR, MODERATE, GOOD and HIGH, see A), which are obtained by equally subdividing $[0, 1]$ and are therefore: $(0.00, 0.25, 0.50, 0.75, 1.00)$. In case of an ascending indicator, zero is taken as the minimum possible value $\underline{m}$ while r as the maximum. The range $\rho = r - \underline{m}$ is subdivided in five different subranges, by using as segmentation points four predefined percentages $(p_{1_{I,T}}, \ldots, p_{4_{I,T}})$ (expressed in the unit interval) which can be set differently on the basis of I and T by the environmental experts. Formally the normalization function $\overline{\mu}$ is:

$$y = l_{i+1} \text{ if } \psi_i \leq x < \psi_{i+1} \text{ , } i = 0, \ldots, 4 \tag{4.1}$$

Where $\psi_0 = -\infty$, $\psi_5 = +\infty$ and $\psi_j = \underline{m} + (r - \underline{m}) \cdot p_{j_{I,T}}$ for $j = 1, \ldots, 4$.

In Figure 4.6 an illustrative graph is presented where $r = 10$, $(p_1 = 0.2, p_2 = 0.4, p_3 = 0.6, p_4 = 0.8)$.

In the case of a descending indicator's type the procedure is merely the same, but the normalization function definition changes, posing $\overline{m}$ as the maximum indicator's value, the normalization function $\underline{\mu}$ is:

$$y = l_{i+1} \text{ if } \psi_{5-(i+1)} < x \leq \psi_{5-i} \text{ , } i = 0, \ldots, 4 \tag{4.2}$$

Where $\psi_0 = -\infty$, $\psi_5 = +\infty$ and $\psi_j = r + (\overline{m} - r) \cdot p_{j_{I,T}}$ for $j = 1, \ldots, 4$.

As we are in a fuzzy environment and segmentation points percentages are set by environmental experts, they cannot be treated as crisp thresholds but rather some uncertainty should be present. The methodology uses a fixed percentage of uncertainty

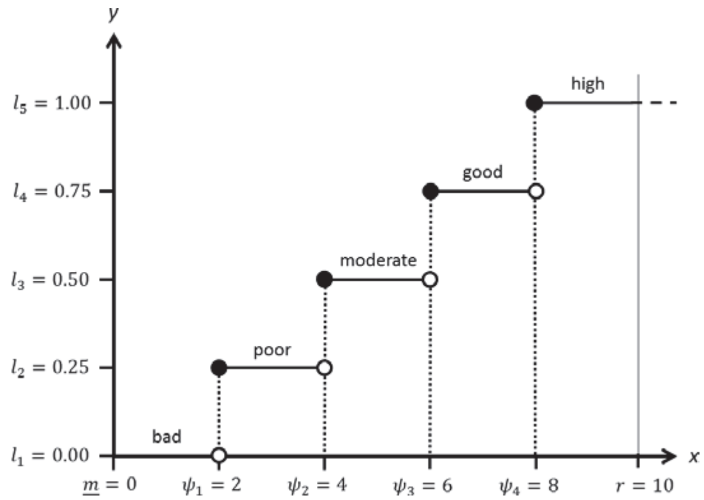

Figure 4.6: Example of a Biological indicator's normalization function

$u = 0.25$ which is used to derive new fuzzy segmentation points, this fraction of $\frac{1}{4}$ derives from the observations of [van de Bund, 2008]. In order to obtain the actual uncertainty value between all segments, a parameterized function $U_u(s_1, s_2)$ is used which takes the length of two adjacent segments s_1, s_2 as arguments and supplies the corresponding uncertainty value. U_u is defined as follows:

$$U_u(s_1, s_2) = \min((s_1 \cdot u + s_2 \cdot u),\ \min(s_1, s_2)) \tag{4.3}$$

The idea is to sum up $\frac{1}{4}$ of s_1 with a $\frac{1}{4}$ of s_2 and, if this value is greater than either s_1 or s_2 cut it to the smallest. Denoting by ψ the original point of segmentation and Δ the obtained uncertainty value, new points of segmentation ψ_1 and ψ_2 are obtained as: $\psi_1 = \psi - (\frac{\Delta}{2})$, $\psi_2 = \psi + (\frac{\Delta}{2})$. The original graph represented in Figure 4.6 is then transformed as shown in Figure 4.7.

Normalization functions of the non-Biological related indicators are obtained in a similar way as the Biological related ones, the differences consists of: (i) the set of output classes (i.e. l values) is made by just three classes: NON_GOOD, GOOD and HIGH; (ii) a percentage of the reference value r is still used as the GOOD / HIGH segmentation point ψ_2 but the other point ψ_1 is an absolute value set by the environmental experts rather than another percentage of r; and (iii) also non monotonic concave ($\cap$) indicators types are present.

The fact that ψ_1 is an absolute value and ψ_2 a relative one may introduce errors in the definition of the normalization function. It can in fact happen that, for exam-

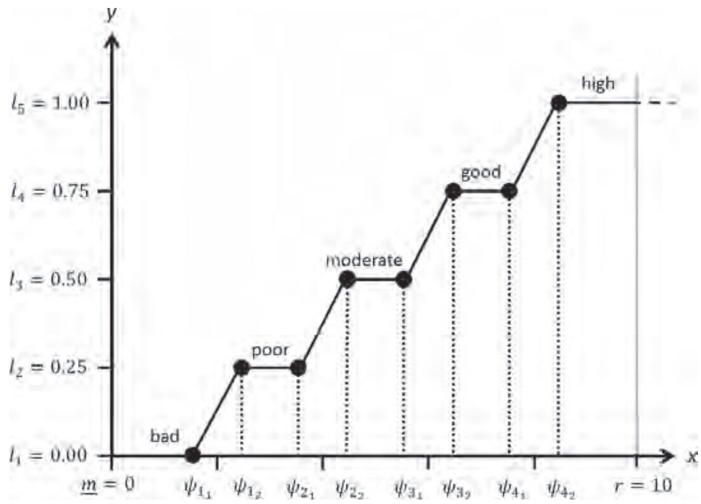

Figure 4.7: Example of a Biological indicator's normalization function with uncertainty

ple in an ascending indicator, $\psi_2 < \psi_1$. If this happens the indicator is considered "misspelled", it can be corrected by the user in the MODELKEY DSS or, otherwise, it is discarded from further operations.

Aggregation of Normalized indicators into Subcategories

This is the simplest aggregation level as it is just composed by basic aggregation operators. In fact, for each subcategory environmental experts can set the aggregation operator among: average, minimum and maximum.

Aggregation of Subcategories into Categories and Categories into LoEs

As reported in Figure 4.5 the aggregation applied from Subcategories to Categories and from Categories to LoEs is the same, namely TSK (Takagi-Sugeno and Kang) which was explained in section 3.3.5. The TSK output functions are in the simplest form of numerical constants and are set by the environmental experts as they can be seen as scores to assign to each of the antecedents. These scores can be asked to experts just by posing questions like "if subcategory1 is GOOD and subcategory2 is BAD what score between 0 and 1 would you give to their category?".

The TSK applied in MODELKEY has a peculiarity which makes it different from the usual form. In fact the criteria's values which are taken into account for aggregation are not the whole set of subcategories' values $c_1, \ldots, c_n$ but rather their average c_a and minimum c_m. This is due to the following considerations: (i) the number of criteria to be aggregated can become too big in order to fill up all the required scores; (ii) different scores should be set for every possible set of criteria in the system; and (iii) average and minimum are the aggregation methods most widely used by experts in environmental assessments. This criteria limitation not only has simplified the process of filling up scores for the antecedents but also has allowed to further decrease the number of possible alternatives as, obviously, the average can never be less than the minimum. The degrees of truth of the antecedents has been obtained by the classical TSK methodology:

- classification of the criteria into fuzzy sets; and
- aggregation of the degrees of truth of the antecedents.

The classification step has been made by using triangular membership functions centered on the values corresponding to the five WFD classes (i.e. BAD=0, POOR=0.25, MODERATE=0.5, GOOD=0.75 and HIGH=1) as reported in Figure 4.8. Because all the antecedents are in the conjunctive form (i.e. they use the AND connective) the aggregation has been performed by the use of a t-norm, in particular the minimum.

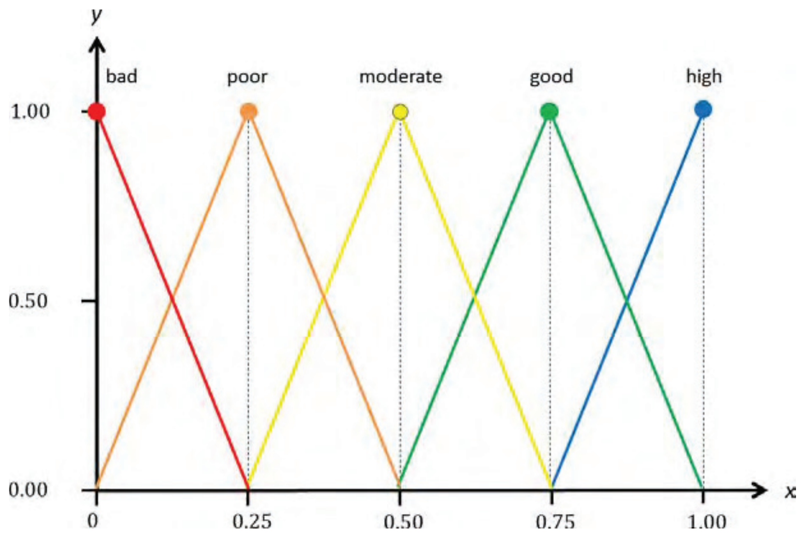

Figure 4.8: Triangular membership functions for the classification of environmental criteria

Aggregation of LoEs into environmental status

This last step of aggregation is performed, as requested by the WFD, by the application of a confirmation flow-chart. The basic idea is that the initial HIGH or GOOD quality status obtained by the Biological LoE must be confirmed by the other LoEs in order to classify the ecological status as HIGH or GOOD. This confirmation is obtained by eventually decreasing the initial biological status if other LoEs statuses are lower e.g. if the Biological status is HIGH but the Chemical status is GOOD then the Ecological status is GOOD. The final output represents the overall quality evaluation and classification of sampling sites and again it is expressed as percentage of membership to one or two adjacent WFD status classes. The original flow-chart for ecological status classification recommended by the CIS working group ECOSTAT [EC, 2005a] has been modified for MODELKEY purposes through the inclusion of the ecotoxicological QE (i.e. LoE Ecotoxicology) and the addition of the two compliance levels for Hydromorphology. LoE Ecotoxicology was included in the integration process to support LoE Chemistry in the definition of good or moderate status, as it can confirm (or reject) the hazardousness of water and sediment contamination. The modified version of the flow-chart is shown in Figure 4.9.

4.3.2 Socio-economic model

The socio-economic model is aimed at evaluating the Socio-Economic Indices (SEI). SEI, also called *socio-economic importance*, resides on the top of the assessment hierarchy reported in Table 4.2, the other levels in descending order are: 1) categories, 2) sub-categories and 3) indicators. Each level of the aggregation hierarchy aggregates its criteria by means of a specific aggregation operator as reported in Figure 4.10.

In the next paragraphs the aggregation procedure is examined following the natural flow of information from indicators to socio-economic importance. The considerations about socio-economic indicators are similar to those already discussed for environmental indicators as they both present a vast diversified set of possible codomains.

Normalization

The normalization procedure of socio-economic indices is very similar to the environmental's one, the difference resides in the choice of segmentation points for the normalization staircase function. Socio-economic data are subdivided in just three classes: LOW, MEDIUM and HIGH. The socio-economic experts can set the two points of segmentation (between LOW and MEDIUM and between MEDIUM and HIGH) manually, otherwise these points are derived from the actual data just by subdividing the data space equally in three parts. Formally:

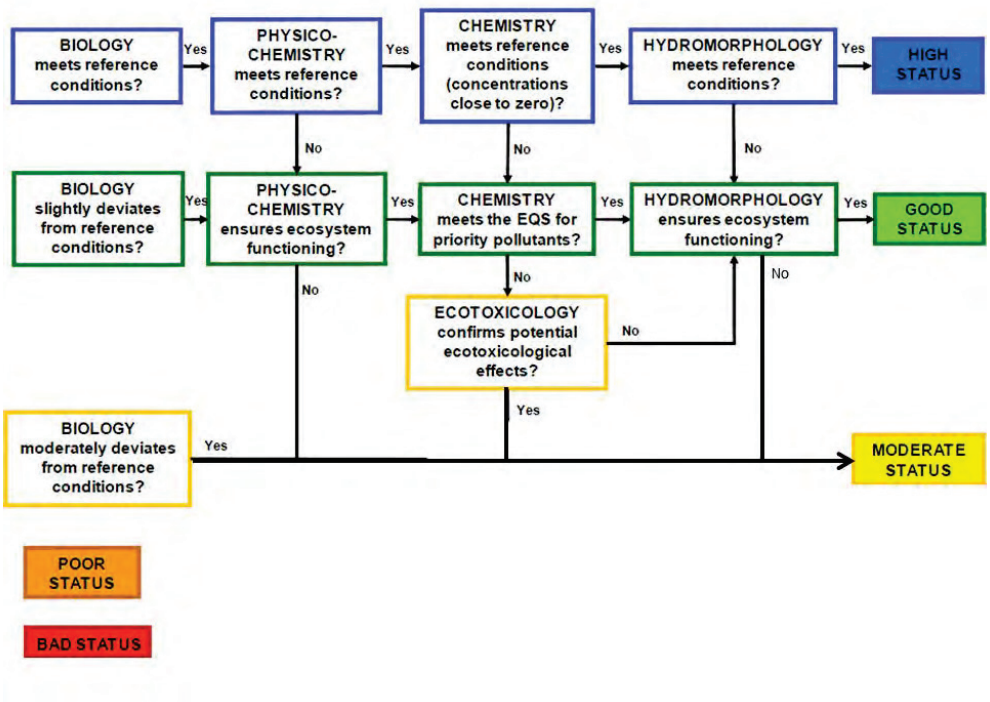

Figure 4.9: MODELKEY version of the WFD confirmation flow-chart for the aggregation of LoEs

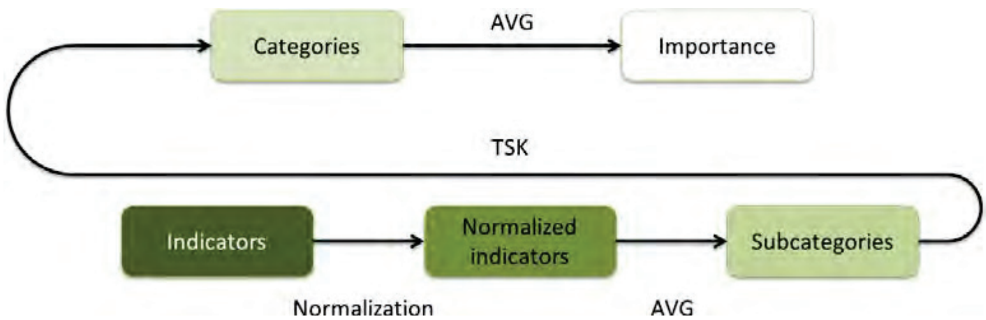

Figure 4.10: Aggregation sequence for socio-economic data

Table 4.2: Socio-economic model hierarchical structure

STATUS TYPE	CATEGORIES OF SOCIO-ECONOMIC INDICATORS (1 ... n)	SUBCATEGORIES OF SOCIO-ECONOMIC INDICATORS
SOCIO-ECONOMIC IMPORTANCE	Agricultural use	Consumption
		Efficiency
		Competition
	Industrial use	Consumption
		Efficiency
		Competition
	Energy production	Consumption
		Efficiency
		Competition
	Residential use	Consumption
		Competition
	Recreational use	Consumption
	...	---
	n	1,3

$$\psi_i = \underline{m} + \left(\frac{\overline{m} - \underline{m}}{3}\right) \cdot i \qquad \text{i=1,2} \tag{4.4}$$

Where ψ_1 and ψ_2 are the segmentation points, $\underline{m}$ is the minimum value and $\overline{m}$ is the maximum.

Also in the case of socio-economic data, uncertainty takes its role by converting the initial staircase function into a continuous piecewise linear function similar to the one presented above for environmental indicators (see Figure 4.7) The mathematical procedure in order to establish the quantity of uncertainty is also the same as in the environmental case (see Equation (4.3)).

Aggregations

This first and last level aggregations (aggregation of Normalized indicators into Subcategories and of Categories into Socio-economic importance) are very simple as they consist in just the application of a plain average to the values of their criteria. The aggregation of subcategories into categories is more interesting as, like in the environmental case, the Takagi-Sugeno and Kang (TSK) aggregation is used. In this case, as before, the output functions are intended to be simple constants set by the environmental experts, the difference resides in the criteria to be aggregated. In fact, in the environmental version, average and minimum of the criteria were used as representative values to be aggregated whereas, in the socio-economic version, canonical TSK is performed as the entire set of criteria is aggregated. This is feasible in the case of socio-economic factors because the number of subcategories to be aggregated is at most three. As in the environmental module the antecedents are all in the conjunctive form and the minimum t-norm is used to obtain their degree of truth.

4.3.3 Prioritization model

If we just consider the environmental viewpoint, prioritization is simple to be understood and addressed: the lower the water quality is the higher the priority of that site is, since a consistent management action is urgently needed to restore the "good" status by 2015 as required by WFD. In the MODELKEY DSS the prioritization of hot spots along river basins is achieved by taking into account both environmental and socio-economic perspectives. In this context prioritization becomes more complex and its meaning changes: sites are ranked according to both their water quality conditions and their water socio-economic importance. Specifically, the higher the socio-economic valuation of water resource usage is (e.g. large request of clean water from residents/consumers or economic sectors, high productivity or efficiency of economic activities) the higher the priority of that site is, since there is a strong social or economic interest in protecting those water uses by means of appropriate management actions directed to water quality improvement. Consequently, one site where water resource is strongly utilized for specific purposes (e.g. industrial, agricultural, etc.) will always have higher priority than another site where neither residents/consumers nor economic sectors are interested in river waters.

The hot spots prioritization is based on three main criteria as shown in Figure 4.11. The first criterion considers water quality scores in relation to the pressures that can insist on the river basin (i.e. organic pollution, eutrophication, acidification, toxic pressure and Hydromorphological pressure; for more information related to pressures please refer to [Gottardo, 2008]). By examining the previous Table 4.1 information about pressures is spread over the five different categories composing the Biological LoE, prioritization is instead related to the effects of the different pressures separately and not to their aggregated values. In order to obtain these pressure related values, another type of aggregation hierarchy, reported in Table 4.3, is used which starts from the Biological subcategories and aggregates them by different groups which are related to pressures. In order to aggregate the pressures values the same aggregation technique used for the Biological categories is adopted, namely TSK.

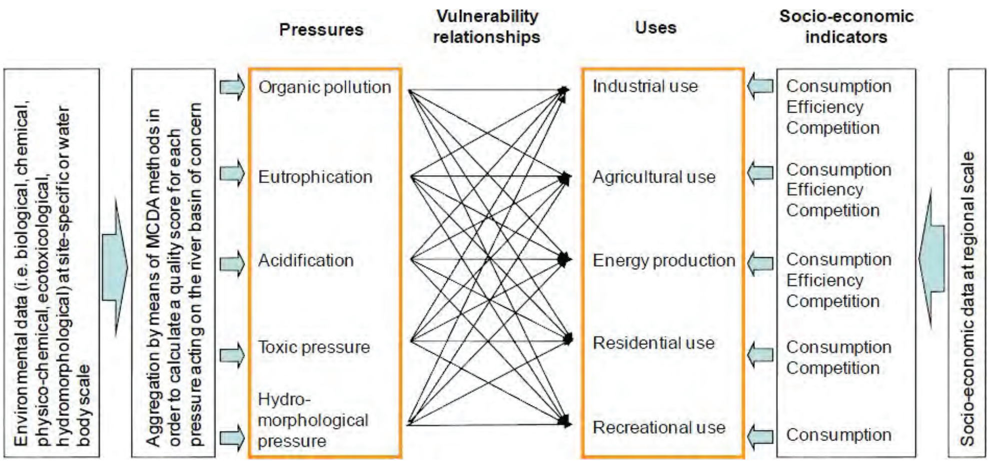

Figure 4.11: Criteria considered in the hot spots prioritization.

The second criterion to be evaluated for prioritization of hot spots is the vulnerability of the considered water uses (i.e. industrial, agricultural, energy production, residential, recreational) to the different pressures. The expert (with long experience and good knowledge on water uses concerns) is involved in evaluating vulnerability relationships between uses and pressures in qualitative terms (i.e. very high, high, medium, low, null vulnerability). Basically the expert has to fill in a two-way table like the one presented in Table 4.4 where for each pair pressure/use a vulnerability

Table 4.3: Pressures model hierarchical structure

PRESSURES	CATEGORIES RELATED INDICATORS
General degradation	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes
eutrophication	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes
acidification	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes
organic pollution	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes
hydromorphological pressure	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes
toxic pressure	Invertebrate fauna, Fish, Phytobenthos, Phytoplankton, Macrophytes

value $\mu_{p,u}$ is selected (empty i.e. no vulnerability = 0.0; low vulnerability = 0.25; medium vulnerability = 0.50; high vulnerability = 0.75; very high vulnerability = 1.00).

Table 4.4: Example of pressures/uses vulnerability two-way table. Empty cells represent 0.0 values, i.e. no vulnerability

		PRESSURES				
		Eutrophication	Organic pollution	Acidification	Toxic pressure	Hydromorphological pressure
USES	Agriculture		LOW	LOW	HIGH	
	Industrial	MEDIUM		LOW		MEDIUM
	Energy production	LOW			VERY HIGH	
	Residential		HIGH	LOW	HIGH	LOW
	Recreational	MEDIUM	VERY HIGH	MEDIUM		LOW

As vulnerability could indeed be considered as a corrective factor of the potential deterioration that the low water quality due to the action of a pressure can cause on a specific use, a low water quality is not a sufficient condition of actually making the use compromised if the use itself is not really vulnerable to that specific pressure. The aggregation between pressures and vulnerabilities leads to the calculation of a score in $[0, 1]$ which indicates, for each use, the potential to be actually compromised by a specific pressure, i.e. the potential *deterioration*. In this way 0 means not deteriorated (i.e. when the quality in relation to the pressure is optimal and/or the use vulnerability to the pressure is null) and 1 means strongly deteriorated (i.e. when the quality in relation to the pressure is very scarce and/or the use vulnerability to the pressure is high). Formally, for the set of pressure values $\{p_1, \ldots, p_n\}$ and vulnerabilities $\{\mu_{1,1}, \ldots, \mu_{1,m}, \ldots, \mu_{n,m}\}$ where m is the number of uses, the deterioration $D_{p,u}$ related to each pair pressure/use is calculated as:

$$D_{i,j} = p_i \cdot \mu_{i,j} \qquad \text{i=1,...,n j=1,...,m} \tag{4.5}$$

After this first step, a single deterioration degree has to be calculated for each use in relation to all pressures. This is obtained just by summing up all damage values related to the same use and then limit it to 1. This because the presence of a mixture of pressures that cause a deterioration degree exceeding the threshold 1 is sufficient to assume the use as highly deteriorated. Formally:

$$D_j = \min\left(\sum_{i=1}^{n} D_{i,j}, 1\right) \tag{4.6}$$

In order to aggregate deteriorations $D_1, \ldots, D_m$ and socio-economic importance of water uses $u_1, \ldots, u_m$, which were evaluated as categories in the socio-economic assessment (see Table 4.2), into a use-related priority value, again the TSK methodology is used where:

1. antecedents are composed by all the possible permutations obtained by dividing deterioration and socio-economic importance values between LOW, MEDIUM and HIGH (e.g. IF <deterioration is LOW> AND <socio-economic importance is HIGH> THEN <use-related priority is 0.75>;

2. output functions are constants values set by the socio-economic expert; and

3. the degree of truth of antecedents is obtained through the minimum t-norm.

The resulting use-related priority P_j is then aggregated into a single priority value by means of a simple average. The larger the number of potentially deteriorated but consistent, efficient and competitive water uses is and the higher the overall priority of the site or water body of concern becomes:

$$P = \frac{\sum_{j=1}^{m} P_j}{m} \tag{4.7}$$

4.4 Technical solutions

The MODELKEY DSS has been developed by the use of the *Java* programming language as a set of *Eclipse's Rich Client Platforms*. Eclipse is a multi-language software development environment comprising an Integrated Development Environment (IDE) and an extensible plug-in system. Eclipse employs plug-ins in order to provide all its functionalities on top of (and including) the runtime system, in contrast to some other applications where functionalities are typically hard coded. This plug-in mechanism is a lightweight software component framework. With the exception of a small run-time kernel, everything in Eclipse is a plug-in. This means that every developed plug-in integrates with Eclipse in exactly the same way as other plug-ins; in this respect, all features are "created equal". Eclipse provides plug-ins for a wide variety of features, some of which are supplied by third parties through free or commercial models. While the Eclipse platform is designed to serve as an open tool platform, it is structured so that any client application could be build just by the use of its components. The minimal set of plug-ins needed to build a rich client application is collectively known as the *Rich Client Platform*. Any kind of application can be built using a subset of the platform. These rich applications are still based on a dynamic plug-in model, and the user interface is built using the same toolkits and extension points. The layout and function of the workbench is under fine-grained control of the plug-in developer in this case.

As reported in Figure 4.12 the MODELKEY DSS is structured as a set of separated stand alone modules (one software module for each logical model) guided by the core DSS module which acts as a kind of orchestrator. The orchestrator and the Graphical User Interface (GUI) engine are embedded inside a third party GIS (which will be introduced further on) so that they are able to utilize its GIS capabilities. The orchestrator collects user's requests and then launches the corresponding module by passing to it the selected arguments. Three separated modules perform the three phases of the complete assessment, namely: *environmental* module, *socio-economic* module and *prioritization* module. These modules are all stand alone modules which do not need the presence of the orchestrator in order to work. Each module is connected to a unique DataBase Management System which contains data and results shared among all modules. Finally a particular tool called "Access to Postgres" is present which is useful in order to transport the data owned by users in their DBMS into the DBMS used by the system (further details in section 4.4.2).

One important general remark about the MODELKEY DSS concerns its capabilities of being adapted to different types of assessment. In fact the assessment hierarchy is not hard-coded inside the program but rather is part of the configuration files. This means that every kind of hierarchy can be used. More than this the system is capable to apply to each level of the assessment hierarchy different types of aggregations simultaneously generating multiple outputs. Users can specify how many aggregation structures to use and for each aggregation structure different types of aggregations can be applied at each level of the hierarchy. Also colors and names of the classes can be modified by configuration files. Once the hierarchy to be used is established, configuration tables, inside the case-study specific database, specify, for each indicator, where to connect it in the hierarchy and its inherent characteristics, so that every kind of indicator can be embedded in the system. More in depth explanations will be supplied in section 4.4.3.1.

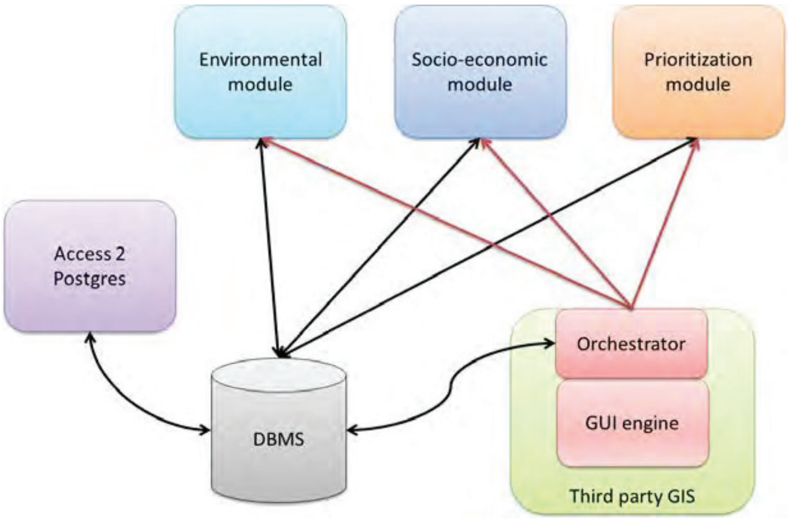

Figure 4.12: MODLEKEY DSS software modules architecture

4.4.1 The DBMS

The DBMS which has been used in the MODELKEY DSS is PostgreSQL 8.2 (also called just Postgres). It is an open source Object-Relational DataBase Management System (ORDBMS), one of the most advanced open source DBMS and also one of the best DBMS overall. The choice of Postgres not only originates from its capabilities and reliability but also because of its PostGIS geospatial extension. PostGIS is an open source software program that adds support for geographic objects to Postgres. As stated before all of the MODELKEY DSS modules were developed in Java, therefore, in order to be able to connect and work with the Postgres DBMS a JDBC (Java DataBase Connectivity) module has been used. JDBCs are generic modules written in the C programming language which allow to connect indifferently to every kind of DBMS. In order to achieve better performances and use more Postgres specific SQL commands the specific PostgreSQL JDBC Driver[1], provided by Postgres developers, has been adopted. This driver is written in the Java language and has been seamlessly adopted in the software.

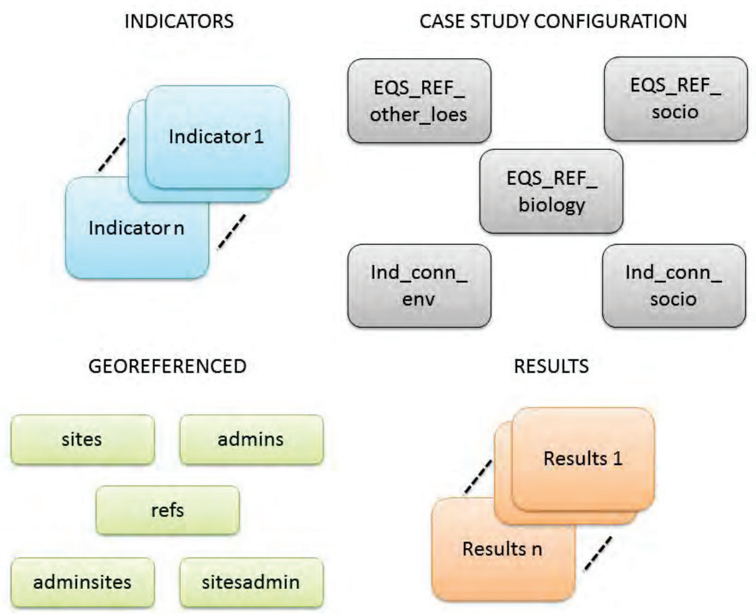

Figure 4.13: MODELKEY DSS data tables logical organization

The logical structure of the database is reported in Figure 4.13. Four sets of tables are present: indicators' tables, case study configuration tables, georeferenced tables and results tables. *Indicators' tables*, whose structure is reported in Table 4.5, are the tables containing data related to the indicators which are used as the basic data at the bottom of the aggregation hierarchy used by the MODELKEY methodology. Each table can contain data regarding one or more indicators (specified in the *name_* column), moreover, as far as the date is concerned, indicators can be calculated:

- Once per day: in this case the three date fields (*year_*, *month_*, *day_*) must be inserted.

- Once per month: in this case the fields *year_* and *month_* must be set, while the field *day_* must be NULL.

[1] `http://jdbc.postgresql.org`

– Once per year: in this case the field *year_* must be inserted, while the fields *month_* and *day_* must be NULL.

It is worth noting that the same indicator can be calculated at different time frames (e.g. both month and year). In order to obtain a single value per month and/or year of a certain indicator a set of basic aggregation operators, i.e. average, minimum and maximum, can be performed directly by the MODELKEY DSS. If the aggregation operator to be used is not one of the predefined operators (e.g. an indicator might be evaluated per month by taking the first day of the month as the representative value for the whole month), then the computation has to be performed separately and indicator's values per month and/or year have to be inserted into the table.

<**Name of the Indicator's table**>: data about the indicator		
name_	Text	Name of the indicator. This name must be the same name used to identify the indicator in the "ind_conn" and "EQS_refs" tables (see tables 4.6, 4.7 and 4.8).
id_	Text	Site identifier. For each available sampling site, it must correspond to the "id column" in the "sites" table (see the *Georeferenced tables* paragraph on page 87).
year_	Integer	Evaluation year.
month_	Integer	Evaluation month (it can be NULL).
day_	Integer	Evaluation day (it can be NULL).
value_	Integer	Numeric value of the indicator.

Table 4.5: Indicator's table structure

The *case study configuration tables* are tables strictly related to the data under assessment, they are used by the application in order to understand how to treat and normalize indicators. The three *EQS_ref* tables (*biology*, *other_loes* and *socio*) contain information, derived from environmental experts, on how to normalize indicators, while the *ind_conn* tables contain information on how to connect the indicators into the assessment hierarchy.

In the case of biological data, the *EQS_ref_biology* table (see Table 4.6) is composed by: the type of normalization function (ascending or descending), the percentages where to put the segmentation points and a default reference value. These information can be set differently for the same indicator for every typology. If segmentation points values are missing they are obtained by equally subdividing the $[0, 1]$ space.

The *EQS_ref_other_loes* table (see Table 4.7) contains the same information but related to indicators belonging to LoEs which are not biological. In this case there is no distinction about typologies, the data to be specified regards: the type of normalization function (ascending, descending or concave), the segmentation points position,

EQS_REF_biology: data about EQS and reference values for biological indicators		
name_	Text	Name of the indicator (must be the same as in the indicator's table and in the "ind_conn" table)
type	Text	Type of the normalization curve, that can be ASC (ascending), or DESC (descending), based on the original scale of values of each indicator.
bad_poor	Double precision	Value in [0,1] pointing out where the classification changes from BAD to POOR. Can be NULL.
poor_moderate	Double precision	Value in [0,1] pointing out where the classification changes from POOR to MODERATE. It can be NULL.
moderate_good	Double precision	Value in [0,1] pointing out where the classification changes from MODERATE to GOOD. It can be NULL.
good_high	Double precision	Value in [0,1] pointing out where the classification changes from GOOD to HIGH. It can be NULL.
ref	Text	Absolute reference value to be used in case of missing reference sites.
typology	Text	Habitat typology for which these thresholds apply

Table 4.6: EQS_REF_biology's table structure

the default reference value and whether or not using the calculated reference value is considered better then using the default reference value. In normal conditions real reference values are used if present but there are some particular cases (e.g. when the reference value is a threshold fixed by law) that requests the use of the default reference value even if a real reference value was calculated.

Finally the *EQS_ref_socio* table (see Table 4.8) contains only segmentation points position as the typology of the normalization curve is always ascending and the concept of reference is not present.

The *ind_conn_env* and *ind_conn_socio* tables are structured identically (see Table 4.9), they both contain information on which indicators have to be used during the assessment and where to connect them in the assessment hierarchy (the *parent* column). The *ind_conn_env* table contains information regarding the environmental assessment while the *ind_conn_socio* table about socio-economic assessment. Also information about the LoE of concern (its *name_*, *tablename* and whether it is biological or not *eqs_ref_type*) is present alongside with information about the time spans which are considered valid for the specific indicator (column *datelevels*).

Georeferenced tables are tables containing information about the elements which are the targets of the assessment (i.e. sampling sites along the river network and socio-economic administrative regions) alongside with their spatial shapes and positions. The *sites* table contains information about sampling sites, the *refs* table contains the

EQS_REF_other_loes: data about EQS and reference values for environmental indicators which are not biological		
name_	Text	Name of the indicator (must be the same as in the indicator's table and in the "ind_conn" table)
type	Text	Type of the normalization curve that can be ASC (ascending), DESC (descending) or CONC (concave), based on the original scale of values of each indicator.
not_good_good	Double precision	Absolute value on the original scale pointing out where the classification changes from NOT GOOD to GOOD.
good_high	Text	Can be an absolute value defined by the expert or the word "Ref" (without the double quotes). In the latter case, the word Ref, states that reference values are used to calculate the threshold. In both cases this column points out where the classification changes from GOOD to HIGH.
precref	Boolean	TRUE if the reference values in real sampling sites are considered as dominant and therefore always used when present, FALSE when good_high values are used as reference even if reference values in real sampling sites are present in the database.

Table 4.7: EQS_REF_other_loes's table structure

EQS_REF_socio: data about EQS values for socio economic indicators		
name_	Text	Name of the indicator (must be the same as in the indicator's table and in the ind_conn table)
low_medium	Double precision	Absolute value pointing out where the classification changes from LOW to MEDIUM. It can be NULL.
medium_high	Double precision	Absolute value pointing out where the classification changes from MEDIUM to HIGH. It can be NULL.

Table 4.8: EQS_REF_socio's table structure

ind_conn_env, ind_conn_socio: data about environmental indicators to be used		
parent	Text	Name of the lowest indicator's parent node in the assessment hierarchy tree.
name_	Text	Name of the indicator (must be the same as in the indicator's table and in the "EQS_REF_biology" and "EQS_REF_other_loes" tables)
datelevels	Text	Comma separated list of date frames with available data for this indicator (e.g. [year], [year,month], etc.)
tablename	Text	Name of the table containing data of this indicator
eqs_ref_type	Text	Type of "EQS_REF" table ("EQS_REF_biology" or "EQS_REF_other_loes" (for non biological indicators, e.g. chemical, physico-chemical, etc.)

Table 4.9: ind_conn_env's table structure

same information but restricted to the reference sites. The *admins* table contains the administrative regions information. The *adminsites* and *sitesadmin* tables are derived tables useful for the assessment. The first one (*adminsites*) contains one point inside each administrative region polygon, it is useful for visualization purposes as evaluation results for administrative regions are placed in these points. The second one (*sitesadmin*) contains the same information present in the *sites* table plus the name of the embedding administrative region (obtained by intersection) which is necessary when evaluating the prioritization index because each sampling site must be associated to the corresponding administrative region.

Finally *results tables* are tables containing the results of the assessment for each level of the hierarchy. As stated before many aggregation structures can be applied to the same aggregation hierarchy simultaneously, therefore a results table is generated for each different aggregation structure.

4.4.2 Migration from Access to Postgres

Because the MODELKEY project related database (as many databases used in environmental related research centers) is a Microsoft Access database, the first problem to be solved by the user in order to utilize the MODELKEY DSS is the migration of his/her data from Microsoft Access to Postgres. To this aim the "Access to Postgres" application was developed which allows users to perform six utility functions related to their database as Figure 4.14 illustrates:

- create a new Postgres database;
- migrate data from Access to Postgres;

– georeference the sites table;

– import administrative regions' shapefile into Postgres;

– create a single site, for visualization purposes, inside each administrative region;

– perform intersection between sampling sites and administrative regions.

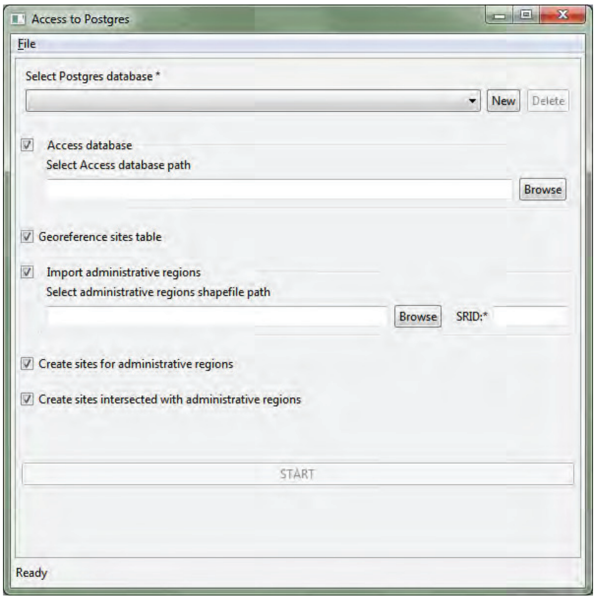

Figure 4.14: Access to Postgres main user interface

The first two functions are straightforward to understand. As far as the georeferentiation of the sites table is concerned, this function transforms the sites table from an ordinary table to a georeferenced one by using the information regarding coordinates and projection contained within. The fourth function is useful when administrative regions are supplied as ESRI's shapefiles (a popular geospatial vector data format created by ESRI). By just specifying the shapefile's related SRID (Spatial Reference System Identifier, a unique value used to unambiguously identify projected, unprojected and local spatial coordinate system definitions) the data contained within are transposed inside a correspondent table in Postgis. Finally the last two functions are related respectively, to the creation of the adminsites and sitesadmin tables presented before (see section 4.4.1).

4.4.3 Assessment related common library

As stated before the complete MODELKEY DSS is composed by four different modules (see Figure 4.12). In many cases the same procedures and classes are useful in different modules, that's why a common shared library named *iriCommons* is present. In this shared library basic classes are present which perform tasks related to: database connection, object-relational data mapping, configuration files management, control of the wizard user interface and of the business models. This java project is the biggest in the whole MODELKEY solution, it is composed by 21 packages and 81 java classes.

4.4.3.1 Configuration files

The MODELKEY DSS is an open configuration software, this means that users can change many aspects of the software. In particular users can edit:

- assessment hierarchy;
- aggregation structures;
- class colors; and
- default values for aggregation questionnaires.

These configurations can be modified by the users just by opening and editing the related CSV (Comma-Separated Values) file. CSV files are plain text format files containing data structured in a database table form where fields are divided by commas. As a future development a GUI should be built that helps users in the editing of these configuration files. As explained inSection 4.4 different aggregation structures can be evaluated by the system simultaneously. The MODELKEY DSS in fact comes with a built in default configuration which consists in the evaluation of two aggregation structures. One aggregation structure is coherent with the assessment model presented in Section 4.3, the other (just slightly different) generates results by following the strict suggestions of the WFD (i.e. by utilizing always the minimum aggregation operator as requested by the "One-Out-All-Out" principle instead of using TSK).

4.4.4 Environmental module

The environmental module concerns the environmental assessment of sampling sites related data with regard to the five environmental LoEs utilized by the MODELKEY project's assessment methodology. Basically the software performs a four steps procedure, as reported in Figure 4.15:

1. hierarchy tree creation;
2. connection of indicators;
3. collection of indicator's data; and
4. aggregations and results generation.

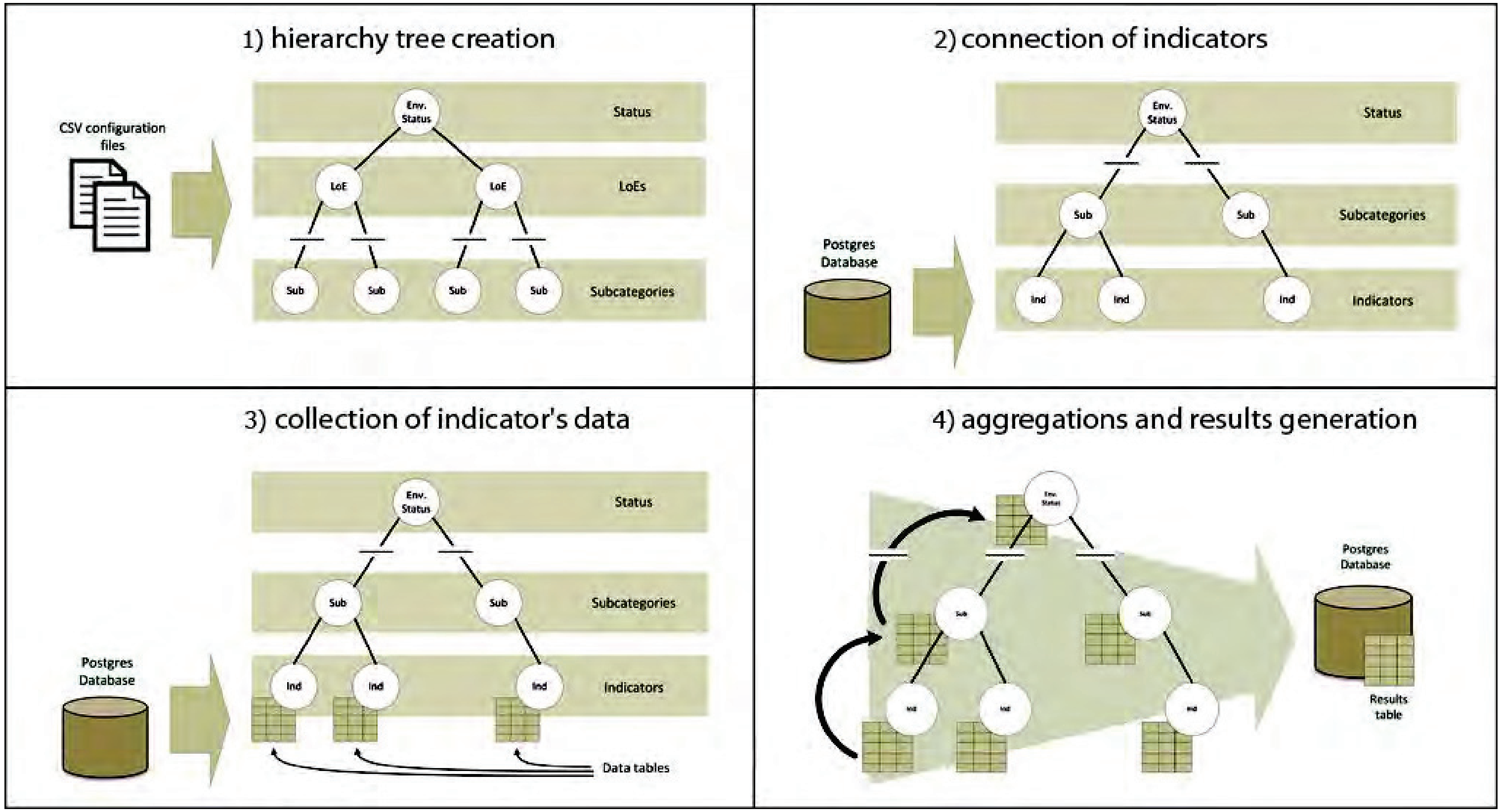

Figure 4.15: The four steps procedure of the environmental module

The first phase, *hierarchy tree creation*, concerns reading the configuration files and, on the basis of their contents, build a tree structure (Figure 4.15 - 1) where each node contains information about its hierarchical level of concern and about the aggregation operator to be applied to its childs in order to calculate its value (e.g. indicators' values related to one subcategory node are aggregated on the basis of the information contained in the subcategory node himself). In the second step, *connection of indicators*, the *ind_conn_env* table, which contains information related to the connection of the indicators to the hierarchy tree, is read from the Postgres database and, basing on its contents, indicators nodes are created as hierarchy tree's leaves (Figure 4.15 - 2). In the third phase, *collection of indicator's data*, the system collects data about indicators on the basis of user's selections and adds them to the indicators' nodes (Figure 4.15 - 3). In the last phase, *aggregations and results generation*, the aggregation tree is traversed by a bottom-up approach and aggregations are performed at each node. As soon as a node has completed the aggregation of its data the result is written to the results table in the Postgres database. When the root node (i.e. ecological status) finishes its elaboration and stores its results the computation is finished.

4.4.5 Socio-economic module

This module is related to the obtainment of the socio-economic evaluations of administrative regions. The procedure is composed by the same steps as the environmental module: hierarchy tree creation, indicator's integration, indicator's data connection and aggregations and results generation. The difference is basically related to the data to be elaborated and to some very little specific concerns; the system is generic enough to be applied seamlessly to every kind of assessment just by changing the configuration files.

4.4.6 Prioritization module

The prioritization module is aimed at collecting both environmental and socio-economic data and aggregate them into a single prioritization index. The basic steps of the prioritization module are:

1. read configuration files and tables;
2. perform aggregations; and
3. store results.

Initially configurations files containing the aggregation hierarchy and the default weights to be used in the aggregations are read. Then, after the user eventually changed the default values, the aggregations are preformed and finally the results are stored back to the Postgres database. Even if the aggregation methodology is quite different from those of the environmental and socio-economic modules (see Section 4.3.3), still this module makes large use of the *iriCommons* library.

4.4.7 Orchestrator module

This module is the core part of the DSS in the sense that it composes the main interface and acts as a controller for the other modules. The orchestrator module has been architectured in a completely different way with respect to the previously presented modules. In fact all other modules were built as Eclipse RCPs (i.e. stand alone desktop programs based on the Eclipse framework) while this module is a plain Eclipse plug-in; this means that it cannot be used without an Eclipse application which embed it. This because we decided to embed the MODELKEY DSS inside a third party GIS software.

We decided to use a third party GIS because it was not feasible to rebuild a GIS inside our project but nevertheless basic GIS functionalities were necessary for the DSS in order to become usable. A set of open source desktop GIS applications have been tested in order to choose the best GIS development platform for the MODELKEY DSS software system. The criteria used for the comparative analysis were: desktop application, open source, multi-functionality GIS, user friendly, modular and flexible, customizable, Open Geospatial Consortium (OGC) compliant application. These criteria have been selected for various reasons. The choice of a desktop application came from both, the concern of project involved users in upload their data and the huge amount of data to be potentially uploaded. The use of an open source product came from the aim to keep the whole project the most transparent. GIS functionalities are useful for users performing MODELKEY's embedded assessments, at least visualization GIS features are required as MODELKEY is a GIS based DSS. User friendliness is something that is always required when delivering an application to non trained users. Modularity is one of most important features for an application that has to deal with external modules (like our models). It is a good practice to always be OGC compliant when dealing with spatial assessments.

Based on these criteria the uDig (User-friendly Desktop Internet GIS, `http://udig.refractions.net`) application has been considered the best development platform solution for the MODELKEY DSS user interface with GIS capabilities. uDig is an open source desktop GIS development platform and also a working open source desktop GIS application. It is written in Java and based on the Eclipse platform. uDig has been considered as the best GIS application for building the MODELKEY DSS interface because it has sufficient modular design elements and innovative technological solutions. uDig is designed to integrate as many GIS file formats, databases and web services. As a platform, uDig provides modular Java development components allowing the developers to embed geospatial functionalities in any Eclipse application. The uDig environment can be extended or it can be used as an extension. The uDig platform can also be customized with standard Eclipse plugins. uDig has multilanguage facilities: all text strings in the platform are not hard coded into the source but are part of external files. The uDig platform currently has translations for German, Spanish, French and Italian. This is useful considering the possibility that in future the DSS interfaces will be translated into Member States national languages to make it widely applicable for end users all over Europe.

The orchestrator module is subdivided in two main parts, on the one hand it provides a single starting interface to manage the other modules, on the other hand it provides advanced visualization tools which enrich the uDig GUI by adding MODELKEY related interfaces. As far as the former functionalities users are able to select the type of assessment to be performed and the database which should be used. Regarding the MODELKEY related interfaces more details will be explained later in Section 4.5. An important remark is related to the fact that uDig doesn't supply pie-chart visualizations in its maps. This is related to the lack of a standard concerning this particular visualization. Nevertheless the MODELKEY DSS still needed such kind of visualization, therefore we built it by ourselves.

4.4.8 The installation package

Although in a prototype form, the complete MODELKEY DSS suite as part of the Modelkey project, has been developed in order to be freely available for everyone who could be interested. To this aim an automatic installation package has been created which is able to: (i) check for the presence of the JRE (Java Runtime Environment) and redirect the user to the appropriate download site in case of missing; (ii) check for presence and eventually install the PostgreSQL 8.2 DBMS; and (iii) install the Modelkey DSS and create the appropriate shortcuts. More than this also an uninstall procedure is present which not only removes the DSS software but also the Postgres software, user and data so that the machine can return back to its original state.

The installation package was built by using the NSIS (Nullsoft Scriptable Install System) scripting language. NSIS is a professional open source system able to create Windows installers. It is designed to be as small and flexible as possible and it is therefore very suitable for internet distributions. The final downloadable distribution of the MODELKEY DSS can be found at `http://www.modelkey.org`, it is freely downloadable after being registered to the modelkey site.

4.5 Usage

After installation and start up, the MODELKEY DSS application user's main interfaces will show up on the uDig workbench. The tool is now ready to run. As shown in Figure 4.16, the MODELKEY DSS main user's interface presents two functionalities:

- Status of river basins assessment and evaluation; and
- Direct models application.

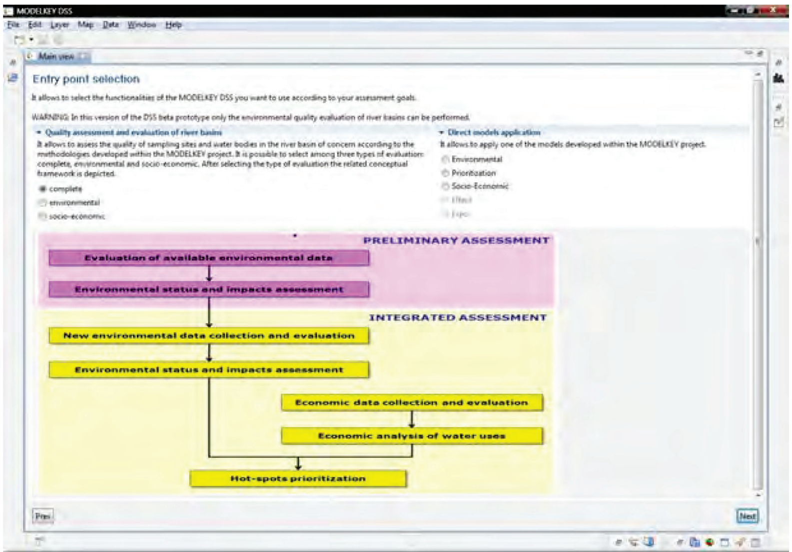

Figure 4.16: Conceptual framework of the MODELKEY DSS after selecting the entry point (e.g. complete).

The first functionality allows the user to assess the environmental status and impacts of sampling sites and water bodies (environmental module), to estimate the socioeconomic importance of water uses in different administrative regions (socio-economic module) and to prioritize hot spots along the river basin of concern (prioritization module). Accordingly it is possible to select among three different entry points:

- complete evaluation (applying a combination of the three modules);
- environmental evaluation (applying only the environmental module); and

– socio-economic evaluation (applying only the socio-economic module).

After selecting the most appropriated entry point, the related conceptual framework is depicted as visualized for the complete evaluation entry point in Figure 4.16. This framework provides a guideline to the user on the types of analysis offered by the DSS according to the user's selection. The conceptual framework shows that two different phases are considered: preliminary assessment and integrated assessment. Since the MODELKEY DSS does not require a minimum dataset, in the first phase the user can preliminarily apply the DSS on the existing environmental dataset exploring the final results, related uncertainty and data gaps. If further monitoring data are needed, the user can run again the DSS in order to obtain more reliable results on the environmental status. Then ecological information is aggregated with socio-economic data on water uses with the ultimate aim of identifying hot spots in need of urgent management.

The second functionality "Direct models application" allows to apply one of the models developed by other partners within the MODELKEY project and embedded in the DSS. This functionality is not very related to the MODLEKEY DSS development and will not be further examined as it just acts as a launcher for modules produced by other partners like for example models related to dispersion of chemical particles in water.

After the selection of the entry point of interest, data to be used for the analysis must be selected. As shown in Figure 4.17, it is possible both to select a database related to the user's case study (supported by the "how to..." link) or to use the database of one of the case studies of the MODELKEY project: *Llobregat*, *Scheldt* and *Elbe* river basins. Moreover, five reports concerning the application of the DSS to the three case studies are available for visualization.

Only the environmental module's interface will be presented further on as the interfaces and use of the other two modules, i.e. socio-economic and prioritization modules, are basically the same.

After selecting the Environmental entry point the related environmental module is open showing the interface reported in Figure 4.18 where the steps to be performed are shown. The application of the environmental module to a river basin requires seven steps starting from selection of river basin's habitat typology to the aggregation of environmental indicators and integration of the five Lines of Evidence (LoE). The environmental module is designed as a "wizard" which will guide the user step by step into the application of this module.

In the river basin's habitat typology step (Figure 4.19) the user visualizes the distribution of habitat typologies over the river basin. The user is then asked to choose the typology of interest: the DSS will apply the assessment procedure only on those sampling sites belonging to the selected typology. If the user is interested in more than one typology the application has to be repeated from the beginning.

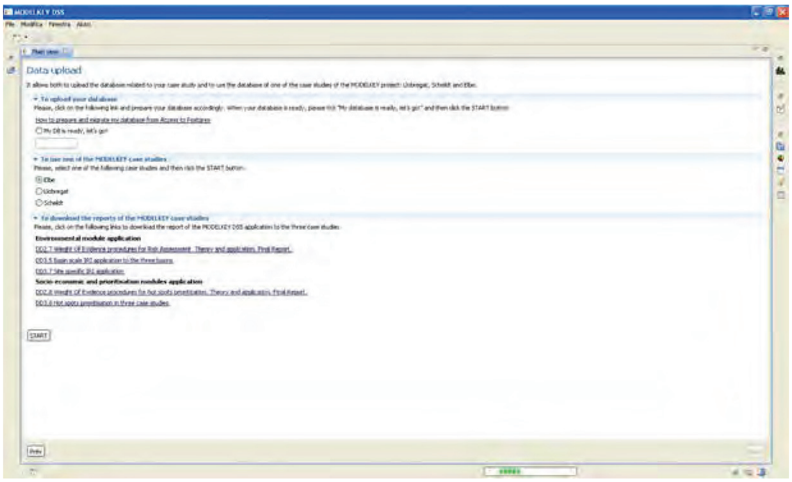

Figure 4.17: Data selection interface

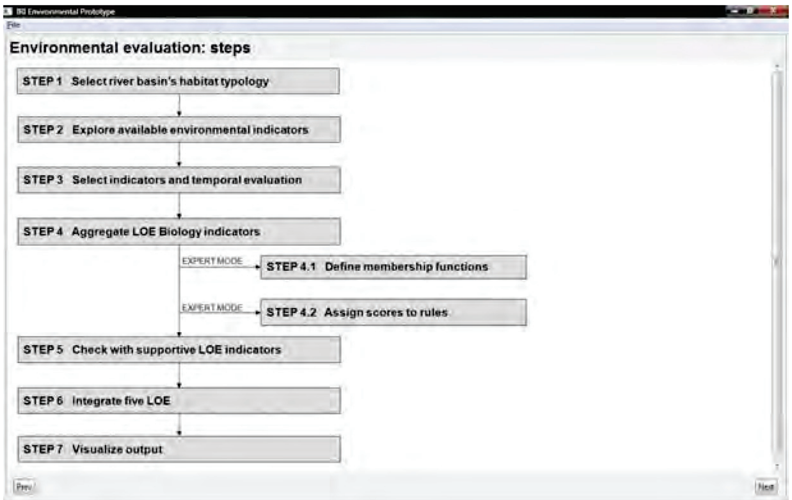

Figure 4.18: Steps of the environmental module

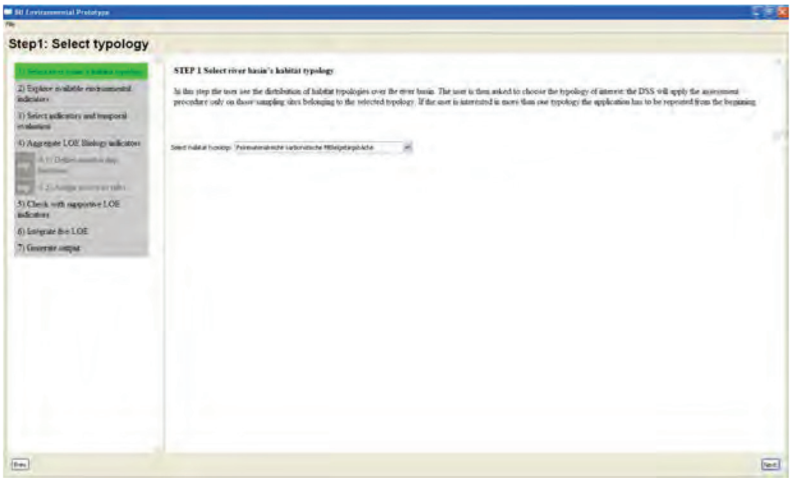

Figure 4.19: Habitat typology selection interface

The explore available environmental indicators interface shows the list of all available environmental indicators currently considered and calculable by the MODELKEY DSS, listed in Figure 4.20. The available environmental indicators are organised into five tables, one for each LoE, and grouped by categories and sub-categories of information according to the defined assessment hierarchy.

In the selection of temporal data aggregations (Figure 4.21) the user can first of all choose:

- to undertake the annual status and impacts evaluation, the monthly status and impacts evaluation or to investigate a specific date for both sampling sites and reference sites; and
- to aggregate the values of each indicator available in a certain sampling site and in the previously selected temporal range by means of an arithmetic average, by taking the minimum value or by taking the maximum value.

It is possible to choose a different aggregation method for each LoE and in this case it is applied to all indicators belonging to the same LoE. Or it is possible to assign a specific aggregation method to each indicator. A matrix shows for each indicator (belonging to a specific LoE) how many sampling sites and reference sites have enough monitoring data to calculate it year by year. If the goal is to carry out the annual evaluation the user can choose the year of interest based on data availability and then proceed with the following steps. If the goal is to carry out the monthly evaluation,

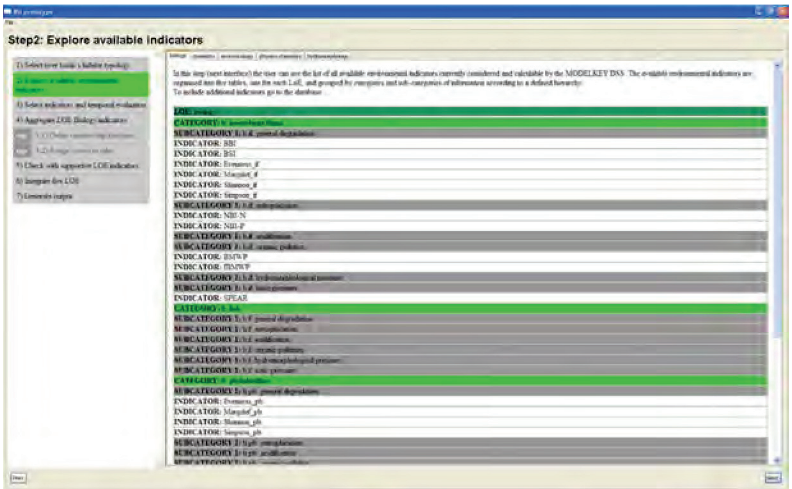

Figure 4.20: Available environmental indicators

after selecting the year of interest the user has to click on "Go to monthly evaluation" and then on "Next" and the number of sampling sites available month by month are shown in the matrix. The same procedure holds for the day level assessment.

To support the selection of indicators and temporal evaluation the optimal choice (year/month/day) for each indicator is highlighted by the DSS in red color. The optimal situation would be to have a considerable amount of data in the present year but, as this is usually not feasible, the system selects data related to the most recent date which presents a number of available sampling sites higher than a threshold calculated by means of the following algorithm (e.g. for the year time frame selection):

- Evaluate the maximum number of sampled sites in a year *symax*.
- Start from the most recent year and compare its number of sampled sites *sy* with $0.8 \cdot symax$. If $sy \geq 0.8 \cdot symax$ stop the search. This year will be called the main year.
    - If $sy < 0.8 \cdot symax$ consider the previous year and repeat the comparison procedure.

Once the main year is set, a year containing a sufficient amount of samplings which is also within a narrow temporal neighborhood with respect to the main year must be selected for each indicator independently. The procedure to select indicator's year is, for each indicator:

– Calculate the average number of sampling sites per year among all years$syavg$.

– Start from the main year and compare its sampling sites number sy with $0.2 \cdot syavg$. If $sy \geq 0.2 \cdot syavg$ select this year otherwise:

  – try with the next two years;

  – if even those are not valid try with the previous two years;

  – if no one of the previous years is elected as valid, the specific indicator will not be calculated.

The above presented algorithm is based on a pair of fixed percentages (0.8 and 0.2), both values were selected empirically by performing a sufficient amount of trials.

Each indicator can be colored by the DSS to highlight a specific problem according to the legend reported on the top of the interfaces. Specifically, the yellow color indicates that there are not reference values (reference sites or default values) available for the specific indicators, therefore the indicators will not be calculated and included in the environmental evaluation; in the other hand, the grey color indicates that none of the possible dates were selected and therefore the specific indicators will not be calculated and included in the environmental evaluation. In case the subsequent time span is selected (i.e. from year to month, from month to day) the list of applicable indicators will be automatically reduced by deleting the indicators highlighted (in the previous interface) in yellow and grey color as well as the indicators for which the assessment on the new selected time-span is not possible. Indicators can be excluded from the experimental application in case the number of sites with enough data for calculation is very low. To this end it is sufficient not to select any year, month, day on the row of that indicator.

The next three steps are "Expert mode" steps which can be reached only by selecting the correspondent button before going on with the assessment. The first expert step (interface reported in Figure 4.22) concerns the modification of the membership function defined for each indicator. For a thorough explanation of the normalization issues please refer to Section 4.3.1. In the interface reported in the next Figure 4.22 the user is allowed to modify both boundaries and uncertainty ranges according to his/her expert judgement.

After that the user can proceed with step 4.2 in which he/she can assign a score lying on a scale ranging from 0 to 1 to each antecedent in the TSK aggregations related to the aggregations of subcategories into categories and of categories into LoEs (as explained in Section 4.3.1). The first questionnaire (Figure 4.23) refers to aggregation of the response obtained from various impact typologies in order to quantify the overall status of certain biological community. For each rule the status class obtained by applying the Min and the status class obtained by applying the Avg are provided. The user is asked to give a score according to his/her own expert judgment: he/she can decide to be conservative and then rely on the Min operator (e.g. he/she retains

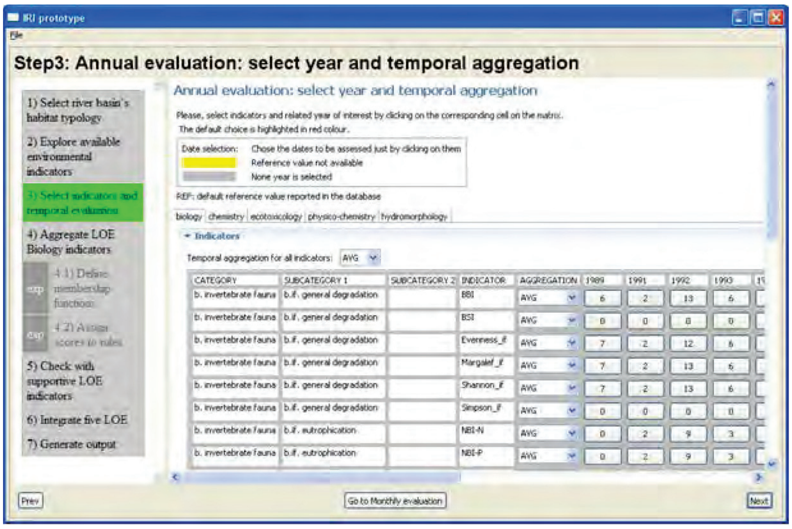

Figure 4.21: Temporal data aggregations selection

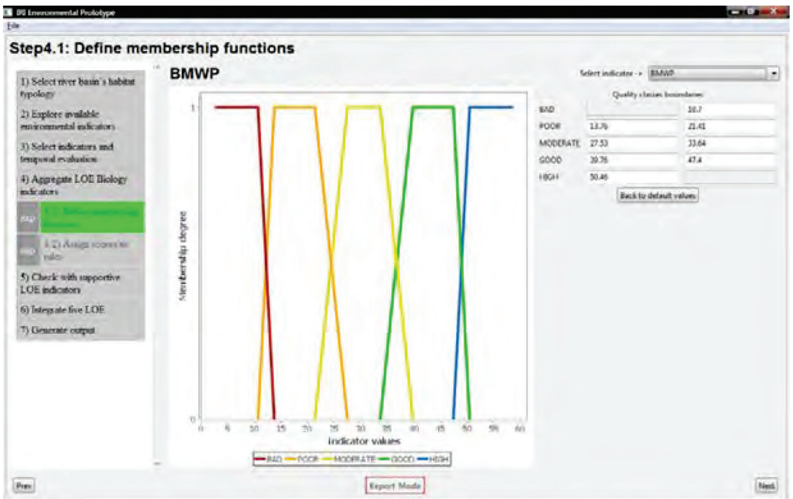

Figure 4.22: Modification of normalization functions

the largest impact caused by one individual stressor as representative of the overall status of that biological community and sufficient to totally deteriorate its structure and functioning), to be compensative and then rely on the Avg operator (e.g. he/she retains the overall status in a multi-stressor environment better represented by an average value where largest impacts are balanced with lowest impacts) or to assign an intermediate score corresponding to a combination of both operators (e.g. he retains that the more realistic picture is provided by an average status adjusted on the largest impacts). The default option is set be between the Avg an Min operators. The second questionnaire refers to aggregation of the responses obtained from the five biological communities in order to quantify the overall status of the entire aquatic ecosystem.

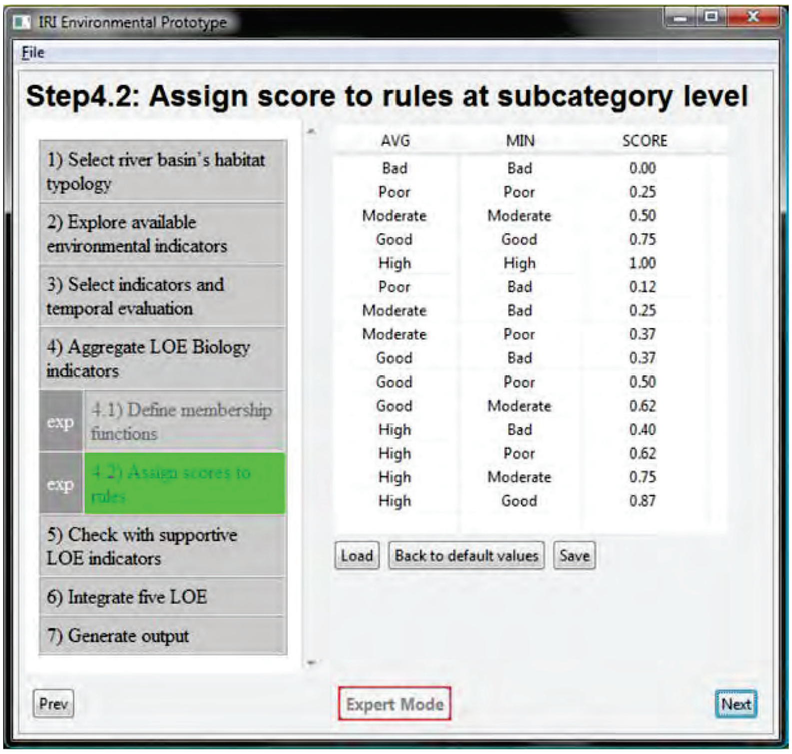

Figure 4.23: Questionnaire related to TSK aggregation

At this point the software is able to perform all the required operations without the participation of the user, the calculus is performed and a final interface reporting the end of the process is shown. Right after the environmental module application is closed the uDig interface gaing focus again and presents the elaborated results.

In figure 4.24 the main interface is reported where the two interfaces related to the MODELKEY DSS are highlighted. The bottom one is related to basin scale result evaluation while the right side one is related to the exploration of punctual site scale results.

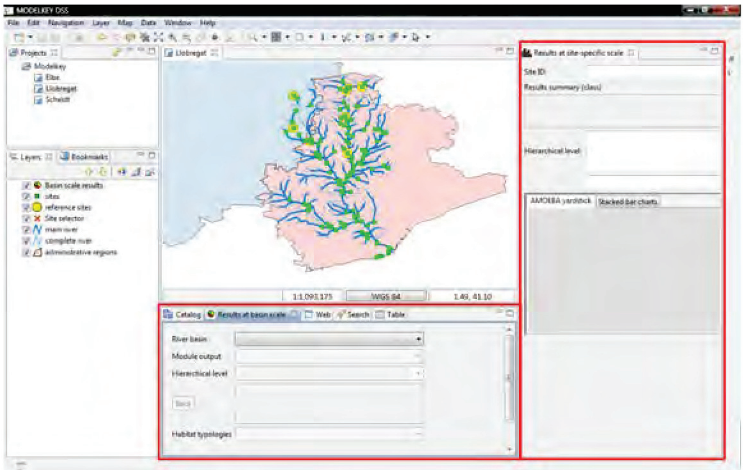

Figure 4.24: MODELKEY DSS main interface

As shown in Figure 4.25, in order to visualize the results at basin scale, first the river of concern has to be selected from the river basin combo, then the module output combo shows a list of possible results (e.g. env_status_fuzzy, socio_economic) according to the performed entry points. After selecting a module output, the map layer will refresh drawing the correspondent results pie charts. Moreover, the hierarchy level combo is used to visualize the results of each element contributing to the selected module output according to the defined hierarchy. Finally, the habitat typologies combo allows to select results related to a specific river basin typology or to all the typologies considered in the selected river basin.

The main output of the MODELKEY DSS is a GIS map visualizing a pie chart over each sampling site. The chart shows the sampling point membership degree to one (100%) or two (complementary percentages) WFD status classes, i.e. high, good, moderate, poor and bad, represented by using WFD standard colors coding (i.e. blue, green, yellow, orange, red respectively): slices are larger or thinner according to the membership degree to each status class. The MODELKEY DSS provides map results for:

– Environmental status (according to both fuzzy logic and WFD approaches);

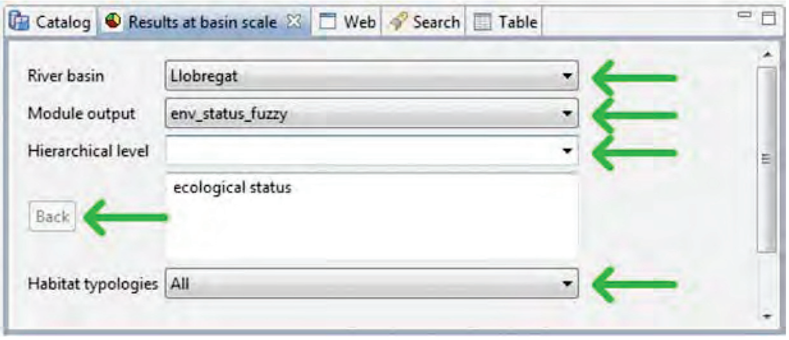

Figure 4.25: Basin scale results evaluation interface

– Chemical status;

– Pressures status;

– Socio-economic status; and

– Hot spot prioritization.

All these results are visualized at the Basin scale following the selections made in the "Results at basin scale" view (see Figure 4.26).

As shown in Figure 4.27 there are two additional functionalities. The first one allows to visualize the results on the map according to the assigned classes or to the obtained score. The default option is set on "class" and allows to visualize the pie chart colored according to the WFD status classes as shown in the previous Figure 4.26. By clicking on "score" the pie charts on the map are refreshed and colored according to the obtained score (from 0 to 1, form white to red) and the "prioritization table" appears on the right site, where sites are again ordered and colored according to their priority. By double clicking on one site on the prioritization table it is possible to visualize where the site is located on the map (i.e. the site selector layer is activated and a red cross appears on the selected site). The second functionality allows to modify the pie chart radius in the map layer by using the pie chart radius scrollbar.

To explore the results at site-specific scale, first a site needs to be selected. There are two ways to proceed: (i) select the site on the map; or (ii) insert the site name in site id text box. After selecting a sampling site on the map or writing the site id on the textbox, the "results at site-specific scale" view on the right side will show selected site's intermediate results as depicted in Figure 4.28. By using the "hierarchical level" combo it is possible to change the element to be visualized and explored (i.e. LOE, category, subcategory or indicator) according to the defined hierarchy.

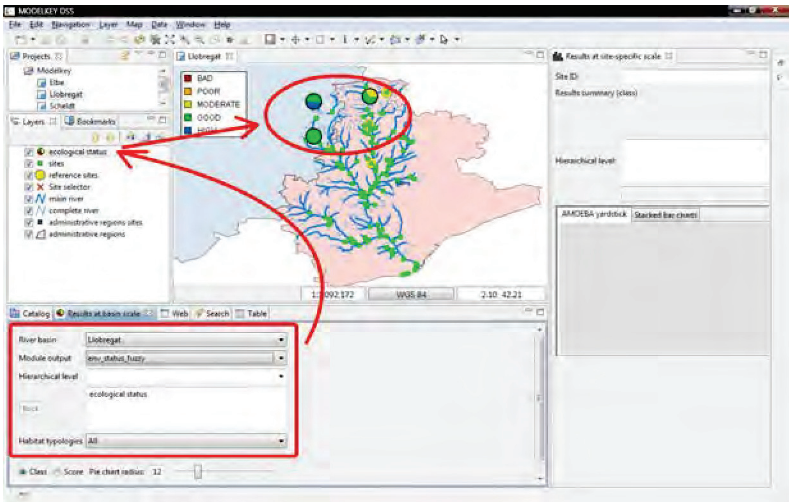

Figure 4.26: Basin scale results

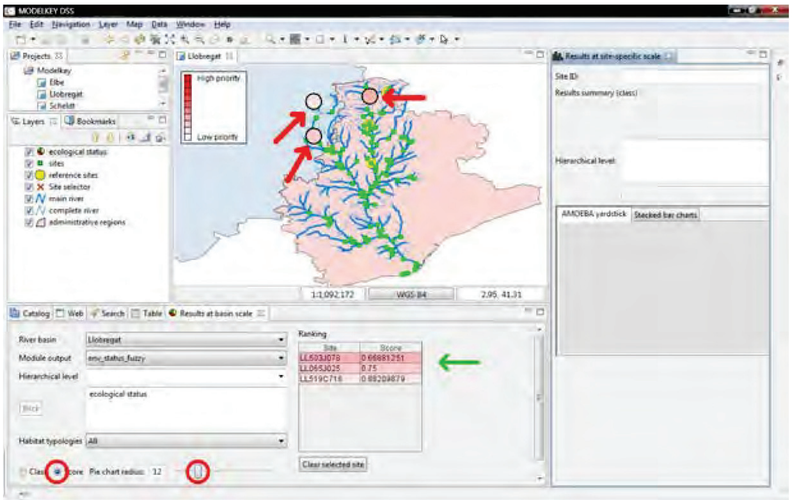

Figure 4.27: Basin scale prioritization results

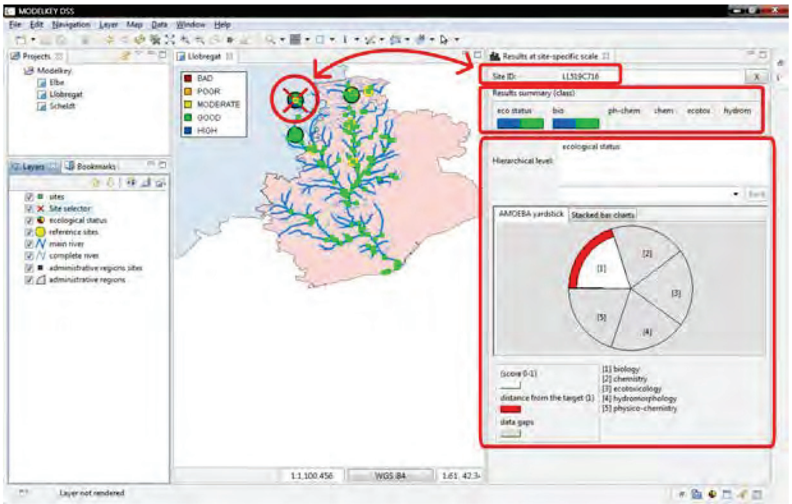

Figure 4.28: Site scale results visualization

First of all, the "Results summary" matrix allows to visualize the ecological status and the results obtained by each Line of Evidence. As shown in Figure 4.29, the ecological status and the Biology LOE results are reported on a bar chart as membership degree to one (100%) or two (complementary percentages) WFD status classes. For the remaining LoEs (phjysico-chemistry, chemistry, ecotoxicology and hydromorphology) the following symbols are used:

- blue tick to confirm the High status;
- green tick to confirm the Good status;
- red cross to reject Good status; and
- no symbol means that information related to a specific LOE is missing.

Figure 4.29: Site scale results summary matrix

Then, the "Results details" can be explored by means of both AMOEBA graphs [ten Brink *et al.*, 1991] or stack bar histograms just by selecting the appropriate tab as shown in Figure 4.30. In both the graphs the target value (i.e. the optimal value obtainable by the correspondent element) is colored in red while the actual value of the visualized element is depicted in white. In this way it is possible to see how much the site-specific condition meets the pre-defined target. When a slice or a bar is not colored (i.e. grey colored) it means that in the investigated sampling site the information related to a specific LOE/category/subcategory/indicator is missing.

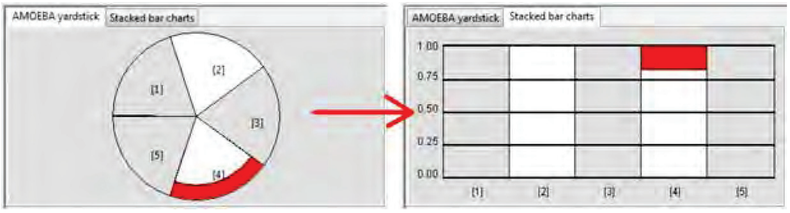

Figure 4.30: Site scale results details AMOEBA and stack bar histogram graphs

4.6 Results

The MODELKEY DSS has been successfully applied to the three case studies comprehended in the project: Llobregat, Elbe and Scheldt. Although environmental and socio-economic data related to the three case studies were supplied by the project partners in the form of a Microsoft Access database and Microsoft Excel sheets respectively, some work still has been done in order to find and prepare administrative regions maps along with their land use specifications which were lacking. In order to present the results obtained by the application of the DSS, only a small part of the Llobregat case study is presented as it was the most deeply analyzed and is perfectly suitable as an exemplificative case. Results obtained from the testing of the FIS for LoE Biology to the Llobregat case study were first of all visualized on maps for each individual habitat typology (i.e. the *Ríos de montaña mediterránea de caudal elevado*, MMEC and *Ríos mediterráneos de caudal variable*, RMCV typologies) and then compared with the response coming from the WFD-strict mode (where the assessment is performed by strictly following the WFD suggestions and therefore always applying the minimum aggregation operator) as depicted in figure 4.31.

The LoE Biology classification for both typologies is based on data referring to *invertebrate fauna*. Except from the two reference sites (LL020J118 and LL035J080) which are classified as 100% high status by applying both modes (fuzzy and WFD-strict), the Ecological Status (ES) classification of sampling sites in both cases decreases when moving from the upper Llobregat to the coast. However the fuzzy output (left side) returns a slightly better status along the river basin. This discrepancy is

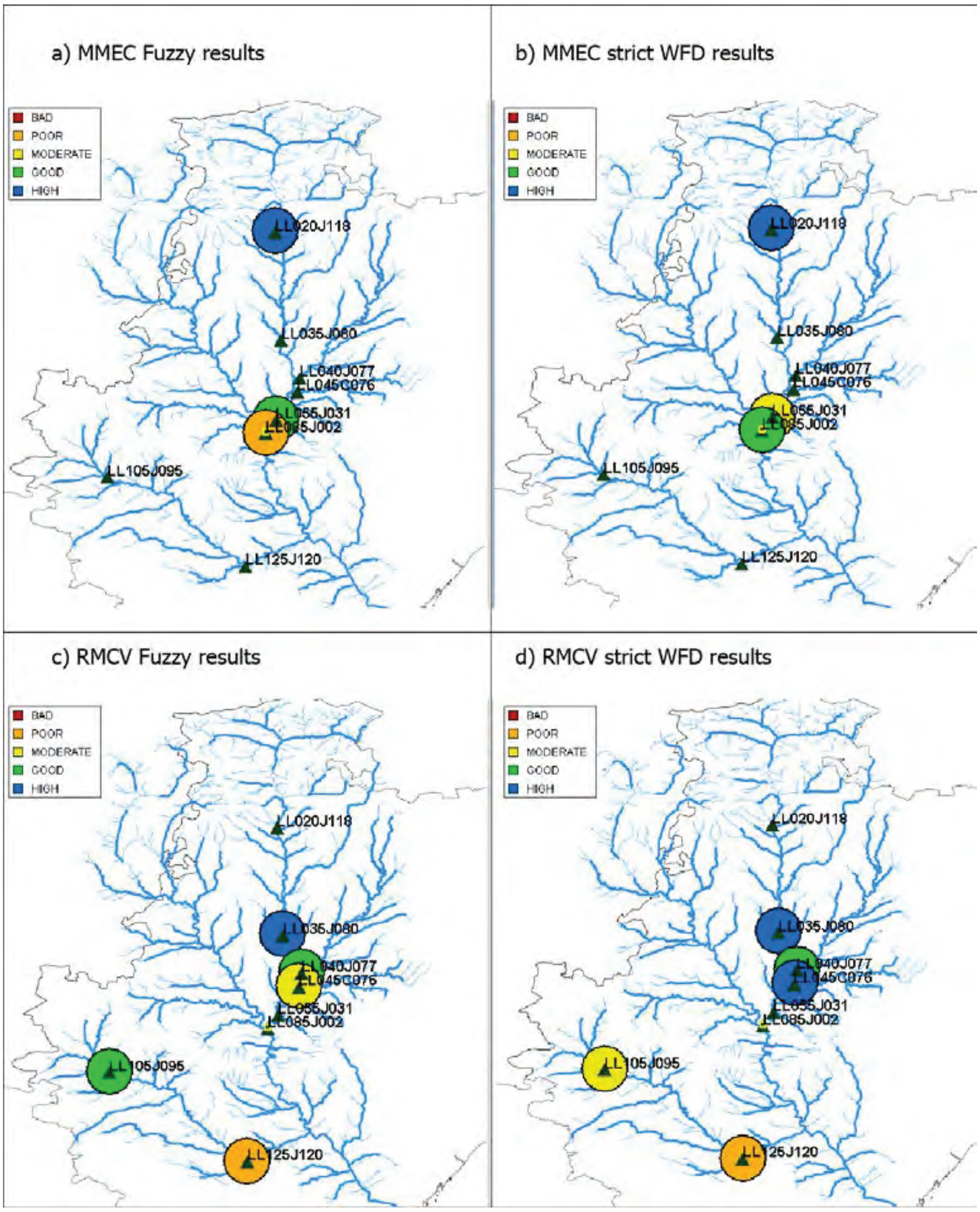

Figure 4.31: Comparison between LoE Biology classification provided as fuzzy output (left side) and obtained according to the WFD-strict mode (right side) for three sampling sites belonging to MMEC river type (a) and five sampling sites referring to RMCV river type (b).

due to less conservative but, from a science point of view, more realistic rules used for aggregation of biological indicators that take into account uncertainty in classification by evaluating several Min-Avg combinations. The scores assigned by the experts to the inference rules reflect the following assumptions: the more biological communities are in low status, the worse the site classification is; one stressor heavily acting on the basin is considered enough to totally destroy individual biological communities; the presence of multiple stressors moderately affecting the basin is likely able to bring similar negative consequences.

The classification of *invertebrate fauna* status according to *organic pollution* and *toxic pressure* in both typologies is visualized in Figure 4.32 while Figure 4.33 illustrates the general degradation output. In general both stressors give a relevant contribution to downgrading the status of *invertebrate fauna* in the central-lower part of the Llobregat but the relative importance varies site by site. Conversely indicators of *general degradation* are not able to reflect such an alteration and give a response ranging from good to high in all sampling sites (except one case where a small membership degree to moderate status is present). This means that even if there is evidence of two stressors causing alteration, the general conditions (i.e. overall structure and functioning) of invertebrate fauna seem not to be totally compromised yet.

As far as MMEC is concerned, the most interesting example is LL085J002 that in Figure 4.31 (right side) turns out to be the worst sampling site having full membership (100%) to poor status according to the WFD strict mode. As illustrated in Figure 4.34, where AMOEBA yardsticks of individual sampling sites are reported, this is mostly due to one indicator, i.e. *IBMWP* representing *organic pollution*, while the remaining indicators values range from moderate (i.e. *Margalef* and *Simpson*) to good (i.e. *SPEAR* and *Shannon*) and high (i.e. *Eveness*). Accordingly the more realistic fuzzy rules reflect the uncertainty in the classification of this site assigning two complementary membership degrees: 70% to moderate status (due to *toxic pressure* and *general degradation* output) and 30% to poor status (due to *organic pollution*).

Regarding RMCV, Figure 4.31 clearly shows that the fuzzy-based procedure assigns a consistent membership degree to the upper class with respect to the WFD-strict output in three sampling sites. This demonstrates that the uncertainty is larger in the lower part of the Llobregat and that the WFD strict assessment is probably not the right tool to be applied in order to reflect the real ES. If stressors are considered (Figure 4.32) two sites (LL040J077 and LL125J120) show the same output regardless the stressor of concern (i.e. good and poor respectively) while the other two sites have opposite situations: LL045C076 is upgraded from moderate (*IBMWP*) to high status (*SPEAR*), LL105J095 is downgraded from good (*IBMWP*) to moderate (*SPEAR*). In spite of the membership degrees assigned by *IBMWP* and *SPEAR* to lower classes such as moderate and poor status, the general conditions of *invertebrate fauna* highlighted in Figure 4.33 are quite good everywhere for RMCV habitat typology too. An interesting case is the LL045C076 site (Figure 4.35) where one stressor, i.e. *or-*

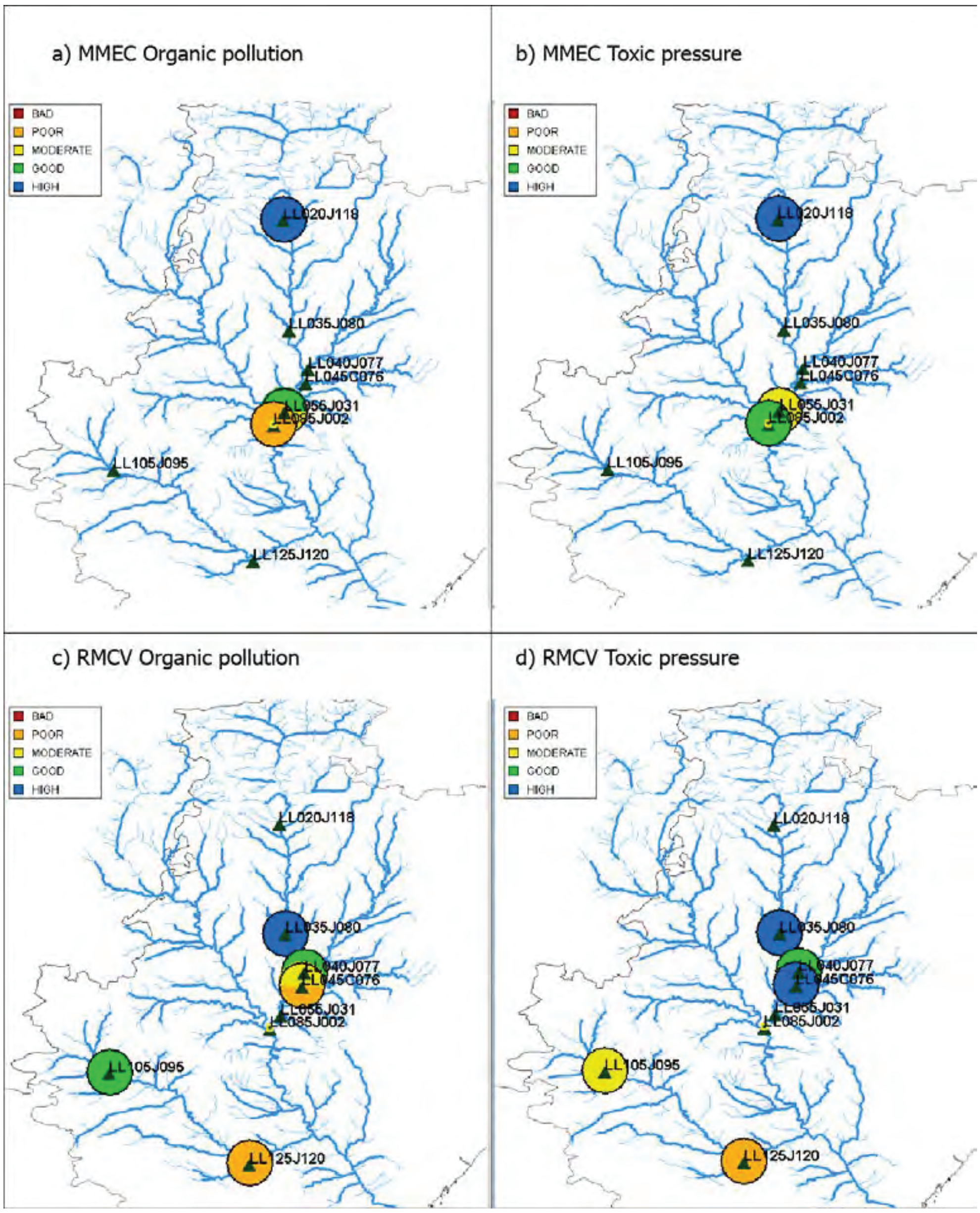

Figure 4.32: Classification of *invertebrate fauna* due to *organic pollution* (left side) and *toxic pressure* (right side) in sampling sites belonging to MMEC (a) and RMCV (b) habitat typologies.

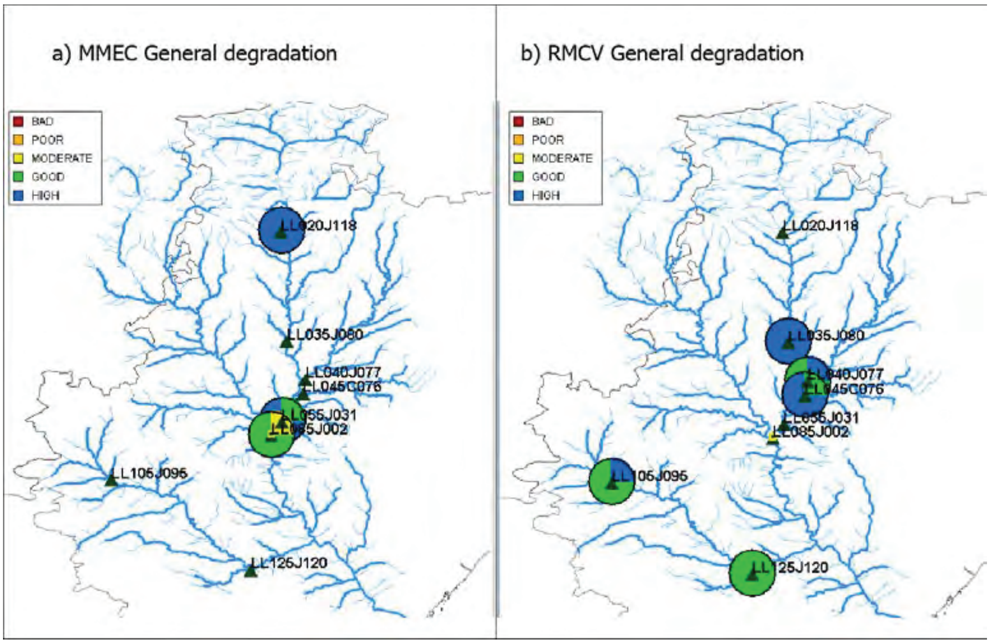

Figure 4.33: Classification of *invertebrate fauna* according to *general degradation* impact in sampling sites belonging to MMEC (left side) and RMCV (right side) habitat typologies.

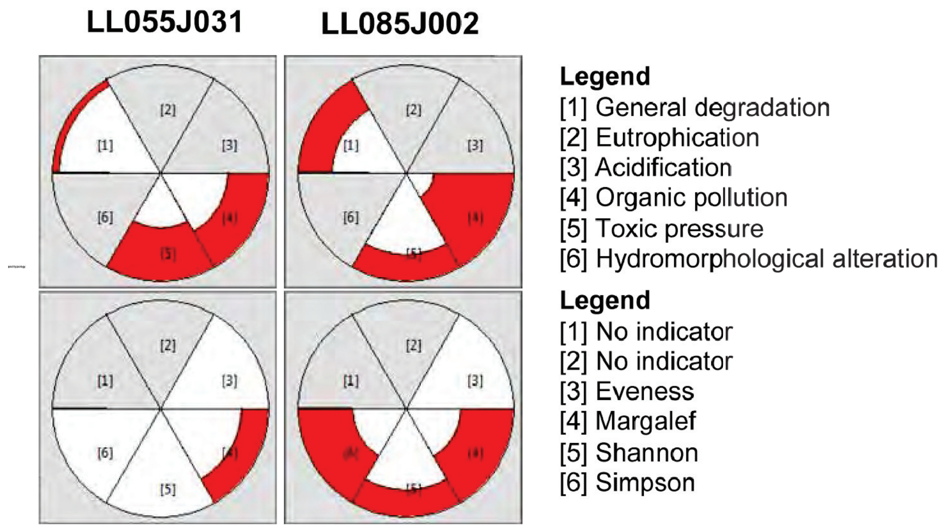

Figure 4.34: AMOEBA yardsticks for sampling sites belonging to MMEC river type. The first row is related to impact typologies, the second row to general degradation.

ganic pollution, is moderately affecting *invertebrate fauna* while *toxic pressure* does not exist at all according to *SPEAR* results (white slice). As far as *general degradation* is considered conditions are close to the reference values and high concordance exists among indicators (the *Margalef* index as the only exception). The resulting fuzzy-based classification consequently assigns 55% to moderate status and 45% to good status due to the conclusive judgment for impact scores aggregation equal to 0.62 assigned to the rule "if Min is Moderate and Avg is Good".

The available visualization tools represented by GIS maps and AMOEBA yardsticks allow the assessment of results both at basin and site-specific scale respectively, thus supporting the identification of different management needs as well as aiding the planning of targeted monitoring programmes along the river basin. In the Llobregat case-study management intervention should therefore be planned in the central-lower part of the river to reduce the stressor levels (i.e. mainly *organic pollution*) and avoid further alteration of *invertebrate fauna*. Moreover additional impact typologies (e.g. hydromorphological alteration) and biological communities (e.g. phytobenthos, fish) should be monitored in order to obtain a more comprehensive and consequently realistic picture of the ES of the aquatic system as a whole.

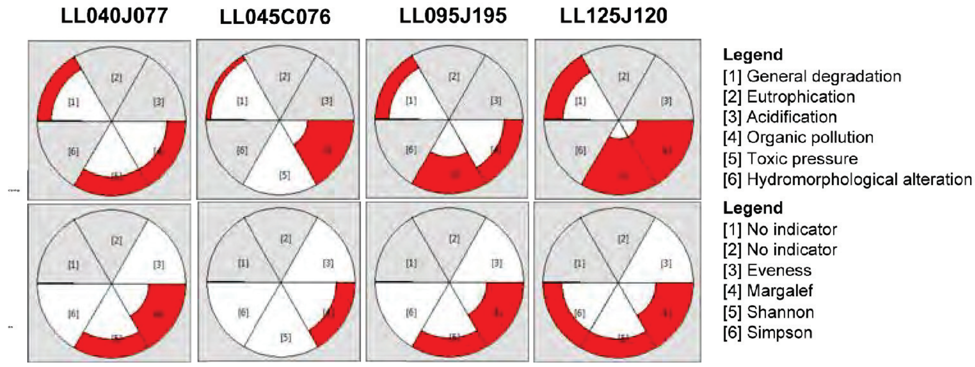

Figure 4.35: AMOEBA yardsticks for sampling sites belonging to RMCV river type. The first row is related to impact typologies the second row to general degradation.

4.7 Comparisons

In order to evaluate the quality and contribute to research that the Modelkey tool implies, it should be compared with other similar tools like those presented in Section 2.3. In the next paragraphs such comparison is performed showing that new interesting features are introduced by the MODELKEY DSS.

All DSSs presented in Section 2.3 were developed through European Union fundings with the clear objective of supporting the implementation of the Community legislation framework. In particular they were designed to address several issues affecting water bodies by integrating through the assessment process environmental and socio-economic aspects as required by the WFD. However some limitations are still present as applied models are often built according to specific issues. For better appreciate the originality of MODELKEY-DSS is necessary to identify the limits of these existing DSSs.

The *DITTY DSS* was designed to help competent authorities toward a correct management of coastal lagoon areas with undergoing socio-economic exploitation by producing different cost-benefit based scenarios and ranking them toward the definition of the best choice. Even if an assessment of the environmental status of the surface water is present in the DITTY model, it is not the main outcome of the system which is specifically designed to find out the best exploitation scenario. Also this DSS is specifically based on lagoons which are a very small part of the whole surface water typologies.

The *Elbe river DSS* was designed to help competent authorities in defining the program of measures for the German Elbe river basin in order to improve its socio-economic usage (e.g. navigability), to define the sustainable level of protections against flooding, to improve the environmental status and reduce pollutants loads. However, models comprised in the DSS are designed to solve Elbe river specific problems and also the system only simulates impacts determined by management actions on water quality by assessing ecological and chemical status, and considering the socio-economic development. Concluding, the Elbe river DSS is too specific to be generically applied to water management and also it is not strictly devoted to the application of the WFD but more to the production of remediation scenarios and their consequences.

The *MULINO DSS* project was developed as a general methodology and DSS tool able to tackle problems related to integrated and holistic approaches to protection and management of water resources as required by the WFD. This system is a generic system for the application of the DPSIR framework toward scenarios production and assessment. It is a generic product which can be applied to many surface water typologies and at the same be moulded to fulfil specific decision maker's issues. The drawbacks of this solution are related to its elevated complexity in configuration and use (due to its high level of generality) and to its lack of GIS based interfaces which made difficult for a decision maker to identify the regions for prior intervention.

The aim of *RiverLife DSS* is to help decision makers in planning sustainable land use, control water pollution and manage river basins. The system is composed by different models which are joined together in order to perform assessments related to the status of the river of concern. One positive aspect of the RiverLife DSS is its web oriented nature, the problem is that it was not originally created for the implementation of the WFD recommendations and, more than this, it has not a comprehensive structure but rather is just a complex mixture of originally separated modules. This last aspect makes it hardly adoptable for river management and also it would be very complex to adapt it to different rivers because embedded models must be configured accordingly.

The main goal of the *TRANSCAT* project is create an operational and integrated comprehensive DSS for optimal water management of catchments in borderland regions. These goals are achieved by collecting different models and assessment tools and make them communicate and share results. *TRANSCAT* is a web based orchestrator of external resources and therefore it has not a peculiar methodology to be followed. TRANSCAT is hardly comparable with the other tools, it is just a very complex models' container. The considerations about this DSS are related to its specific application only to transboundary catchments and also to the fact that the correct functioning of many different tools is never a simple task.

Finally, the *WadBOS DSS* is an information system aimed at supporting policy making in the Dutch Wadden Sea. It is built to be able to create different scenarios, perform integrated assessments as requested by the WFD and compare the scenarios related to the adoption of a set of remediation strategies. The system obtains its results by the use of complex internal models and supplies georeferenced information. It is an interesting system but its tight association with the Dutch Wadden Sea and the complexity of use makes it almost unapplicable by water management stakeholders.

In spite of all the above presented contenders the MODELKEY DSS is the most user friendly product. It is based on a small amount of simple to understand interfaces which hide the complex elaborations occurring within. In fact most of the presented products are too unbalanced in the research direction. These tools are difficult to understand and the information contained in their results are usually hardly discoverable. More than this the MODELKEY DSS was created with the primary objective of applying the WFD while others are suitable for the WFD application but their fundamental aim is usually the comparison of different remediation alternatives. The MODELKEY DSS is also highly flexible, it allows the assessment of different case studies and regulations just by setting up different configurations. Finally its results are very simple to evaluate and verify as they are embedded in a user friendly GIS which can give an idea of the obtained results at a glance.

Chapter 5

Conclusions and future work

5.1 Conclusions

The uprising level of attention related to risk assessment and management issues demonstrated by people and legislators in these years yielded the necessity of novel and precise methodologies and tools. New environmental rules has been created in order to support the hoped transition from a polluting society to a greener one. One of the most important enactment of the European Union is the Water Framework Directive 2000/60/CE (WFD).

The WFD introduced a new vision of water management totally different from the past guidelines, which is not only limited to an assessment of the water's chemical status but rather to an holistic assessment of the ecological status integrated with socio-economic evaluation, which together define the level of well-being that a good water quality management implies.

In this thesis the studies performed during my PhD course are presented. My work in these years were strictly related to the Modelkey project and comprehended two separated complex activities: the development of the underlying mathematical model and the design and development of the software application. My research objectives were to identify and develop a novel risk assessment methodology based on MCDA techniques and to develop a state of the art environmental DSS with GIS capabilities. These objectives have been put into practice through the Modelkey project with the aim of fulfill the WFD requirements.

The MCDA methodology which demonstrated to be the most suitable with respect to environmental experts involved in the project was a hierarchical Fuzzy Inference System (FIS) which utilizes a different aggregation function at each level of the hierarchy. Two of these functions are relevant related to my research objectives. The most interesting is the aggregation adopted in the penultimate level of the hierarchy, it is a modified version of the Takagi-Sugeno-Kang aggregation of fuzzy variables. The main difference from the original version is the use, as input variables, of two aggregated values (minimum and average) instead of the row values. This method was selected because it was perfectly suitable in a situation where too many variables has to be aggregated with respect to user's preferences. Also the obtained results were judged positively by the experts. The other interesting aggregation function is the one used on the top level of the hierarchy which consists in the application of a flow-chart in order to integrate the fuzzy variables of concern. The flow-chart is based on the relations between the different variables where biology is the most important which has to be confirmed by the other variables.

As far as the Modelkey DSS is concerned, it met my research requirements as it is a completely flexible model-based DSS which utilizes GIS capabilities mostly for presentation purposes. It presents the results bt the use of Amoeba yardsticks which are not used in other environmental DSSs.

Many future enhancements should be applied. First of all GUIs can be provided for editing the configuration files and tables in the database. This is an important enhancement as the manual compilation of such tables is error prone. In general all interfaces can be improved, especially as far as the results exploration is concerned (e.g. by using an expandable tree based selection interface in order to traverse the hierarchy of results). More than this, GIS capabilities may be utilized in the indicators date selection phase in order to show to the decision makers not only the quantity of sampled sites per date but also their position along the river basin (it can be more interesting to assess less wide sprained sites than many clustered sites). Another module should be created which, starting by examining the present sampling stations' position and sampled data, should be able to suggest where to put new sampling stations and what data to sample. An important improvement is related to the inclusion of a results' reliability factor which should inform the user about the credibility of a particular result based on the amount of missing parameters in its calculation. Automatically generated questionnaires could be proposed by a suitable Data-mining algorithm in order to ease the utilization of the software.

As far as the mathematical model is concerned it could be an interesting exercise to evaluate two aspects. First, a sensitivity analysis could be performed in order to understand how the use, in the TSK based aggregations, of minimum and average, instead of the actual criteria values, influences the final results. This can be achieved by the use of scores selected by a single environmental expert both for min-avg based questionnaires as well as criteria based questionnaires and the comparison of discrepancies in the related results in the four case studies and also in hypothetical case studies based on random selected values. Secondary it would be interesting to evaluate the sensitivity of the system as far as the decision to use the minimum T-norm in the TSK based aggregations. Different runs of the procedure could be performed by using other notable T-norms like the probabilistic, Lukasiewicz and drastic T-norms. Also in this case the elaborations should be performed by the use of the actual case studies and randomized case studies. By examining the results and asking to experts to evaluate the best fitting ones, it could be interesting to rank the different alternatives and find out if the selection of the minimum t-norms was the better solution.

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Appendix A

Water framework directive

►B **DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL**

of 23 October 2000

establishing a framework for Community action in the field of water policy

(OJ L 327, 22.12.2000, p. 1)

Amended by:

		Official Journal		
		No	page	date
►M1	Decision No 2455/2001/EC of the European Parliament and of the Council of 20 November 2001	L 331	1	15.12.2001
►M2	Directive 2008/32/EC of the European Parliament and of the Council of 11 March 2008	L 81	60	20.3.2008
►M3	Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008	L 348	84	24.12.2008

▼B

DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 23 October 2000

establishing a framework for Community action in the field of water policy

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty establishing the European Community, and in particular Article 175(1) thereof,

Having regard to the proposal from the Commission ([1]),

Having regard to the opinion of the Economic and Social Committee ([2]),

Having regard to the opinion of the Committee of the Regions ([3]),

Acting in accordance with the procedure laid down in Article 251 of the Treaty ([4]), and in the light of the joint text approved by the Conciliation Committee on 18 July 2000,

Whereas:

(1) Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such.

(2) The conclusions of the Community Water Policy Ministerial Seminar in Frankfurt in 1988 highlighted the need for Community legislation covering ecological quality. The Council in its resolution of 28 June 1988 ([5]) asked the Commission to submit proposals to improve ecological quality in Community surface waters.

(3) The declaration of the Ministerial Seminar on groundwater held at The Hague in 1991 recognised the need for action to avoid long-term deterioration of freshwater quality and quantity and called for a programme of actions to be implemented by the year 2000 aiming at sustainable management and protection of freshwater resources. In its resolutions of 25 February 1992 ([6]), and 20 February 1995 ([7]), the Council requested an action programme for groundwater and a revision of Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances ([8]), as part of an overall policy on freshwater protection.

(4) Waters in the Community are under increasing pressure from the continuous growth in demand for sufficient quantities of good

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([1]) OJ C 184, 17.6.1997, p. 20,
OJ C 16, 20.1.1998, p. 14 and
OJ C 108, 7.4.1998, p. 94.

([2]) OJ C 355, 21.11.1997, p. 83.

([3]) OJ C 180, 11.6.1998, p. 38.

([4]) Opinion of the European Parliament of 11 February 1999 (OJ C 150, 28.5.1999, p. 419), confirmed on 16 September 1999, and Council Common Position of 22 October 1999 (OJ C 343, 30.11.1999, p. 1). Decision of the European Parliament of 7 September 2000 and Decision of the Council of 14 September 2000.

([5]) OJ C 209, 9.8.1988, p. 3.

([6]) OJ C 59, 6.3.1992, p. 2.

([7]) OJ C 49, 28.2.1995, p. 1.

([8]) OJ L 20, 26.1.1980, p. 43. Directive as amended by Directive 91/692/EEC (OJ L 377, 31.12.1991, p. 48).

▼B

quality water for all purposes. On 10 November 1995, the European Environment Agency in its report 'Environment in the European Union - 1995' presented an updated state of the environment report, confirming the need for action to protect Community waters in qualitative as well as in quantitative terms.

(5) On 18 December 1995, the Council adopted conclusions requiring, inter alia, the drawing up of a new framework Directive establishing the basic principles of sustainable water policy in the European Union and inviting the Commission to come forward with a proposal.

(6) On 21 February 1996 the Commission adopted a communication to the European Parliament and the Council on European Community water policy setting out the principles for a Community water policy.

(7) On 9 September 1996 the Commission presented a proposal for a Decision of the European Parliament and of the Council on an action programme for integrated protection and management of groundwater ([1]). In that proposal the Commission pointed to the need to establish procedures for the regulation of abstraction of freshwater and for the monitoring of freshwater quality and quantity.

(8) On 29 May 1995 the Commission adopted a communication to the European Parliament and the Council on the wise use and conservation of wetlands, which recognised the important functions they perform for the protection of water resources.

(9) It is necessary to develop an integrated Community policy on water.

(10) The Council on 25 June 1996, the Committee of the Regions on 19 September 1996, the Economic and Social Committee on 26 September 1996, and the European Parliament on 23 October 1996 all requested the Commission to come forward with a proposal for a Council Directive establishing a framework for a European water policy.

(11) As set out in Article 174 of the Treaty, the Community policy on the environment is to contribute to pursuit of the objectives of preserving, protecting and improving the quality of the environment, in prudent and rational utilisation of natural resources, and to be based on the precautionary principle and on the principles that preventive action should be taken, environmental damage should, as a priority, be rectified at source and that the polluter should pay.

(12) Pursuant to Article 174 of the Treaty, in preparing its policy on the environment, the Community is to take account of available scientific and technical data, environmental conditions in the various regions of the Community, and the economic and social development of the Community as a whole and the balanced development of its regions as well as the potential benefits and costs of action or lack of action.

(13) There are diverse conditions and needs in the Community which require different specific solutions. This diversity should be taken into account in the planning and execution of measures to ensure protection and sustainable use of water in the framework of the river basin. Decisions should be taken as close as possible to the locations where water is affected or used. Priority should be given to action within the responsibility of Member States through the drawing up of programmes of measures adjusted to regional and local conditions.

([1]) OJ C 355, 25.11.1996, p. 1.

▼B

(14) The success of this Directive relies on close cooperation and coherent action at Community, Member State and local level as well as on information, consultation and involvement of the public, including users.

(15) The supply of water is a service of general interest as defined in the Commission communication on services of general interest in Europe [1].

(16) Further integration of protection and sustainable management of water into other Community policy areas such as energy, transport, agriculture, fisheries, regional policy and tourism is necessary. This Directive should provide a basis for a continued dialogue and for the development of strategies towards a further integration of policy areas. This Directive can also make an important contribution to other areas of cooperation between Member States, *inter alia*, the European spatial development perspective (ESDP).

(17) An effective and coherent water policy must take account of the vulnerability of aquatic ecosystems located near the coast and estuaries or in gulfs or relatively closed seas, as their equilibrium is strongly influenced by the quality of inland waters flowing into them. Protection of water status within river basins will provide economic benefits by contributing towards the protection of fish populations, including coastal fish populations.

(18) Community water policy requires a transparent, effective and coherent legislative framework. The Community should provide common principles and the overall framework for action. This Directive should provide for such a framework and coordinate and integrate, and, in a longer perspective, further develop the overall principles and structures for protection and sustainable use of water in the Community in accordance with the principles of subsidiarity.

(19) This Directive aims at maintaining and improving the aquatic environment in the Community. This purpose is primarily concerned with the quality of the waters concerned. Control of quantity is an ancillary element in securing good water quality and therefore measures on quantity, serving the objective of ensuring good quality, should also be established.

(20) The quantitative status of a body of groundwater may have an impact on the ecological quality of surface waters and terrestrial ecosystems associated with that groundwater body.

(21) The Community and Member States are party to various international agreements containing important obligations on the protection of marine waters from pollution, in particular the Convention on the Protection of the Marine Environment of the Baltic Sea Area, signed in Helsinki on 9 April 1992 and approved by Council Decision 94/157/EC [2], the Convention for the Protection of the Marine Environment of the North-East Atlantic, signed in Paris on 22 September 1992 and approved by Council Decision 98/249/EC [3], and the Convention for the Protection of the Mediterranean Sea Against Pollution, signed in Barcelona on 16 February 1976 and approved by Council Decision 77/585/EEC [4], and its Protocol for the Protection of the Mediterranean Sea Against Pollution from Land-Based Sources, signed in Athens on 17 May 1980 and approved by Council Decision 83/101/EEC [5]. This Directive is to make a

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[1] OJ C 281, 26.9.1996, p. 3.
[2] OJ L 73, 16.3.1994, p. 19.
[3] OJ L 104, 3.4.1998, p. 1.
[4] OJ L 240, 19.9.1977, p 1.
[5] OJ L 67, 12.3.1983, p. 1.

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contribution towards enabling the Community and Member States to meet those obligations.

(22) This Directive is to contribute to the progressive reduction of emissions of hazardous substances to water.

(23) Common principles are needed in order to coordinate Member States' efforts to improve the protection of Community waters in terms of quantity and quality, to promote sustainable water use, to contribute to the control of transboundary water problems, to protect aquatic ecosystems, and terrestrial ecosystems and wetlands directly depending on them, and to safeguard and develop the potential uses of Community waters.

(24) Good water quality will contribute to securing the drinking water supply for the population.

(25) Common definitions of the status of water in terms of quality and, where relevant for the purpose of the environmental protection, quantity should be established. Environmental objectives should be set to ensure that good status of surface water and groundwater is achieved throughout the Community and that deterioration in the status of waters is prevented at Community level.

(26) Member States should aim to achieve the objective of at least good water status by defining and implementing the necessary measures within integrated programmes of measures, taking into account existing Community requirements. Where good water status already exists, it should be maintained. For groundwater, in addition to the requirements of good status, any significant and sustained upward trend in the concentration of any pollutant should be identified and reversed.

(27) The ultimate aim of this Directive is to achieve the elimination of priority hazardous substances and contribute to achieving concentrations in the marine environment near background values for naturally occurring substances.

(28) Surface waters and groundwaters are in principle renewable natural resources; in particular, the task of ensuring good status of groundwater requires early action and stable long-term planning of protective measures, owing to the natural time lag in its formation and renewal. Such time lag for improvement should be taken into account in timetables when establishing measures for the achievement of good status of groundwater and reversing any significant and sustained upward trend in the concentration of any pollutant in groundwater.

(29) In aiming to achieve the objectives set out in this Directive, and in establishing a programme of measures to that end, Member States may phase implementation of the programme of measures in order to spread the costs of implementation.

(30) In order to ensure a full and consistent implementation of this Directive any extensions of timescale should be made on the basis of appropriate, evident and transparent criteria and be justified by the Member States in the river basin management plans.

(31) In cases where a body of water is so affected by human activity or its natural condition is such that it may be unfeasible or unreasonably expensive to achieve good status, less stringent environmental objectives may be set on the basis of appropriate, evident and transparent criteria, and all practicable steps should be taken to prevent any further deterioration of the status of waters.

(32) There may be grounds for exemptions from the requirement to prevent further deterioration or to achieve good status under

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specific conditions, if the failure is the result of unforeseen or exceptional circumstances, in particular floods and droughts, or, for reasons of overriding public interest, of new modifications to the physical characteristics of a surface water body or alterations to the level of bodies of groundwater, provided that all practicable steps are taken to mitigate the adverse impact on the status of the body of water.

(33) The objective of achieving good water status should be pursued for each river basin, so that measures in respect of surface water and groundwaters belonging to the same ecological, hydrological and hydrogeological system are coordinated.

(34) For the purposes of environmental protection there is a need for a greater integration of qualitative and quantitative aspects of both surface waters and groundwaters, taking into account the natural flow conditions of water within the hydrological cycle.

(35) Within a river basin where use of water may have transboundary effects, the requirements for the achievement of the environmental objectives established under this Directive, and in particular all programmes of measures, should be coordinated for the whole of the river basin district. For river basins extending beyond the boundaries of the Community, Member States should endeavour to ensure the appropriate coordination with the relevant non-member States. This Directive is to contribute to the implementation of Community obligations under international conventions on water protection and management, notably the United Nations Convention on the protection and use of transboundary water courses and international lakes, approved by Council Decision 95/308/EC [1] and any succeeding agreements on its application.

(36) It is necessary to undertake analyses of the characteristics of a river basin and the impacts of human activity as well as an economic analysis of water use. The development in water status should be monitored by Member States on a systematic and comparable basis throughout the Community. This information is necessary in order to provide a sound basis for Member States to develop programmes of measures aimed at achieving the objectives established under this Directive.

(37) Member States should identify waters used for the abstraction of drinking water and ensure compliance with Council Directive 80/778/EEC of 15 July 1980 relating to the quality of water intended for human consumption [2].

(38) The use of economic instruments by Member States may be appropriate as part of a programme of measures. The principle of recovery of the costs of water services, including environmental and resource costs associated with damage or negative impact on the aquatic environment should be taken into account in accordance with, in particular, the polluter-pays principle. An economic analysis of water services based on long-term forecasts of supply and demand for water in the river basin district will be necessary for this purpose.

(39) There is a need to prevent or reduce the impact of incidents in which water is accidentally polluted. Measures with the aim of doing so should be included in the programme of measures.

(40) With regard to pollution prevention and control, Community water policy should be based on a combined approach using control of pollution at source through the setting of emission limit values and of environmental quality standards.

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(1) OJ L 186, 5.8.1995, p. 42.

(2) OJ L 229, 30.8.1980, p. 11. Directive as last amended by Directive 98/83/EC (OJ L 330, 5.12.1998, p. 32).

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(41) For water quantity, overall principles should be laid down for control on abstraction and impoundment in order to ensure the environmental sustainability of the affected water systems.

(42) Common environmental quality standards and emission limit values for certain groups or families of pollutants should be laid down as minimum requirements in Community legislation. Provisions for the adoption of such standards at Community level should be ensured.

(43) Pollution through the discharge, emission or loss of priority hazardous substances must cease or be phased out. The European Parliament and the Council should, on a proposal from the Commission, agree on the substances to be considered for action as a priority and on specific measures to be taken against pollution of water by those substances, taking into account all significant sources and identifying the cost-effective and proportionate level and combination of controls.

(44) In identifying priority hazardous substances, account should be taken of the precautionary principle, relying in particular on the determination of any potentially adverse effects of the product and on a scientific assessment of the risk.

(45) Member States should adopt measures to eliminate pollution of surface water by the priority substances and progressively to reduce pollution by other substances which would otherwise prevent Member States from achieving the objectives for the bodies of surface water.

(46) To ensure the participation of the general public including users of water in the establishment and updating of river basin management plans, it is necessary to provide proper information of planned measures and to report on progress with their implementation with a view to the involvement of the general public before final decisions on the necessary measures are adopted.

(47) This Directive should provide mechanisms to address obstacles to progress in improving water status when these fall outside the scope of Community water legislation, with a view to developing appropriate Community strategies for overcoming them.

(48) The Commission should present annually an updated plan for any initiatives which it intends to propose for the water sector.

(49) Technical specifications should be laid down to ensure a coherent approach in the Community as part of this Directive. Criteria for evaluation of water status are an important step forward. Adaptation of certain technical elements to technical development and the standardisation of monitoring, sampling and analysis methods should be adopted by committee procedure. To promote a thorough understanding and consistent application of the criteria for characterisation of the river basin districts and evaluation of water status, the Commission may adopt guidelines on the application of these criteria.

(50) The measures necessary for the implementation of this Directive should be adopted in accordance with Council Decision 1999/468/EC of 28 June 1999 laying down the procedures for the exercise of implementing powers conferred on the Commission ([1]).

(51) The implementation of this Directive is to achieve a level of protection of waters at least equivalent to that provided in certain earlier acts, which should therefore be repealed once the relevant provisions of this Directive have been fully implemented.

([1]) OJ C 184, 17.7.1999, p. 23.

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(52) The provisions of this Directive take over the framework for control of pollution by dangerous substances established under Directive 76/464/EEC [1]. That Directive should therefore be repealed once the relevant provisions of this Directive have been fully implemented.

(53) Full implementation and enforcement of existing environmental legislation for the protection of waters should be ensured. It is necessary to ensure the proper application of the provisions implementing this Directive throughout the Community by appropriate penalties provided for in Member States' legislation. Such penalties should be effective, proportionate and dissuasive,

HAVE ADOPTED THIS DIRECTIVE:

Article 1

Purpose

The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which:

(a) prevents further deterioration and protects and enhances the status of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands directly depending on the aquatic ecosystems;

(b) promotes sustainable water use based on a long-term protection of available water resources;

(c) aims at enhanced protection and improvement of the aquatic environment, *inter alia*, through specific measures for the progressive reduction of discharges, emissions and losses of priority substances and the cessation or phasing-out of discharges, emissions and losses of the priority hazardous substances;

(d) ensures the progressive reduction of pollution of groundwater and prevents its further pollution, and

(e) contributes to mitigating the effects of floods and droughts

and thereby contributes to:

— the provision of the sufficient supply of good quality surface water and groundwater as needed for sustainable, balanced and equitable water use,

— a significant reduction in pollution of groundwater,

— the protection of territorial and marine waters, and

— achieving the objectives of relevant international agreements, including those which aim to prevent and eliminate pollution of the marine environment, by Community action under Article 16(3) to cease or phase out discharges, emissions and losses of priority hazardous substances, with the ultimate aim of achieving concentrations in the marine environment near background values for naturally occurring substances and close to zero for man-made synthetic substances.

Article 2

Definitions

For the purposes of this Directive the following definitions shall apply:

(1) OJ L 129, 18.5.1976, p. 23. Directive as amended by Directive 91/692/EEC (OJ L 377, 31.12.1991, p. 48).

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1. 'Surface water' means inland waters, except groundwater; transitional waters and coastal waters, except in respect of chemical status for which it shall also include territorial waters.

2. 'Groundwater' means all water which is below the surface of the ground in the saturation zone and in direct contact with the ground or subsoil.

3. 'Inland water' means all standing or flowing water on the surface of the land, and all groundwater on the landward side of the baseline from which the breadth of territorial waters is measured.

4. 'River' means a body of inland water flowing for the most part on the surface of the land but which may flow underground for part of its course.

5. 'Lake' means a body of standing inland surface water.

6. 'Transitional waters' are bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows.

7. 'Coastal water' means surface water on the landward side of a line, every point of which is at a distance of one nautical mile on the seaward side from the nearest point of the baseline from which the breadth of territorial waters is measured, extending where appropriate up to the outer limit of transitional waters.

8. 'Artificial water body' means a body of surface water created by human activity.

9. 'Heavily modified water body' means a body of surface water which as a result of physical alterations by human activity is substantially changed in character, as designated by the Member State in accordance with the provisions of Annex II.

10. 'Body of surface water' means a discrete and significant element of surface water such as a lake, a reservoir, a stream, river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water.

11. 'Aquifer' means a subsurface layer or layers of rock or other geological strata of sufficient porosity and permeability to allow either a significant flow of groundwater or the abstraction of significant quantities of groundwater.

12. 'Body of groundwater' means a distinct volume of groundwater within an aquifer or aquifers.

13. 'River basin' means the area of land from which all surface run-off flows through a sequence of streams, rivers and, possibly, lakes into the sea at a single river mouth, estuary or delta.

14. 'Sub-basin' means the area of land from which all surface run-off flows through a series of streams, rivers and, possibly, lakes to a particular point in a water course (normally a lake or a river confluence).

15. 'River basin district' means the area of land and sea, made up of one or more neighbouring river basins together with their associated groundwaters and coastal waters, which is identified under Article 3(1) as the main unit for management of river basins.

16. 'Competent Authority' means an authority or authorities identified under Article 3(2) or 3(3).

17. 'Surface water status' is the general expression of the status of a body of surface water, determined by the poorer of its ecological status and its chemical status.

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18. 'Good surface water status' means the status achieved by a surface water body when both its ecological status and its chemical status are at least 'good'.

19. 'Groundwater status' is the general expression of the status of a body of groundwater, determined by the poorer of its quantitative status and its chemical status.

20. 'Good groundwater status' means the status achieved by a groundwater body when both its quantitative status and its chemical status are at least 'good'.

21. 'Ecological status' is an expression of the quality of the structure and functioning of aquatic ecosystems associated with surface waters, classified in accordance with Annex V.

22. 'Good ecological status' is the status of a body of surface water, so classified in accordance with Annex V.

23. 'Good ecological potential' is the status of a heavily modified or an artificial body of water, so classified in accordance with the relevant provisions of Annex V.

24. 'Good surface water chemical status' means the chemical status required to meet the environmental objectives for surface waters established in Article 4(1)(a), that is the chemical status achieved by a body of surface water in which concentrations of pollutants do not exceed the environmental quality standards established in Annex IX and under Article 16(7), and under other relevant Community legislation setting environmental quality standards at Community level.

25. 'Good groundwater chemical status' is the chemical status of a body of groundwater, which meets all the conditions set out in table 2.3.2 of Annex V.

26. 'Quantitative status' is an expression of the degree to which a body of groundwater is affected by direct and indirect abstractions.

27. 'Available groundwater resource' means the long-term annual average rate of overall recharge of the body of groundwater less the long-term annual rate of flow required to achieve the ecological quality objectives for associated surface waters specified under Article 4, to avoid any significant diminution in the ecological status of such waters and to avoid any significant damage to associated terrestrial ecosystems.

28. 'Good quantitative status' is the status defined in table 2.1.2 of Annex V.

29. 'Hazardous substances' means substances or groups of substances that are toxic, persistent and liable to bio-accumulate, and other substances or groups of substances which give rise to an equivalent level of concern.

30. 'Priority substances' means substances identified in accordance with Article 16(2) and listed in Annex X. Among these substances there are 'priority hazardous substances' which means substances identified in accordance with Article 16(3) and (6) for which measures have to be taken in accordance with Article 16(1) and (8).

31. 'Pollutant' means any substance liable to cause pollution, in particular those listed in Annex VIII.

32. 'Direct discharge to groundwater' means discharge of pollutants into groundwater without percolation throughout the soil or subsoil.

33. 'Pollution' means the direct or indirect introduction, as a result of human activity, of substances or heat into the air, water or land which may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems directly depending on aquatic ecosystems, which result in damage to material property, or which

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impair or interfere with amenities and other legitimate uses of the environment.

34. 'Environmental objectives' means the objectives set out in Article 4.

35. 'Environmental quality standard' means the concentration of a particular pollutant or group of pollutants in water, sediment or biota which should not be exceeded in order to protect human health and the environment.

36. 'Combined approach' means the control of discharges and emissions into surface waters according to the approach set out in Article 10.

37. 'Water intended for human consumption' has the same meaning as under Directive 80/778/EEC, as amended by Directive 98/83/EC.

38. 'Water services' means all services which provide, for households, public institutions or any economic activity:

(a) abstraction, impoundment, storage, treatment and distribution of surface water or groundwater,

(b) waste-water collection and treatment facilities which subsequently discharge into surface water.

39. '*Water use*' means water services together with any other activity identified under Article 5 and Annex II having a significant impact on the status of water.

This concept applies for the purposes of Article 1 and of the economic analysis carried out according to Article 5 and Annex III, point (b).

40. '*Emission limit values*' means the mass, expressed in terms of certain specific parameters, concentration and/or level of an emission, which may not be exceeded during any one or more periods of time. Emission limit values may also be laid down for certain groups, families or categories of substances, in particular for those identified under Article 16.

The emission limit values for substances shall normally apply at the point where the emissions leave the installation, dilution being disregarded when determining them. With regard to indirect releases into water, the effect of a waste-water treatment plant may be taken into account when determining the emission limit values of the installations involved, provided that an equivalent level is guaranteed for protection of the environment as a whole and provided that this does not lead to higher levels of pollution in the environment.

41. '*Emission controls*' are controls requiring a specific emission limitation, for instance an emission limit value, or otherwise specifying limits or conditions on the effects, nature or other characteristics of an emission or operating conditions which affect emissions. Use of the term 'emission control' in this Directive in respect of the provisions of any other Directive shall not be held as reinterpreting those provisions in any respect.

Article 3

Coordination of administrative arrangements within river basin districts

1. Member States shall identify the individual river basins lying within their national territory and, for the purposes of this Directive, shall assign them to individual river basin districts. Small river basins may be combined with larger river basins or joined with neighbouring small basins to form individual river basin districts where appropriate.

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Where groundwaters do not fully follow a particular river basin, they shall be identified and assigned to the nearest or most appropriate river basin district. Coastal waters shall be identified and assigned to the nearest or most appropriate river basin district or districts.

2. Member States shall ensure the appropriate administrative arrangements, including the identification of the appropriate competent authority, for the application of the rules of this Directive within each river basin district lying within their territory.

3. Member States shall ensure that a river basin covering the territory of more than one Member State is assigned to an international river basin district. At the request of the Member States involved, the Commission shall act to facilitate the assigning to such international river basin districts.

Each Member State shall ensure the appropriate administrative arrangements, including the identification of the appropriate competent authority, for the application of the rules of this Directive within the portion of any international river basin district lying within its territory.

4. Member States shall ensure that the requirements of this Directive for the achievement of the environmental objectives established under Article 4, and in particular all programmes of measures are coordinated for the whole of the river basin district. For international river basin districts the Member States concerned shall together ensure this coordination and may, for this purpose, use existing structures stemming from international agreements. At the request of the Member States involved, the Commission shall act to facilitate the establishment of the programmes of measures.

5. Where a river basin district extends beyond the territory of the Community, the Member State or Member States concerned shall endeavour to establish appropriate coordination with the relevant non-Member States, with the aim of achieving the objectives of this Directive throughout the river basin district. Member States shall ensure the application of the rules of this Directive within their territory.

6. Member States may identify an existing national or international body as competent authority for the purposes of this Directive.

7. Member States shall identify the competent authority by the date mentioned in Article 24.

8. Member States shall provide the Commission with a list of their competent authorities and of the competent authorities of all the international bodies in which they participate at the latest six months after the date mentioned in Article 24. For each competent authority the information set out in Annex I shall be provided.

9. Member States shall inform the Commission of any changes to the information provided according to paragraph 8 within three months of the change coming into effect.

Article 4

Environmental objectives

1. In making operational the programmes of measures specified in the river basin management plans:

(a) for surface waters

(i) Member States shall implement the necessary measures to prevent deterioration of the status of all bodies of surface water, subject to the application of paragraphs 6 and 7 and without prejudice to paragraph 8;

(ii) Member States shall protect, enhance and restore all bodies of surface water, subject to the application of subparagraph

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(iii) for artificial and heavily modified bodies of water, with the aim of achieving good surface water status at the latest 15 years after the date of entry into force of this Directive, in accordance with the provisions laid down in Annex V, subject to the application of extensions determined in accordance with paragraph 4 and to the application of paragraphs 5, 6 and 7 without prejudice to paragraph 8;

(iii) Member States shall protect and enhance all artificial and heavily modified bodies of water, with the aim of achieving good ecological potential and good surface water chemical status at the latest 15 years from the date of entry into force of this Directive, in accordance with the provisions laid down in Annex V, subject to the application of extensions determined in accordance with paragraph 4 and to the application of paragraphs 5, 6 and 7 without prejudice to paragraph 8;

(iv) Member States shall implement the necessary measures in accordance with Article 16(1) and (8), with the aim of progressively reducing pollution from priority substances and ceasing or phasing out emissions, discharges and losses of priority hazardous substances

without prejudice to the relevant international agreements referred to in Article 1 for the parties concerned;

(b) for groundwater

(i) Member States shall implement the measures necessary to prevent or limit the input of pollutants into groundwater and to prevent the deterioration of the status of all bodies of groundwater, subject to the application of paragraphs 6 and 7 and without prejudice to paragraph 8 of this Article and subject to the application of Article 11(3)(j);

(ii) Member States shall protect, enhance and restore all bodies of groundwater, ensure a balance between abstraction and recharge of groundwater, with the aim of achieving good groundwater status at the latest 15 years after the date of entry into force of this Directive, in accordance with the provisions laid down in Annex V, subject to the application of extensions determined in accordance with paragraph 4 and to the application of paragraphs 5, 6 and 7 without prejudice to paragraph 8 of this Article and subject to the application of Article 11(3)(j);

(iii) Member States shall implement the measures necessary to reverse any significant and sustained upward trend in the concentration of any pollutant resulting from the impact of human activity in order progressively to reduce pollution of groundwater.

Measures to achieve trend reversal shall be implemented in accordance with paragraphs 2, 4 and 5 of Article 17, taking into account the applicable standards set out in relevant Community legislation, subject to the application of paragraphs 6 and 7 and without prejudice to paragraph 8;

(c) for protected areas

Member States shall achieve compliance with any standards and objectives at the latest 15 years after the date of entry into force of this Directive, unless otherwise specified in the Community legislation under which the individual protected areas have been established.

2. Where more than one of the objectives under paragraph 1 relates to a given body of water, the most stringent shall apply.

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3. Member States may designate a body of surface water as artificial or heavily modified, when:

(a) the changes to the hydromorphological characteristics of that body which would be necessary for achieving good ecological status would have significant adverse effects on:

(i) the wider environment;

(ii) navigation, including port facilities, or recreation;

(iii) activities for the purposes of which water is stored, such as drinking-water supply, power generation or irrigation;

(iv) water regulation, flood protection, land drainage, or

(v) other equally important sustainable human development activities;

(b) the beneficial objectives served by the artificial or modified characteristics of the water body cannot, for reasons of technical feasibility or disproportionate costs, reasonably be achieved by other means, which are a significantly better environmental option.

Such designation and the reasons for it shall be specifically mentioned in the river basin management plans required under Article 13 and reviewed every six years.

4. The deadlines established under paragraph 1 may be extended for the purposes of phased achievement of the objectives for bodies of water, provided that no further deterioration occurs in the status of the affected body of water when all of the following conditions are met:

(a) Member States determine that all necessary improvements in the status of bodies of water cannot reasonably be achieved within the timescales set out in that paragraph for at least one of the following reasons:

(i) the scale of improvements required can only be achieved in phases exceeding the timescale, for reasons of technical feasibility;

(ii) completing the improvements within the timescale would be disproportionately expensive;

(iii) natural conditions do not allow timely improvement in the status of the body of water.

(b) Extension of the deadline, and the reasons for it, are specifically set out and explained in the river basin management plan required under Article 13.

(c) Extensions shall be limited to a maximum of two further updates of the river basin management plan except in cases where the natural conditions are such that the objectives cannot be achieved within this period.

(d) A summary of the measures required under Article 11 which are envisaged as necessary to bring the bodies of water progressively to the required status by the extended deadline, the reasons for any significant delay in making these measures operational, and the expected timetable for their implementation are set out in the river basin management plan. A review of the implementation of these measures and a summary of any additional measures shall be included in updates of the river basin management plan.

5. Member States may aim to achieve less stringent environmental objectives than those required under paragraph 1 for specific bodies of water when they are so affected by human activity, as determined in accordance with Article 5(1), or their natural condition is such that the achievement of these objectives would be infeasible or disproportionately expensive, and all the following conditions are met:

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(a) the environmental and socioeconomic needs served by such human activity cannot be achieved by other means, which are a significantly better environmental option not entailing disproportionate costs;

(b) Member States ensure,

— for surface water, the highest ecological and chemical status possible is achieved, given impacts that could not reasonably have been avoided due to the nature of the human activity or pollution,

— for groundwater, the least possible changes to good groundwater status, given impacts that could not reasonably have been avoided due to the nature of the human activity or pollution;

(c) no further deterioration occurs in the status of the affected body of water;

(d) the establishment of less stringent environmental objectives, and the reasons for it, are specifically mentioned in the river basin management plan required under Article 13 and those objectives are reviewed every six years.

6. Temporary deterioration in the status of bodies of water shall not be in breach of the requirements of this Directive if this is the result of circumstances of natural cause or *force majeure* which are exceptional or could not reasonably have been foreseen, in particular extreme floods and prolonged droughts, or the result of circumstances due to accidents which could not reasonably have been foreseen, when all of the following conditions have been met:

(a) all practicable steps are taken to prevent further deterioration in status and in order not to compromise the achievement of the objectives of this Directive in other bodies of water not affected by those circumstances;

(b) the conditions under which circumstances that are exceptional or that could not reasonably have been foreseen may be declared, including the adoption of the appropriate indicators, are stated in the river basin management plan;

(c) the measures to be taken under such exceptional circumstances are included in the programme of measures and will not compromise the recovery of the quality of the body of water once the circumstances are over;

(d) the effects of the circumstances that are exceptional or that could not reasonably have been foreseen are reviewed annually and, subject to the reasons set out in paragraph 4(a), all practicable measures are taken with the aim of restoring the body of water to its status prior to the effects of those circumstances as soon as reasonably practicable, and

(e) a summary of the effects of the circumstances and of such measures taken or to be taken in accordance with paragraphs (a) and (d) are included in the next update of the river basin management plan.

7. Member States will not be in breach of this Directive when:

— failure to achieve good groundwater status, good ecological status or, where relevant, good ecological potential or to prevent deterioration in the status of a body of surface water or groundwater is the result of new modifications to the physical characteristics of a surface water body or alterations to the level of bodies of groundwater, or

— failure to prevent deterioration from high status to good status of a body of surface water is the result of new sustainable human development activities

and all the following conditions are met:

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(a) all practicable steps are taken to mitigate the adverse impact on the status of the body of water;

(b) the reasons for those modifications or alterations are specifically set out and explained in the river basin management plan required under Article 13 and the objectives are reviewed every six years;

(c) the reasons for those modifications or alterations are of overriding public interest and/or the benefits to the environment and to society of achieving the objectives set out in paragraph 1 are outweighed by the benefits of the new modifications or alterations to human health, to the maintenance of human safety or to sustainable development, and

(d) the beneficial objectives served by those modifications or alterations of the water body cannot for reasons of technical feasibility or disproportionate cost be achieved by other means, which are a significantly better environmental option.

8. When applying paragraphs 3, 4, 5, 6 and 7, a Member State shall ensure that the application does not permanently exclude or compromise the achievement of the objectives of this Directive in other bodies of water within the same river basin district and is consistent with the implementation of other Community environmental legislation.

9. Steps must be taken to ensure that the application of the new provisions, including the application of paragraphs 3, 4, 5, 6 and 7, guarantees at least the same level of protection as the existing Community legislation.

Article 5

Characteristics of the river basin district, review of the environmental impact of human activity and economic analysis of water use

1. Each Member State shall ensure that for each river basin district or for the portion of an international river basin district falling within its territory:

— 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

is undertaken according to the technical specifications set out in Annexes II and III and that it is completed at the latest four years after the date of entry into force of this Directive.

2. The analyses and reviews mentioned under paragraph 1 shall be reviewed, and if necessary updated at the latest 13 years after the date of entry into force of this Directive and every six years thereafter.

Article 6

Register of protected areas

1. Member States shall ensure the establishment of a register or registers of all areas lying within each river basin district which have been designated as requiring special protection under specific Community legislation for the protection of their surface water and groundwater or for the conservation of habitats and species directly depending on water. They shall ensure that the register is completed at the latest four years after the date of entry into force of this Directive.

2. The register or registers shall include all bodies of water identified under Article 7(1) and all protected areas covered by Annex IV.

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3. For each river basin district, the register or registers of protected areas shall be kept under review and up to date.

Article 7

Waters used for the abstraction of drinking water

1. Member States shall identify, within each river basin district:

— all bodies of water used for the abstraction of water intended for human consumption providing more than 10 m^3 a day as an average or serving more than 50 persons, and

— those bodies of water intended for such future use.

Member States shall monitor, in accordance with Annex V, those bodies of water which according to Annex V, provide more than 100 m^3 a day as an average.

2. For each body of water identified under paragraph 1, in addition to meeting the objectives of Article 4 in accordance with the requirements of this Directive, for surface water bodies including the quality standards established at Community level under Article 16, Member States shall ensure that under the water treatment regime applied, and in accordance with Community legislation, the resulting water will meet the requirements of Directive 80/778/EEC as amended by Directive 98/83/EC.

3. Member States shall ensure the necessary protection for the bodies of water identified with the aim of avoiding deterioration in their quality in order to reduce the level of purification treatment required in the production of drinking water. Member States may establish safeguard zones for those bodies of water.

Article 8

Monitoring of surface water status, groundwater status and protected areas

1. Member States shall ensure the establishment of programmes for the monitoring of water status in order to establish a coherent and comprehensive overview of water status within each river basin district:

— for surface waters such programmes shall cover:

  (i) the volume and level or rate of flow to the extent relevant for ecological and chemical status and ecological potential, and

  (ii) the ecological and chemical status and ecological potential;

— for groundwaters such programmes shall cover monitoring of the chemical and quantitative status,

— for protected areas the above programmes shall be supplemented by those specifications contained in Community legislation under which the individual protected areas have been established.

2. These programmes shall be operational at the latest six years after the date of entry into force of this Directive unless otherwise specified in the legislation concerned. Such monitoring shall be in accordance with the requirements of Annex V.

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3. Technical specifications and standardised methods for analysis and monitoring of water status shall be laid down. Those measures, designed to amend non-essential elements of this Directive by supplementing it, shall be adopted in accordance with the regulatory procedure with scrutiny referred to in Article 21(3).

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Article 9

Recovery of costs for water services

1. Member States shall take account of the principle of recovery of the costs of water services, including environmental and resource costs, having regard to the economic analysis conducted according to Annex III, and in accordance in particular with the polluter pays principle.

Member States shall ensure by 2010

— that water-pricing policies provide adequate incentives for users to use water resources efficiently, and thereby contribute to the environmental objectives of this Directive,

— an adequate contribution of the different water uses, disaggregated into at least industry, households and agriculture, to the recovery of the costs of water services, based on the economic analysis conducted according to Annex III and taking account of the polluter pays principle.

Member States may in so doing have regard to the social, environmental and economic effects of the recovery as well as the geographic and climatic conditions of the region or regions affected.

2. Member States shall report in the river basin management plans on the planned steps towards implementing paragraph 1 which will contribute to achieving the environmental objectives of this Directive and on the contribution made by the various water uses to the recovery of the costs of water services.

3. Nothing in this Article shall prevent the funding of particular preventive or remedial measures in order to achieve the objectives of this Directive.

4. Member States shall not be in breach of this Directive if they decide in accordance with established practices not to apply the provisions of paragraph 1, second sentence, and for that purpose the relevant provisions of paragraph 2, for a given water-use activity, where this does not compromise the purposes and the achievement of the objectives of this Directive. Member States shall report the reasons for not fully applying paragraph 1, second sentence, in the river basin management plans.

Article 10

The combined approach for point and diffuse sources

1. Member States shall ensure that all discharges referred to in paragraph 2 into surface waters are controlled according to the combined approach set out in this Article.

2. Member States shall ensure the establishment and/or implementation of:

(a) the emission controls based on best available techniques, or

(b) the relevant emission limit values, or

(c) in the case of diffuse impacts the controls including, as appropriate, best environmental practices

set out in:

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— Council Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control [1],

— Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment [2],

— Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources [3],

— the Directives adopted pursuant to Article 16 of this Directive,

— the Directives listed in Annex IX,

— any other relevant Community legislation

at the latest 12 years after the date of entry into force of this Directive, unless otherwise specified in the legislation concerned.

3. Where a quality objective or quality standard, whether established pursuant to this Directive, in the Directives listed in Annex IX, or pursuant to any other Community legislation, requires stricter conditions than those which would result from the application of paragraph 2, more stringent emission controls shall be set accordingly.

Article 11

Programme of measures

1. Each Member State shall ensure the establishment for each river basin district, or for the part of an international river basin district within its territory, of a programme of measures, taking account of the results of the analyses required under Article 5, in order to achieve the objectives established under Article 4. Such programmes of measures may make reference to measures following from legislation adopted at national level and covering the whole of the territory of a Member State. Where appropriate, a Member State may adopt measures applicable to all river basin districts and/or the portions of international river basin districts falling within its territory.

2. Each programme of measures shall include the ‘basic’ measures specified in paragraph 3 and, where necessary, ‘supplementary’ measures.

3. ‘Basic measures’ are the minimum requirements to be complied with and shall consist of:

(a) those measures required to implement Community legislation for the protection of water, including measures required under the legislation specified in Article 10 and in part A of Annex VI;

(b) measures deemed appropriate for the purposes of Article 9;

(c) measures to promote an efficient and sustainable water use in order to avoid compromising the achievement of the objectives specified in Article 4;

(d) measures to meet the requirements of Article 7, including measures to safeguard water quality in order to reduce the level of purification treatment required for the production of drinking water;

(e) controls over the abstraction of fresh surface water and groundwater, and impoundment of fresh surface water, including a register or registers of water abstractions and a requirement of prior authorisation for abstraction and impoundment. These controls shall be periodically reviewed and, where necessary, updated. Member

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(1) OJ L 257, 10.10.1996, p. 26.

(2) OJ L 135, 30.5.1991, p. 40. Directive as amended by Commission Directive 98/15/EC (OJ L 67, 7.3.1998, p. 29).

(3) OJ L 375, 31.12.1991, p. 1.

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States can exempt from these controls, abstractions or impoundments which have no significant impact on water status;

(f) controls, including a requirement for prior authorisation of artificial recharge or augmentation of groundwater bodies. The water used may be derived from any surface water or groundwater, provided that the use of the source does not compromise the achievement of the environmental objectives established for the source or the recharged or augmented body of groundwater. These controls shall be periodically reviewed and, where necessary, updated;

(g) for point source discharges liable to cause pollution, a requirement for prior regulation, such as a prohibition on the entry of pollutants into water, or for prior authorisation, or registration based on general binding rules, laying down emission controls for the pollutants concerned, including controls in accordance with Articles 10 and 16. These controls shall be periodically reviewed and, where necessary, updated;

(h) for diffuse sources liable to cause pollution, measures to prevent or control the input of pollutants. Controls may take the form of a requirement for prior regulation, such as a prohibition on the entry of pollutants into water, prior authorisation or registration based on general binding rules where such a requirement is not otherwise provided for under Community legislation. These controls shall be periodically reviewed and, where necessary, updated;

(i) for any other significant adverse impacts on the status of water identified under Article 5 and Annex II, in particular measures to ensure that the hydromorphological conditions of the bodies of water are consistent with the achievement of the required ecological status or good ecological potential for bodies of water designated as artificial or heavily modified. Controls for this purpose may take the form of a requirement for prior authorisation or registration based on general binding rules where such a requirement is not otherwise provided for under Community legislation. Such controls shall be periodically reviewed and, where necessary, updated;

(j) a prohibition of direct discharges of pollutants into groundwater subject to the following provisions:

Member States may authorise reinjection into the same aquifer of water used for geothermal purposes.

They may also authorise, specifying the conditions for:

— injection of water containing substances resulting from the operations for exploration and extraction of hydrocarbons or mining activities, and injection of water for technical reasons, into geological formations from which hydrocarbons or other substances have been extracted or into geological formations which for natural reasons are permanently unsuitable for other purposes. Such injections shall not contain substances other than those resulting from the above operations,

— reinjection of pumped groundwater from mines and quarries or associated with the construction or maintenance of civil engineering works,

— injection of natural gas or liquefied petroleum gas (LPG) for storage purposes into geological formations which for natural reasons are permanently unsuitable for other purposes,

— injection of natural gas or liquefied petroleum gas (LPG) for storage purposes into other geological formations where there is an overriding need for security of gas supply, and where the injection is such as to prevent any present or future danger of deterioration in the quality of any receiving groundwater,

— construction, civil engineering and building works and similar activities on, or in the ground which come into contact with

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groundwater. For these purposes, Member States may determine that such activities are to be treated as having been authorised provided that they are conducted in accordance with general binding rules developed by the Member State in respect of such activities,

— discharges of small quantities of substances for scientific purposes for characterisation, protection or remediation of water bodies limited to the amount strictly necessary for the purposes concerned

provided such discharges do not compromise the achievement of the environmental objectives established for that body of groundwater;

(k) in accordance with action taken pursuant to Article 16, measures to eliminate pollution of surface waters by those substances specified in the list of priority substances agreed pursuant to Article 16(2) and to progressively reduce pollution by other substances which would otherwise prevent Member States from achieving the objectives for the bodies of surface waters as set out in Article 4;

(l) any measures required to prevent significant losses of pollutants from technical installations, and to prevent and/or to reduce the impact of accidental pollution incidents for example as a result of floods, including through systems to detect or give warning of such events including, in the case of accidents which could not reasonably have been foreseen, all appropriate measures to reduce the risk to aquatic ecosystems.

4. 'Supplementary' measures are those measures designed and implemented in addition to the basic measures, with the aim of achieving the objectives established pursuant to Article 4. Part B of Annex VI contains a non-exclusive list of such measures.

Member States may also adopt further supplementary measures in order to provide for additional protection or improvement of the waters covered by this Directive, including in implementation of the relevant international agreements referred to in Article 1.

5. Where monitoring or other data indicate that the objectives set under Article 4 for the body of water are unlikely to be achieved, the Member State shall ensure that:

— the causes of the possible failure are investigated,

— relevant permits and authorisations are examined and reviewed as appropriate,

— the monitoring programmes are reviewed and adjusted as appropriate, and

— additional measures as may be necessary in order to achieve those objectives are established, including, as appropriate, the establishment of stricter environmental quality standards following the procedures laid down in Annex V.

Where those causes are the result of circumstances of natural cause or *force majeure* which are exceptional and could not reasonably have been foreseen, in particular extreme floods and prolonged droughts, the Member State may determine that additional measures are not practicable, subject to Article 4(6).

6. In implementing measures pursuant to paragraph 3, Member States shall take all appropriate steps not to increase pollution of marine waters. Without prejudice to existing legislation, the application of measures taken pursuant to paragraph 3 may on no account lead, either directly or indirectly to increased pollution of surface waters. This requirement shall not apply where it would result in increased pollution of the environment as a whole.

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7. The programmes of measures shall be established at the latest nine years after the date of entry into force of this Directive and all the measures shall be made operational at the latest 12 years after that date.

8. The programmes of measures shall be reviewed, and if necessary updated at the latest 15 years after the date of entry into force of this Directive and every six years thereafter. Any new or revised measures established under an updated programme shall be made operational within three years of their establishment.

Article 12

Issues which can not be dealt with at Member State level

1. Where a Member State identifies an issue which has an impact on the management of its water but cannot be resolved by that Member State, it may report the issue to the Commission and any other Member State concerned and may make recommendations for the resolution of it.

2. The Commission shall respond to any report or recommendations from Member States within a period of six months.

Article 13

River basin management plans

1. Member States shall ensure that a river basin management plan is produced for each river basin district lying entirely within their territory.

2. In the case of an international river basin district falling entirely within the Community, Member States shall ensure coordination with the aim of producing a single international river basin management plan. Where such an international river basin management plan is not produced, Member States shall produce river basin management plans covering at least those parts of the international river basin district falling within their territory to achieve the objectives of this Directive.

3. In the case of an international river basin district extending beyond the boundaries of the Community, Member States shall endeavour to produce a single river basin management plan, and, where this is not possible, the plan shall at least cover the portion of the international river basin district lying within the territory of the Member State concerned.

4. The river basin management plan shall include the information detailed in Annex VII.

5. River basin management plans may be supplemented by the production of more detailed programmes and management plans for sub-basin, sector, issue, or water type, to deal with particular aspects of water management. Implementation of these measures shall not exempt Member States from any of their obligations under the rest of this Directive.

6. River basin management plans shall be published at the latest nine years after the date of entry into force of this Directive.

7. River basin management plans shall be reviewed and updated at the latest 15 years after the date of entry into force of this Directive and every six years thereafter.

Article 14

Public information and consultation

1. Member States shall encourage the active involvement of all interested parties in the implementation of this Directive, in particular

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in the production, review and updating of the river basin management plans. Member States shall ensure that, for each river basin district, they publish and make available for comments to the public, including users:

(a) a timetable and work programme for the production of the plan, including a statement of the consultation measures to be taken, at least three years before the beginning of the period to which the plan refers;

(b) an interim overview of the significant water management issues identified in the river basin, at least two years before the beginning of the period to which the plan refers;

(c) draft copies of the river basin management plan, at least one year before the beginning of the period to which the plan refers.

On request, access shall be given to background documents and information used for the development of the draft river basin management plan.

2. Member States shall allow at least six months to comment in writing on those documents in order to allow active involvement and consultation.

3. Paragraphs 1 and 2 shall apply equally to updated river basin management plans.

Article 15

Reporting

1. Member States shall send copies of the river basin management plans and all subsequent updates to the Commission and to any other Member State concerned within three months of their publication:

(a) for river basin districts falling entirely within the territory of a Member State, all river management plans covering that national territory and published pursuant to Article 13;

(b) for international river basin districts, at least the part of the river basin management plans covering the territory of the Member State.

2. Member States shall submit summary reports of:

— the analyses required under Article 5, and

— the monitoring programmes designed under Article 8

undertaken for the purposes of the first river basin management plan within three months of their completion.

3. Member States shall, within three years of the publication of each river basin management plan or update under Article 13, submit an interim report describing progress in the implementation of the planned programme of measures.

Article 16

Strategies against pollution of water

1. The European Parliament and the Council shall adopt specific measures against pollution of water by individual pollutants or groups of pollutants presenting a significant risk to or via the aquatic environment, including such risks to waters used for the abstraction of drinking water. For those pollutants measures shall be aimed at the progressive reduction and, for priority hazardous substances, as defined in Article 2(30), at the cessation or phasing-out of discharges, emissions and losses. Such measures shall be adopted acting on the proposals presented by the Commission in accordance with the procedures laid down in the Treaty.

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2. The Commission shall submit a proposal setting out a list of priority substances selected amongst those which present a significant risk to or via the aquatic environment. Substances shall be prioritised for action on the basis of risk to or via the aquatic environment, identified by:

(a) risk assessment carried out under Council Regulation (EEC) No 793/93 ([1]), Council Directive 91/414/EEC ([2]), and Directive 98/8/EC of the European Parliament and of the Council ([3]), or

(b) targeted risk-based assessment (following the methodology of Regulation (EEC) No 793/93) focusing solely on aquatic ecotoxicity and on human toxicity via the aquatic environment.

When necessary in order to meet the timetable laid down in paragraph 4, substances shall be prioritised for action on the basis of risk to, or via the aquatic environment, identified by a simplified risk-based assessment procedure based on scientific principles taking particular account of:

— evidence regarding the intrinsic hazard of the substance concerned, and in particular its aquatic ecotoxicity and human toxicity via aquatic exposure routes, and

— evidence from monitoring of widespread environmental contamination, and

— other proven factors which may indicate the possibility of widespread environmental contamination, such as production or use volume of the substance concerned, and use patterns.

3. The Commission's proposal shall also identify the priority hazardous substances. In doing so, the Commission shall take into account the selection of substances of concern undertaken in the relevant Community legislation regarding hazardous substances or relevant international agreements.

4. The Commission shall review the adopted list of priority substances at the latest four years after the date of entry into force of this Directive and at least every four years thereafter, and come forward with proposals as appropriate.

5. In preparing its proposal, the Commission shall take account of recommendations from the Scientific Committee on Toxicity, Ecotoxicity and the Environment, Member States, the European Parliament, the European Environment Agency, Community research programmes, international organisations to which the Community is a party, European business organisations including those representing small and medium-sized enterprises, European environmental organisations, and of other relevant information which comes to its attention.

6. For the priority substances, the Commission shall submit proposals of controls for:

— the progressive reduction of discharges, emissions and losses of the substances concerned, and, in particular

— the cessation or phasing-out of discharges, emissions and losses of the substances as identified in accordance with paragraph 3, including an appropriate timetable for doing so. The timetable shall not exceed 20 years after the adoption of these proposals by the European Parliament and the Council in accordance with the provisions of this Article.

In doing so it shall identify the appropriate cost-effective and proportionate level and combination of product and process controls for both

([1]) OJ L 84, 5.4.1993, p. 1.
([2]) OJ L 230, 19.8.1991, p. 1. Directive as last amended by Directive 98/47/EC (OJ L 191, 7.7.1998, p. 50).
([3]) OJ L 123, 24.4.1998, p. 1.

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point and diffuse sources and take account of Community-wide uniform emission limit values for process controls. Where appropriate, action at Community level for process controls may be established on a sector-by-sector basis. Where product controls include a review of the relevant authorisations issued under Directive 91/414/EEC and Directive 98/8/EC, such reviews shall be carried out in accordance with the provisions of those Directives. Each proposal for controls shall specify arrangements for their review, updating and for assessment of their effectiveness.

7. The Commission shall submit proposals for quality standards applicable to the concentrations of the priority substances in surface water, sediments or biota.

8. The Commission shall submit proposals, in accordance with paragraphs 6 and 7, and at least for emission controls for point sources and environmental quality standards within two years of the inclusion of the substance concerned on the list of priority substances. For substances included in the first list of priority substances, in the absence of agreement at Community level six years after the date of entry into force of this Directive, Member States shall establish environmental quality standards for these substances for all surface waters affected by discharges of those substances, and controls on the principal sources of such discharges, based, *inter alia*, on consideration of all technical reduction options. For substances subsequently included in the list of priority substances, in the absence of agreement at Community level, Member States shall take such action five years after the date of inclusion in the list.

9. The Commission may prepare strategies against pollution of water by any other pollutants or groups of pollutants, including any pollution which occurs as a result of accidents.

10. In preparing its proposals under paragraphs 6 and 7, the Commission shall also review all the Directives listed in Annex IX. It shall propose, by the deadline in paragraph 8, a revision of the controls in Annex IX for all those substances which are included in the list of priority substances and shall propose the appropriate measures including the possible repeal of the controls under Annex IX for all other substances.

All the controls in Annex IX for which revisions are proposed shall be repealed by the date of entry into force of those revisions.

11. The list of priority substances of substances mentioned in paragraphs 2 and 3 proposed by the Commission shall, on its adoption by the European Parliament and the Council, become Annex X to this Directive. Its revision mentioned in paragraph 4 shall follow the same procedure.

Article 17

Strategies to prevent and control pollution of groundwater

1. The European Parliament and the Council shall adopt specific measures to prevent and control groundwater pollution. Such measures shall be aimed at achieving the objective of good groundwater chemical status in accordance with Article 4(1)(b) and shall be adopted, acting on the proposal presented within two years after the entry into force of this Directive, by the Commission in accordance with the procedures laid down in the Treaty.

2. In proposing measures the Commission shall have regard to the analysis carried out according to Article 5 and Annex II. Such measures shall be proposed earlier if data are available and shall include:

(a) criteria for assessing good groundwater chemical status, in accordance with Annex II.2.2 and Annex V 2.3.2 and 2.4.5;

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(b) criteria for the identification of significant and sustained upward trends and for the definition of starting points for trend reversals to be used in accordance with Annex V 2.4.4.

3. Measures resulting from the application of paragraph 1 shall be included in the programmes of measures required under Article 11.

4. In the absence of criteria adopted under paragraph 2 at Community level, Member States shall establish appropriate criteria at the latest five years after the date of entry into force of this Directive.

5. In the absence of criteria adopted under paragraph 4 at national level, trend reversal shall take as its starting point a maximum of 75% of the level of the quality standards set out in existing Community legislation applicable to groundwater.

Article 18

Commission report

1. The Commission shall publish a report on the implementation of this Directive at the latest 12 years after the date of entry into force of this Directive and every six years thereafter, and shall submit it to the European Parliament and to the Council.

2. The report shall include the following:

(a) a review of progress in the implementation of the Directive;

(b) a review of the status of surface water and groundwater in the Community undertaken in coordination with the European Environment Agency;

(c) a survey of the river basin management plans submitted in accordance with Article 15, including suggestions for the improvement of future plans;

(d) a summary of the response to each of the reports or recommendations to the Commission made by Member States pursuant to Article 12;

(e) a summary of any proposals, control measures and strategies developed under Article 16;

(f) a summary of the responses to comments made by the European Parliament and the Council on previous implementation reports.

3. The Commission shall also publish a report on progress in implementation based on the summary reports that Member States submit under Article 15(2), and submit it to the European Parliament and the Member States, at the latest two years after the dates referred to in Articles 5 and 8.

4. The Commission shall, within three years of the publication of each report under paragraph 1, publish an interim report describing progress in implementation on the basis of the interim reports of the Member States as mentioned in Article 15(3). This shall be submitted to the European Parliament and to the Council.

5. The Commission shall convene when appropriate, in line with the reporting cycle, a conference of interested parties on Community water policy from each of the Member States, to comment on the Commission's implementation reports and to share experiences.

Participants should include representatives from the competent authorities, the European Parliament, NGOs, the social and economic partners, consumer bodies, academics and other experts.

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Article 19

Plans for future Community measures

1. Once a year, the Commission shall for information purposes present to the Committee referred to in Article 21 an indicative plan of measures having an impact on water legislation which it intends to propose in the near future, including any emerging from the proposals, control measures and strategies developed under Article 16. The Commission shall make the first such presentation at the latest two years after the date of entry into force of this Directive.

2. The Commission will review this Directive at the latest 19 years after the date of its entry into force and will propose any necessary amendments to it.

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Article 20

Technical adaptations to the Directive

1. Annexes I, III and section 1.3.6 of Annex V may be adapted to scientific and technical progress taking account of the periods for review and updating of the river basin management plans as referred to in Article 13. Those measures, designed to amend non-essential elements of this Directive, shall be adopted in accordance with the regulatory procedure with scrutiny referred to in Article 21(3).

Where necessary, the Commission may adopt guidelines on the implementation of Annexes II and V in accordance with the regulatory procedure referred to in Article 21(2).

2. For the purpose of transmission and processing of data, including statistical and cartographic data, technical formats for the purpose of paragraph 1 may be adopted in accordance with the regulatory procedure referred to in Article 21(2).

Article 21

Committee procedure

1. The Commission shall be assisted by a committee.

2. Where reference is made to this paragraph, Articles 5 and 7 of Decision 1999/468/EC shall apply, having regard to the provisions of Article 8 thereof.

The period laid down in Article 5(6) of Decision 1999/468/EC shall be set at three months.

3. Where reference is made to this paragraph, Article 5a(1) to (4) and Article 7 of Decision 1999/468/EC shall apply, having regard to the provisions of Article 8 thereof.

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Article 22

Repeals and transitional provisions

1. The following shall be repealed with effect from seven years after the date of entry into force of this Directive:

— Directive 75/440/EEC of 16 June 1975 concerning the quality required of surface water intended for the abstraction of drinking water in the Member States [1],

(1) OJ L 194, 25.7.1975, p. 26. Directive as last amended by Directive 91/692/EEC.

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— Council Decision 77/795/EEC of 12 December 1977 establishing a common procedure for the exchange of information on the quality of surface freshwater in the Community (1),

— Council Directive 79/869/EEC of 9 October 1979 concerning the methods of measurement and frequencies of sampling and analysis of surface water intended for the abstraction of drinking waters in the Member States (2).

2. The following shall be repealed with effect from 13 years after the date of entry into force of this Directive:

— Council Directive 78/659/EEC of 18 July 1978 on the quality of freshwaters needing protection or improvement in order to support fish life (3),

— Council Directive 79/923/EEC of 30 October 1979 on the quality required of shellfish waters (4),

— Council Directive 80/68/EEC of 17 December 1979 on the protection of groundwater against pollution caused by certain dangerous substances,

— Directive 76/464/EEC, with the exception of Article 6, which shall be repealed with effect from the entry into force of this Directive.

3. The following transitional provisions shall apply for Directive 76/464/EEC:

(a) the list of priority substances adopted under Article 16 of this Directive shall replace the list of substances prioritised in the Commission communication to the Council of 22 June 1982;

(b) for the purposes of Article 7 of Directive 76/464/EEC, Member States may apply the principles for the identification of pollution problems and the substances causing them, the establishment of quality standards, and the adoption of measures, laid down in this Directive.

4. The environmental objectives in Article 4 and environmental quality standards established in Annex IX and pursuant to Article 16(7), and by Member States under Annex V for substances not on the list of priority substances and under Article 16(8) in respect of priority substances for which Community standards have not been set, shall be regarded as environmental quality standards for the purposes of point 7 of Article 2 and Article 10 of Directive 96/61/EC.

5. Where a substance on the list of priority substances adopted under Article 16 is not included in Annex VIII to this Directive or in Annex III to Directive 96/61/EC, it shall be added thereto.

6. For bodies of surface water, environmental objectives established under the first river basin management plan required by this Directive shall, as a minimum, give effect to quality standards at least as stringent as those required to implement Directive 76/464/EEC.

(1) OJ L 334, 24.12.1977, p. 29. Decision as last amended by the 1994 Act of Accession.
(2) OJ L 271, 29.10.1979, p. 44. Directive as last amended by the 1994 Act of Accession.
(3) OJ L 222, 14.8.1978, p. 1. Directive as last amended by the 1994 Act of Accession.
(4) OJ L 281, 10.11.1979, p. 47. Directive as amended by Directive 91/692/EEC.

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Article 23

Penalties

Member States shall determine penalties applicable to breaches of the national provisions adopted pursuant to this Directive. The penalties thus provided for shall be effective, proportionate and dissuasive.

Article 24

Implementation

1. Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive at the latest 22 December 2003. They shall forthwith inform the Commission thereof.

When Member States adopt these measures, they shall contain a reference to this Directive or shall be accompanied by such a reference on the occasion of their official publication. The methods of making such a reference shall be laid down by the Member States.

2. Member States shall communicate to the Commission the texts of the main provisions of national law which they adopt in the field governed by this Directive. The Commission shall inform the other Member States thereof.

Article 25

Entry into force

DieThis Directive shall enter into force on the day of its publication in the *Official Journal of the European Communities*.

Article 26

Addressees

This Directive is addressed to the Member States.

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ANNEX I

INFORMATION REQUIRED FOR THE LIST OF COMPETENT AUTHORITIES

As required under Article 3(8), the Member States shall provide the following information on all competent authorities within each of its river basin districts as well as the portion of any international river basin district lying within their territory.

(i) Name and address of the competent authority — the official name and address of the authority identified under Article 3(2).

(ii) Geographical coverage of the river basin district — the names of the main rivers within the river basin district together with a precise description of the boundaries of the river basin district. This information should as far as possible be available for introduction into a geographic information system (GIS) and/or the geographic information system of the Commission (GISCO).

(iii) Legal status of competent authority — a description of the legal status of the competent authority and, where relevant, a summary or copy of its statute, founding treaty or equivalent legal document.

(iv) Responsibilities — a description of the legal and administrative responsibilities of each competent authority and of its role within each river basin district.

(v) Membership — where the competent authority acts as a coordinating body for other competent authorities, a list is required of these bodies together with a summary of the institutional relationships established in order to ensure coordination.

(vi) International relationships — where a river basin district covers the territory of more than one Member State or includes the territory of non-Member States, a summary is required of the institutional relationships established in order to ensure coordination.

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ANNEX II

1 SURFACE WATERS

1.1. **Characterisation of surface water body types**

Member States shall identify the location and boundaries of bodies of surface water and shall carry out an initial characterisation of all such bodies in accordance with the following methodology. Member States may group surface water bodies together for the purposes of this initial characterisation.

(i) The surface water bodies within the river basin district shall be identified as falling within either one of the following surface water categories — rivers, lakes, transitional waters or coastal waters — or as artificial surface water bodies or heavily modified surface water bodies.

(ii) For each surface water category, the relevant surface water bodies within the river basin district shall be differentiated according to type. These types are those defined using either 'system A' or 'system B' identified in section 1.2.

(iii) If system A is used, the surface water bodies within the river basin district shall first be differentiated by the relevant ecoregions in accordance with the geographical areas identified in section 1.2 and shown on the relevant map in Annex XI. The water bodies within each ecoregion shall then be differentiated by surface water body types according to the descriptors set out in the tables for system A.

(iv) If system B is used, Member States must achieve at least the same degree of differentiation as would be achieved using system A. Accordingly, the surface water bodies within the river basin district shall be differentiated into types using the values for the obligatory descriptors and such optional descriptors, or combinations of descriptors, as are required to ensure that type specific biological reference conditions can be reliably derived.

(v) For artificial and heavily modified surface water bodies the differentiation shall be undertaken in accordance with the descriptors for whichever of the surface water categories most closely resembles the heavily modified or artificial water body concerned.

(vi) Member States shall submit to the Commission a map or maps (in a GIS format) of the geographical location of the types consistent with the degree of differentiation required under system A.

1.2. **Ecoregions and surface water body types**

1.2.1. Rivers

System A

Fixed typology	Descriptors
Ecoregion	Ecoregions shown on map A in Annex XI
Type	Altitude typology high: >800 m mid-altitude: 200 to 800 m lowland: <200 m Size typology based on catchment area small: 10 to 100 km^2 medium: >100 to 1 000 km^2 large: >1 000 to 10 000 km^2 very large: >10 000 km^2 Geology calcareous siliceous organic

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System B

Alternative characterisation	Physical and chemical factors that determine the characteristics of the river or part of the river and hence the biological population structure and composition
Obligatory factors	altitude latitude longitude geology size
Optional factors	distance from river source energy of flow (function of flow and slope) mean water width mean water depth mean water slope form and shape of main river bed river discharge (flow) category valley shape transport of solids acid neutralising capacity mean substratum composition chloride air temperature range mean air temperature precipitation

1.2.2. L a k e s

System A

Fixed typology	Descriptors
Ecoregion	Ecoregions shown on map A in Annex XI
Type	Altitude typology high: >800 m mid-altitude: 200 to 800 m lowland: <200 m Depth typology based on mean depth <3 m 3 to 15 m >15 m Size typology based on surface area 0,5 to 1 km^2 1 to 10 km^2 10 to 100 km^2 >100 km^2 Geology calcareous siliceous organic

System B

Alternative characterisation	Physical and chemical factors that determine the characteristics of the lake and hence the biological population structure and composition
Obligatory factors	altitude latitude longitude depth

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Alternative characterisation	Physical and chemical factors that determine the characteristics of the lake and hence the biological population structure and composition
	geology size
Optional factors	mean water depth lake shape residence time mean air temperature air temperature range mixing characteristics (e.g. monomictic, dimictic, polymictic) acid neutralising capacity background nutrient status mean substratum composition water level fluctuation

1.2.3. Transitional Waters

System A

Fixed typology	Descriptors
Ecoregion	The following as identified on map B in Annex XI: Baltic Sea Barents Sea Norwegian Sea North Sea North Atlantic Ocean Mediterranean Sea
Type	Based on mean annual salinity <0,5‰: freshwater 0,5 to <5‰: oligohaline 5 to <18‰: mesohaline 18 to <30‰: polyhaline 30 to <40‰: euhaline Based on mean tidal range <2 m: microtidal 2 to 4 m: mesotidal >4 m: macrotidal

System B

Alternative characterisation	Physical and chemical factors that determine the characteristics of the transitional water and hence the biological population structure and composition
Obligatory factors	latitude longitude tidal range salinity
Optional factors	depth current velocity wave exposure residence time mean water temperature mixing characteristics turbidity mean substratum composition shape water temperature range

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1.2.4. Coastal Waters

System A

Fixed typology	Descriptors
Ecoregion	The following as identified on map B in Annex XI: Baltic Sea Barents Sea Norwegian Sea North Sea North Atlantic Ocean Mediterranean Sea
Type	Based on mean annual salinity <0,5‰: freshwater 0,5 to <5‰: oligohaline 5 to <18‰: mesohaline 18 to <30‰: polyhaline 30 to <40‰: euhaline Based on mean depth shallow waters: <30 m intermediate: (30 to 200 m) deep: >200 m

System B

Alternative characterisation	Physical and chemical factors that determine the characteristics of the coastal water and hence the biological community structure and composition
Obligatory factors	latitude longitude tidal range salinity
Optional factors	current velocity wave exposure mean water temperature mixing characteristics turbidity retention time (of enclosed bays) mean substratum composition water temperature range

1.3. **Establishment of type-specific reference conditions for surface water body types**

(i) For each surface water body type characterised in accordance with section 1.1, type-specific hydromorphological and physicochemical conditions shall be established representing the values of the hydromorphological and physicochemical quality elements specified in point 1.1 in Annex V for that surface water body type at high ecological status as defined in the relevant table in point 1.2 in Annex V. Type-specific biological reference conditions shall be established, representing the values of the biological quality elements specified in point 1.1 in Annex V for that surface water body type at high ecological status as defined in the relevant table in section 1.2 in Annex V.

(ii) In applying the procedures set out in this section to heavily modified or artificial surface water bodies references to high ecological status shall be construed as references to maximum ecological potential as defined in table 1.2.5 of Annex V. The values for maximum ecological potential for a water body shall be reviewed every six years.

(iii) Type-specific conditions for the purposes of points (i) and (ii) and type-specific biological reference conditions may be either spatially based or based on modelling, or may be derived using a combi-

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nation of these methods. Where it is not possible to use these methods, Member States may use expert judgement to establish such conditions. In defining high ecological status in respect of concentrations of specific synthetic pollutants, the detection limits are those which can be achieved in accordance with the available techniques at the time when the type-specific conditions are to be established.

(iv) For spatially based type-specific biological reference conditions, Member States shall develop a reference network for each surface water body type. The network shall contain a sufficient number of sites of high status to provide a sufficient level of confidence about the values for the reference conditions, given the variability in the values of the quality elements corresponding to high ecological status for that surface water body type and the modelling techniques which are to be applied under paragraph (v).

(v) Type-specific biological reference conditions based on modelling may be derived using either predictive models or hindcasting methods. The methods shall use historical, palaeological and other available data and shall provide a sufficient level of confidence about the values for the reference conditions to ensure that the conditions so derived are consistent and valid for each surface water body type.

(vi) Where it is not possible to establish reliable type-specific reference conditions for a quality element in a surface water body type due to high degrees of natural variability in that element, not just as a result of seasonal variations, then that element may be excluded from the assessment of ecological status for that surface water type. In such circumstances Member States shall state the reasons for this exclusion in the river basin management plan.

1.4. **Identification of Pressures**

Member States shall collect and maintain information on the type and magnitude of the significant anthropogenic pressures to which the surface water bodies in each river basin district are liable to be subject, in particular the following.

Estimation and identification of significant point source pollution, in particular by substances listed in Annex VIII, from urban, industrial, agricultural and other installations and activities, based, *inter alia,* on information gathered under:

(i) Articles 15 and 17 of Directive 91/271/EEC;

(ii) Articles 9 and 15 of Directive 96/61/EC [1];

and for the purposes of the initial river basin management plan:

(iii) Article 11 of Directive 76/464/EEC; and

(iv) Directives 75/440/EC, 76/160/EEC [2], 78/659/EEC and 79/923/EEC [3].

Estimation and identification of significant diffuse source pollution, in particular by substances listed in Annex VIII, from urban, industrial, agricultural and other installations and activities; based, *inter alia*, on information gathered under:

(i) Articles 3, 5 and 6 of Directive 91/676/EEC [4];

(ii) Articles 7 and 17 of Directive 91/414/EEC;

(iii) Directive 98/8/EC;

and for the purposes of the first river basin management plan:

(iv) Directives 75/440/EEC, 76/160/EEC, 76/464/EEC, 78/659/EEC and 79/923/EEC.

(1) OJ L 135, 30.5.1991, p. 40. Directive as last amended by Directive 98/15/EC (OJ L 67, 7.3.1998, p. 29).
(2) OJ L 31, 5.2.1976, p. 1. Directive as last amended by the 1994 Act of Accession.
(3) OJ L 281, 10.11.1979, p. 47. Directive as amended by Directive 91/692/EEC (OJ L 377, 31.12.1991, p. 48).
(4) OJ L 375, 31.12.1991, p. 1.

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Estimation and identification of significant water abstraction for urban, industrial, agricultural and other uses, including seasonal variations and total annual demand, and of loss of water in distribution systems.

Estimation and identification of the impact of significant water flow regulation, including water transfer and diversion, on overall flow characteristics and water balances.

Identification of significant morphological alterations to water bodies.

Estimation and identification of other significant anthropogenic impacts on the status of surface waters.

Estimation of land use patterns, including identification of the main urban, industrial and agricultural areas and, where relevant, fisheries and forests.

1.5. **Assessment of Impact**

Member States shall carry out an assessment of the susceptibility of the surface water status of bodies to the pressures identified above.

Member States shall use the information collected above, and any other relevant information including existing environmental monitoring data, to carry out an assessment of the likelihood that surface waters bodies within the river basin district will fail to meet the environmental quality objectives set for the bodies under Article 4. Member States may utilise modelling techniques to assist in such an assessment.

For those bodies identified as being at risk of failing the environmental quality objectives, further characterisation shall, where relevant, be carried out to optimise the design of both the monitoring programmes required under Article 8, and the programmes of measures required under Article 11.

2. GROUNDWATERS

2.1. **Initial characterisation**

Member States shall carry out an initial characterisation of all groundwater bodies to assess their uses and the degree to which they are at risk of failing to meet the objectives for each groundwater body under Article 4. Member States may group groundwater bodies together for the purposes of this initial characterisation. This analysis may employ existing hydrological, geological, pedological, land use, discharge, abstraction and other data but shall identify:

— the location and boundaries of the groundwater body or bodies,

— the pressures to which the groundwater body or bodies are liable to be subject including:

  — diffuse sources of pollution

  — point sources of pollution

  — abstraction

  — artificial recharge,

— the general character of the overlying strata in the catchment area from which the groundwater body receives its recharge,

— those groundwater bodies for which there are directly dependent surface water ecosystems or terrestrial ecosystems.

2.2. **Further characterisation**

Following this initial characterisation, Member States shall carry out further characterisation of those groundwater bodies or groups of bodies which have been identified as being at risk in order to establish a more precise assessment of the significance of such risk and identification of any measures to be required under Article 11. Accordingly, this characterisation shall include relevant information on the impact of human activity and, where relevant, information on:

— geological characteristics of the groundwater body including the extent and type of geological units,

— hydrogeological characteristics of the groundwater body including hydraulic conductivity, porosity and confinement,

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- characteristics of the superficial deposits and soils in the catchment from which the groundwater body receives its recharge, including the thickness, porosity, hydraulic conductivity, and absorptive properties of the deposits and soils,
- stratification characteristics of the groundwater within the groundwater body,
- an inventory of associated surface systems, including terrestrial ecosystems and bodies of surface water, with which the groundwater body is dynamically linked,
- estimates of the directions and rates of exchange of water between the groundwater body and associated surface systems,
- sufficient data to calculate the long term annual average rate of overall recharge,
- characterisation of the chemical composition of the groundwater, including specification of the contributions from human activity. Member States may use typologies for groundwater characterisation when establishing natural background levels for these bodies of groundwater.

2.3. **Review of the impact of human activity on groundwaters**

For those bodies of groundwater which cross the boundary between two or more Member States or are identified following the initial characterisation undertaken in accordance with paragraph 2.1 as being at risk of failing to meet the objectives set for each body under Article 4, the following information shall, where relevant, be collected and maintained for each groundwater body:

(a) the location of points in the groundwater body used for the abstraction of water with the exception of:

  - points for the abstraction of water providing less than an average of 10 m^3 per day, or,
  - points for the abstraction of water intended for human consumption providing less than an average of 10 m^3 per day or serving less than 50 persons,

(b) the annual average rates of abstraction from such points,

(c) the chemical composition of water abstracted from the groundwater body,

(d) the location of points in the groundwater body into which water is directly discharged,

(e) the rates of discharge at such points,

(f) the chemical composition of discharges to the groundwater body, and

(g) land use in the catchment or catchments from which the groundwater body receives its recharge, including pollutant inputs and anthropogenic alterations to the recharge characteristics such as rainwater and run-off diversion through land sealing, artificial recharge, damming or drainage.

2.4. **Review of the impact of changes in groundwater levels**

Member States shall also identify those bodies of groundwater for which lower objectives are to be specified under Article 4 including as a result of consideration of the effects of the status of the body on:

(i) surface water and associated terrestrial ecosystems

(ii) water regulation, flood protection and land drainage

(iii)human development.

2.5. **Review of the impact of pollution on groundwater quality**

Member States shall identify those bodies of groundwater for which lower objectives are to be specified under Article 4(5) where, as a result of the impact of human activity, as determined in accordance with Article 5(1), the body of groundwater is so polluted that

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achieving good groundwater chemical status is infeasible or disproportionately expensive.

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ANNEX III

ECONOMIC ANALYSIS

The economic analysis shall contain enough information in sufficient detail (taking account of the costs associated with collection of the relevant data) in order to:

(a) make the relevant calculations necessary for taking into account under Article 9 the principle of recovery of the costs of water services, taking account of long term forecasts of supply and demand for water in the river basin district and, where necessary:

— estimates of the volume, prices and costs associated with water services, and

— estimates of relevant investment including forecasts of such investments;

(b) make judgements about the most cost-effective combination of measures in respect of water uses to be included in the programme of measures under Article 11 based on estimates of the potential costs of such measures.

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ANNEX IV

PROTECTED AREAS

1. The register of protected areas required under Article 6 shall include the following types of protected areas:

   (i) areas designated for the abstraction of water intended for human consumption under Article 7;

   (ii) areas designated for the protection of economically significant aquatic species;

   (iii) bodies of water designated as recreational waters, including areas designated as bathing waters under Directive 76/160/EEC;

   (iv) nutrient-sensitive areas, including areas designated as vulnerable zones under Directive 91/676/EEC and areas designated as sensitive areas under Directive 91/271/EEC; and

   (v) areas designated for the protection of habitats or species where the maintenance or improvement of the status of water is an important factor in their protection, including relevant Natura 2000 sites designated under Directive 92/43/EEC ([1]) and Directive 79/409/EEC ([2]).

2. The summary of the register required as part of the river basin management plan shall include maps indicating the location of each protected area and a description of the Community, national or local legislation under which they have been designated.

([1]) OJ L 206, 22.7.1992, p. 7. Directive as last amended by Directive 97/62/EC (OJ L 305, 8.11.1997, p. 42).

([2]) OJ L 103, 25.4.1979, p. 1. Directive as last amended by Directive 97/49/EC (OJ L 223, 13.8.1997, p. 9).

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ANNEX V

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2.2. **Monitoring of groundwater quantitative status**

2.2.1. Groundwater level monitoring network

2.2.2. Density of monitoring sites

2.2.3. Monitoring frequency

2.2.4. Interpretation and presentation of groundwater quantitative status

2.3. **Groundwater chemical status**

2.3.1. Parameters for the determination of groundwater chemical status

2.3.2. Definition of good groundwater chemical status

2.4. **Monitoring of groundwater chemical status**

2.4.1. Groundwater monitoring network

2.4.2. Surveillance monitoring

2.4.3. Operational monitoring

2.4.4. Identification of trends in pollutants

2.4.5. Interpretation and presentation of groundwater chemical status

2.5. **Presentation of groundwater status**

1. SURFACE WATER STATUS

1.1. **Quality elements for the classification of ecological status**

1.1.1. Rivers

Biological elements

Composition and abundance of aquatic flora

Composition and abundance of benthic invertebrate fauna

Composition, abundance and age structure of fish fauna

Hydromorphological elements supporting the biological elements

Hydrological regime

quantity and dynamics of water flow

connection to groundwater bodies

River continuity

Morphological conditions

river depth and width variation

structure and substrate of the river bed

structure of the riparian zone

Chemical and physico-chemical elements supporting the biological elements

General

Thermal conditions

Oxygenation conditions

Salinity

Acidification status

Nutrient conditions

Specific pollutants

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Pollution by all priority substances identified as being discharged into the body of water

Pollution by other substances identified as being discharged in significant quantities into the body of water

1.1.2. Lakes

Biological elements

Composition, abundance and biomass of phytoplankton

Composition and abundance of other aquatic flora

Composition and abundance of benthic invertebrate fauna

Composition, abundance and age structure of fish fauna

Hydromorphological elements supporting the biological elements

Hydrological regime

quantity and dynamics of water flow

residence time

connection to the groundwater body

Morphological conditions

lake depth variation

quantity, structure and substrate of the lake bed

structure of the lake shore

Chemical and physico-chemical elements supporting the biological elements

General

Transparency

Thermal conditions

Oxygenation conditions

Salinity

Acidification status

Nutrient conditions

Specific pollutants

Pollution by all priority substances identified as being discharged into the body of water

Pollution by other substances identified as being discharged in significant quantities into the body of water

1.1.3. Transitional waters

Biological elements

Composition, abundance and biomass of phytoplankton

Composition and abundance of other aquatic flora

Composition and abundance of benthic invertebrate fauna

Composition and abundance of fish fauna

Hydro-morphological elements supporting the biological elements

Morphological conditions

depth variation

quantity, structure and substrate of the bed

structure of the intertidal zone

Tidal regime

freshwater flow

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wave exposure

Chemical and physico-chemical elements supporting the biological elements

General

Transparency

Thermal conditions

Oxygenation conditions

Salinity

Nutrient conditions

Specific pollutants

Pollution by all priority substances identified as being discharged into the body of water

Pollution by other substances identified as being discharged in significant quantities into the body of water

1.1.4. Coastal waters

Biological elements

Composition, abundance and biomass of phytoplankton

Composition and abundance of other aquatic flora

Composition and abundance of benthic invertebrate fauna

Hydromorphological elements supporting the biological elements

Morphological conditions

depth variation

structure and substrate of the coastal bed

structure of the intertidal zone

Tidal regime

direction of dominant currents

wave exposure

Chemical and physico-chemical elements supporting the biological elements

General

Transparency

Thermal conditions

Oxygenation conditions

Salinity

Nutrient conditions

Specific pollutants

Pollution by all priority substances identified as being discharged into the body of water

Pollution by other substances identified as being discharged in significant quantities into the body of water

1.1.5. Artificial and heavily modified surface water bodies

The quality elements applicable to artificial and heavily modified surface water bodies shall be those applicable to whichever of the four natural surface water categories above most closely resembles the heavily modified or artificial water body concerned.

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1.2. Normative definitions of ecological status classifications

Table 1.2. *General definition for rivers, lakes, transitional waters and coastal waters*

The following text provides a general definition of ecological quality. For the purposes of classification the values for the quality elements of ecological status for each surface water category are those given in tables 1.2.1 to 1.2.4 below.

Element	High status	Good status	Moderate status
General	There are no, or only very minor, anthropogenic alterations to the values of the physico-chemical and hydromorphological quality elements for the surface water body type from those normally associated with that type under undisturbed conditions. The values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion. These are the type-specific conditions and communities.	The values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.	The values of the biological quality elements for the surface water body type deviate moderately from those normally associated with the surface water body type under undisturbed conditions. The values show moderate signs of distortion resulting from human activity and are significantly more disturbed than under conditions of good status.

Waters achieving a status below moderate shall be classified as poor or bad.

Waters showing evidence of major alterations to the values of the biological quality elements for the surface water body type and in which the relevant biological communities deviate substantially from those normally associated with the surface water body type under undisturbed conditions, shall be classified as poor.

Waters showing evidence of severe alterations to the values of the biological quality elements for the surface water body type and in which large portions of the relevant biological communities normally associated with the surface water body type under undisturbed conditions are absent, shall be classified as bad.

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1.2.1. Definitions for high, good and moderate ecological status in rivers

Biological quality elements

Element	High status	Good status	Moderate status
Phytoplankton	The taxonomic composition of phytoplankton corresponds totally or nearly totally to undisturbed conditions. The average phytoplankton abundance is wholly consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions. Planktonic blooms occur at a frequency and intensity which is consistent with the type-specific physico-chemical conditions.	There are slight changes in the composition and abundance of planktonic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbances to the balance of organisms present in the water body or to the physico-chemical quality of the water or sediment. A slight increase in the frequency and intensity of the type-specific planktonic blooms may occur.	The composition of planktonic taxa differs moderately from the type-specific communities. Abundance is moderately disturbed and may be such as to produce a significant undesirable disturbance in the values of other biological and physico-chemical quality elements. A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months.
Macrophytes and phytobenthos	The taxonomic composition corresponds totally or nearly totally to undisturbed conditions. There are no detectable changes in the average macrophytic and the average phytobenthic abundance.	There are slight changes in the composition and abundance of macrophytic and phytobenthic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of phytobenthos or higher forms of plant life resulting in undesirable disturbances to the balance of organisms present in the water body or to the physico-chemical quality of the water or sediment. The phytobenthic community is not adversely affected by bacterial tufts and coats present due to anthropogenic activity.	The composition of macrophytic and phytobenthic taxa differs moderately from the type-specific community and is significantly more distorted than at good status. Moderate changes in the average macrophytic and the average phytobenthic abundance are evident. The phytobenthic community may be interfered with and, in some areas, displaced by bacterial tufts and coats present as a result of anthropogenic activities.

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Element	High status	Good status	Moderate status
Benthic invertebrate fauna	The taxonomic composition and abundance correspond totally or nearly totally to undisturbed conditions. The ratio of disturbance sensitive taxa to insensitive taxa shows no signs of alteration from undisturbed levels. The level of diversity of invertebrate taxa shows no sign of alteration from undisturbed levels.	There are slight changes in the composition and abundance of invertebrate taxa from the type-specific communities. The ratio of disturbance-sensitive taxa to insensitive taxa shows slight alteration from type-specific levels. The level of diversity of invertebrate taxa shows slight signs of alteration from type-specific levels.	The composition and abundance of invertebrate taxa differ moderately from the type-specific communities. Major taxonomic groups of the type-specific community are absent. The ratio of disturbance-sensitive taxa to insensitive taxa, and the level of diversity, are substantially lower than the type-specific level and significantly lower than for good status.
Fish fauna	Species composition and abundance correspond totally or nearly totally to undisturbed conditions. All the type-specific disturbance-sensitive species are present. The age structures of the fish communities show little sign of anthropogenic disturbance and are not indicative of a failure in the reproduction or development of any particular species.	There are slight changes in species composition and abundance from the type-specific communities attributable to anthropogenic impacts on physico-chemical and hydromorphological quality elements. The age structures of the fish communities show signs of disturbance attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements, and, in a few instances, are indicative of a failure in the reproduction or development of a particular species, to the extent that some age classes may be missing.	The composition and abundance of fish species differ moderately from the type-specific communities attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements. The age structure of the fish communities shows major signs of anthropogenic disturbance, to the extent that a moderate proportion of the type specific species are absent or of very low abundance.

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Hydromorphological quality elements

Element	High status	Good status	Moderate status
Hydrological regime	The quantity and dynamics of flow, and the resultant connection to groundwaters, reflect totally, or nearly totally, undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
River continuity	The continuity of the river is not disturbed by anthropogenic activities and allows undisturbed migration of aquatic organisms and sediment transport.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological conditions	Channel patterns, width and depth variations, flow velocities, substrate conditions and both the structure and condition of the riparian zones correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

Physico-chemical quality elements (1)

Element	High status	Good status	Moderate status
General conditions	The values of the physico-chemical elements correspond totally or nearly totally to undisturbed conditions. Nutrient concentrations remain within the range normally associated with undisturbed conditions. Levels of salinity, pH, oxygen balance, acid neutralising capacity and temperature do not show signs of anthropogenic disturbance and remain within the range normally associated with undisturbed conditions.	Temperature, oxygen balance, pH, acid neutralising capacity and salinity do not reach levels outside the range established so as to ensure the functioning of the type specific ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

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Element	High status	Good status	Moderate status
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with undisturbed conditions (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 [2] without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

(1) The following abbreviations are used: bgl = background level, EQS = environmental quality standard.
(2) Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels: (EQS >bgl).

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1.2.2. Definitions for high, good and moderate ecological status in lakes

Biological quality elements

Element	High status	Good status	Moderate status
Phytoplankton	The taxonomic composition and abundance of phytoplankton correspond totally or nearly totally to undisturbed conditions. The average phytoplankton biomass is consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions. Planktonic blooms occur at a frequency and intensity which is consistent with the type specific physico-chemical conditions.	There are slight changes in the composition and abundance of planktonic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water or sediment. A slight increase in the frequency and intensity of the type specific planktonic blooms may occur.	The composition and abundance of planktonic taxa differ moderately from the type-specific communities. Biomass is moderately disturbed and may be such as to produce a significant undesirable disturbance in the condition of other biological quality elements and the physico-chemical quality of the water or sediment. A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months.
Macrophytes and phytobenthos	The taxonomic composition corresponds totally or nearly totally to undisturbed conditions. There are no detectable changes in the average macrophytic and the average phytobenthic abundance.	There are slight changes in the composition and abundance of macrophytic and phytobenthic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of phytobenthos or higher forms of plant life resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water. The phytobenthic community is not adversely affected by bacterial tufts and coats present due to anthropogenic activity.	The composition of macrophytic and phytobenthic taxa differ moderately from the type-specific communities and are significantly more distorted than those observed at good quality. Moderate changes in the average macrophytic and the average phytobenthic abundance are evident. The phytobenthic community may be interfered with, and, in some areas, displaced by bacterial tufts and coats present as a result of anthropogenic activities.

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Element	High status	Good status	Moderate status
Benthic invertebrate fauna	The taxonomic composition and abundance correspond totally or nearly totally to the undisturbed conditions. The ratio of disturbance sensitive taxa to insensitive taxa shows no signs of alteration from undisturbed levels. The level of diversity of invertebrate taxa shows no sign of alteration from undisturbed levels.	There are slight changes in the composition and abundance of invertebrate taxa compared to the type-specific communities. The ratio of disturbance sensitive taxa to insensitive taxa shows slight signs of alteration from type-specific levels. The level of diversity of invertebrate taxa shows slight signs of alteration from type-specific levels.	The composition and abundance of invertebrate taxa differ moderately from the type-specific conditions. Major taxonomic groups of the type-specific community are absent. The ratio of disturbance sensitive to insensitive taxa, and the level of diversity, are substantially lower than the type-specific level and significantly lower than for good status.
Fish fauna	Species composition and abundance correspond totally or nearly totally to undisturbed conditions. All the type-specific sensitive species are present. The age structures of the fish communities show little sign of anthropogenic disturbance and are not indicative of a failure in the reproduction or development of a particular species.	There are slight changes in species composition and abundance from the type-specific communities attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements. The age structures of the fish communities show signs of disturbance attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements, and, in a few instances, are indicative of a failure in the reproduction or development of a particular species, to the extent that some age classes may be missing.	The composition and abundance of fish species differ moderately from the type-specific communities attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements. The age structure of the fish communities shows major signs of disturbance, attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements, to the extent that a moderate proportion of the type specific species are absent or of very low abundance.

Hydromorphological quality elements

Element	High status	Good status	Moderate status
Hydrological regime	The quantity and dynamics of flow, level, residence time, and the resultant connection to groundwaters, reflect totally or nearly totally undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

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Element	High status	Good status	Moderate status
Morphological conditions	Lake depth variation, quantity and structure of the substrate, and both the structure and condition of the lake shore zone correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

Physico-chemical quality elements (1)

Element	High status	Good status	Moderate status
General conditions	The values of physico-chemical elements correspond totally or nearly totally to undisturbed conditions. Nutrient concentrations remain within the range normally associated with undisturbed conditions. Levels of salinity, pH, oxygen balance, acid neutralising capacity, transparency and temperature do not show signs of anthropogenic disturbance and remain within the range normally associated with undisturbed conditions.	Temperature, oxygen balance, pH, acid neutralising capacity, transparency and salinity do not reach levels outside the range established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with undisturbed conditions (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 (2) without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

(1) The following abbreviations are used: bgl = background level, EQS = environmental quality standard.
(2) Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels: (EQS >bgl).

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1.2.3. Definitions for high, good and moderate ecological status in transitional waters

Biological quality elements

Element	High status	Good status	Moderate status
Phytoplankton	The composition and abundance of the phytoplanktonic taxa are consistent with undisturbed conditions. The average phytoplankton biomass is consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions. Planktonic blooms occur at a frequency and intensity which is consistent with the type specific physico-chemical conditions.	There are slight changes in the composition and abundance of phytoplanktonic taxa. There are slight changes in biomass compared to the type-specific conditions. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water. A slight increase in the frequency and intensity of the type specific planktonic blooms may occur.	The composition and abundance of phytoplanktonic taxa differ moderately from type-specific conditions. Biomass is moderately disturbed and may be such as to produce a significant undesirable disturbance in the condition of other biological quality elements. A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months.
Macroalgae	The composition of macroalgal taxa is consistent with undisturbed conditions. There are no detectable changes in macroalgal cover due to anthropogenic activities.	There are slight changes in the composition and abundance of macroalgal taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of phytobenthos or higher forms of plant life resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water.	The composition of macroalgal taxa differs moderately from type-specific conditions and is significantly more distorted than at good quality. Moderate changes in the average macroalgal abundance are evident and may be such as to result in an undesirable disturbance to the balance of organisms present in the water body.
Angiosperms	The taxonomic composition corresponds totally or nearly totally to undisturbed conditions. There are no detectable changes in angiosperm abundance due to anthropogenic activities.	There are slight changes in the composition of angiosperm taxa compared to the type-specific communities. Angiosperm abundance shows slight signs of disturbance.	The composition of the angiosperm taxa differs moderately from the type-specific communities and is significantly more distorted than at good quality. There are moderate distortions in the abundance of angiosperm taxa.

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Element	High status	Good status	Moderate status
Benthic invertebrate fauna	The level of diversity and abundance of invertebrate taxa is within the range normally associated with undisturbed conditions. All the disturbance-sensitive taxa associated with undisturbed conditions are present.	The level of diversity and abundance of invertebrate taxa is slightly outside the range associated with the type-specific conditions. Most of the sensitive taxa of the type-specific communities are present.	The level of diversity and abundance of invertebrate taxa is moderately outside the range associated with the type-specific conditions. Taxa indicative of pollution are present. Many of the sensitive taxa of the type-specific communities are absent.
Fish fauna	Species composition and abundance is consistent with undisturbed conditions.	The abundance of the disturbance-sensitive species shows slight signs of distortion from type-specific conditions attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements.	A moderate proportion of the type-specific disturbance-sensitive species are absent as a result of anthropogenic impacts on physico-chemical or hydromorphological quality elements.

Hydromorphological quality elements

Element	High status	Good status	Moderate status
Tidal regime	The freshwater flow regime corresponds totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological conditions	Depth variations, substrate conditions, and both the structure and condition of the intertidal zones correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

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Physico-chemical quality elements (1)

Element	High status	Good status	Moderate status
General conditions	Physico-chemical elements correspond totally or nearly totally to undisturbed conditions. Nutrient concentrations remain within the range normally associated with undisturbed conditions. Temperature, oxygen balance and transparency do not show signs of anthropogenic disturbance and remain within the range normally associated with undisturbed conditions.	Temperature, oxygenation conditions and transparency do not reach levels outside the ranges established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with undisturbed conditions (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 (2) without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

(1) The following abbreviations are used: bgl = background level, EQS = environmental quality standard.
(2) Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels: (EQS >bgl).

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1.2.4. Definitions for high, good and moderate ecological status in coastal waters

Biological quality elements

Element	High status	Good status	Moderate status
Phytoplankton	The composition and abundance of phytoplanktonic taxa are consistent with undisturbed conditions. The average phytoplankton biomass is consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions. Planktonic blooms occur at a frequency and intensity which is consistent with the type specific physico-chemical conditions.	The composition and abundance of phytoplanktonic taxa show slight signs of disturbance. There are slight changes in biomass compared to type-specific conditions. Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the quality of the water. A slight increase in the frequency and intensity of the type-specific planktonic blooms may occur.	The composition and abundance of planktonic taxa show signs of moderate disturbance. Algal biomass is substantially outside the range associated with type-specific conditions, and is such as to impact upon other biological quality elements. A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months.
Macroalgae and angiosperms	All disturbance-sensitive macroalgal and angiosperm taxa associated with undisturbed conditions are present. The levels of macroalgal cover and angiosperm abundance are consistent with undisturbed conditions.	Most disturbance-sensitive macroalgal and angiosperm taxa associated with undisturbed conditions are present. The level of macroalgal cover and angiosperm abundance show slight signs of disturbance.	A moderate number of the disturbance-sensitive macroalgal and angiosperm taxa associated with undisturbed conditions are absent. Macroalgal cover and angiosperm abundance is moderately disturbed and may be such as to result in an undesirable disturbance to the balance of organisms present in the water body.
Benthic invertebrate fauna	The level of diversity and abundance of invertebrate taxa is within the range normally associated with undisturbed conditions. All the disturbance-sensitive taxa associated with undisturbed conditions are present.	The level of diversity and abundance of invertebrate taxa is slightly outside the range associated with the type-specific conditions. Most of the sensitive taxa of the type-specific communities are present.	The level of diversity and abundance of invertebrate taxa is moderately outside the range associated with the type-specific conditions. Taxa indicative of pollution are present. Many of the sensitive taxa of the type-specific communities are absent.

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Hydromorphological quality elements

Element	High status	Good status	Moderate status
Tidal regime	The freshwater flow regime and the direction and speed of dominant currents correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological conditions	The depth variation, structure and substrate of the coastal bed, and both the structure and condition of the inter-tidal zones correspond totally or nearly totally to the undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

Physico-chemical quality elements ([1])

Element	High status	Good status	Moderate status
General conditions	The physico-chemical elements correspond totally or nearly totally to undisturbed conditions. Nutrient concentrations remain within the range normally associated with undisturbed conditions. Temperature, oxygen balance and transparency do not show signs of anthropogenic disturbance and remain within the ranges normally associated with undisturbed conditions.	Temperature, oxygenation conditions and transparency do not reach levels outside the ranges established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

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Element	High status	Good status	Moderate status
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with undisturbed conditions (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 (²) without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

(1) The following abbreviations are used: bgl = background level, EQS = environmental quality standard.
(2) Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels: (EQS >bgl).

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1.2.5. Definitions for maximum, good and moderate ecological potential for heavily modified or artificial water bodies

Element	Maximum ecological potential	Good ecological potential	Moderate ecological potential
Biological quality elements	The values of the relevant biological quality elements reflect, as far as possible, those associated with the closest comparable surface water body type, given the physical conditions which result from the artificial or heavily modified characteristics of the water body.	There are slight changes in the values of the relevant biological quality elements as compared to the values found at maximum ecological potential.	There are moderate changes in the values of the relevant biological quality elements as compared to the values found at maximum ecological potential. These values are significantly more distorted than those found under good quality.
Hydromorphological elements	The hydromorphological conditions are consistent with the only impacts on the surface water body being those resulting from the artificial or heavily modified characteristics of the water body once all mitigation measures have been taken to ensure the best approximation to ecological continuum, in particular with respect to migration of fauna and appropriate spawning and breeding grounds.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Physico-chemical elements			
General conditions	Physico-chemical elements correspond totally or nearly totally to the undisturbed conditions associated with the surface water body type most closely comparable to the artificial or heavily modified body concerned. Nutrient concentrations remain within the range normally associated with such undisturbed conditions. The levels of temperature, oxygen balance and pH are consistent with the those found in the most closely comparable surface water body types under undisturbed conditions.	The values for physico-chemical elements are within the ranges established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements. Temperature and pH do not reach levels outside the ranges established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

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Element	Maximum ecological potential	Good ecological potential	Moderate ecological potential
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with the undisturbed conditions found in the surface water body type most closely comparable to the artificial or heavily modified body concerned (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 [1] without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.

[1] Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels.

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1.2.6. Procedure for the setting of chemical quality standards by Member States

In deriving environmental quality standards for pollutants listed in points 1 to 9 of Annex VIII for the protection of aquatic biota, Member States shall act in accordance with the following provisions. Standards may be set for water, sediment or biota.

Where possible, both acute and chronic data shall be obtained for the taxa set out below which are relevant for the water body type concerned as well as any other aquatic taxa for which data are available. The 'base set' of taxa are:

— algae and/or macrophytes

— daphnia or representative organisms for saline waters

— fish.

Setting the environmental quality standard

The following procedure applies to the setting of a maximum annual average concentration:

(i) Member States shall set appropriate safety factors in each case consistent with the nature and quality of the available data and the guidance given in section 3.3.1 of Part II of

'Technical guidance document in support of Commission Directive 93/67/EEC on risk assessment for new notified substances and Commission Regulation (EC) No 1488/94 on risk assessment for existing substances'

and the safety factors set out in the table below:

	Safety factor
At least one acute $L(E)C_{50}$ from each of three trophic levels of the base set	1 000
One chronic NOEC (either fish or daphnia or a representative organism for saline waters)	100
Two chronic NOECs from species representing two trophic levels (fish and/or daphnia or a representative organism for saline waters and/or algae)	50
Chronic NOECs from at least three species (normally fish, daphnia or a representative organism for saline waters and algae) representing three trophic levels	10
Other cases, including field data or model ecosystems, which allow more precise safety factors to be calculated and applied	Case-by-case assessment

(ii) where data on persistence and bioaccumulation are available, these shall be taken into account in deriving the final value of the environmental quality standard;

(iii) the standard thus derived should be compared with any evidence from field studies. Where anomalies appear, the derivation shall be reviewed to allow a more precise safety factor to be calculated;

(iv) the standard derived shall be subject to peer review and public consultation including to allow a more precise safety factor to be calculated.

1.3. **Monitoring of ecological status and chemical status for surface waters**

The surface water monitoring network shall be established in accordance with the requirements of Article 8. The monitoring network shall be designed so as to provide a coherent and compre-

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hensive overview of ecological and chemical status within each river basin and shall permit classification of water bodies into five classes consistent with the normative definitions in section 1.2. Member States shall provide a map or maps showing the surface water monitoring network in the river basin management plan.

On the basis of the characterisation and impact assessment carried out in accordance with Article 5 and Annex II, Member States shall for each period to which a river basin management plan applies, establish a surveillance monitoring programme and an operational monitoring programme. Member States may also need in some cases to establish programmes of investigative monitoring.

Member States shall monitor parameters which are indicative of the status of each relevant quality element. In selecting parameters for biological quality elements Member States shall identify the appropriate taxonomic level required to achieve adequate confidence and precision in the classification of the quality elements. Estimates of the level of confidence and precision of the results provided by the monitoring programmes shall be given in the plan.

1.3.1. Design of surveillance monitoring

Objective

Member States shall establish surveillance monitoring programmes to provide information for:

— supplementing and validating the impact assessment procedure detailed in Annex II,

— the efficient and effective design of future monitoring programmes,

— the assessment of long-term changes in natural conditions, and

— the assessment of long-term changes resulting from widespread anthropogenic activity.

The results of such monitoring shall be reviewed and used, in combination with the impact assessment procedure described in Annex II, to determine requirements for monitoring programmes in the current and subsequent river basin management plans.

Selection of monitoring points

Surveillance monitoring shall be carried out of sufficient surface water bodies to provide an assessment of the overall surface water status within each catchment or subcatchments within the river basin district. In selecting these bodies Member States shall ensure that, where appropriate, monitoring is carried out at points where:

— the rate of water flow is significant within the river basin district as a whole; including points on large rivers where the catchment area is greater than 2 500 km^2,

— the volume of water present is significant within the river basin district, including large lakes and reservoirs,

— significant bodies of water cross a Member State boundary,

— sites are identified under the Information Exchange Decision 77/795/EEC, and

at such other sites as are required to estimate the pollutant load which is transferred across Member State boundaries, and which is transferred into the marine environment.

Selection of quality elements

Surveillance monitoring shall be carried out for each monitoring site for a period of one year during the period covered by a river basin management plan for:

— parameters indicative of all biological quality elements,

— parameters indicative of all hydromorphological quality elements,

— parameters indicative of all general physico-chemical quality elements,

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— priority list pollutants which are discharged into the river basin or sub-basin, and

— other pollutants discharged in significant quantities in the river basin or sub-basin,

unless the previous surveillance monitoring exercise showed that the body concerned reached good status and there is no evidence from the review of impact of human activity in Annex II that the impacts on the body have changed. In these cases, surveillance monitoring shall be carried out once every three river basin management plans.

1.3.2. Design of operational monitoring

Operational monitoring shall be undertaken in order to:

— establish the status of those bodies identified as being at risk of failing to meet their environmental objectives, and

— assess any changes in the status of such bodies resulting from the programmes of measures.

The programme may be amended during the period of the river basin management plan in the light of information obtained as part of the requirements of Annex II or as part of this Annex, in particular to allow a reduction in frequency where an impact is found not to be significant or the relevant pressure is removed.

Selection of monitoring sites

Operational monitoring shall be carried out for all those bodies of water which on the basis of either the impact assessment carried out in accordance with Annex II or surveillance monitoring are identified as being at risk of failing to meet their environmental objectives under Article 4 and for those bodies of water into which priority list substances are discharged. Monitoring points shall be selected for priority list substances as specified in the legislation laying down the relevant environmental quality standard. In all other cases, including for priority list substances where no specific guidance is given in such legislation, monitoring points shall be selected as follows:

— for bodies at risk from significant point source pressures, sufficient monitoring points within each body in order to assess the magnitude and impact of the point source. Where a body is subject to a number of point source pressures monitoring points may be selected to assess the magnitude and impact of these pressures as a whole,

— for bodies at risk from significant diffuse source pressures, sufficient monitoring points within a selection of the bodies in order to assess the magnitude and impact of the diffuse source pressures. The selection of bodies shall be made such that they are representative of the relative risks of the occurrence of the diffuse source pressures, and of the relative risks of the failure to achieve good surface water status,

— for bodies at risk from significant hydromorphological pressure, sufficient monitoring points within a selection of the bodies in order to assess the magnitude and impact of the hydromorphological pressures. The selection of bodies shall be indicative of the overall impact of the hydromorphological pressure to which all the bodies are subject.

Selection of quality elements

In order to assess the magnitude of the pressure to which bodies of surface water are subject Member States shall monitor for those quality elements which are indicative of the pressures to which the body or bodies are subject. In order to assess the impact of these pressures, Member States shall monitor as relevant:

— parameters indicative of the biological quality element, or elements, most sensitive to the pressures to which the water bodies are subject,

— all priority substances discharged, and other pollutants discharged in significant quantities,

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— parameters indicative of the hydromorphological quality element most sensitive to the pressure identified.

1.3.3. Design of investigative monitoring

Objective

Investigative monitoring shall be carried out:

— where the reason for any exceedances is unknown,

— where surveillance monitoring indicates that the objectives set out in Article 4 for a body of water are not likely to be achieved and operational monitoring has not already been established, in order to ascertain the causes of a water body or water bodies failing to achieve the environmental objectives, or

— to ascertain the magnitude and impacts of accidental pollution,

and shall inform the establishment of a programme of measures for the achievement of the environmental objectives and specific measures necessary to remedy the effects of accidental pollution.

1.3.4. Frequency of monitoring

For the surveillance monitoring period, the frequencies for monitoring parameters indicative of physico-chemical quality elements given below should be applied unless greater intervals would be justified on the basis of technical knowledge and expert judgement. For biological or hydromorphological quality elements monitoring shall be carried out at least once during the surveillance monitoring period.

For operational monitoring, the frequency of monitoring required for any parameter shall be determined by Member States so as to provide sufficient data for a reliable assessment of the status of the relevant quality element. As a guideline, monitoring should take place at intervals not exceeding those shown in the table below unless greater intervals would be justified on the basis of technical knowledge and expert judgement.

Frequencies shall be chosen so as to achieve an acceptable level of confidence and precision. Estimates of the confidence and precision attained by the monitoring system used shall be stated in the river basin management plan.

Monitoring frequencies shall be selected which take account of the variability in parameters resulting from both natural and anthropogenic conditions. The times at which monitoring is undertaken shall be selected so as to minimise the impact of seasonal variation on the results, and thus ensure that the results reflect changesin the water body as a result of changes due to anthropogenic pressure. Additional monitoring during different seasons of the same year shall be carried out, where necessary, to achieve this objective.

Quality element	Rivers	Lakes	Transitional	Coastal
Biological				
Phytoplankton	6 months	6 months	6 months	6 months
Other aquatic flora	3 years	3 years	3 years	3 years
Macro invertebrates	3 years	3 years	3 years	3 years
Fish	3 years	3 years	3 years	
Hydromorphological				
Continuity	6 years			
Hydrology	continuous	1 month		
Morphology	6 years	6 years	6 years	6 years

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Quality element	Rivers	Lakes	Transitional	Coastal
Physico-chemical				
Thermal conditions	3 months	3 months	3 months	3 months
Oxygenation	3 months	3 months	3 months	3 months
Salinity	3 months	3 months	3 months	
Nutrient status	3 months	3 months	3 months	3 months
Acidification status	3 months	3 months		
Other pollutants	3 months	3 months	3 months	3 months
Priority substances	1 month	1 month	1 month	1 month

1.3.5. Additional monitoring requirements for protected areas

The monitoring programmes required above shall be supplemented in order to fulfil the following requirements:

Drinking water abstraction points

Bodies of surface water designated in Article 7 which provide more than 100 m^3 a day as an average shall be designated as monitoring sites and shall be subject to such additional monitoring as may be necessary to meet the requirements of that Article. Such bodies shall be monitored for all priority substances discharged and all other substances discharged in significant quantities which could affect the status of the body of water and which are controlled under the provisions of the Drinking Water Directive. Monitoring shall be carried out in accordance with the frequencies set out below:

Community served	Frequency
<10 000	4 per year
10 000 to 30 000	8 per year
>30 000	12 per year.

Habitat and species protection areas

Bodies of water forming these areas shall be included within the operational monitoring programme referred to above where, on the basis of the impact assessment and the surveillance monitoring, they are identified as being at risk of failing to meet their environmental objectives under Article 4. Monitoring shall be carried out to assess the magnitude and impact of all relevant significant pressures on these bodies and, where necessary, to assess changes in the status of such bodies resulting from the programmes of measures. Monitoring shall continue until the areas satisfy the water-related requirements of the legislation under which they are designated and meet their objectives under Article 4.

1.3.6. Standards for monitoring of quality elements

Methods used for the monitoring of type parameters shall conform to the international standards listed below or such other national or international standards which will ensure the provision of data of an equivalent scientific quality and comparability.

Macroinvertebrate sampling

ISO 5667-3:1995	Water quality — Sampling — Part 3: Guidance on the preservation and handling of samples

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EN 27828:1994	Water quality — Methods for biological sampling — Guidance on hand net sampling of benthic macroinvertebrates
EN 28265:1994	Water quality — Methods of biological sampling — Guidance on the design and use of quantitative samplers for benthic macroinvertebrates on stony substrata in shallow waters
EN ISO 9391:1995	Water quality — Sampling in deep waters for macroinvertebrates — Guidance on the use of colonisation, qualitative and quantitative samplers
EN ISO 8689-1:1999	Biological classification of rivers PART I: Guidance on the interpretation of biological quality data from surveys of benthic macroinvertebrates in running waters
EN ISO 8689-2:1999	Biological classification of rivers PART II: Guidance on the presentation of biological quality data from surveys of benthic macroinvertebrates in running waters

Macrophyte sampling

Relevant CEN / ISO standards when developed

Fish sampling

Relevant CEN / ISO standards when developed

Diatom sampling

Relevant CEN/ISO standards when developed

Standards for physico-chemical parameters

Any relevant CEN/ISO standards

Standards for hydromorphological parameters

Any relevant CEN/ISO standards

1.4. **Classification and presentation of ecological status**

1.4.1. Comparability of biological monitoring results

(i) Member States shall establish monitoring systems for the purpose of estimating the values of the biological quality elements specified for each surface water category or for heavily modified and artificial bodies of surface water. In applying the procedure set out below to heavily modified or artificial water bodies, references to ecological status should be construed as references to ecological potential. Such systems may utilise particular species or groups of species which are representative of the quality element as a whole.

(ii) In order to ensure comparability of such monitoring systems, the results of the systems operated by each Member State shall be expressed as ecological quality ratios for the purposes of classification of ecological status. These ratios shall represent the relationship between the values of the biological parameters observed for a given body of surface water and the values for these parameters in the reference conditions applicable to that body. The ratio shall be expressed as a numerical value between zero and one, with high ecological status represented by values close to one and bad ecological status by values close to zero.

(iii) Each Member State shall divide the ecological quality ratio scale for their monitoring system for each surface water category into five classes ranging from high to bad ecological status, as defined in Section 1.2, by assigning a numerical value to each of the boundaries between the classes. The value for the boundary between the classes of

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high and good status, and the value for the boundary between good and moderate status shall be established through the intercalibration exercise described below.

(iv) The Commission shall facilitate this intercalibration exercise in order to ensure that these class boundaries are established consistent with the normative definitions in Section 1.2 and are comparable between Member States.

(v) As part of this exercise the Commission shall facilitate an exchange of information between Members States leading to the identification of a range of sites in each ecoregion in the Community; these sites will form an intercalibration network. The network shall consist of sites selected from a range of surface water body types present within each ecoregion. For each surface water body type selected, the network shall consist of at least two sites corresponding to the boundary between the normative definitions of high and good status, and at least two sites corresponding to the boundary between the normative definitions of good and moderate status. The sites shall be selected by expert judgement based on joint inspections and all other available information.

(vi) Each Member State monitoring system shall be applied to those sites in the intercalibration network which are both in the ecoregion and of a surface water body type to which the system will be applied pursuant to the requirements of this Directive. The results of this application shall be used to set the numerical values for the relevant class boundaries in each Member State monitoring system.

▼M2

(vii) The Commission shall prepare a draft register of sites to form the intercalibration network. The final register of sites shall be established in accordance with the regulatory procedure referred to in Article 21(2).

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(viii) The Commission and Member States shall complete the intercalibration exercise within 18 months of the date on which the finalised register is published.

▼M2

(ix) The results of the intercalibration exercise and the values established for the Member State monitoring system classifications in accordance with points (i) to (viii) and designed to amend non-essential elements of this Directive by supplementing it, shall be adopted in accordance with the regulatory procedure with scrutiny referred to in Article 21(3) and published within six months of the completion of the intercalibration exercise.

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1.4.2. Presentation of monitoring results and classification of ecological status and ecological potential

(i) For surface water categories, the ecological status classification for the body of water shall be represented by the lower of the values for the biological and physico-chemical monitoring results for the relevant quality elements classified in accordance with the first column of the table set out below. Member States shall provide a map for each river basin district illustrating the classification of the ecological status foreach body of water, colour-coded in accordance with the second column of the table set out below to reflect the ecological status classification of the body of water:

Ecological status classification	Colour code
High	Blue
Good	Green

▼B

Ecological status classification	Colour code
Moderate	Yellow
Poor	Orange
Bad	Red

(ii) For heavily modified and artificial water bodies, the ecological potential classification for the body of water shall be represented by the lower of the values for the biological and physico-chemical monitoring results for the relevant quality elements classified in accordance with the first column of the table set out below. Member States shall provide a map for each river basin district illustrating the classification of the ecological potential for each body of water, colour-coded, in respect of artificial water bodies in accordance with the second column of the table set out below, and in respect of heavily modified water bodies in accordance with the third column of that table:

Ecological potential classification	Colour code	
	Artificial Water Bodies	Heavily Modified
Good and above	Equal green and light grey stripes	Equal green and dark grey stripes
Moderate	Equal yellow and light grey stripes	Equal yellow and dark grey stripes
Poor	Equal orange and light grey stripes	Equal orange and dark grey stripes
Bad	Equal red and light grey stripes	Equal red and dark grey stripes

(iii) Member States shall also indicate, by a black dot on the map, those bodies of water where failure to achieve good status or good ecological potential is due to non-compliance with one or more environmental quality standards which have been established for that body of water in respect of specific synthetic and non-synthetic pollutants (in accordance with the compliance regime established by the Member State).

1.4.3. Presentation of monitoring results and classification of chemical status

Where a body of water achieves compliance with all the environmental quality standards established in Annex IX, Article 16 and under other relevant Community legislation setting environmental quality standards it shall be recorded as achieving good chemical status. If not, the body shall be recorded as failing to achieve good chemical status.

Member States shall provide a map for each river basin district illustrating chemical status for each body of water, colour-coded in accordance with the second column of the table set out below to reflect the chemical status classification of the body of water:

Chemical status classification	Colour code
Good	Blue
Failing to achieve good	Red

▼B

2. GROUNDWATER

2.1. **Groundwater quantitative status**

2.1.1. Parameter for the classification of quantitative status

Groundwater level regime

2.1.2. Definition of quantitative status

Elements	Good status
Groundwater level	The level of groundwater in the groundwater body is such that the available groundwater resource is not exceeded by the long-term annual average rate of abstraction. Accordingly, the level of groundwater is not subject to anthropogenic alterations such as would result in: — failure to achieve the environmental objectives specified under Article 4 for associated surface waters, — any significant diminution in the status of such waters, — any significant damage to terrestrial ecosystems which depend directly on the groundwater body, and alterations to flow direction resulting from level changes may occur temporarily, or continuously in a spatially limited area, but such reversals do not cause saltwater or other intrusion, and do not indicate a sustained and clearly identified anthropogenically induced trend in flow direction likely to result in such intrusions.

2.2. **Monitoring of groundwater quantitative status**

2.2.1. *Groundwater level monitoring network*

The groundwater monitoring network shall be established in accordance with the requirements of Articles 7 and 8. The monitoring network shall be designed so as to provide a reliable assessment of the quantitative status of all groundwater bodies or groups of bodies including assessment of the available groundwater resource. Member States shall provide a map or maps showing the groundwater monitoring network in the river basin management plan.

2.2.2. Density of monitoring sites

The network shall include sufficient representative monitoring points to estimate the groundwater level in each groundwater body or group of bodies taking into account short and long-term variations in recharge and in particular:

— for groundwater bodies identified as being at risk of failing to achieve environmental objectives under Article 4, ensure sufficient density of monitoring points to assess the impact of abstractions and discharges on the groundwater level,

— for groundwater bodies within which groundwater flows across a Member State boundary, ensure sufficient monitoring points are provided to estimate the direction and rate of groundwater flow across the Member State boundary.

2.2.3. Monitoring frequency

The frequency of observations shall be sufficient to allow assessment of the quantitative status of each groundwater body or group of bodies taking into account short and long-term variations in recharge. In particular:

— for groundwater bodies identified as being at risk of failing to achieve environmental objectives under Article 4, ensure

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sufficient frequency of measurement to assess the impact of abstractions and discharges on the groundwater level,

— for groundwater bodies within which groundwater flows across a Member State boundary, ensure sufficient frequency of measurement to estimate the direction and rate of groundwater flow across the Member State boundary.

2.2.4. Interpretation and presentation of groundwater quantitative status

The results obtained from the monitoring network for a groundwater body or group of bodies shall be used to assess the quantitative status of that body or those bodies. Subject to point 2.5. Member States shall provide a map of the resulting assessment of groundwater quantitative status, colour-coded in accordance with the following regime:

Good: green

Poor: red

2.3. **Groundwater chemical status**

2.3.1. Parameters for the determination of groundwater chemical status

Conductivity

Concentrations of pollutants

2.3.2. Definition of good groundwater chemical status

Elements	Good status
General	The chemical composition of the groundwater body is such that the concentrations of pollutants: — as specified below, do not exhibit the effects of saline or other intrusions — do not exceed the quality standards applicable under other relevant Community legislation in accordance with Article 17 — are not such as would result in failure to achieve the environmental objectives specified under Article 4 for associated surface waters nor any significant diminution of the ecological or chemical quality of such bodies nor in any significant damage to terrestrial ecosystems which depend directly on the groundwater body
Conductivity	Changes in conductivity are not indicative of saline or other intrusion into the groundwater body

2.4. **Monitoring of groundwater chemical status**

2.4.1. Groundwater monitoring network

The groundwater monitoring network shall be established in accordance with the requirements of Articles 7 and 8. The monitoring network shall be designed so as to provide a coherent and comprehensive overview of groundwater chemical status within each river basin and to detect the presence of long-term anthropogenically induced upward trends in pollutants.

On the basis of the characterisation and impact assessment carried out in accordance with Article 5 and Annex II, Member States shall for each period to which a river basin management plan applies, establish a surveillance monitoring programme. The results of this programme shall be used to establish an operational monitoring programme to be applied for the remaining period of the plan.

Estimates of the level of confidence and precision of the results provided by the monitoring programmes shall be given in the plan.

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2.4.2. Surveillance monitoring

Objective

Surveillance monitoring shall be carried out in order to:

— supplement and validate the impact assessment procedure,

— provide information for use in the assessment of long term trends both as a result of changes in natural conditions and through anthropogenic activity.

Selection of monitoring sites

Sufficient monitoring sites shall be selected for each of the following:

— bodies identified as being at risk following the characterisation exercise undertaken in accordance with Annex II,

— bodies which cross a Member State boundary.

Selection of parameters

The following set of core parameters shall be monitored in all the selected groundwater bodies:

— oxygen content

— pH value

— conductivity

— nitrate

— ammonium

Bodies which are identified in accordance with Annex II as being at significant risk of failing to achieve good status shall also be monitored for those parameters which are indicative of the impact of these pressures.

Transboundary water bodies shall also be monitored for those parameters which are relevant for the protection of all of the uses supported by the groundwater flow.

2.4.3. Operational monitoring

Objective

Operational monitoring shall be undertaken in the periods between surveillance monitoring programmes in order to:

— establish the chemical status of all groundwater bodies or groups of bodies determined as being at risk,

— establish the presence of any long term anthropogenically induced upward trend in the concentration of any pollutant.

Selection of monitoring sites

Operational monitoring shall be carried out for all those groundwater bodies or groups of bodies which on the basis of both the impact assessment carried out in accordance with Annex II and surveillance monitoring are identified as being at risk of failing to meet objectives under Article 4. The selection of monitoring sites shall also reflect an assessment of how representative monitoring data from that site is of the quality of the relevant groundwater body or bodies.

Frequency of monitoring

Operational monitoring shall be carried out for the periods between surveillance monitoring programmes at a frequency sufficient to detect the impacts of relevant pressures but at a minimum of once per annum.

2.4.4. Identification of trends in pollutants

Member States shall use data from both surveillance and operational monitoring in the identification of long term anthropogenically induced upward trends in pollutant concentrations and the reversal of such trends. The base year or period from which trend identification is to be calculated shall be identified. The calculation of

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trends shall be undertaken for a body or, where appropriate, group of bodies of groundwater. Reversal of a trend shall be demonstrated statistically and the level of confidence associated with the identification stated.

2.4.5. Interpretation and presentation of groundwater chemical status

In assessing status, the results of individual monitoring points within a groundwater body shall be aggregated for the body as a whole. Without prejudice to the Directives concerned, for good status to be achieved for a groundwater body, for those chemical parameters for which environmental quality standards have been set in Community legislation:

— the mean value of the results of monitoring at each point in the groundwater body or group of bodies shall be calculated, and

— in accordance with Article 17 these mean values shall be used to demonstrate compliance with good groundwater chemical status.

Subject to point 2.5, Member States shall provide a map of groundwater chemical status, colour-coded as indicated below:

Good: green

Poor: red

Member States shall also indicate by a black dot on the map, those groundwater bodies which are subject to a significant and sustained upward trend in the concentrations of any pollutant resulting from the impact of human activity. Reversal of a trend shall be indicated by a blue dot on the map.

These maps shall be included in the river basin management plan.

2.5. **Presentation of Groundwater Status**

Member States shall provide in the river basin management plan a map showing for each groundwater body or groups of groundwater bodies both the quantitative status and the chemical status of that body or group of bodies, colour-coded in accordance with the requirements of points 2.2.4 and 2.4.5. Member States may choose not to provide separate maps under points 2.2.4 and 2.4.5 but shall in that case also provide an indication in accordance with the requirements of point 2.4.5 on the map required under this point, of those bodies which are subject to a significant and sustained upward trend in the concentration of any pollutant or any reversal in such a trend.

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ANNEX VI

LISTS OF MEASURES TO BE INCLUDED WITHIN THE PROGRAMMES OF MEASURES

PART A

Measures required under the following Directives:

(i) The Bathing Water Directive (76/160/EEC);

(ii) The Birds Directive (79/409/EEC) ([1]);

(iii) The Drinking Water Directive (80/778/EEC) as amended by Directive (98/83/EC);

(iv) The Major Accidents (Seveso) Directive (96/82/EC) ([2]);

(v) The Environmental Impact Assessment Directive (85/337/EEC) ([3]);

(vi) The Sewage Sludge Directive (86/278/EEC) ([4]);

(vii) The Urban Waste-water Treatment Directive (91/271/EEC);

(viii) The Plant Protection Products Directive (91/414/EEC);

(ix) The Nitrates Directive (91/676/EEC);

(x) The Habitats Directive (92/43/EEC) ([5]);

(xi) The Integrated Pollution Prevention Control Directive (96/61/EC).

PART B

The following is a non-exclusive list of supplementary measures which Member States within each river basin district may choose to adopt as part of the programme of measures required under Article 11(4):

(i) legislative instruments

(ii) administrative instruments

(iii) economic or fiscal instruments

(iv) negotiated environmental agreements

(v) emission controls

(vi) codes of good practice

(vii) recreation and restoration of wetlands areas

(viii) abstraction controls

(ix) demand management measures, *inter alia*, promotion of adapted agricultural production such as low water requiring crops in areas affected by drought

(x) efficiency and reuse measures, *inter alia*, promotion of water-efficient technologies in industry and water-saving irrigation techniques

(xi) construction projects

(xii) desalination plants

(xiii) rehabilitation projects

(xiv) artificial recharge of aquifers

(xv) educational projects

(xvi) research, development and demonstration projects

(xvii) other relevant measures

([1]) OJ L 103, 25.4.1979, p. 1.
([2]) OJ L 10, 14.1.1997, p. 13.
([3]) OJ L 175, 5.7.1985, p. 40. Directive as amended by Directive 97/11/EC (OJ L 73, 14.3.1997, p. 5).
([4]) OJ L 181, 8.7.1986, p. 6.
([5]) OJ L 206, 22.7.1992, p. 7.

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ANNEX VII

RIVER BASIN MANAGEMENT PLANS

A. River basin management plans shall cover the following elements:

1. a general description of the characteristics of the river basin district required under Article 5 and Annex II. This shall include:

1.1. for surface waters:

— mapping of the location and boundaries of water bodies,

— mapping of the ecoregions and surface water body types within the river basin,

— identification of reference conditions for the surface water body types;

1.2. for groundwaters:

— mapping of the location and boundaries of groundwater bodies;

2. a summary of significant pressures and impact of human activity on the status of surface water and groundwater, including:

— estimation of point source pollution,

— estimation of diffuse source pollution, including a summary of land use,

— estimation of pressures on the quantitative status of water including abstractions,

— analysis of other impacts of human activity on the status of water;

3. identification and mapping of protected areas as required by Article 6 and Annex IV;

4. a map of the monitoring networks established for the purposes of Article 8 and Annex V, and a presentation in map form of the results of the monitoring programmes carried out under those provisions for the status of:

4.1. surface water (ecological and chemical);

4.2. groundwater (chemical and quantitative);

4.3. protected areas;

5. a list of the environmental objectives established under Article 4 for surface waters, groundwaters and protected areas, including in particular identification of instances where use has been made of Article 4(4), (5), (6) and (7), and the associated information required under that Article;

6. a summary of the economic analysis of water use as required by Article 5 and Annex III;

7. a summary of the programme or programmes of measures adopted under Article 11, including the ways in which the objectives established under Article 4 are thereby to be achieved;

7.1. a summary of the measures required to implement Community legislation for the protection of water;

7.2. a report on the practical steps and measures taken to apply the principle of recovery of the costs of water use in accordance with Article 9;

7.3. a summary of the measures taken to meet the requirements of Article 7;

7.4. a summary of the controls on abstraction and impoundment of water, including reference to the registers and identifications of the cases where exemptions have been made under Article 11(3)(e);

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7.5. a summary of the controls adopted for point source discharges and other activities with an impact on the status of water in accordance with the provisions of Article 11(3)(g) and 11(3)(i);

7.6. an identification of the cases where direct discharges to groundwater have been authorised in accordance with the provisions of Article 11(3)(j);

7.7. a summary of the measures taken in accordance with Article 16 on priority substances;

7.8. a summary of the measures taken to prevent or reduce the impact of accidental pollution incidents;

7.9. a summary of the measures taken under Article 11(5) for bodies of water which are unlikely to achieve the objectives set out under Article 4;

7.10. details of the supplementary measures identified as necessary in order to meet the environmental objectives established;

7.11. details of the measures taken to avoid increase in pollution of marine waters in accordance with Article 11(6);

8. a register of any more detailed programmes and management plans for the river basin district dealing with particular sub-basins, sectors, issues or water types, together with a summary of their contents;

9. a summary of the public information and consultation measures taken, their results and the changes to the plan made as a consequence;

10. a list of competent authorities in accordance with Annex I;

11. the contact points and procedures for obtaining the background documentation and information referred to in Article 14(1), and in particular details of the control measures adopted in accordance with Article 11(3)(g) and 11(3)(i) and of the actual monitoring data gathered in accordance with Article 8 and Annex V.

B. The first update of the river basin management plan and all subsequent updates shall also include:

1. a summary of any changes or updates since the publication of the previous version of the river basin management plan, including a summary of the reviews to be carried out under Article 4(4), (5), (6) and (7);

2. an assessment of the progress made towards the achievement of the environmental objectives, including presentation of the monitoring results for the period of the previous plan in map form, and an explanation for any environmental objectives which have not been reached;

3. a summary of, and an explanation for, any measures foreseen in the earlier version of the river basin management plan which have not been undertaken;

4. a summary of any additional interim measures adopted under Article 11(5) since the publication of the previous version of the river basin management plan.

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ANNEX VIII

INDICATIVE LIST OF THE MAIN POLLUTANTS

1. Organohalogen compounds and substances which may form such compounds in the aquatic environment.
2. Organophosphorous compounds.
3. Organotin compounds.
4. Substances and preparations, or the breakdown products of such, which have been proved to possess carcinogenic or mutagenic properties or properties which may affect steroidogenic, thyroid, reproduction or other endocrine-related functions in or via the aquatic environment.
5. Persistent hydrocarbons and persistent and bioaccumulable organic toxic substances.
6. Cyanides.
7. Metals and their compounds.
8. Arsenic and its compounds.
9. Biocides and plant protection products.
10. Materials in suspension.
11. Substances which contribute to eutrophication (in particular, nitrates and phosphates).
12. Substances which have an unfavourable influence on the oxygen balance (and can be measured using parameters such as BOD, COD, etc.).

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ANNEX IX

EMISSION LIMIT VALUES AND ENVIRONMENTAL QUALITY STANDARDS

The 'limit values' and 'quality objectives' established under the re Directives of Directive 76/464/EEC shall be considered emission limit values and environmental quality standards, respectively, for the purposes of this Directive. They are established in the following Directives:

(i) The Mercury Discharges Directive (82/176/EEC) ([1]);

(ii) The Cadmium Discharges Directive (83/513/EEC) ([2]);

(iii) The Mercury Directive (84/156/EEC) ([3]);

(iv) The Hexachlorocyclohexane Discharges Directive (84/491/EEC) ([4]); and

(v) The Dangerous Substance Discharges Directive (86/280/EEC) ([5]).

([1]) OJ L 81, 27.3.1982, p. 29.
([2]) OJ L 291, 24.10.1983, p. 1.
([3]) OJ L 74, 17.3.1984, p. 49.
([4]) OJ L 274, 17.10.1984, p. 11.
([5]) OJ L 181, 4.7.1986, p. 16.

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ANNEX X

LIST OF PRIORITY SUBSTANCES IN THE FIELD OF WATER POLICY

Number	CAS number [1]	EU number [2]	Name of priority substance [3]	Identified as priority hazardous substance
(1)	15972-60-8	240-110-8	Alachlor	
(2)	120-12-7	204-371-1	Anthracene	X
(3)	1912-24-9	217-617-8	Atrazine	
(4)	71-43-2	200-753-7	Benzene	
(5)	not applicable	not applicable	Brominated diphenylether [4]	X [5]
	32534-81-9	not applicable	Pentabromodiphenylether (congener numbers 28, 47, 99, 100, 153 and 154)	
(6)	7440-43-9	231-152-8	Cadmium and its compounds	X
(7)	85535-84-8	287-476-5	Chloroalkanes, C_{10-13} [4]	X
(8)	470-90-6	207-432-0	Chlorfenvinphos	
(9)	2921-88-2	220-864-4	Chlorpyrifos (Chlorpyrifos-ethyl)	
(10)	107-06-2	203-458-1	1,2-dichloroethane	
(11)	75-09-2	200-838-9	Dichloromethane	
(12)	117-81-7	204-211-0	Di(2-ethylhexyl)phthalate (DEHP)	
(13)	330-54-1	206-354-4	Diuron	
(14)	115-29-7	204-079-4	Endosulfan	X
(15)	206-44-0	205-912-4	Fluoranthene [6]	
(16)	118-74-1	204-273-9	Hexachlorobenzene	X
(17)	87-68-3	201-765-5	Hexachlorobutadiene	X
(18)	608-73-1	210-158-9	Hexachlorocyclohexane	X
(19)	34123-59-6	251-835-4	Isoproturon	
(20)	7439-92-1	231-100-4	Lead and its compounds	
(21)	7439-97-6	231-106-7	Mercury and its compounds	X
(22)	91-20-3	202-049-5	Naphthalene	
(23)	7440-02-0	231-111-14	Nickel and its compounds	
(24)	25154-52-3	246-672-0	Nonylphenol	X
	104-40-5	203-199-4	(4-nonylphenol)	X
(25)	1806-26-4	217-302-5	Octylphenol	
	140-66-9	not applicable	(4-(1,1′,3,3′-tetramethylbutyl)-phenol)	
(26)	608-93-5	210-172-5	Pentachlorobenzene	X
(27)	87-86-5	231-152-8	Pentachlorophenol	
(28)	not applicable	not applicable	Polyaromatic hydrocarbons	X
	50-32-8	200-028-5	(Benzo(a)pyrene)	X
	205-99-2	205-911-9	(Benzo(b)fluoranthene)	X
	191-24-2	205-883-8	(Benzo(g,h,i)perylene)	X
	207-08-9	205-916-6	(Benzo(k)fluoranthene)	X
	193-39-5	205-893-2	(Indeno(1,2,3-cd)pyrene)	X
(29)	122-34-9	204-535-2	Simazine	

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Number	CAS number (1)	EU number (2)	Name of priority substance (3)	Identified as priority hazardous substance
(30)	not applicable	not applicable	Tributyltin compounds	X
	36643-28-4	not applicable	(Tributyltin-cation)	X
(31)	12002-48-1	234-413-4	Trichlorobenzenes	
(32)	67-66-3	200-663-8	Trichloromethane (chloroform)	
(33)	1582-09-8	216-428-8	Trifluralin	

(1) CAS: Chemical Abstracts Service.

(2) EU number: European Inventory of Existing Commercial Substances (Einecs) or European List of Notified Chemical Substances (Elincs).

(3) Where groups of substances have been selected, typical individual representatives are listed as indicative parameters (in brackets and without number). For these groups of substances, the indicative parameter must be defined through the analytical method.

(4) These groups of substances normally include a considerable number of individual compounds. At present, appropriate indicative parameters cannot be given.

(5) Only Pentabromobiphenylether (CAS-number 32534-81-9).

(6) Fluoranthene is on the list as an indicator of other, more dangerous polyaromatic hydrocarbons.

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ANNEX XI

MAP A

System A: Ecoregions for rivers and lakes

1. Iberic-Macaronesian region
2. Pyrenees
3. Italy, Corsica and Malta
4. Alps
5. Dinaric western Balkan
6. Hellenic western Balkan
7. Eastern Balkan
8. Western highlands
9. Central highlands
10. The Carpathians
11. Hungarian lowlands
12. Pontic province
13. Western plains
14. Central plains
15. Baltic province
16. Eastern plains
17. Ireland and Northern Ireland
18. Great Britain
19. Iceland

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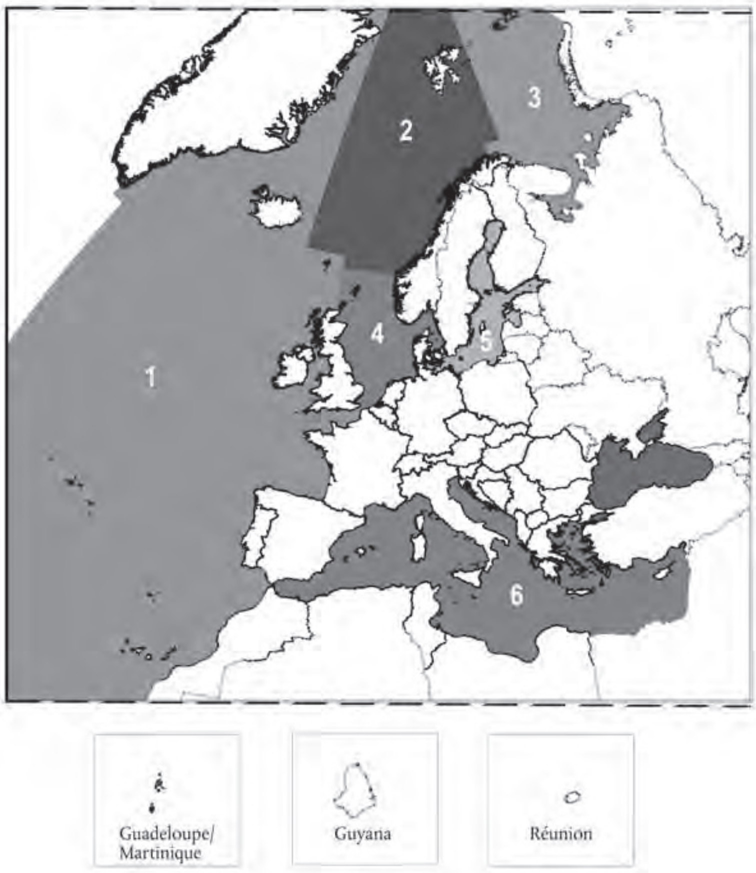
20. Borealic uplands
21. Tundra
22. Fenno-Scandian shield
23. Taiga
24. The Caucasus
25. Caspic depression

▼B

MAP B

System A: Ecoregions for transitional waters and coastal waters



1. Atlantic Ocean
2. Norwegian Sea
3. Barents Sea
4. North Sea
5. Baltic Sea
6. Mediterranean Sea

Appendix B

DPSIR

EEA internal working paper

Environmental Indicators: Typology and Use in Reporting

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August 2003

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European Environment Agency

Contents

1. Introduction

A wide variety of environmental indicators is presently in use. These indicators reflect trends in the environment and monitor the progress made in realising environmental policy targets. As such, environmental indicators have become indispensable to policy-makers.

However, it is becoming more and more difficult for policy-makers to grasp the relevance and meaning of the existing environmental indicators, given the number and diversity of indicators presently in use. Moreover, new sets of environmental indicators are still being developed. Therefore, some means of structuring and analysing indicators and related environment/society inter-connections is needed.

The purpose of this report is to introduce the DPSIR framework (Driving forces, Pressure, State, Impact, and Response) and the 'Typology of Indicators' used by the European Environment Agency (EEA) in its reporting activities. The current report is an update of Technical report No 25 published in 1999. A main change compared with the previous version is the introduction of a category of "policy effectiveness indicators", which in itself marks the increased attention for the analysis of the developments depicted by the indicators.

The line of reasoning already present in the previous edition, that posing the right questions must precede selection of indicators, is elaborated in Chapter 5 of the current report which describes the process of indicator-based reporting.

This report still focuses purely on environmental indicators. It is envisaged that the next update of this typology report will cover the sustainable development context of environmental indicators, including a discussion on the global context of the DPSIR model.

We hope that the current paper will be useful to the EEA and all cooperating institutes in the EIONET by defining common standards for indicator reports. If we succeed in communicating a well-structured message to the users of our information through our reports and presentations, and if these users in return take relevant actions based on environmental indicators, then this report will have fulfilled its purpose.

2. Why do we need environmental indicators?

Communication is the main function of indicators: they should enable or promote information exchange regarding the issue they address. Our body temperature is an example of an indicator we use regularly. It provides critical information on our physical condition. Likewise, environmental indicators provide information on phenomena that are regarded typical for and/or critical to environmental quality. The abundance of Black Terns in a certain area and the total volume of substances emitted by industry over a certain period are only two of the numerous indicators that enable communication on environmental issues.

Communication demands simplicity. Indicators always simplify a complex reality. They focus on certain aspects, which are regarded as relevant and on which data are available. But their significance goes beyond that obtained directly from the observed properties. To know the number of Black Terns in a certain area may be satisfying in itself. It may be more relevant to compare the number in this specific area with the abundance of Black Terns in a similar, but less disturbed area. Then, the real significance is in the message the abundance of these birds conveys regarding environmental quality in that specific area. Environmental indicators communicate those aspects regarded as critical or typical for the complex interrelations between natural species and abiotic components of the environmental system.

In relation to policy-making, environmental indicators are used for four major purposes:

1. To supply information on environmental problems, in order to enable policy-makers to evaluate their seriousness;
2. To support policy development and priority setting, by identifying key factors that cause pressure on the environment;
3. To monitor the effects and effectiveness of policy responses, and
4. To raise public awareness on environmental issues. Providing information on driving forces, impacts and policy responses is a common strategy to strengthen public support for policy measures.

Box 2.1. What is an indicator?

An indicator is an observed value representative of a phenomenon of study. In general, indicators quantify information by aggregating different and multiple data. The resulting information is therefore synthesised. In short, indicators simplify information that can help to reveal complex phenomena.

Box 2.2. What is a good indicator?

An indicator that communicates in a sound way a simplified reality should:

- match the interest of the target audience;
- be attractive to the eye and accessible;
- be easy to interpret;
- invite action (read further, investigate, ask questions, do something);
- be representative of the issue or area being considered;
- show developments over a relevant time interval (a period in which changes can be shown;
- go with a reference value for comparing changes over time;
- go with an explanation of causes behind the trends;
- be comparable with other indicators that describe similar areas, sectors or activities;
- be scientifically well-founded; and
- be based on sound statistics.

3. Analytical framework

The analytical framework used for an assessment helps to determine the variety of indicators that are chosen to communicate the outcomes of that assessment. For its assessments of the relations between human activities and the environment, EEA uses an extended version of the well known OECD-model, which is called the Driving forces - Pressures - State - Impact - Responses (**DPSIR**) framework (see figure 3.1).

According to this systems analysis view, social and economic developments exert *pressure* on the environment and, as a consequence, the *state* of the environment changes. This leads to *impacts* on e.g. human health, ecosystems and materials that may elicit a societal *response* that feeds back on the *driving forces*, on the pressures or on the state or impacts directly, through adaptation or curative action. This model describes a dynamic situation, with attention for the various feedbacks in the system. By their nature, indicators take a snapshot picture of a constantly changing system, while the assessments that accompany the indicators can highlight the dynamic relations.

Most sets of indicators presently used by nations and international bodies are based on this DPSIR-framework or a subset of it. These sets are used to characterize the main environmental issues, such as climate change, acidification, toxic contamination and wastes in relation to the geographical levels at which these issues manifest themselves or are on which they are managed. In designing indicators for each of these problems on every geographic scale, the simplicity of the DPSIR framework is its strength: the principles are very easy to communicate. However, a simple concept needs to be applied where it can be applied, but not overstretched.

3.1. A short history of DPSIR

In describing environmental issues, environmental indicators often follow a causality chain. The first indicator framework commonly known is the Stress-Response framework developed by two scientists working at Statistics Canada, Anthony Friend and David Rapport (Rapport and Friend, 1979). Their STRESS framework was based on ecosystem behaviour: they distinguished: environmental stress (pressures on the ecosystem), the state of the ecosystem, and the (eco)system response. For the latter, one could think of, for instance, algae blooms in reaction to the higher availability of nutrients. The original ideas, however, encompassed all kinds of ecosystem and societal responses.

When the STRESS framework was presented to OECD, the ecosystem response was removed in order to make the concept suitable for the approach used by OECD. The rephrasing of "response" to mean societal response only, led to the OECD Pressure State Response (PSR) model (OECD, 1991). Pressures were all releases or abstractions by human activities of substances, radiation and other physical disturbances, and species in or from the environment. State was in the beginning limited to the concentrations of substances and distribution of species.

Because environmental statisticians dealt not only with data on pressures, state and responses, but also with their origins in economic activities, at various statistical offices an early DPSIR model came into use as an organising principle for environment statistics in the early 90s. This framework described: Human activities, Pressures, State of the environment, Impacts on ecosystems, human health and materials, and Responses. The Dobris report (EEA, 1995) also built on this idea.

With the development of the large environmental models such as RAINS and IMAGE by IIASA and RIVM, the DPSIR model became further formalised, with a more precise differentiation between driving forces, pressures, the resulting state of systems, the impacts (among others on the economy) and policy responses. The EEA helped to make this final DPSIR framework more widely known in Europe. The report “A general strategy for Integrated Environmental Assessment at EEA” (1995), which was accepted by the EEA Management Board as the basic document for the development of integrated environmental assessment, made DPSIR the main framework for EEA assessments and related activities.

During these twenty years of history, the framework has developed from a tool to describe natural ecosystems under stress to a framework for describing human - environment interactions and the related information flows. At the same time the need to define the categories precisely and consistently has grown, which is the main purpose of the next section.

As already noted in the introduction, the current DPSIR model is an evolving model. For example, practitioners in environment and health indicators have added additional steps to give DPSEEA, with: Exposure, Effect and Action as the last steps.

3.2. The DPSIR framework in detail

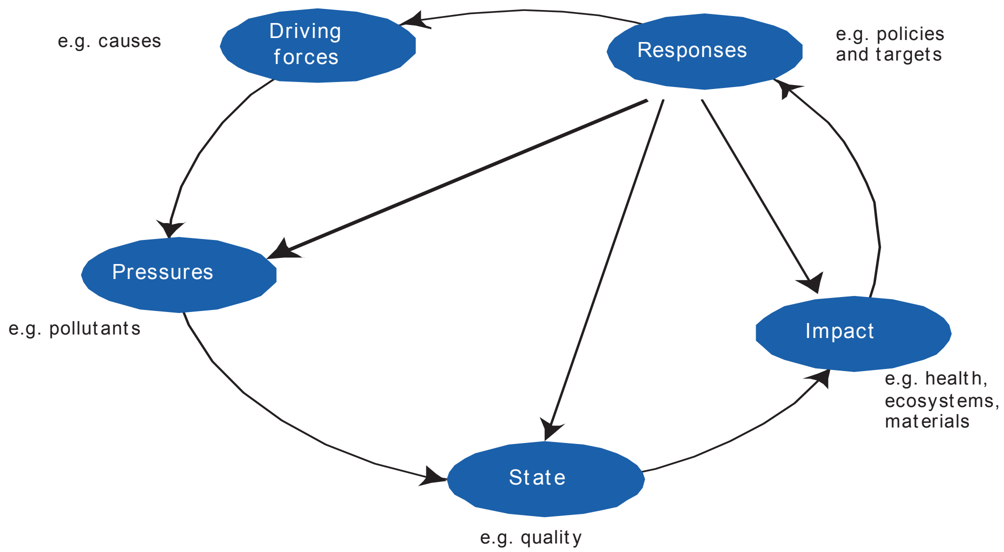
From a policy point of view, there is a need for clear and specific information on:

(i) *Driving forces* and
(ii) The resulting environmental *Pressures*, on
(iii) The *State* of the environment and the
(iv) *Impacts* resulting from changes in environmental quality and on
(v) The societal *Responses* to these changes in the environment.

Although the information needs of policy-makers may be rather wide, including statistics, background information, and summaries, the focus here is on indicators to communicate the most relevant features of the environment and other issues included in the assessments and policy analyses.

In order to meet this need, environmental indicators should reflect all elements of the chain between human activities, their environmental impacts, and the societal responses to these impacts (fig 3.1).

Figure 3.1. *The DPSIR framework for reporting on environmental issues*



Indicators for *Driving forces* describe the social, demographic and economic developments in societies and the corresponding changes in lifestyles, overall levels of consumption and production patterns. Primary driving forces are population growth and developments in the needs and activities of individuals. These primary driving forces provoke changes in the overall levels of production and consumption. Through these changes in production and consumption, the driving forces exert pressure on the environment.

Pressure indicators describe developments in release of substances (emissions), physical and biological agents, the use of resources and the use of land by human activities. The pressures exerted by society are transported and transformed in a variety of natural processes to manifest themselves in changes in environmental conditions. Examples of pressure indicators are CO_2-emissions per sector, the use of rock, gravel and sand for construction and the amount of land used for roads.

State indicators give a description of the quantity and quality of physical phenomena (such as temperature), biological phenomena (such as fish stocks) and chemical phenomena (such as atmospheric CO_2-concentrations) in a certain area. State indicators may, for instance, describe the forest and wildlife resources present, the concentration of phosphorus and sulphur in lakes, or the level of noise in the neighbourhood of airports.

Due to pressure on the environment, the state of the environment changes. These changes then have impacts on the functions of the environment, such as human and ecosystem health, resources availability, losses of manufactured capital, and biodiversity. *Impact* indicators are used to describe changes in these conditions. Although effects of human change in the environment occur in a sequence: air pollution may cause changes in the radiation balance (primary effect but still a state indicator), which may in turn cause an increase in temperature (secondary effect, also a state indicator), which may provoke a rise of sea level (tertiary effect, but still a state of the environment), it is only the last step: loss of terrestrial biodiversity, that should be called the impact indicator. It is the change in the availability of species that influences human use of the environment. In the strict definition impacts are only those parameters that directly reflect changes in environmental use functions by humans. As humans are a part of the environment, impacts also include health impacts.

Response indicators refer to responses by groups (and individuals) in society, as well as government attempts to prevent, compensate, ameliorate or adapt to changes in the state of the environment. Some societal responses may be regarded as negative driving forces, since they aim at redirecting prevailing trends in consumption and production patterns. Other responses aim at raising the efficiency of products and processes, through stimulating the development and penetration of clean technologies. Examples of response indicators are the relative amount of cars with catalytic converters and recycling rates of domestic waste. An often used 'overall' response indicator is an indicator describing environmental expenditures.

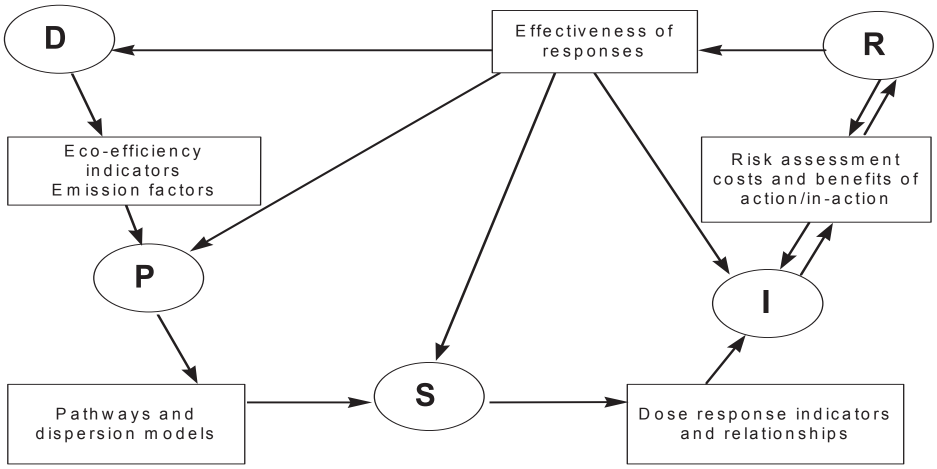
Although it is tempting to look at the DPSIR framework as a descriptive analysis with a specific focus on individual elements in the economic, social and environmental system, it is the relationships between the elements that introduce the dynamics into the framework and bring about changes. A focus *on the links between* the DPSIR elements reveals a number of processes and indicators describing these (see figure 3.2):

- Eco-efficiency indicators such as 'energy productivity' (or its inverse 'energy intensity') help determine the relationship between the driving forces and pressures. Increasing eco-efficiency means that economic activities can expand without an equivalent increase in pressure on the environment. This kind of information contributes to answering the question: are we making technological progress?
- The relationship between the pressure indicator: 'release of nutrients from agriculture' and the state indicator: 'development of nitrate concentration in surface waters' is mainly determined by the pathways and dispersion patterns of the nutrients. The combination of these indicators tells a story of time delay in natural processes and the 'time bombs' created in the environment. Knowledge of dispersion patterns can be useful to model current and future changes in the state of the environment and in impacts.
- Similarly, dose/response relationships determine the impacts of a certain state of the environment. 'Respiratory diseases in children' are through such a relationship linked to 'concentrations of sulphur and nitrogen dioxides'. Knowledge of dose/response relationships can be used to predict or quantify the health impacts of air pollution, or help in choosing the most appropriate state indicator to act as an early warning.
- The relationship between environmental impacts and societal responses such as taxes and regulation is often governed by societal perception that the impacts are serious, and this often requires data on the economic costs of the impact.
- Policy-effectiveness indicators generally summarise the relations between the response and targets for expected change in driving forces or pressures and sometimes in responses, state or even impacts. In general there is little information available on the effectiveness of environmental measures (EEA, 2001a).

The strength of these "in-between" indicators is that they express, more than other indicators, the dynamics of the interactions in the DPSIR system. Sometimes the information can be used in predictions of future changes in pressures, states, impacts, and responses.

The existence of these interrelations also shows that the DPSIR framework, although often presented as a linear chain or a circle, in fact resembles a very complex web of many interacting factors some of which may represent highly non-linear dynamics. In many cases the change in the state of the environment or impacts has several causes, some of which may be immediate and of local origin, others may be exerting their influence on a continental or even global scale. Reductions in pressures often result from a mixture of policy responses and changes in various driving forces.

Figure 3.2. Indicators and information linking DPSIR elements



3.3 Indicators and their relevance to the policy life cycle

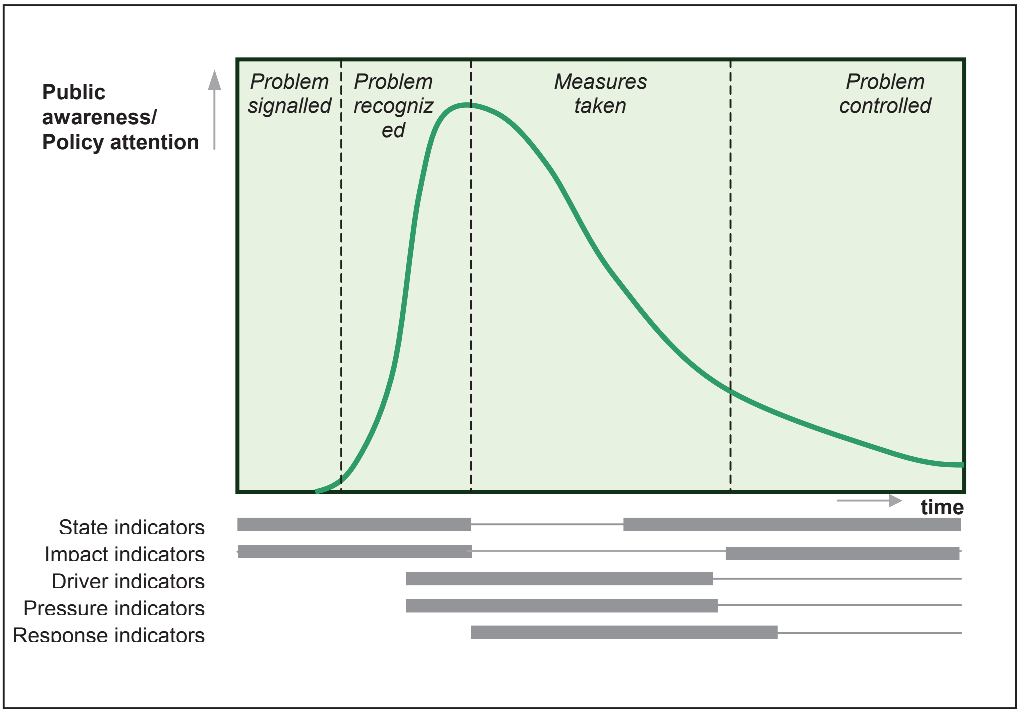
Indicators from different parts of the DPSIR framework have more or less relevance to policy makers depending on what stage the policy life cycle has reached (see figure 3.3). For problems that are in the beginning of their policy life cycle, that is, in the stage of problem identification, indicators on the state of the environment and on impacts play a major role. They will be mainly descriptive indicators, which identify alarming developments in the state of the environment. The most well known cases of 'state'and 'impact' indicators that gave rise to policy reactions are those on the sudden decline of selected species (fish in acidified Scandinavian lakes, seals in the Dutch Waddensea, for instance), surface water quality (concentrations of salt in the river Rhine which was used for irrigation in horticulture, for example) and on air quality in cities (summer smog in Paris and Athens). It is also in the problem recognition stage that estimates of externalities and other costs are relevant. The problem signalling function of 'state' and 'impact' indicators is thus limited in time: as soon as a problem is politically accepted and measures are being designed, the attention shifts to 'pressure' and 'driving force' indicators.

There is, however, a long period in which 'state' and 'impact' indicators support the process of getting political acceptance of policy responses. Greenhouse gas policies provide clear examples where indicators on climate change and its impacts, in terms of average temperatures, movement of the tree line or species distribution, are being used to gather political support for signing the Kyoto protocol.

In the next and longer stages of the policy cycle (formulation of policy responses, implementation of measures and control) policy-makers focus on what they can influence, the driving forces through volume measures, the pressures with technical measures and educational projects. Performance indicators on changes in driving forces and pressures are the most used. In this phase, the need for policy-effectiveness indicators is highest, but few of these have been developed thus far (see Section 4.4). The state of the environment is only a derived result of activities in society and policy reactions and hence 'state'-indicators are of lesser importance. The exception is, of course, management of biodiversity as such or when organisms play a role in the solution of environmental problems. In these situations indicators such as biomass production, forests as carbon dioxide sinks and forest composition can be important measures of progress.

In the last, the control phase of the policy cycle, ‘state’ and ‘impact’ indicators become important again to watch the recovery of the environment and a limited number of these indicators will be used to continuously monitor the state of the environment. They will be accompanied by an equally limited number of indicators on ‘driving forces’, ‘pressures’ and ‘responses’ to monitor the behaviour of the whole system.

Figure 3.3. *DPSIR indicator use in the policy life cycle*



Note: over time environmental problems pass through a policy life cycle with first increasing, and as the problem is more controlled, decreasing attention of the public and policy-makers. The horizontal bars under the graph illustrate the relative role of DPSIR-indicators in this process. The ‘linkage’ indicators in-between the DPSIR elements follow more or less the same pattern.

4. Indicator design – the EEA indicator typology

The DPSIR framework refers to the analytical significance of indicators in a policy context. Regardless of its position in the DPSIR system, an indicator should always convey a clear message, based on relevant variables. For this purpose, EEA uses a limited number of indicator designs, which are linked with an equal number of assessment approaches needed to produce and explain the indicator. Although some of these assessments and indicator presentations are generally applicable, most of them are particularly appropriate in certain sections of the DPSIR cycle.

4.1. A short history of the EEA indicator typology

In the preparations of the RIO+5 conference on sustainable development, the EU Commissioner for the Environment asked the EEA to bring some clarity to the discussion on indicators: the sheer amount of proposals for indicators of all kinds caused confusion and there were doubts on their effectiveness.

A simple set of questions: what is happening (A) is this relevant (B) can we make progress in improving the way we do things (C), and does this contribute to our overall welfare (D)?, led to a first typology of indicators. The typology was used to demonstrate that (in 1997) the majority of indicators used in state of the environment reports and indicator sets were descriptive, answering only the question "what is happening?". The list of indicators developed consequently for the Transport and Environment Reporting Mechanism showed for the first time that moving from descriptive indicators (A-type) to performance and eco-efficiency indicators (B- and C-type) delivered more policy relevant information.

During the discussions on the EEA core set of indicators around 2000-2002, the typology of questions with the loosely connected indicator types given above, developed into the more formal typology of indicator designs and assessments presented below. At the same time an extra category of policy effectiveness indicators has been inserted.

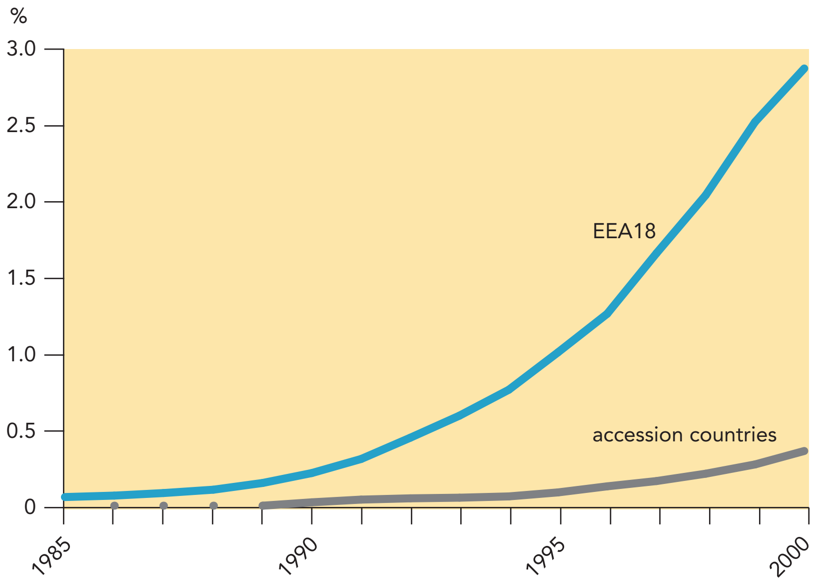
With these changes the typology can still be used (as in the original context) to discuss the kind of information generated by a certain indicator set and, in the case of imbalances, to clarify systematically the possibilities to move to more advanced indicators. In addition, the typology allows for a structured discussion on the type of assessments that are needed for the various variables used for describing a problem. E.g. an assessment of policy actions to reduce water use (evaluated on the basis of water consumption distance to targets, type B), would be accompanied by water use efficiency in main sectors (type C) and water pricing (type A).

4.2 Descriptive indicators (Type A)

Descriptive indicators are usually presented as a line diagram showing the development of a variable over time, for example 'cadmium contents in blue mussels', 'number of indigenous species in biogeographical regions', or 'share of organic farming in total agricultural area' (see figure 4.1). They are most commonly used as state, pressure or impact indicators.

If descriptive indicators are presented using an absolute scale, such as in "mg/kg dry matter", the relevance of the numbers given is often difficult to assess for a layman. Presentation in comparison with another relevant variable (such as in figure 4.1) or as a performance indicator (see next section) often improves their communicative value.

Figure 4.1. *Example of a descriptive indicator: Share of organic farming in total agricultural area, EEA18 and accession countries*



Source: *FAO; Eurostat; Lampkin*

4.3. Performance indicators (Type B)

Performance indicators may use the same variables as descriptive indicators but are connected with target values. They measure the 'distance(s)' between the current environmental situation and the desired situation (target): 'distance to target' assessment. Performance indicators are relevant if specific groups or institutions may be held accountable for changes in environmental pressures or states. They are typically state, pressure or impact indicators that clearly link to policy responses.

Most countries and international bodies currently develop performance indicators on the basis of (nationally or internationally) accepted policy targets or tentative approximations of sustainability levels (often called Sustainable Reference Values) The choice between policy targets and sustainability levels has important implications for the presentation and the analysis of the indicators. Typical performance indicators are shown in figures 4.2 and 4.3.

Figure 4.2. *Example of a performance indicator: EU greenhouse gas emissions*

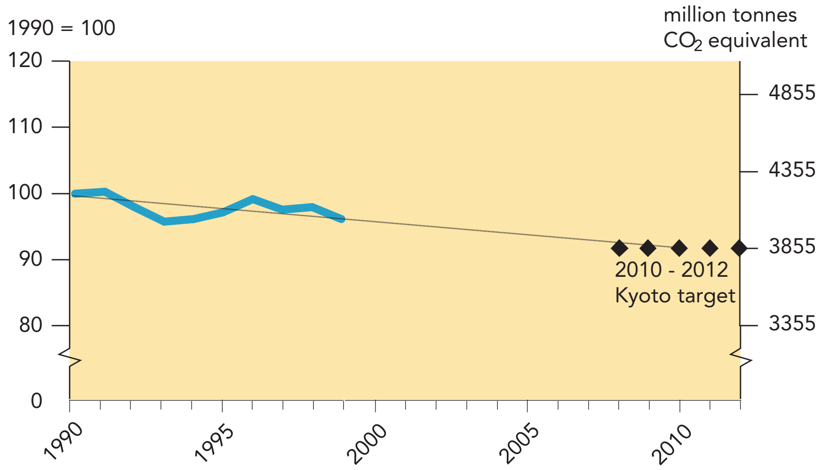
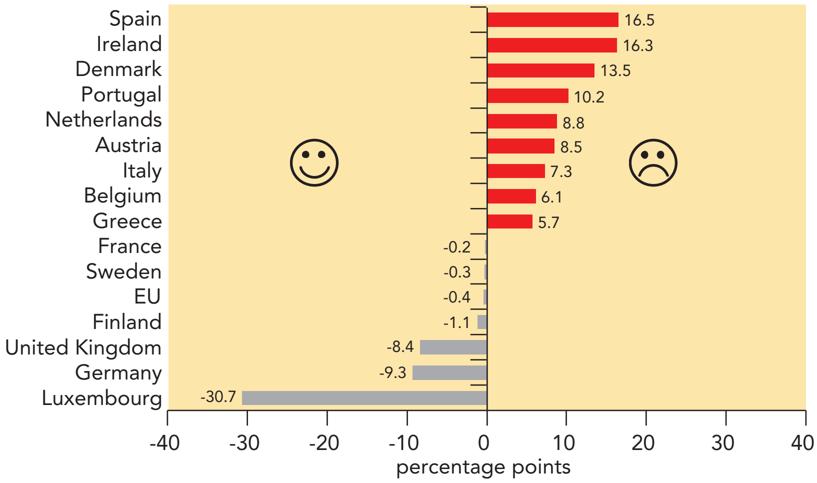


Figure 4.3. *Example of a performance indicator: Distance-to-target for greenhouse gas emissions for EU Member States in 1999 (Kyoto Protocol and EU burden sharing targets)*



Note: This is a specific variant of distance-to-target indicators in the sense that it does not show the absolute distance-to-target, but it gives a presentation of how close the current emissions (1999) are to a linear path of emissions reductions (or allowed increases) from 1990 to the Kyoto target for 2008-2012. The unit is percentage points with 1990 emissions being 100 %. For example, if a country's target is 10 % (by 2008-2012) from 1990 levels, the theoretical 'target' in 1999 would be a reduction of 4.5 %. If the actual emission in 1999 is an increase by 3 % the 'distance to target' index is 3+4.5 or 7.5 percent points.
Source: EEA, based on Member States data reported to UNFCCC and European Commission

4.4. Efficiency indicators (Type C)

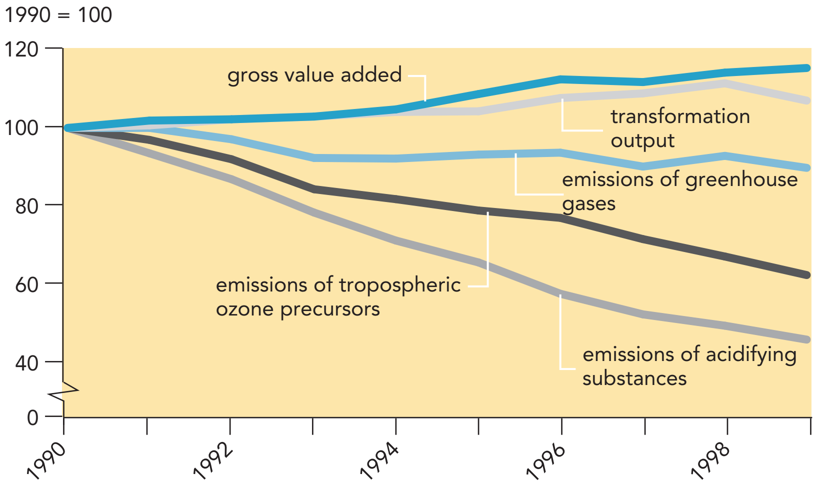
These indicators relate drivers to pressures. They provide insight into the efficiency of products and processes in terms of resources, emissions and waste per unit output. The environmental efficiency of a nation may be described in terms of the level of emissions and waste generated per unit of GDP. The energy efficiency of cars may be described as the volume of fuel used per person per kilometer travelled.

Most relevant for policy-making are indicators that show the most direct relation between environmental pressures and human activities. Sometimes an output measure in monetary terms, such as value added, can be a good representation of the development of human activities, but in many cases a physical output measure is more appropriate.
For clarity reasons, these indicators are best presented with separate lines rather than as a ratio. This is because eco-efficiency is a relative concept. If the growth of an activity outweighs the eco-efficiency gains, then the burden on the environment still increases. Therefore and absolute decoupling of environmental pressure from economic development is often necessary. Figure 4.4. gives a good example for the energy supply sector. The diverging lines for gross value added and transformation output on the one hand, and the emissions on the other, indicate increasing eco-efficiency.

Presented in this way, eco-efficiency indicators combine pressure and driving force indicators in one graph.

We speak of a relative decoupling if the pressure is still increasing though at a lower rate than the driving force variable. If the pressure decreases with an increase of the driving force, then an absolute decoupling of the two variables occurs.

__Figure 4.4.__ Example of an eco-efficiency indicator: eco-efficiency in the energy supply sector, EU



Note: Gross value added of fuel and power products is at constant 1995 prices. Energy supply sector emissions include emissions from energy industries and fugitive emissions. Weighting factors have been used to aggregate emissions of individual substances according to their potential polluting effect.
Source: EEA; Eurostat; NTUA

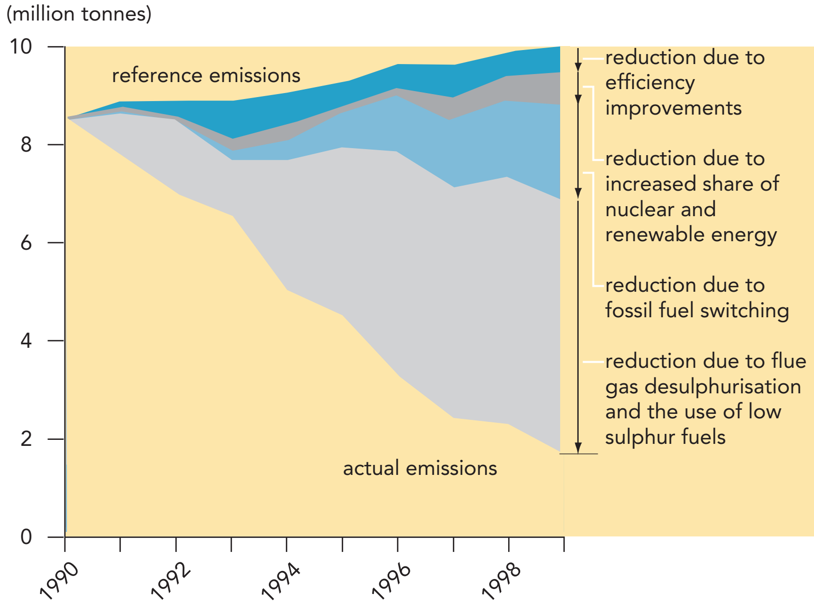
4.5. Policy-effectiveness indicators (Type D)

Policy effectiveness indicators relate the actual change of environmental variables to policy efforts. As such they are a link between response indicators on one hand and state, driving force, pressure or impact indicators on the other. They are crucial in understanding the reasons for observed developments. The Dutch yearly environmental indicator report (RIVM, 2000) contains several examples of this type of indicator. First examples for the EU have been published in EEA's Environmental signals report (EEA, 2001b and EEA, 2002).

Whereas for the previously mentioned indicators an assessment text is necessary to communicate the background information on the reasons behind the development of an indicator, for policy-effectiveness indicators much of this information is included in the graph. The production of this type of indicator requires a considerable amount of quantitative data and expert knowledge. With the expected increase in national and European capacities to do policy analysis, it is likely that this type of indicator will develop from the current model which links with technical measures (such as "desulphurisation" in the graph below) to a model that makes the link with the policy decisions that started off these technological changes.

Apart from the indicator as shown in fig. 4.5, there are several other ways to present information on the effects of policy measures. Often a presentation of two elements in one figure is used, for instance the development of a pressure indicator together with information on, for example, the timing of policy measures, or the price effect of economic instruments.

__Figure 4.5.__ Example of a policy-effectiveness indicator: Reduction of emissions of sulphur dioxide in the electricity sector, EU



Source: EEA

4.6. Total Welfare indicators (Type E)

In any discussion on sustainability and human welfare, the balance between economic, social and environmental development will ultimately be crucial. Efforts are underway to design balanced sets of individual indicators to support decision-making. However for an integral assessment, some measure of total sustainability would be desirable to answer the question: "are we on the whole better off?". A variant of 'Green GDP', such as the Index of Sustainable Economic Welfare (ISEW) or "genuine savings", may be used for this purpose. In a possible next edition of this typology, more attention will be given to these indicators in the framework of a general discussion on sustainable development indicators.

5. Indicator based reporting

A framework and some understanding of various ways of presentation of indicators are, however, not enough to develop a working list of indicators and an indicator-based report. It is EEA's experience that a framework and a typology of indicators are only tools in an indicator development process. Setting up such a process and involving the various partners is equally important as scientific and technical knowledge of the issue.

This paragraph is a first description of requirements of an indicators based reporting process. Any good process of indicator based reporting can be summarised in six steps:

Box 5.1. *Indicator based reporting summarised*

1. Agree on a story: a description of the problem and its solutions;
2. List (most important) policy questions that arise from the problem description;
3. Select (ideal and actual) indicators that come close to answering these;
4. Data compilation;
5. Assessment;
6. Conclusion and communication of key messages (and modify, adapt, update and iterate).

Many coordinators of indicator reporting processes jump immediately to Step 3 and begin with a discussion on the selection of indicators. Instead it is better to start with Step 1 and agree on what the indicators should report about. This discussion about how the problem should be framed, should involve all relevant stakeholders to ensure that they "own" the resulting indicators. Ideally, the stakeholder consultation must include policy-makers, but also representatives of the non-governmental organisations involved in the problem as well as scientists. Together they should develop what is here called "the story": a description of the stakeholders' view on the problem and the ways they see it solved. The "story" focuses and frames the problem. It is here that the understanding of the DPSIR framework and its dynamics enters the process. DPSIR-thinking helps to systematise the causes of a problem and the various responses.
The "story" also describes the demarcation of the problem area. For instance, during the development of indicator based reporting on waste, the inclusion or exclusion of nuclear waste issues needs to be discussed.

Of course, there is a close relation between policies and strategies in an area and the indicators "story". The latter however, may go deeper into causes and measures that are slightly outside a specific policy and make the link with other policies and developments in society. The indicators' "story" will often also pay more attention to describing the scientific knowledge regarding a problem, to allow for a proper communication of all relevant factors in environmental and societal processes, like multi-causality, critical thresholds and incompatibility of the use of various functions of the environment. By doing that a possibly more complete overview of all possible policy levers is provided.

One should be clear that the development of the "story" brings out the hopes, beliefs and the ethical standpoints of those involved in developing the indicators, including the policy-makers who designed the policies the indicator are intended to follow.
An example of a short "story" on transport problems in Western Europe is given in box 5.2.

Box 5.2. *Description of transport problem in the EU*

- Growing greenhouse gas emissions from the transport sector jeopardise the achievement of EU's emission reduction target under the Kyoto Protocol;
- Impacts on air quality, noise nuisance and the increasing fragmentation of EU's territory, are equally worrying;
- Transport growth - which remains closely linked to economic growth - and the shift towards road and aviation are the main drivers behind this development;
- Technology and fuel improvements prove to be only partly effective to reduce impacts;
- They need to be complemented with measures to restrain the growth in transport and to redress the modal balance.

The next step is to become more precise on the issues and questions policy-makers are wrestling with. Within the framework of the "story" the main questions need to be defined. Ideally there should be a balance in questions related to causes, effects and solutions to the problem. Box 5.3 lists the main questions belonging to the transport storyline, which can be easily adapted to other sectors and issues. It should be noted that apart from describing the issue, there is a fair amount of attention to the various policy levers that might bring changes to the situation: planning tools, investment strategies, pricing policies, technology policy and improving the knowledge.

Box 5.3. *Seven key questions on transport and the environment in the EU*

1. Is the environmental performance of the transport sector improving?
2. Are we getting better at managing transport demand and at improving the modal split?
3. Are spatial and transport planning becoming better coordinated so as to match transport demand to the needs of access?
4. Are we optimising the use of existing transport infrastructure capacity and moving towards a better-balanced intermodal transport system?
5. Are we moving towards a fairer and more efficient pricing system, which ensures that external costs are internalised?
6. How rapidly are improved technologies being implemented and how efficiently are vehicles being used?
7. How effectively are environmental management and monitoring tools being used to support policy and decision-making?

The list of policy questions then becomes the main driver for the selection of indicators. The indicators will become the main tools to communicate the answers to the questions formulated. Hence, step 3 in the process is to select and define the indicators linked to the policy questions. It is important not only to consider indicators for which data are currently available, but also to define indicators for the future. This step results in a list of 'available' and 'desirable' indicators.

Of course, not all policy questions can be linked to a quantitative indicator for tracking progress. For example, a policy intention such as "to prevent smuggling of CFCs" should theoretically be followed up by an indicator on illegal imports and exports of CFCs, but in practice data for this are lacking. Still it is EEA's experience that the majority of policy questions phrased can be approached by indicators that are reasonably suited for tracking progress.

There is a connection between the kind of policy questions and the type of indicator and assessment (see the previous chapter) that is used to provide an answer to the questions. Generally questions on environmental performance will be answered using descriptive or, preferably, performance indicators. For questions regarding improvement of processes, eco-efficiency indicators are the most appropriate. For questions regarding the effectiveness of policies (such as # 7 in box 5.3) policy-effectiveness indicators would be ideal.

Often, indicators are constructed using various datasets. Before starting the data collection it is important to unravel the data requirements of the indicators proposed. Table 1.4 in the Guidelines for the data collection for the Kiev report (EEA, 2001c) provides an example of the splitting up of indicators in the individual datasets needed to compile them. The next step is then the gathering of the data.

Having done that, one of the most important steps in indicator reporting begins: the writing of the indicator-based assessment. Based on existing knowledge, outcomes of more detailed studies, literature, the comparison with other data and indicators, an explanation is provided on the reasons why an indicator is developing as it does. As far as possible the various factors steering the development of an indicator should be distinguished. These factors being: natural processes, changes in the size and structure of the economy or society, and finally changes deliberately brought about by environmental policies. If data are available, costs and other effects of the measures taken should be mentioned, as well as possible difficulties on the way to reaching targets or reference values. Specific regional phenomena influencing the indicator should be highlighted, such as for example a strong economic growth, or extreme poverty in one specific region.

Having done the analysis for each of the indicators, an assessment should be made on the developments as shown by the whole set of indicators. In this phase connections should be made between the processes influencing all indicators. This synthesising analysis should bring out successes and failures of environmental and other policies in the wider context of the problem. This phase also includes the identification of side effects of these policies, such as those identified and proposed in “multi-pollutant–multi-effect” strategies, or the intended and unintended impacts of the use of many economic instruments. The analysis may also show where the policy framework is fragmented. Often this writing stage involves the completion of the coverage of the report in areas, which cannot be described satisfactory with indicators. Descriptive text, supporting and anecdotic data help to complete the full picture.

In addition, assessments usually pay attention to what we do not know about the causes of environmental change or the effects of measures. Datagaps and uncertainties may be highlighted and possible new problems or policy options introduced.

The last and very important stage is the communication of the outcomes and conclusions to the network of people making or influencing decisions. The assessments are generally published in indicator reports, indicator bulletins or on the Internet, but in the six months after publication ample time should be reserved for reaching out with dedicated presentations.

Simultaneously preparations are made for an improved next round of reporting.

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Appendix C

Abstract

Estratto per riassunto della tesi di dottorato

L'estratto (max. 1000 battute) deve essere redatto sia in lingua italiana che in lingua inglese e nella lingua straniera eventualmente indicata dal Collegio dei docenti.

L'estratto va firmato e rilegato come ultimo foglio della tesi.

Studente: ALEX ZABEO ______________________________ matricola: 955381 ____________

Dottorato: INFORMATICA – INF/01 ____

Ciclo: XXII_________

Titolo della tesi[1] : A Decision Support System for the Assessment and Management of Surface Waters

Abstract:

Water protection is one of the priorities in the preservation of human health and environmental sustainable conditions. Since 2000, the European Union Water Framework Directive (EU-WFD), which establishes a framework for community action in the field of water policy, asks Member States to adopt appropriate assessment methods and management solutions to reach a good ecological status of water bodies by 2015.

In this context the lack of appropriate risk-based methodologies and decision support tools was identified. For this reason, we developed a novel Multi Criteria Decision Analysis (MCDA) based methodology inside a Geographic Information System (GIS) tool for surface water quality and socio-economic evaluations. The resulting Decision Support System (DSS) is called MODELKEY.

The MODELKEY DSS is a freeware application built as a Rich Client Platform and Eclipse plug-in for a Java/Eclipse based open source GIS framework (uDig). It has been successfully applied to three case studies representing European key areas: the rivers Llobregat (Spain), Elbe (Czech Republic, Germany) and Scheldt (France, Belgium and The Netherlands). This work is part of the FP6 European project MODELKEY (Contract-No. 511237 (GOCE)).

La protezione dell'acqua è una delle priorità nella conservazione della salute umana e di condizioni ambientali sostenibili. A partire dal 2000, la direttiva quadro sulle acque emanata dall'unione Europea (EU-WFD), la quale stabilisce un insieme comune di azioni da intraprendere nell'ambito delle politiche relative alle acque, richiede agli stati membri di adottare modelli di valutazione e soluzioni manageriali appropriate al fine di raggiungere uno stato ecologico buono delle corpi idrici entro il 2015.

In questo contesto è stata identificata la mancanza di metodologie e sistemi di supporto alle decisioni appropriati che siano basati sul rischio. Per questo motivo abbiamo sviluppato una metodologia innovativa basata sull'analisi multicriteriale (MCDA) sviluppata all'interno di un Geographic Information System (GIS)allo scopo di valutare lo stato delle acque anche in relazione alle condizioni socio-economiche circostanti. Il sistema di supporto alle decisioni (DSS) che ne è scaturito si chiama MODELKEY.

Il MODELKEY DSS è un'applicazione gratuita creata come Rich Client Platform (RCP) e plug-in per nel sistema Java/Eclipse che si appoggia ad un GIS open source (uDig). Il DSS è stato applicato con successo a tre casi di studio che rappresentano altrettante aree di interesse a livello Europeo: i fiumi Llobregat (Spagna), Elba (Repubblica Ceca e Germania) e Schelda (Francia, Belgio e Olanda). Questo lavoro è parte del progetto europeo Modelkey all'interno dell'FP6 (Contract-No. 511237 (GOCE)).

Firma dello studente

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[1] Il titolo deve essere quello definitivo, uguale a quello che risulta stampato sulla copertina dell'elaborato consegnato.

Università Ca'Foscari Venezia

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DICHIARAZIONE SOSTITUTIVA DELL'ATTO DI NOTORIETA'
(Art. 47 D.P.R. 445 del 28/12/2000 e relative modifiche)

Io sottoscritto Alex Zabeo

nato **a** Mestre **(prov.** VE **) il** 17/07/1976

residente a Salzano **in** via Diaz **n.** 14

Matricola (se posseduta) 955381 **Autore della tesi di dottorato dal titolo:**

A Decision Support System for the Assessment and Management of Surface Waters.

Dottorato di ricerca in Informatica

(in cotutela con ....**)**

Ciclo XXII

Anno di conseguimento del titolo 2009/2010

DICHIARO

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