

Topic report No 1/1999

# Lakes and reservoirs in the EEA area

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# Preface

This report presents the results of the lakes and reservoirs database project undertaken by the European Topic Centre on Inland Waters (ETC/IW) on behalf of the European Environment Agency (EEA). The study was carried out by the International Office for Water (IOW, France) and the Institut Français de l'Environnement (IFEN, France), with contributions from CEDEX (Spain). The co-operation of the International Commission on Large Dams (ICOLD) and the European Topic Centre on Nature Conservation is gratefully acknowledged.

An important element of the project was the collection of data by means of two questionnaires (large reservoirs questionnaire in 1995-7 and the nutrients questionnaire in 1997) from National Focal Points in eighteen EEA member European countries. Data provided from fifteen of these countries have been used in this report. Where possible, data available from the literature has been used to fill in the gaps for the missing countries (Belgium, Greece and Liechtenstein).

The chapter on eutrophication has been developed in parallel with the EEA Monograph on Nutrients (EEA, 1998). The chapter on acidification is based on recent European and international reports on this subject.

## **Notes**

*In processing the questionnaire responses, it has become apparent that the reservoir capacity and area data provided in the World Register of Dams (ICOLD 1984/1988), upon which some of the figures in this report are based, contain a number of important errors - in some cases, order of magnitude errors. Since verification of the ICOLD data was carried out by only a few countries, it should be noted that basic data (capacity/area) for approximately one-third of the reservoirs currently in the database has **not** been verified. As a result and despite best efforts, it is possible that significant errors in national totals for reservoir capacity and areas may occur in this report.*

*The following units are used in this report:*

*1 hm<sup>3</sup> = 1 million m<sup>3</sup>*

*1 ha = 10 000 m<sup>2</sup>*

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# Executive summary

This report presents the results of work carried out between 1995 and 1997 by the European Topic Centre on Inland Waters (ETC/IW) within the framework of the European Environment Agency (EEA) Multiannual Work Programme 1994-98.

The objectives were to overview the physical, chemical and ecological characteristics of lakes and reservoirs, as well as to describe their uses and evaluate their environmental state and trends. The geographical scope of the report was the 18 EEA member countries but only 15 supplied data.

A database, known as the **European Lakes, Dams and Reservoirs Database (ELDRED)**, was constructed to organise data collected from National Focal Points through two questionnaires. One questionnaire concerned only major reservoirs (responses received in 1995-1997) and the other questionnaire was part of the collection effort in 1997 for the report "Europe's Environment: The Second Assessment" (EEA, 1998) focusing on nutrient-related problems. Other information from the World Register of Dams and from OECD/Eurostat publications was also entered in the database. The ELDRED database now contains information concerning over 3500 reservoirs and over 300 natural lakes.

The results of the project are of interest for two reasons. The difficulties experienced by the National Focal Points in assembling the required information, due to important differences between national lake and reservoir monitoring programmes, serve to illustrate problems which may be encountered in the setting-up of the EEA information network for still waters. Although the lack of available information means that a complete picture cannot be drawn across Europe, the project has, nevertheless, been able to identify and provide some indication of the extent of the main issues concerning lakes and reservoirs and should serve as a framework upon which to base the future EEA monitoring programmes. Bearing in mind the two points above, it is recommended that the future EEA still water information network should be based on a limited number of key priority variables and should include only a limited number of still water bodies.

The study indicates a wide range of environmental situations for lakes and reservoirs in Europe. Two main themes emerged: environmental problems affecting lakes and reservoirs ecosystems and uses, and impacts on the environment caused directly or indirectly by reservoir construction.

**Eutrophication** affects significant numbers of lakes and reservoirs across the whole of Europe. It can render these water bodies unsuitable for human use, causing serious problems for public water supply, and also impacting the lake ecosystem. In most cases, phosphorus is the principal cause of eutrophication. Only in sparsely populated regions such as parts of

the Nordic regions, Ireland and Scotland are there a high proportion of lakes with low phosphorus concentrations.

Certain lakes have been the subject of detailed studies and efficient action programmes to reduce nutrient loads in the catchment and several are showing signs of improvement. Some of these lakes will nevertheless require several decades and strong preventive and curative measures for restoration because of nutrient accumulation in the lakes and in their catchments.

Although the lack of data does not permit satisfactory conclusions, it would appear that the proportion of lakes with high phosphorus concentrations has gradually decreased over the last few decades, in all likelihood due to specific action programmes and general improvements in wastewater treatment facilities. However, the state of European lakes and reservoirs is still of concern, since the situation seems to be worsening in many other lakes with previously moderate or low phosphorus levels.

The marked contrasts in reservoir use (and importance) across Europe reflect both geographical influences (water resource availability) and national energy policies (hydropower production). The numerous hydropower reservoirs often located in mountainous or Nordic regions can be distinguished from the generally smaller irrigation and public water supply reservoirs situated in lowland and southern regions, which tend to have longer renewal times. These latter reservoirs are more likely to be subject to higher nutrient loads and their uses are particularly sensitive to eutrophication issues.

**Acidification** is a more regional issue, and some signs of improvement due to earlier atmospheric sulphur reductions are being observed. However, nitrate leaching would appear likely to be an increasingly important factor in determining acidification.

In certain reservoirs, **sedimentation** can be a significant problem with important long term impacts, requiring careful catchment management and drastic curative measures.

Although historic **drainage** of lakes has led to the destruction of important lake habitats, in some cases it has at the same time created new wetland habitats.

Lakes and reservoirs ecosystems and uses are particularly sensitive to several types of water quality pollution because of their tendency to accumulate pollutants in water or in sediments. Occurrences of **heavy metals and persistent organic pollutants** have been observed in several lakes and reservoirs in the EEA area.

The '**artificialisation**' effects on rivers and their ecosystems as a result of dam/reservoir construction and operations were also considered significant.



Dams constructed in earlier periods when environmental considerations were not systematically integrated into their design tend to lack facilities which would enable their environmental impact to be minimised. Examples of such facilities include permanent constructions such as fish ladders or outlets sized so as to permit emptying during less sensitive periods.

Impacts on flow regime, temperature regime and water levels are particularly apparent in the case of some hydropower dams, since they are often located in remote sensitive mountainous regions. However, impacts have also been reported for other types of reservoir - for example impacts due to poor water quality during emptying operations or the creation of migration barriers for fish.

# 1. Introduction

## 1.1. Scope of the report

As well as being an integral part of any ecosystem, still waters are also an important economic and social asset. Although often under-valued, lakes (artificial or natural) represent an important water resource in Europe:

- they satisfy many different human uses or requirements, such as drinking or irrigation water supply, navigation, recreation and fisheries. To make optimal use of this asset, man has also constructed dams, which can control and impound water.
- they also support particularly rich ecosystems, which often provide a vital interaction with river ecosystems.

In this report, a lake is considered to be an enclosed body of (usually) freshwater surrounded by land with no direct access to the sea. In some cases, the distinction between a slow-flowing river and a rapidly renewed lake may be ambiguous. We have distinguished lakes formed by natural processes (**natural lakes**) from artificial lakes formed by man (**reservoirs**). Many lakes may in fact be semi-artificial: small natural lakes which have been artificially enlarged by man. Reservoirs, by definition, are created by **dams**, which result in both a water resource asset and a substantial modification to the environment. For this reason, dams have been considered in this assessment of reservoir usage and their environmental conditions.

Some countries have extensive national or regional natural lake monitoring programmes, aimed at assessing specific issues such as acidification or eutrophication. But many countries do not have such monitoring programmes: natural lake management is left to local authorities or owners and data are not available or difficult to obtain.

Although reservoirs represent an important water resource, very few monitoring networks devoted exclusively to European reservoirs exist. It is known, however, that monitoring of many major reservoirs is carried out, although data are generally held by numerous diverse organisations (in particular, reservoir owners), making efficient data collection problematic.

The study presented in this report aims to provide a review and assessment of the environmental conditions of lakes and reservoirs. This report is based on information and data available to the European Topic Centre on Inland Waters (ETC/IW) in 1997. With the support of the NFPs, the future EURO-WATERNET information network should ensure better representativity and availability of data.

## 1.2. Project objectives

This report presents the results of work carried out between 1995 and 1997 by the European Topic Centre on Inland Waters (ETC/IW) within the framework of the European Environment Agency (EEA) Multiannual Work Programme 1994-98. This work was designed to provide support for:

- The development and establishment of the European water quality monitoring network and databases (intended to build on recommendations from the report “ Design of a freshwater monitoring network for the EEA area ” (EEA, 1996);
- Water resources evaluation.

The objectives for the work were defined as follows:

- to overview the physical characteristics and locations of lakes and reservoirs and the development over time of reservoirs;
- to overview the importance of ecological functions and human uses of natural lakes;
- to overview the importance of reservoir use and construction in relation to water resource availability and control policies;
- to overview the environmental and water quality problems affecting lakes functions and reservoir usage;
- to overview the environmental and water quality changes effected by reservoirs and dams during their construction and normal operation.

In order to achieve these objectives, it was decided:

- to create a database of lakes and reservoirs in the EEA area, which would allow assessment of the issues described in the points above;
- to base the database on available sources of information and to validate this information and collect further information from National Focal Points (NFPs) for input to the database.

The geographical scope of the report is the 18 EEA member countries.

## 1.3. EEA Lakes and Reservoirs Database (ELDRED)

### ***1.3.1. Objectives***

The database is referred to in this report as ELDRED (**E**uropean **L**akes, **D**ams and **R**eservoirs **D**atabase).

The proposed objective of ELDRED was to constitute a European database on still waters (natural lakes, semi-artificial lakes and reservoirs) which organises historic and up-to-date information concerning environmental problems and impacts related to these water bodies with particular emphasis on eutrophication (but excluding acidification problems at

present). The types of data in ELDRED include location, significant physical and hydrological characteristics, uses, water quality, fauna, flora and owners/authorities of the water bodies. In the case of reservoirs, the database also includes significant environmental information about the associated dam(s).

Copies of the ELDRED database are available on request from the EEA.

### ***1.3.2. History of ELDRED***

In 1995, the first reservoirs task represented a scoping phase, producing a survey of environmental conditions of major European reservoirs and identifying key issues. Amongst the key issues identified were trophic state, impacts on drinking water use, obstacles to fish migration and the downstream impacts of reservoirs on ecological river quality.

A first-step database was constructed to organise data concerning these key issues, pre-filled using information in the World Register of Large Dams (ICOLD 1988) and distributed in the form of a questionnaire to NFPs. Assessment of the key issues was limited due to poor or late responses from many NFPs generally as a result a general lack of directly available data in many countries (absence of monitoring networks, necessity of contacting reservoir operators individually). A number of late responses were received during 1996.

A second-step database was constructed with more user-friendly input forms for use in the 1996-1997 programme. The second-step database was designed to include more data fields for more temporally variable parameters and to allow the integration of natural and semi-artificial lakes.

Data collection was carried out in 1997 through two questionnaires:

- re-initiation of the major reservoirs questionnaire for countries who had not yet responded;
- Dobris+3 (Europe's Environment: The Second Assessment) questionnaire, whose emphasis was on nutrients in representative and reference lakes.

Data collected for the Dobris Assessment report and data collected by EUROSTAT/OECD were also entered into the database.

## **1.4. Sources of Information**

### ***1.4.1. Selection of lakes and reservoirs included in the database***

In 1998, the database includes reservoirs listed in the ICOLD register (see below) and/or water bodies added by official responses by NFPs through the major reservoir and Dobris+3 lake/reservoir questionnaires. In some cases, NFPs have requested that some ICOLD-listed reservoirs should be deleted from the database, in most cases because the reservoir is not

judged to be a significant water body (for example, a large dam or dyke with no large reservoir). It should be noted that the true and current existence of the water body defined in the ICOLD register may or may not have been validated by the NFP.

The database therefore contains quite a heterogeneous selection of still water bodies. For natural lakes, the database essentially contains the largest European lakes as well as lakes judged to be representative or reference by NFPs. For reservoirs, the database contains all the largest reservoirs in Europe, some smaller reservoirs with very large dams and some smaller reservoirs that are considered to be representative by NFPs.

#### **1.4.2. World Register of Dams (maintained by ICOLD)**

The most comprehensive pan-European database of large dams is the 'World Register of Dams', maintained by the International Commission on Large Dams (ICOLD). The latest addendum to this publication (ICOLD 1988), merged with the most recent comprehensive release (ICOLD 1984), was used as the original starting point for the EEA major reservoir database, since it provides much useful information about the reservoir associated with each dam. (In France, the provisional update for 1994 was provided by the French ICOLD correspondent.) The criteria for inclusion in the Register, based primarily on safety considerations, are listed in Table 1.

Table 1: Criteria for inclusion of dams in the ICOLD World Register of Dams

All dams with a height of 15 m or more, measured from the lowest portion of the general foundations to the crest.
Dams between 10 to 15 m can be included under request provided they comply with at least one of the following conditions: <ul style="list-style-type: none"> <li>• the length of the crest is not less than 500 m,</li> <li>• the capacity of the reservoir formed by the dam is not less than 1 000 000 m<sup>3</sup>,</li> <li>• the maximum flood discharge dealt with by the dam is not less than 2 000 m<sup>3</sup> s<sup>-1</sup>,</li> <li>• the dam has special foundations problems or is of unusual design.</li> </ul>

Note: Applicable to all countries with the exception of the USA, continental China and the former USSR

#### **1.4.3. Data input and data source priorities**

The following table describes the data provided by NFPs (Table 2). It should be noted that data in the current database comes from a variety of sources and that these not necessarily concur. There are also many ambiguities that should require a validation stage of the database by NFPs. In all cases, the most recent data received has been taken to take precedence (i.e. delete and replace) any existing data.

Table 2: Data provision by NFPs

Country	Large reservoirs questionnaire (1995-1997)	Dobris+3 questionnaire (lakes and reservoirs section)	Specific bibliography on lakes or reservoirs (provided by NFP or located by IOW)
Austria	F	F	Y
Belgium	N	N	
Denmark	NA	F	
Finland	P	F	
France	P	F	
Germany	P	F	
Greece	N	N	Y
Iceland	F	N	
Ireland	F	N	
Italy	P	N	Y
Liechtenstein	NA	N	
Luxembourg	F	N	
Netherlands	F	F	
Norway	P	F	
Portugal	F	F	
Spain	F	N	
Sweden	N	F	
United Kingdom	N	F	

F = full response

P = partial response

N = no response

NA = not applicable / questionnaire not sent

Y = yes, literature provided

### 1.5. Availability of data by theme

The following table indicates the extent of data available for existing lakes and in-service reservoirs in the ELDRED database.

**Table 3: Data availability in database**

Description	Numbers of water bodies with at least some information	
	Reservoirs	Lakes
Number of water bodies	3510	305
<b>Characteristics</b>		
Capacity/volume	3194	126
Area	3034	224
Date of construction (for reservoirs)	3489	N/A
Average depth	186	150
Residence time	153	131
Monitoring of water quality (Y/N)	296	-
X,Y Coordinates	1758	162
River name	3465	-
Catchment area	1434	149
<b>Water resources</b>		
Water volume draining into water body from catchment	783	-
Uses	3354	42
<b>Water quality</b>		
Trophic state	519	3
Concentration data concerning phosphorus (total P or PO <sub>4</sub> ) <sup>*</sup>	287	184
Concentration data concerning nitrogen (total N, TIN, NO <sub>3</sub> ) <sup>*</sup>	453	179
Concentration data concerning transparency <sup>*</sup>	478	153
Concentration data concerning chlorophyll <sup>*</sup>	132	159
Min/max data concerning dissolved oxygen <sup>*</sup>	413	1
Nitrogen loads to water body	34	2
Phosphorus loads to water body	56	7
Presence/absence of various problems related to water quality	34	26
Presence/absence of preventive measures	33	4
Presence/absence of curative measures	24	3

\* concentration data from any year

- not requested

N/A not applicable

## 2. Overview of major lakes and reservoirs in Europe

### 2.1. Origins

#### ***2.1.1. Origins of natural lakes***

Natural lakes are formed by geological processes such as fluvial damming, volcanic activity and glacial events. The origins of lakes have been described in detail by Hutchinson (1975) and summarised into several major types by Pourriot & Meybeck (1995):

- glacial lakes;
- tectonic lakes (large scale continental crust movements);
- fluvial lakes;
- shoreline lakes (water bodies cut off from the sea due to sedimentation);
- naturally dammed lakes (formed by landslides for example);
- volcanic lakes;
- rock dissolution or karst lakes (formed by percolating water in rocks such as limestone).

Lakes can be terminated by long-term natural processes such as sediment infilling or evaporation. In recent times, lakes have been destroyed by man through drainage or over-exploitation for water supply.

#### ***2.1.2. Historical development of major reservoirs***

Artificial lakes, otherwise referred to in this report as reservoirs, are formed by the construction of a dam or dyke by man. In some cases, semi-artificial lakes can be created when a small lake or pond is enlarged by a dyke.

The earliest large dams are located in Spain and are believed to date from the 2nd century AD (Cornalbo and Prosperpina, with dam heights of 24 and 19 m respectively), suggesting that water supply problems were identified long ago in these regions! Both dams were reconstructed in the early part of this century. Approximately twenty large dams were constructed in the 17th and 18th centuries, in Germany, Spain, France, and in the UK.

During the 19th century, the rate of dam construction in the UK was prolific, responding to the water requirements of the rapidly expanding industrial centres. By 1900, over 200 large British dams (over a third of Britain's present-day total) had been built - more than the total number of large dams on the European mainland at that time. However, the rate of



construction slowed in the early 20th century, just as many other countries began active dam-building programmes (data from ICOLD 1984/1988).

Italy saw several spates of active large dam-building in the first half of this century, notably in the 1920's, 1930's and 1950's. Spain's dam construction programmes followed a very similar pattern to Italy's until the late 1950's, when a period of intense dam building got underway. The rate of Spanish dam completion has been remarkably constant throughout the second half of this century and it continues at the present-day.

France is another country whose dams were built predominantly in the second half of this century, at a steady rate of approximately 8 per year. In comparison to the rest of Europe, France and Spain appear to be the two countries with the highest rate of dam completion in the period 1980-1988. In the UK, Germany and Sweden, Figure 1 indicates that, for the same period, dam-building has come to a virtual halt. Other countries, such as Portugal, Austria and Norway continued to construct dams, but at a slower rate. In several countries (Belgium, Finland, Iceland, Ireland, Luxembourg and the Netherlands), no further large dams have been built since 1980.

The period with the highest overall rate of dam construction in Europe was during 1955-1985. Over a quarter of the total number of reservoirs in Europe have been commissioned in Spain during this period, with an average of 15 reservoirs per year. As a consequence, Spain also has the highest total capacity for this period. However, the statistics on the average size of reservoirs constructed during this period indicate that Greece, Finland, the Netherlands, Sweden and Iceland have commissioned, on average, larger capacity reservoirs, albeit in smaller numbers than Spain.

Dams can be classed as "destroyed" or "disused" for a number of reasons: the dam has been physically destroyed, the dam has been replaced by another dam upstream, etc. As an illustration of this point, several examples can be drawn from the questionnaire responses: in Portugal, INAG reports that the Lindoso dam originally built in 1920 is now in the backwater of a larger reservoir, the Alto Lindoso, constructed in the 1980's. In France, two dams (dating from 1921 and 1962) have been completely dismantled and another no longer contains a water body. Studies are underway in 1997 to look at the advantages and disadvantages of destroying another dam in France (Maison Rouge). In Italy, one dam is no longer used due to a landscape disaster in 1963.

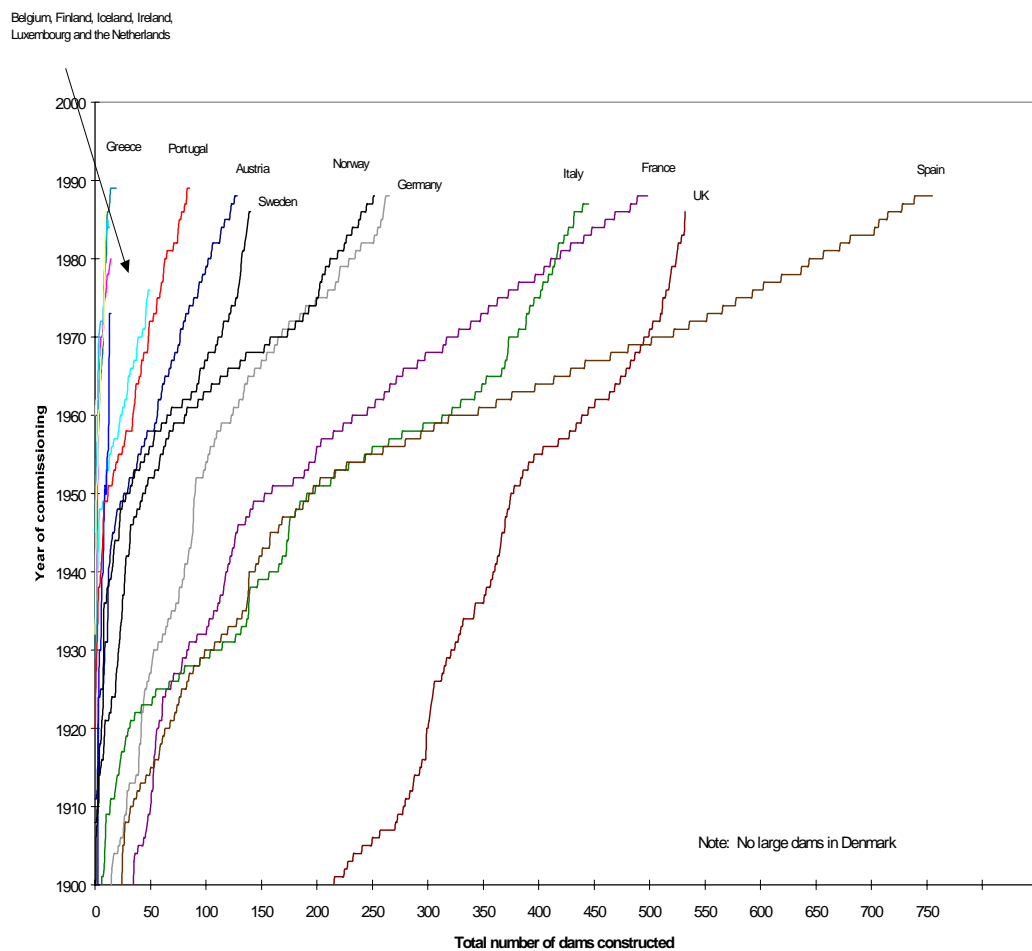
## 2.2. Geographic distribution of lakes and reservoirs

### ***2.2.1. Still water bodies in Europe***

Approximately 500 000 still water bodies over 1 hectare exist in Europe (EEA, 1995). This compares with an estimated figure of 8.3 million lakes worldwide (Pourriot & Meybeck 1995).

The majority of natural lakes in Europe occur in Norway, Sweden and Finland. In terms of numbers, over 134 000, 85 000 and 56 000 lakes over 1 hectare have been counted in Norway, Sweden and Finland respectively (Skjelkvåle *et al.* 1997, EPA Sweden 1992, Wahlström *et al.* 1993). It has been estimated that over 9% of Finland and Sweden are covered by freshwater lakes. Significant numbers of natural lakes also exist in Iceland, Ireland and Scotland. most of the largest European lakes are located in the Nordic countries and in the Alpine regions. Available data concerning numbers in each size category and the total lake surface area in each country are limited, but some examples are given in Table 4.

Figure 1: Dam commissioning in Europe 1900-1988



Data source: ICOLD 1984/1988

**Table 4: Estimated numbers of still water bodies according to size**

Country	0.01-0.1 km <sup>2</sup>	0.1-1 km <sup>2</sup>	1-10 km <sup>2</sup>	10-100 km <sup>2</sup>	>100 km <sup>2</sup>
Austria	9000 (<1 km <sup>2</sup> )		17	7	2
Belgium	NI	NI	NI	NI	NI
Denmark	2857	256	68	6	0
Finland	40309	13114	2283	279	47
France (1)	24068	2011	201	25	2
Germany (2)	≈5000		≈100	≈20	2
Greece	NI	NI	NI	>16	1
Iceland	≈7000	1650	176	17	0
Ireland	≈5500				
Italy	NI	>168	>82	13	5
Liechtenstein	NI	NI	NI	NI	NI
Luxembourg	NI	NI	NI	NI	NI
Netherlands	NI	>100	100	10	2
Norway	116218	16417	2039	164	7
Portugal (3)	NI	30	40	15	0
Spain (3)	482	330	247	63	2
Sweden	71693	20124	3512	369	23
United Kingdom	478	197	146	27	2

Sources of data: EEA (1996) and responses to EEA questionnaire for Dobbris+3 report

(1) Includes lagoons and reservoirs

(2) Only natural lakes

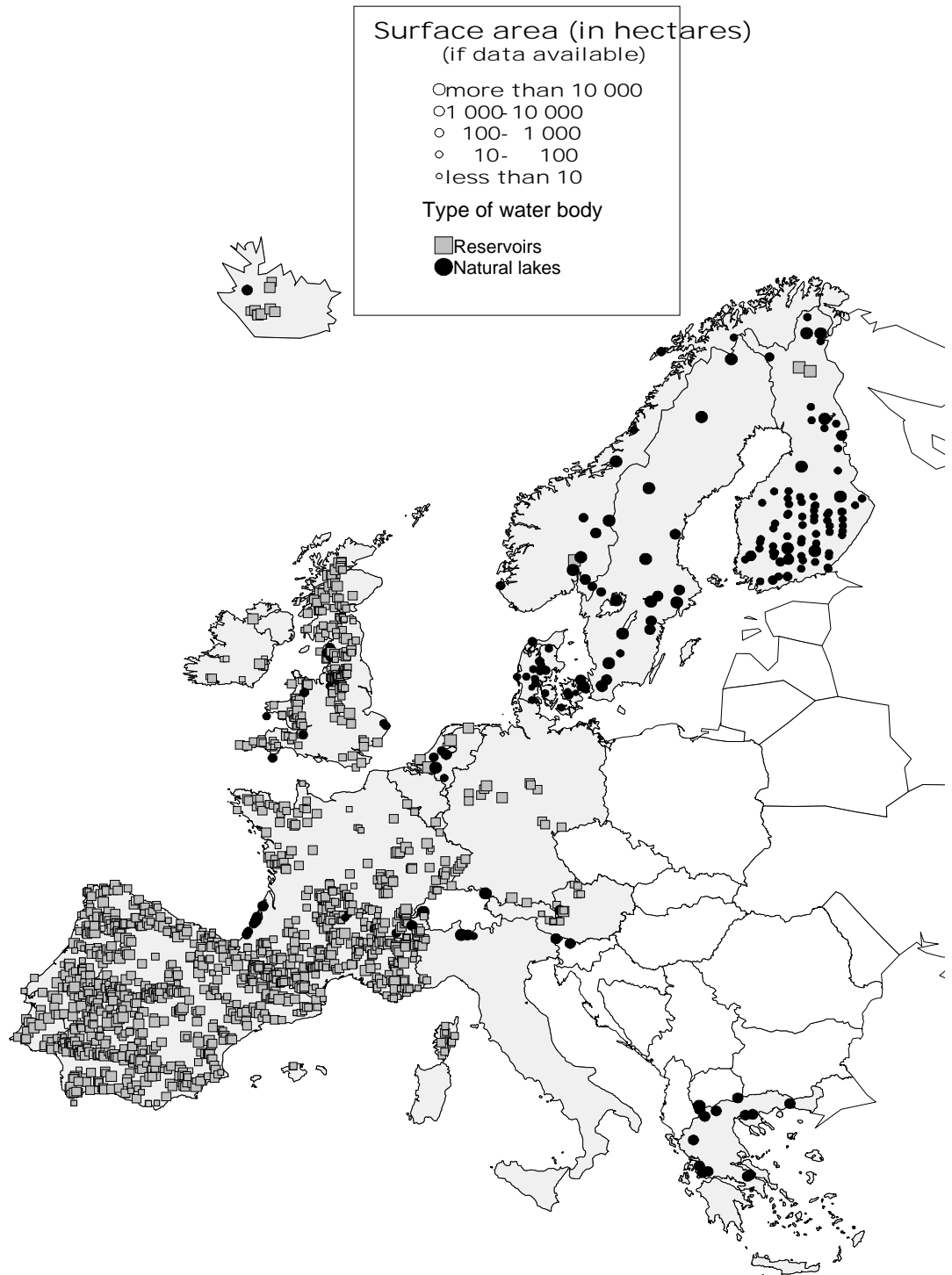
(3) Only reservoirs

NI = no information

### ***2.2.2. Available information on still water bodies***

The distribution of the natural lakes for which co-ordinates were provided or located is presented in Figure 2 (for lakes and reservoirs whose co-ordinates have been provided). This map cannot be taken to be representative of the locations of all lakes and reservoirs in Europe, because of the absence of responses and co-ordinates in many countries. Nevertheless, some patterns can be observed. In Spain, large numbers of reservoirs are distributed across the country, whereas in the UK, most of the large reservoirs are located in the Pennine hills or Scottish and Welsh mountains.

Figure 2: Locations and surface areas of lakes and reservoirs in the ELDRED database (using all available co-ordinate data, updated 11/98)



Information concerning the type of data provided by each country is given in Table 5.

**Table 5: Numbers of still water bodies for which significant amount of data has been entered in ELDRED**

Country	Surface Area of Country (km <sup>2</sup> )	Natural lakes	Reservoirs	Total number of water bodies for which significant information is available	Number of water bodies with quality data	Numbers of still water bodies recommended for EEA monitoring network**
Austria	82730	7	14	21	10	46
Belgium	30250	0	0	0	0	21
Denmark	42370	35	0	35	33	22
Finland	304610	79	7	86	86	179
France	550100	10	242	252	102	279
Germany	349470	22	18	40	29	245
Greece	130850	16	0	16	13	61
Iceland	100250	1	8	9	1	29
Ireland	68890	10	15	25	17	37
Italy*	294060	6	60	66	64	207
Luxembourg	2580	2	1	3	3	2
Netherlands	33920	6	5	11	11	32
Norway*	306830	13	289	302	5	133
Portugal	91950	1	93	94	52	48
Spain	499440	0	324	324	324	236
Sweden	411620	18	0	18	15	188
United Kingdom	241600	20	4	24	17	153
International lakes		6	4	10	3	-
<b>TOTALS</b>	<b>3541520</b>	<b>252</b>	<b>1084</b>	<b>1336</b>	<b>785</b>	<b>1918</b>

\* water quality information only supplied for lakes not for reservoirs

\*\* guideline values proposed by the EEA (1996), excluding the largest lakes in the EEA area (approximately 200)

Note: Information from NFPs through Dobris responses, through ETC/IW major reservoir questionnaire, or from Eurostat or OCDE data compendiums

### **2.2.3. Major reservoirs**

In this report, the expression 'major reservoir' is used to refer to reservoirs formed by dams which correspond to the criteria used in the ICOLD world register of large dams (ICOLD 1984/1988), as summarised in Table 1. It should be noted that the ICOLD criteria (based primarily on dam height) do not include many reservoirs which may be significant in terms of water volume, but have lower dams (this is the case for a large number of reservoirs in for example, Norway).

The total number of in-service major reservoirs on mainland Europe is approximately 3350. With the exception of Denmark, at least one major reservoir is found in each country, as Figure 3 shows (based on ICOLD 1984/1988 data). The number of major reservoirs in each country reflects the interaction of several factors determining dam construction in a country:

Figure 3: Numbers of major reservoirs by country

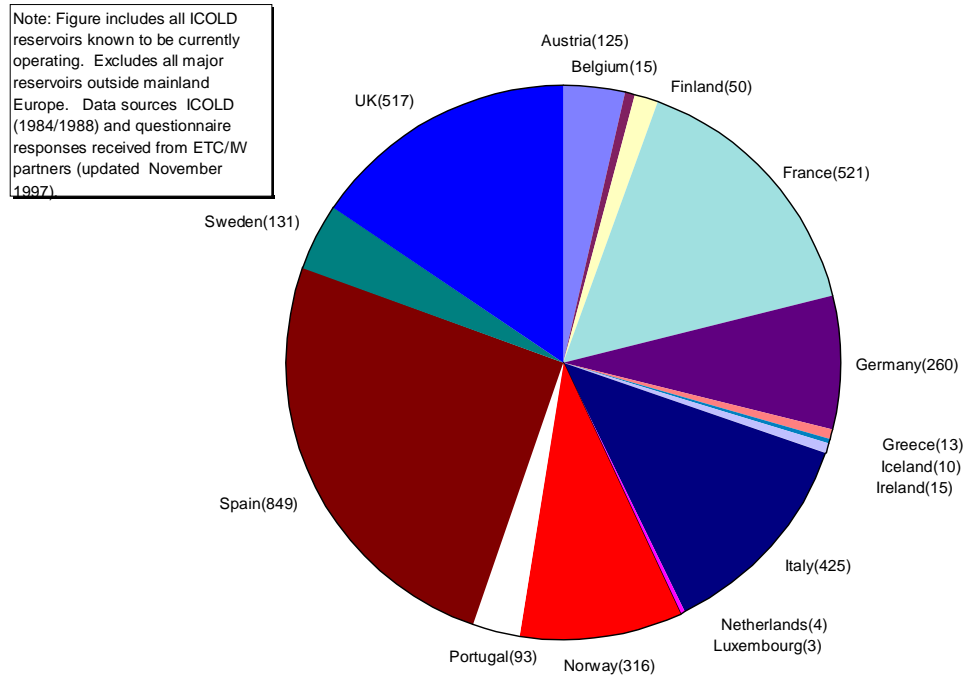


Figure 4: Reservoir capacity in relation to country's population

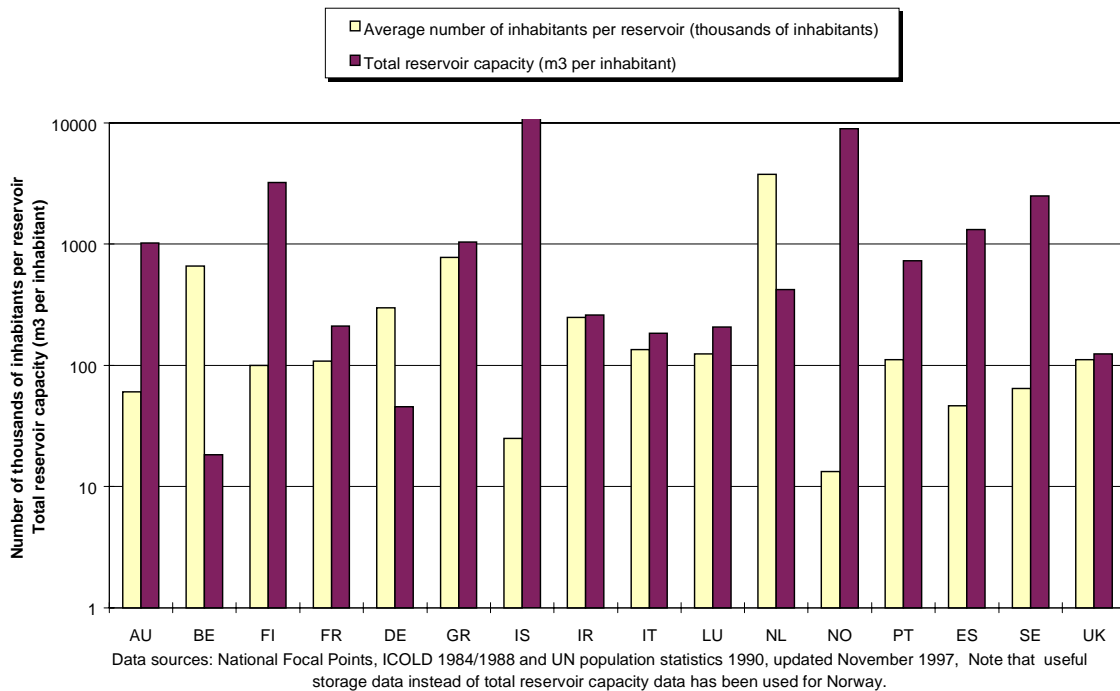
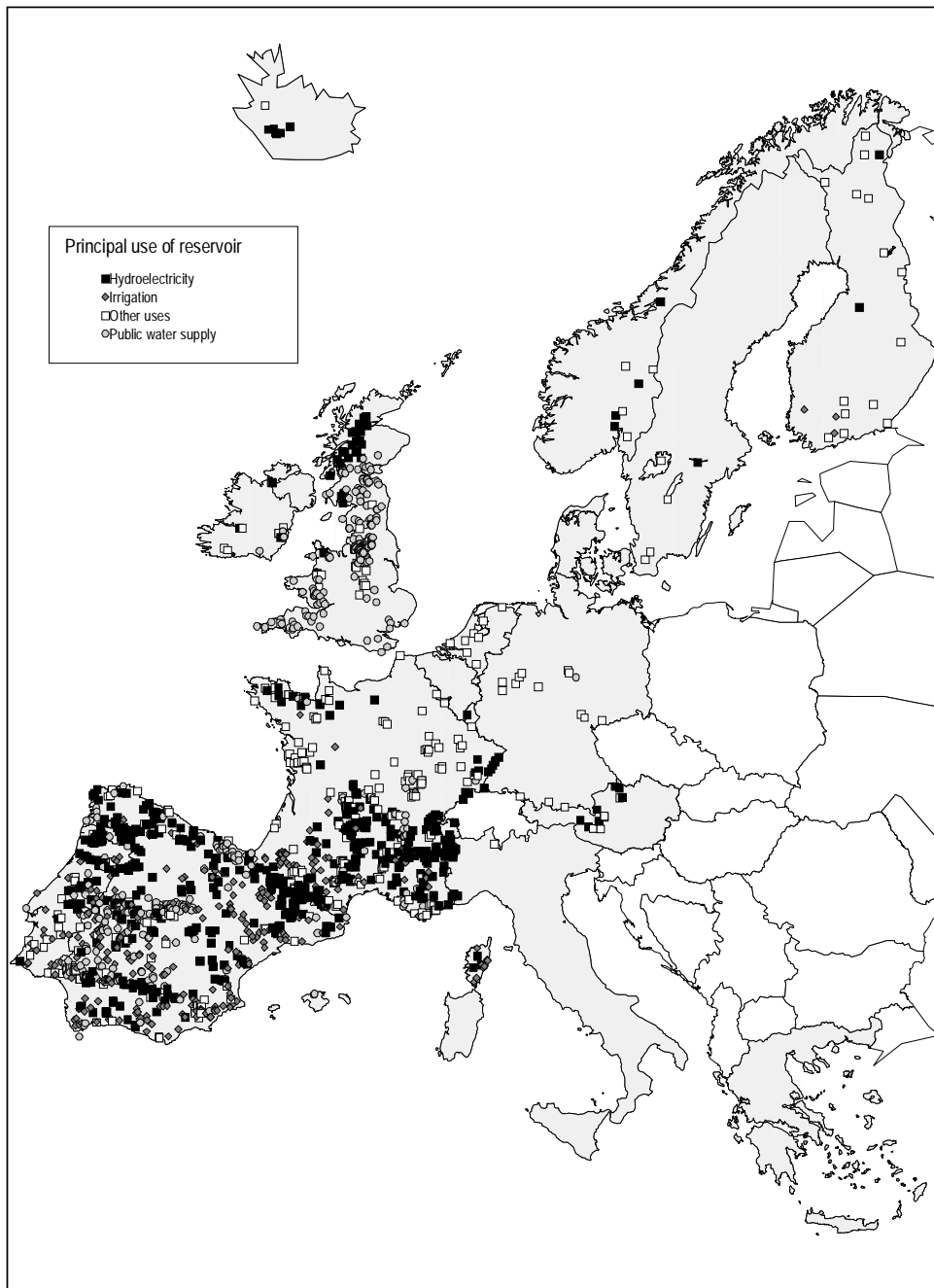


Figure 5: Principal use of major reservoirs in ELDRED



Data source: ELDRED, 11/98

- geographic and climatic situation of the country;
- formal or informal national policies concerning the importance of large reservoirs in water resources management in relation to other water sources (groundwater, river abstractions and small reservoirs);
- formal or informal national policies concerning the importance of hydropower in meeting national energy needs;
- availability of suitable dam sites;
- size, population and industrial make-up of the country.

Spain, France, the UK and Italy have the largest number of major reservoirs (more than 400 in each case). Although Scandinavian countries appear to have lower numbers of reservoirs, these are generally of larger capacity.

Figure 4 shows the numbers and total capacity of major reservoirs in relation to state population (based on questionnaire responses received from National Focal Points, data from ICOLD (1984/1988) and UN Population Division data from 1992 published in World Resources Institute, 1992).

Information about the existence of reservoirs formed by smaller dams (less than 15 m high) is harder to obtain. In Spain there are estimated to be more than 1100 reservoirs with dams higher than 5 m.

In France, a recent study has estimated that there are approximately 1800 dams (of all sizes) in service producing hydroelectricity (CLER 1997). Although many of these sites produce electricity using the river flow (base flow), there is often an associated slow-flowing water body upstream with its dimensions depending on the morphology of the river valley.

The distribution and main use of major reservoirs is presented in Figure 5 (based on co-ordinate data received from some NFPs and supplemented where possible by co-ordinates located by IOW).

Even in its currently incomplete state, a number of interesting points can be observed from the map in Figure 5 which provides a good visual representation of cross-border differences and similarities:

- the large numbers of public water supply dams in central Spain, particularly to the north and west of Madrid and in the upper Ebro catchment - strong linear patterns can also be observed, corresponding to major river valleys;
- the high density of primarily hydropower dams in the Pyrénées on **both** sides of the border and clusters of irrigation dams in the lower Adour catchment (southern France) and lower Ebro catchment (northern Spain);
- the overall concentration of large dams in southern France, but also the importance of public water supply dams in north-west France;
- linear patterns of important hydropower dams along the Rhône/Isère/Durance and the Rhine in France;
- the clear distinction in Portugal between hydropower dams in the north (including the Douro/Duero system) and irrigation dams in the south.

In Germany, it is reported that there are about 450 reservoirs (river dams and flood protection reservoirs) with more than 300 000 m<sup>3</sup> capacity (UBA 1997). They are concentrated in areas with high water use demands from industry and towns. Approximately one-third are located in the



industrialised North Rhine Westfalia, the uplands in the mid-western part of Germany.

## 2.3. Characteristics and typology

### **2.3.1. Types of lakes and reservoirs**

Reservoirs and lakes are more often considered according to their physical and thermal / mixing characteristics than their origins. Processes in lakes are strongly determined by the temperature profile, which depends in turn on climate (solar radiation) and wind, and also on the lake depth. The water in the bottom layers of a lake (the hypolimnion) usually has the highest density (for freshwaters this corresponds to a temperature of 4 °C) and this is overlain by a layer of colder or warmer water (epilimnion). In this way, the lake is described as stratified. When the surface waters cool or warm towards 4 °C (or reach a temperature where a strong wind can induce the same effect), the lake has a near constant temperature and mixing of the water masses occurs.

Lakes can thus be classified according to their thermal/mixing characteristics. In Europe, dimictic lakes are the most common type of lake, corresponding to cool temperate climates. These lakes experience overturn twice a year in spring and autumn. Cold monomictic lakes occur in sub-polar climates and are covered by ice for most of the year, with only one overturn after ice melt. Warm monomictic lakes occur in temperate regions and also only have one overturn each year.

The frequency of overturn in lakes and reservoirs is important in determining chemical exchanges between lake layers, and often has an important influence on oxygenation conditions in deep layers.

### **2.3.2. Physical differences between lakes and reservoirs**

There are important differences between natural lakes and artificial reservoirs. Studies on North American lakes (Thornton *et al.* 1982) have shown that in general:

- reservoir catchments (in relation to the water body surface area) are generally larger than natural lake catchments;
- average and maximum depths are also higher in reservoirs;
- reservoirs receive more water volume per surface area unit than natural lakes and reservoirs have shorter residence times.

Because of their larger catchments, reservoirs also tend to have higher nutrient loads. However, reservoirs with shorter residence times tend to have lower nutrient concentrations.

Many reservoirs are constructed in areas with extreme water resource situations: regulation of low water resources or control of high water

resources. This means that their geographic locations are quite different from natural lakes.

Lakes exist in natural depressions according to local topography. Their catchments are often more or less symmetrical and they are frequently fed by several incoming rivers or streams. In contrast, many reservoirs (but obviously not all) are constructed in the lower part of a river catchment and have a characteristically elongated shape and a matching elongated catchment area (Ryding & Rast 1989). Often, inflowing water and nutrients arrive through only one incoming river, quite far upstream of the dam. This shape results in characteristic nutrient and sediment profiles, influencing the biological productivity and water quality of the reservoir. Unlike natural lakes, outflowing water from reservoirs can generally be controlled and is often released from outlets situated at different levels in the dam.

Figure 6 shows the contrasting morphological characteristics of lakes and reservoirs for which the necessary data are available.

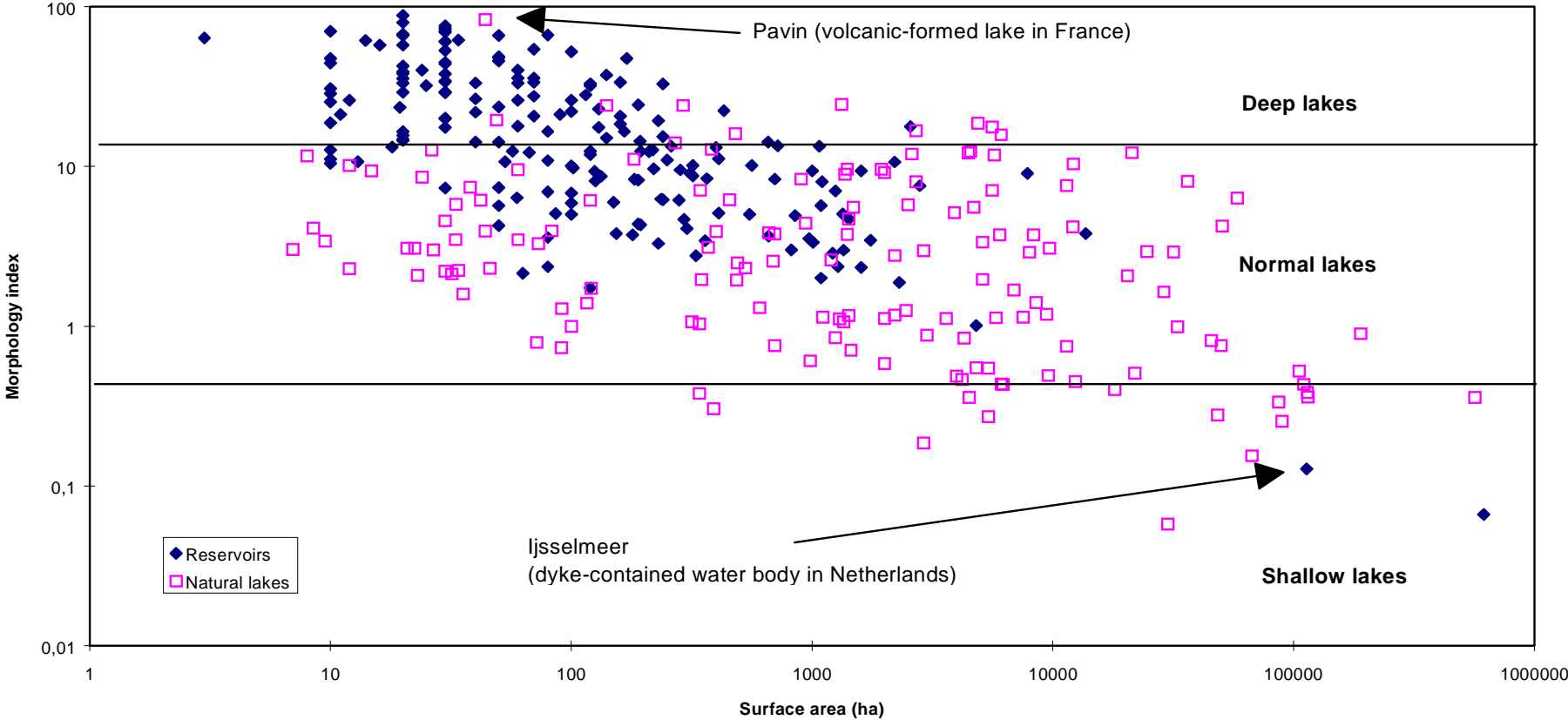
Despite these contrasts in physical form, it is often possible to have a similar approach to management of lakes and reservoirs. However, it should be noted that the more variable physical, chemical and biological gradients in reservoirs often demand more sophisticated sampling methods and that different water quality indicators may be required.

## 2.4. Size characteristics

### ***2.4.1. Size characteristics of still water bodies***

The total freshwater lake surface area in relation to a country's size (called the limnicity) is sometimes a more interesting indicator than the total numbers (Pourriot & Meybeck 1995), and it is nearly always related to the density of lakes in the 10-100 km<sup>2</sup> range. In Europe, limnicity ranges from over 9% in countries such as Sweden (Bernes *et al.* 1992) to approximately 1% in the UK (Pourriot & Meybeck 1995) and less than 0,5% in Greece (Koussouris *et al.* 1989).

Figure 6: Morphology index for natural lakes and reservoirs



Morphology index =  $1000 \times \text{average depth (m)} \times (\text{surface area (m}^2\text{)}^{-0,5})$  (Pourriot & Meybeck 1995)  
 Data for 150 natural lakes and 185 reservoirs presented. Data source: ELDRED (11/97)

National Focal Points were asked to provide physical characteristics and water quality data for a number of representative lakes and reservoirs. Most of the responses contained only data on natural lakes, which has been analysed in this section. The sizes of natural lakes provided by national focal points is presented in Figure 2.

#### ***2.4.2. Size characteristics of major reservoirs and dams***

The gross capacity of major reservoirs is defined as the total volume of water present in the reservoir at its normal maximum water level (not flood level). Data on total gross capacity was available for approximately 94% of major reservoirs. The largest total gross capacity of 5900 million m<sup>3</sup> is contained by the three Suorva dams in Sweden (ICOLD 1984/1988). Similarly the reservoir surface area is defined as the area of water at the normal maximum water level.

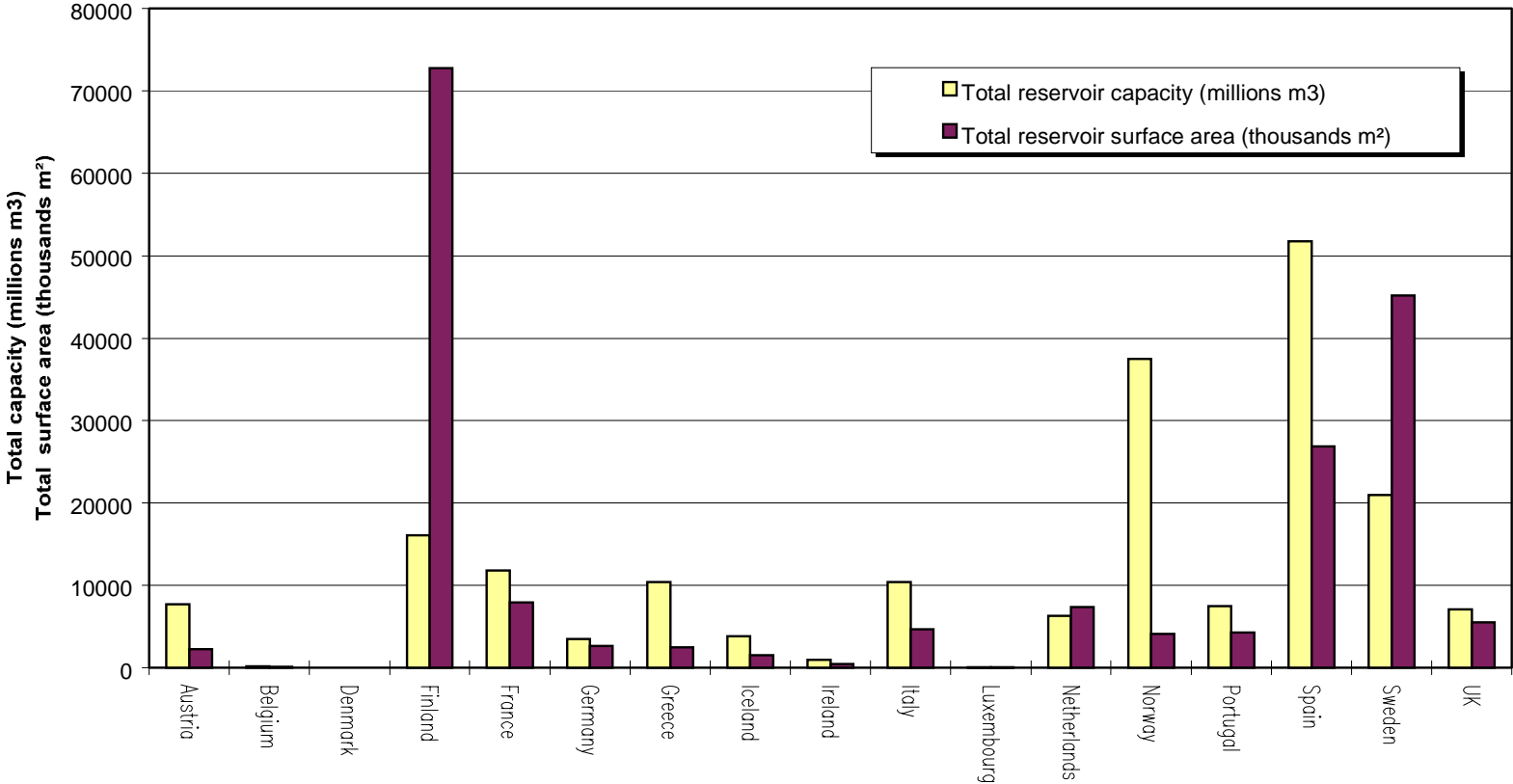
Total reservoir capacity and surface area by country are provided in Figure 7 (based on questionnaire responses and data from ICOLD 1984/1988). A comparison of population and total reservoir capacity is also presented in Figure 4.

Although data concerning total gross capacity for Norwegian reservoirs is not available, useful storage totals for 70% of the country's reservoirs indicate a storage capacity of over 37 000 million m<sup>3</sup>. Considering their smaller numbers, the predominantly hydropower dams in Finland and Sweden stand out as having large total capacity as well as, in particular, huge total surface areas.

In addition, one important reservoir in the Netherlands (Ijsselmeer) which contains 5120 million m<sup>3</sup>, has a marked effect on the country's total reservoir capacity and surface area. This reservoir is used for flood defence, public supply, irrigation, navigation and recreation purposes.

In absolute terms, Spain has the largest total major reservoir capacity (the 849 major reservoirs in ELDRED represent over 50 000 million m<sup>3</sup> of gross capacity), more than twice the total capacity in any other country (with the exception of Norway). However, in terms of gross capacity per inhabitant, Spain has with just over 1 000 m<sup>3</sup> per inhabitant. Interestingly, this compares directly with an annual average renewable resource which is also estimated at just over 1 000 m<sup>3</sup> per inhabitant. This suggests that the maximum Spanish reservoir capacity corresponds to the total average renewable resource available.

Figure 7: Total reservoir capacity and surface area in Europe



Data source: National Focal Points, ICOLD 1984/1988, updated November 1997. Note that significant reservoir area data missing for Norway, For Norway, useful storage data represented since total capacity data lacking.

The ranges of certain characteristics of large dams selected for the project are shown below.

Table 6: Dam and reservoir characteristics (data source: ICOLD 1984/1988)

Characteristic	Number of dams <sup>a</sup>	Minimum	Maximum	Quartiles		
				25%	50%	75%
Dam height (m)	3460	8 <sup>b</sup>	261	19	26	42
Crest length (m)	2547	5	51000 <sup>c</sup>	135	230	410
Volume of dam material (10 <sup>3</sup> m <sup>3</sup> )	2271	0.18	63400	24	88	300
Maximum spillway discharge (m <sup>3</sup> s <sup>-1</sup> )	1995	1	60000	52	170	724
Spillway type	3207	765 controlled 2163 uncontrolled 250 mixed 29 absent				

Notes:

<sup>a</sup> Number of dams for which data have been available (total number of dams in this particular study group was 3480)

<sup>b</sup> By definition, all selected reservoirs have dams with heights greater than 10 m (there are, however, two exceptions, which are both dams of 8m)

<sup>c</sup> There are several extremely long dikes in the study group

## 2.5. Uses and functions

### 2.5.1. Lake usage and functions

Natural lakes form an important resource for human populations living close by the water body. Lakes are used for a variety of different purposes, including:

- water supply, for drinking water, irrigation, industry;
- fisheries, in the commercial sense;
- transport, as an important navigation link;
- recreation, including water sports, tourist attractions and fishing;
- nature conservation areas;
- disposal of wastewater effluents.

Some of these uses are discussed in more detail below with specific reference to reservoirs. Because there are generally many 'official' and 'unofficial' uses, data concerning uses of natural lakes has not been sought.

Lake ecosystems contain a wide variety of habitats which control the extent of primary production and biological activity, including the calm shelf areas, agitated shelf areas, pelagic zone at the surface, euphotic zone (corresponding to the depth to which significant light penetrates), the aphotic zone (into which no significant light penetrates) and a benthic zone.

### **2.5.2. Reservoir usage**

Since dam construction involves significant time, cost and effort, dams are constructed only in response to important human needs. In general, water is transferred, regulated or conserved for one of two main reasons: the need to compensate for spatial or temporal deficiencies in the natural water resource in relation to the water demand (for example, public water supply or irrigation) or the need to control water resource excesses perceived as nuisances (for example, flood defence).

The principal reasons for dam construction are listed in Table 7 which also compares the requirements and characteristics of each dam purpose. Different dam purposes have distinct requirements in terms of location and water quality. In addition to construction constraints, the proximity to the intended water consumers is a determining factor for several types of dam purpose in the location of the dam. Similarly, the water quality in the reservoir is of greater or lesser importance, depending on the intended reservoir use. In those reservoirs where good water quality is of the utmost importance, much effort is dedicated to preventing a deterioration in quality.

In general, the dam purpose is also the major factor in defining the operating rules for the dam. These, in turn, control the water level variations in the reservoir and the flow regime in the downstream river, both important environmental factors. Dams and reservoirs are often multi-purpose, a typical example being a low flow enhancement reservoir which is also used for recreation. In such cases, the water level is lowered during the late summer months, which is the very season in which a constant level is desirable. This can result in conflicts between different reservoir uses, which are generally resolved by prioritising uses and optimising the operating rules.

As well as creating a new water resource, the construction of a dam may also involve substantial modifications to the environment, both during construction and subsequent operation. Such changes may be perceived as beneficial or detrimental to the environment and may result from a number of different sources. For example, reservoirs are often viewed as an improvement to the landscape in Portugal, as well as an important regional economic and tourist asset. In the UK, however, the construction of a reservoir is more often considered to have a detrimental effect on the natural valley landscape (Anon., 1992).

Although legislation in many countries now requires an environmental impact assessment (EIA) to be carried out prior to the construction of a large dam, EIAs were not carried out for older dams and it has been observed that many environmental modifications are difficult or impossible to anticipate (Chabal *et al.* 1995). The possible environmental changes described in a later chapter have been compiled from a detailed literature review - for each particular dam, the impacts will depend on site-specific factors.

### ***2.5.3. Overview***

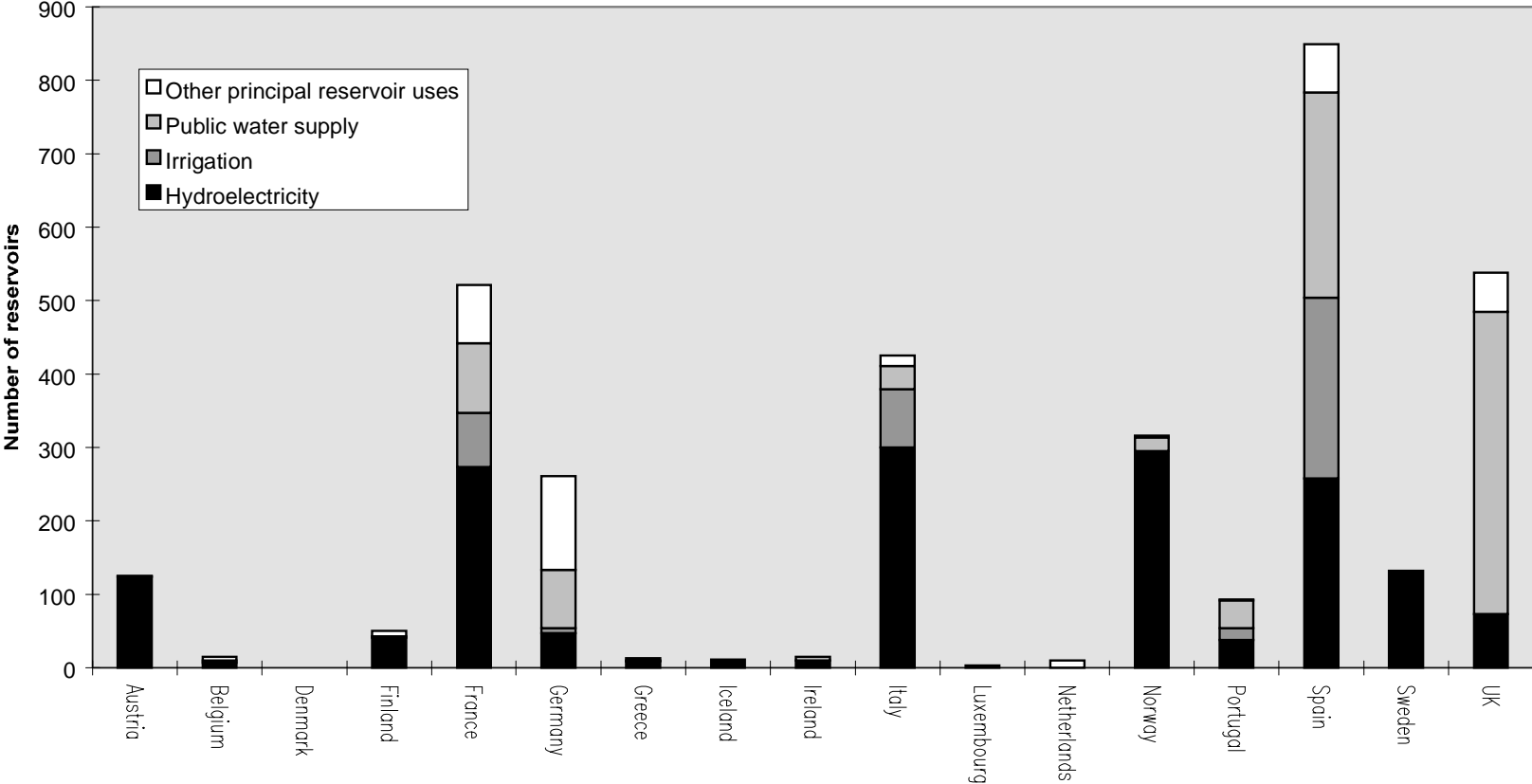
Ten distinct types of major reservoir usage (listed in Table 7) have been differentiated for the purposes of this study. In fact, reservoirs are often multi-purpose, which can lead to conflicting water uses. Nevertheless, the primary purpose of the reservoir is generally considered to be the original reason for construction and, therefore, tends to have the highest priority assigned to it.



**Table 7: Dam purposes and main construction and operation issues**

Purpose of Dam	Factors determining dam location	Water level variations in the reservoir	Discharges into downstream river	Water quality	Observations
<b>Hydropower</b>	To maximise the energy produced (depends on river flow and dam height).	Variable on a daily, seasonal or annual basis, depending on production method.	Possibly extremely variable.	Determined by other possible uses of the reservoir.	May result in water diversion from the main river to another catchment
<b>Public Water Supply</b>	Generally near water consumers/urban agglomerations.	Highly variable.	May be reduced to the legal minimum.	Very good water quality is a primary objective. Must comply with raw drinking water quality standards.	Sedimentation is often an important issue.
<b>Industrial Water Supply</b>	Generally near water consumers/industrial sites.	Highly variable.	May be reduced to the legal minimum.	Good water quality is often very important, however required quality depends on industry type.	Sedimentation is often an important issue.
<b>Fisheries</b>	Variable.	Quasi constant.	Quasi -natural discharge.	Very good water quality is essential.	
<b>Irrigation</b>	Near consumption sites or a channel for water transport.	Seasonally variable. Releases in summer and autumn.	May be reduced to the legal minimum, since water storage is maximised.	A secondary issue.	Sedimentation is a very important issue.
<b>Transport</b>	Dam diverts water into a channel, or acts as a weir, or as a storage facility to allow sluice operation.			Water quality is only an issue if machinery (ships/structures) are affected.	Reservoir may be small or non-existent, but structure can represent a major barrier to fauna migration.
<b>Recreation</b>	Variable, often a secondary purpose of older reservoirs.	Quasi constant (preferred to maintain beach level)	Possible recreation in downstream river (rafting, canoeing etc.) requiring downstream discharges.	Very good water quality essential - in particular, low trophic state and microbiological counts.	Predominantly a reservoir's secondary purpose.
<b>Flood Control</b>	Variable.	Highly variable.	Dependant on reservoir operating rules.		Requires a significant total potential capacity.
<b>Low Flow Enhancement</b>	Variable.	May vary.	The downstream discharges may reverse the natural flow regime (e.g. flood and low water levels)	Should not adversely affect the receiving water body. Usually designed to enhance dilution. Good quality preferred.	Dam outlets must be operated in different ways.
<b>Spoil Storage</b>	Near to industrial areas.	Often contains little water.	Not generally situated on a river.	Impoundment may cause pollution due to leaching.	Type of dam often not relevant to water-related issues.

Figure 8: Principal reservoir use by country



Data source: ICOLD 1984/1988. Note that, as indicated here, public water supply systematically takes priority over other uses in multi-use reservoirs in Spain and Portugal

Figure 9: Reservoirs and lakes in ELDRED used for public water supply



Data source: ELDRED, 11/97

The definition of ‘primary purpose’ and ‘highest priority’ is not the same in all countries. In many cases, the primary purpose determines the design of the dam and associated reservoir. This primary purpose may for instance govern the total capacity created in the reservoir. A secondary purpose may however be assigned the highest priority in case of conflict. For example, in Spain, many reservoirs have irrigation as their ‘primary purpose’. However,

if water shortage is anticipated, ultimate priority is given to public water supply. Similar cases are observed for regulation dams with a low flow enhancement 'primary purpose' and flood defence/hydropower/recreation as a 'secondary purposes', where the highest absolute priority is given to flood defence when high river flows are forecast.

Figure 5 and Figure 8 present primary reservoir uses by country (data based on ICOLD 1984/1988). Notice that the pattern of reservoir usage varies quite markedly from country to country. This is an interesting point, reflecting the characteristics of the country's water resources, water demand and water policy. For instance, in Scandinavia, major reservoirs are used essentially as an energy resource. Whereas, in the UK, major reservoirs are often an important part of the water supply system.

An analysis of the total gross capacity for primary purpose hydroelectricity, irrigation and public water supply uses in the 20th century using data from ICOLD (1984/1988) indicates that the rate of growth of total European capacity of hydropower and irrigation reservoirs appears to increase significantly in the 1960's, whereas the total European capacity of public water supply reservoirs appears to have increased at a steady rate since 1960.

The following sections briefly present each type of reservoir use, along with a discussion of its relative importance amongst the different European countries and a brief review of associated environmental issues. It should be noted that the occurrence of common secondary purposes, such as recreation and fisheries, appear to be under-estimated in the data presented here. This is likely to reflect the original ICOLD data source, which often lists only the primary purpose of a reservoir in most countries and the fact that smaller reservoirs may be generally built for these purposes.

#### ***2.5.4. Public water supply***

Major reservoirs are a key element in the water resources management for public water supply in many countries, with over 800 major European reservoirs serving primarily this purpose.

Figure 9 shows the geographic distribution of reservoirs used for drinking water supply available in the ELDRED database. The UK and Spain have the largest number of reservoirs used for public water supply (approximately 400 and 300 respectively). France, Germany and Italy also have large numbers of such reservoirs. Approximately 180 other major European reservoirs have public water supply as a secondary (or lower priority) purpose. The total capacity of reservoirs used for public water supply (as their primary or lower priority purpose) is about 32000 million m<sup>3</sup>, representing approximately 20% of total European reservoir capacity (all data from ICOLD 1984, 1988).

The majority of these reservoirs are owned by a relatively small number of organisations. In Spain, the state owns over three-quarters of major public water supply reservoirs. In the UK, North West Water (formerly North West Water Authority) owns approximately a quarter of Britain's large public water supply reservoirs (over 100): Yorkshire Water (formerly the Yorkshire Water Authority) owns an additional 89 such reservoirs.

It should be noted that many important public water supply reservoirs in Europe are relatively shallow (<10 m) and will not, therefore, have been selected for the 'major reservoir' data-set presented in this report. This fact may well have an effect on the apparent distribution of these reservoirs in different countries. Another factor is the priority of public water supply usage in multi-use reservoirs: in Spain and Portugal, many reservoirs are used for irrigation and/or hydropower production, but public water supply will always have a higher priority.

Water quality is the prime consideration in public water supply: it is essential to meet rigorous raw drinking water standards with optimal cost-efficiency. Factors that affect raw drinking water quality are as follows:

- physico-chemical parameters, such as pH, conductivity, organic matter and dissolved oxygen
- undesirable substances, such as iron, manganese and nitrate
- toxic or carcinogenic substances, such as heavy metals, pesticides or toxins produced by certain cyanobacteria
- micro-biological parameters, such as faecal coliforms
- taste, smell and colour
- biological parameters, such as chlorophyll a, algae etc.

Water supply reservoirs are often highly susceptible to water quality deterioration since they are frequently located in densely populated areas. There are three issues here: preventing a deterioration in water quality, improving poor reservoir water quality and ensuring adequate water treatment prior to distribution. Prevention measures include the original choice of reservoir site, the control of human activities in the reservoir, the control of discharges in the reservoirs catchment and various reservoir management strategies. If water quality does deteriorate, measures to improve it can be implemented, such as selective withdrawal, de-stratification, aeration, sediment removal and chemical treatment.

Impounded water rarely meets drinking water standards and some sort of water treatment is nearly always needed. Eutrophication is a major problem in public water supply reservoirs because of the problems it can cause in the water treatment process. This and other water quality problems affecting water supply are discussed in detail in later chapters.

### **2.5.5. Hydroelectricity**

Hydropower is considered as one of the cleanest sources of energy available, being renewable and non-polluting. Hydroelectric power plants also operate at 85-90 per cent efficiency, about twice that of fossil fuel power stations and almost three times that of nuclear power stations (Veltrop, 1991). In recent years, the number of pumped-storage plants has increased rapidly, providing a flexible and economical way to store energy/electricity for use in peak demand periods.

In many countries (including Austria, Finland, France, Greece, Iceland, Italy, Norway, Portugal and Sweden), the majority of major reservoirs are used for hydropower production. In particular, the primary purpose of major reservoirs in Norway and Sweden is almost exclusively for hydroelectricity. It is for this reason that dam ownership and expertise in many countries is closely associated with the electricity industry. Electricity production organisations or companies are also often responsible for reservoir management and on-going monitoring. ENEL (Ente Nazionale de Energia Ellectrica) in Italy and EDF (Electricité de France) in France own the largest number of major reservoirs, with over 250 hydroelectricity-producing dams each. The state in Spain and NSHEB in Scotland also own large numbers of such dams (around 100 and 50 dams respectively).

Over 1450 major European reservoirs are used for hydroelectricity production (ICOLD 1984/1988). Approximately 170 other major reservoirs are used to generate hydroelectricity as their secondary purpose.

Hydroelectric dams are often located in remote regions with significant topography, where there are generally more suitable construction sites. They are also often used for other secondary purposes, such as recreation. There are several alternative modes of hydroelectric production, described below (Travade *et al.* 1983):

- Peak production responds rapidly to demand fluctuations, which can vary from hour to hour. As a consequence, discharges can also vary rapidly, resulting in an unstable downstream flow regime if no compensation facility exists. Large capacity is not a prerequisite in this case.
- Seasonal production delays electricity generation until the winter, generally the highest consumption period. The reservoir volume is several orders of magnitude larger than the total daily inflows and is progressively filled during the spring. The maximum level is maintained during the summer and is then progressively lowered during the winter.
- Base (or day-to-day) production uses water that cannot be stocked in a reservoir to generate electricity. In these cases, the total outflows approximate total inflows and there is very little storage. Typically such dams are located on major rivers such as the Rhône or the Rhine, in locations where the creation of a large water body is not feasible.

Water quality is not generally a major concern in hydropower reservoirs: however, such reservoirs can often represent an important environmental threat since their operation results in dramatic changes in the downstream hydraulic regime, temperature patterns and gas saturation, as well as the problems associated with the periodic emptying of such reservoirs, enforced by law in several countries.

#### **2.5.6. Irrigation**

Spain has the largest number of major reservoirs used for irrigation (over 400, nearly 50%). Over 40% of Portugal's reservoirs are also used for irrigation. However, as mentioned above, public water supply takes priority over other uses such as irrigation, as required. Irrigation reservoirs do exist in France and Italy, but represent a much smaller fraction. Irrigation as a primary purpose for major reservoirs appears to be virtually non-existent outside these four countries, although many smaller irrigation reservoirs do, of course, exist in many countries (data from questionnaire responses and ICOLD 1984/1988).

Irrigation represents a very large water demand in the driest seasons, requiring winter storage and summer/autumn releases. For example, the irrigation reservoirs in the Adour-Garonne basin in France, are estimated to consume 70% of the total water impounded, compared to 35% consumption for public water supply reservoirs (Rothe, 1991). In general, the reservoir needs to be in close proximity to the irrigated land, to minimise water loss during transport.

Because of the often huge water demands, irrigation is sometimes considered as a major aggravating force in rivers with low flow problems (Rothe, 1991). Irrigation water can be abstracted from reservoirs, rivers and groundwater, requiring sound water resource management on a catchment scale, if low flows are to be avoided.

#### **2.5.7. Industrial water supply**

Spain has the largest number of major reservoirs built primarily for industrial water supply with a total of 31 reservoirs (10 others are also used for industrial supply as a lower priority purpose). Italy also has 6 reservoirs used primarily for this purpose, although 8 other reservoirs supply industrial water as a secondary purpose. France has 3 industrial supply reservoirs (primary purpose), including Mirgenbach, which is used to supply cooling water to a power station near Metz. Portugal has a total of 8 reservoirs used for industrial supply (data from questionnaire responses).

Industrial water supply falls into two main types: water for production (alimentary products, chemical production or paper production) or water used for cooling purposes (Larre *et al.* 1990). In the first case, the water quality is of the utmost importance: food production requires water of drinking quality standard (and, in some cases, higher standards), chemical production often requires low suspended solids (and may also have more

specific demands, depending on the type of chemicals produced) and paper production is very sensitive to water colour and sulphate content.

For cooling water, quality requirements are less demanding, although demineralisation treatment may be needed. Micro-algae proliferation can also block pumps and affect circuits. Algal proliferation in the Mirgenbach reservoir, used to supply cooling water to Cattenom power station during low flows, have, in the past, necessitated the gathering of large volumes of algae (Larre *et al.* 1990). Although inflow water quality is generally of minor importance for cooling circuits, effluent water quality is a factor that needs to be considered. If cooling water supplied from a reservoir is of poor quality, the effluent discharged to the river may not meet the often strict discharge licence conditions.

However, quantity is generally a more important factor than quality in cooling water supply. A reliable, cheap and plentiful source of water is often a priority. In some cases, water is released from reservoirs into a river in order to dilute an undesirable warm cooling water discharge from a power station. Given a suitable plant location, economics is likely to determine whether a company uses the national water supply or builds a reservoir (either of its own or in partnership with a water company).

#### ***2.5.8. Flood control***

Flood control aims to increase the duration of the flood discharge, so that the instantaneous flow rate is maintained below a safe value. Three main types of dam may produce this effect:

1. dams in long and narrow valleys, where a 'dynamic' capacity is possible due to the slope of water upstream of the dam;
2. large reservoirs situated in plains, where only 'static' capacity is available;
3. dams acting as dikes to prevent the flooding of specific areas.

The uncertain nature of floods mean that the operating rules for flood control dams are often complex. The reservoir needs to be sufficiently empty just before a flood period, in order to provide the anticipated capacity required. However, many flood control dams are also used for other purposes, which often require water storage. For this reason, rapid emptying of such reservoirs may be carried out just before the expected floods. Paradoxically, the increase in water levels downstream of the reservoir, in this case, occurs prior to the real flood. High downstream water levels may also continue during and after the flood. Flood control dams are therefore complex tools, usually equipped with large discharge outlets.



One of the principal adverse effects of such operating rules can be the decrease in the frequency of minor floods, which contribute to river cleaning.

Flood control is the primary purpose of over 170 major reservoirs (ICOLD 1984/1988). Over 100 of these are located in Germany, where an additional 50 dams also have flood control as their secondary purpose. Flood control by dikes (type 3 as specified above) is the main reason for dam construction in the Netherlands. Several of these reservoirs are also used for public water supply.

Many other dams are also used for flood control as a secondary or lower priority purpose. Approximately three-quarters of such dams were commissioned after 1960.

#### ***2.5.9. Low flow enhancement***

Low flow enhancement can have two main objectives: to provide a reliable downstream water supply and to protect the downstream river habitat (including, in some cases, a dilution effect on poor water quality). As an indirect effect, low flow enhancement can also maintain alluvial groundwater tables. In this context, the minimum compensation flow, imposed by many water authorities on dam operators, is not automatically considered as low flow enhancement, unless this is viewed as one of the dam's objectives.

In France, the Naussac reservoir, located in the upper reaches of the river Allier, is used solely for the summer regulation of the rivers Allier and Loire. Many mixed purpose reservoirs (flood control, low flow enhancement and recreation) also exist however: Villerest (Loire basin) and the Seine, Marne and Aube reservoirs (Seine basin). Questionnaire responses reveal that a total of 61 reservoirs have low flow enhancement as one of their purposes.

Two major reservoirs in Spain (Sotiel and El Vicario) are used exclusively for low flow enhancement of the rivers Olivargas (Huelva) and Guadiana (Ciudad Real). Several other Spanish reservoirs are used for low flow enhancement as their secondary purpose. Low flow enhancement is not listed as a use of reservoirs in other countries, however data concerning this aspect of dam/reservoir use may be lacking.

Although it is sometimes stated that certain reservoirs may be used to enhance flows in the event of a pollution accident and so play an important role in diluting the effects of the pollutant on the river's ecosystem, very few examples of this situation have been found in the literature.

Like flood control dams, low flow enhancement dams are specially equipped with facilities such as adjustable outlets and selective withdrawal, allowing discharges of variable values. Such facilities are not usually available in hydropower dams.

### **2.5.10. Recreation**

Recreation is often a secondary use of major reservoirs. The World Register of Dams (ICOLD, 1988) indicates that recreation is a secondary (or lower priority purpose) in over 100 reservoirs. In the UK, recreation is an important alternative use of many large public water supply reservoirs. Recreation is also likely to be an important aspect of nearly all reservoirs, although information on these smaller reservoirs is harder to obtain.

The primary purpose of over 70 reservoirs is listed as recreation (ICOLD 1988). Only a third of these reservoirs have other purposes associated with them (generally public water supply). Compared to other major reservoirs, many of these reservoirs have small capacities, in most cases less than 5 million m<sup>3</sup>. Within the major 'Complexe de l'eau d'Heure' near Charleroi in Belgium, three of the five major reservoirs are used primarily for recreation (the other two are used for transport and hydroelectricity).

Recreation can include a wide range of activities in the reservoir: swimming, other water sports (canoeing, sailing, rowing, motorboats, water skiing, windsurfing etc.) and fishing. In the Haute Isère, Verdon and Allier valleys, Electricité de France has even provided specially large discharges into the downstream river to enable major canoeing competitions to take place on a particular date (Société Hydrotechnique de France, 1986).

Recreation activities can become a very important part of the local tourist economy, although they can cause conflicts with other uses of the reservoir. The recreation season generally coincides with the period when low flow enhancement (necessitating a progressive water level drop) in the downstream river may be required, presenting a dilemma for many water authorities.

To maintain beach levels and prevent unsightly 'bare' banks, a constant water level is preferred during the recreation season. At Serre-Ponçon reservoir in France, an additional smaller upstream reservoir has been constructed with the specific purpose of providing a water body with a fixed water level for recreation. Electricité de France has also been obliged to limit motorboat sports at some of its reservoirs in order to limit significant bank erosion (Société Hydrotechnique de France, 1986).

Reservoir water quality is obviously a key factor for recreation: the 'appearance' of the water can be a strong deterrent to recreation. In particular, algae which cause strong discoloration, odours or scum are a major problem: tourists tend to flee the affected reservoirs (Larre *et al.* 1990). Moreover, a transparency of less than 1 m makes the water unsuitable for bathing, for obvious safety reasons. Blue-green algae (cyanobacteria) are known to produce chemicals which can be toxic to mammals, although there have been no confirmed human deaths directly attributable to this phenomenon. Human illnesses due to recreational activities in affected reservoirs have, however, been confirmed in many countries: common symptoms are skin irritation and gastrointestinal upsets.

Data on bathing water quality were requested in the questionnaire, but, apart from Portugal and France, very few data were received concerning this aspect of reservoir usage.

#### ***2.5.11. Fish farming and fishing***

In this context, the use is understood to mean a commercial fish farm or an important fishing locality, used for professional fishing. According to questionnaire responses and ICOLD data, no major European reservoir has fish farming or fishing described as its primary function. However, many major reservoirs are used for fishing as a low priority purpose. It is considered that fishing is likely in fact to be very common as a reservoir use, since reservoirs are often very suitable fishery habitats.

Reservoir operations can exert a great influence on the fish population. This may explain the absence of fisheries from certain reservoirs where their presence might constrain other uses. Many studies have been carried out on the natural fish populations in reservoirs. Water level variations, emptying operations, stratification, water quality and the trophic state in a reservoir are all important factors in determining the success of different fish species (Belaud *et al.* 1993). Modelling of the temperature and dissolved oxygen profiles in reservoirs suggests that the residence time and the level of selective withdrawal could also exert a powerful influence on fish populations (Travade *et al.* 1983). For migratory fish, the very presence of the dam can represent an insurmountable obstacle - the importance and efficiency of fish ladders is discussed in a later chapter.

The potential impact of a commercial fish farm on reservoir water quality may also be of concern in relation to other uses (particularly public water supply). In Scotland, it is feared that fish farm waste (food, faeces and, potentially, chemicals used in the farm) could affect the sediment and water quality in smaller pristine water bodies, although few incidents have been reported (WRc pers. comm., 1995).

#### ***2.5.12. Navigation/Transport***

Many hydraulic structures have been built on European rivers to create efficient waterway networks. Although in most cases, the structures are small, several large dams are used for this purpose. Their functions vary greatly and can be broadly grouped into the following categories:

- diversion function, where the dam diverts water into a channel
- weir function, where the dam controls water levels in the river, to permit navigation
- storage function, where the dam stores water in order to operate sluice gates

For the purposes of this study, all three types of navigation function were regrouped under the general heading of navigation. However, diversion- and weir-type dams seldom store significant volumes of water.

Approximately 50 European dams are listed as having navigation as their

highest priority use (ICOLD, 1984/1988) and a further 60 dams have navigation as a lower priority. Since the term 'navigation' may be widely interpreted, it may well be that other dams serve a navigation function as a low priority.

Many large dams used for navigation operate within a large water transport network along major rivers. For example, in Portugal, five hydroelectric dams are also used for navigation purpose along the full length of the river Douro. A similar situation can be found along the river Danube in Austria and along the river Rhône in France. Two of the hydroelectric dams along the river Rhine at the French/German border (Gamsheim and Iffezheim) are owned jointly by the two countries and also serve for navigation.

### ***2.5.13. Spoil storage***

A small number of large dams are used for the storage of spoil or waste products. These dams are not located across rivers and contain only minor quantities of water. In France, Eurotunnel/France Manche operate a sedimentation basin (Fond Pignon) which stores spoil resulting from the creation of the Channel tunnel. The dam is 40 m high and contains a total capacity of 6 million m<sup>3</sup>. In the UK, the former Central Electricity Generating Board own four dams (three of which are located in Yorkshire and one in Shropshire), which serve to store pulverised fly ash from power stations (all data from ICOLD 1984/1988).

Since these dams are not directly concerned with water as a resource and are not associated with a water reservoir, they will not be considered in any further detail in this report.

## **2.6. Lake and reservoir monitoring programmes**

### ***2.6.1. Lake monitoring***

Countries with national natural lake monitoring programmes include Denmark, Finland, Ireland, Luxembourg, Norway and Sweden (EEA, 1996). In some cases, (for example in the Netherlands), although there is no specific lakes monitoring programme, lake monitoring is included in the national surface water monitoring network programme. Regional programmes do also exist in many countries.

Important international monitoring programmes also exist for large lakes where International Commissions have been set up to coordinate action programmes. Notable examples include:

- Léman / Lake Génèva - France/Switzerland (protection, navigation, monitoring and abstraction);
- Bodensee (Lake Constance) - Austria/Switzerland/Germany (protection and abstraction);
- Inari - Finland/Norway (regulation of hydropower);

- Lugano - Italy/Switzerland (convention).

Other international cooperation programmes on specific issues also carry out or coordinate monitoring activities on lakes, such as the International Cooperative Programme on Assessment and Monitoring of Acidification in Rivers and Lakes or GEMS/WATER.

Two types of monitoring programme can be distinguished: surveys (large numbers of lakes monitoring at long intervals) and intensive programmes (smaller numbers of lakes with higher frequency monitoring). In some cases, the surveys may be carried out using remote sensing (e.g. the survey in Ireland of 360 lakes in 1989-90).

Surveys provide an indication of the general environmental state of lakes and may serve to identify specific problems for follow-up intensive programmes. Intensive programmes are generally necessary in order to be able to describe the exact environmental state of a lake, but are obviously more costly due to the higher level of detail sought. They can be used to examine seasonal effects and longer term trends.

Some examples of national monitoring programmes and their main objectives are presented below.

Table 8: Examples of national lake monitoring programmes

Country + network no.	Number of lakes	Chemical water quality	Biological status	Nutrients	Acidification	Toxicity	Comments
Denmark 1	31						nutrient loading
Denmark 2	8 (of the 31)						also heavy metals and other dangerous substances in biota, water and sediment
Finland 1	71						water quality
Finland 2	71						biological state
Finland 3	major						toxics
Finland 4	176+200						long term changes in acidification
Ireland	170						water quality
Ireland	360						remote sensing
Luxembourg	3						water quality
Norway 1	355						eutrophication
Norway 2	1005+100						acidification
Norway 3	40						Russian border area
Norway 4	210						heavy metals in fish
Norway 5	-						acidification effects on fish stocks
Norway 6	-						liming projects
Sweden 1	1000						chemical and biological
Sweden 2	85						time series
Sweden 3	15						intensive sampling
UK	-						occurrence of toxic cyanobacteria

Source: EEA, 1996

### **2.6.2. Reservoir monitoring**

Until the 1960s, monitoring concentrated primarily on two aspects of reservoir operations: prior to dam construction, the monitoring of river

flow in order to produce the optimal hydraulic dam design and, during operation, the monitoring of reservoir water level, water inflows, water outflows and in some cases water quality, in order to optimise the reservoir usage. The type of monitoring carried out, therefore, closely reflected the type of reservoir use.

As problems such as eutrophication, chemical pollution and sedimentation have become apparent in reservoirs, monitoring of the affected reservoirs and catchment areas has been stepped up in an effort to find effective solutions. Baseline monitoring of certain parameters prior to construction was also considered prudent as a preventative measure.

More recently, legislation has required that an impact assessment study be carried out for the largest dams, generally prior to construction. During operation, many monitoring studies of specific dams have been carried out in response to pressure groups (such as fishermen) or during dam emptying.

Today, detailed on-going monitoring is generally carried out in those reservoirs in which an environmental problem has been observed or in which an environmental problem is anticipated. Typical reasons for monitoring include:

- optimisation of the water resource (hydrological monitoring)
- the requirement of good water quality for the intended reservoir usage, for example, water supply, recreation (water quality monitoring)
- the reservoir is silting up (sediment monitoring)
- observed impacts on surrounding water users, for example fisheries (fauna monitoring)
- river management, when migratory fishes are present

Reservoir monitoring is carried out by a large number of diverse organisations. In contrast to river or groundwater resources, the concept of ownership is much more important for dams and reservoirs: to create the impounded water resource, a dam must initially be financed. Dam owners, who often carry out or direct reservoir monitoring, include electricity production organisations, water authorities and companies, governmental bodies at a national or local level and individual water supply companies.

Different aspects of monitoring in the same reservoirs may be carried out by different organisations. In particular, water quality and water quantity monitoring data may be collected by separate organisations.

Similarly, monitoring of different aspects of dam and reservoir operations at a national level may also be carried out by different organisations. The responses from each National Focal Point reflected this fact: in Portugal, much information concerning reservoirs, in particular, the annual water supply volumes, is already centralised in a national database.

The only national monitoring network concerning reservoir water quality is in Spain, where many reservoirs are owned by the state in any case. A

regular assessment of the trophic state of important reservoirs is carried out using in situ measurements and using remote sensing techniques.

In France, the safety of large dams is monitored and controlled by several different ministries, according to the dam's purpose. With the exception of regular reservoir emptying (compulsory by law), reservoir operations are not specifically monitored at a national level. However, the resulting data from emptying are not available to external organisations.

In Norway, it is reported that information related to the physical aspects of reservoirs is contained in four different databases: one related to ICOLD dams, another to encroachments on rivers in general, yet another to hydrological monitoring data and finally one database which serves mainly for the geographical mapping of various kinds of catchment information. A national system which divides Norway into units based on hydrometric reference areas has been developed as a key to organise data.

## 2.7. Water supply volumes

For many reservoir uses, water is 'supplied' for a certain purpose. This is the case for public water supply, irrigation, industrial water supply, hydroelectricity and low flow enhancement. The other purposes, such as flood control, recreation and fisheries do not involve water consumption and are not, therefore, considered as supply purposes. (Navigation is a special case and, depending on the dam's function, may or may not involve water supply.)

In many cases, the water 'supplied' may either be released into the downstream river, or released into a different river/catchment or another reservoir, or delivered directly to the consumer. Since the water supplied is generally the dam's 'income', water supply volumes are often closely monitored, either directly or indirectly, and, in some cases, on a continual basis. Many data should in theory, therefore, be accessible concerning this aspect of dam/reservoir operations, which is of direct interest to water resources evaluation. Water supply from natural lakes occurs, but limited data are currently available.

The total average annual water supply volume provides an indication of the actual supply situation and the importance of reservoirs on a regional or national basis. They can also be compared with the annual total river inflows for each reservoir to provide an interesting indication of water budgets.

In order to make an assessment of water supply information, the following variables are therefore required:

Volumes flowing into the reservoir:

- drainage from catchment
- pumped from elsewhere

Volumes flowing out of the reservoir

- released through dam to downstream river
- pumped to another catchment

The difference between the volumes flowing in and those flowing out represents the balance between precipitation, evaporation on the reservoir surface and leakage/inflow through the reservoir bed to a groundwater body.

However, it is important to relate these figures to the purpose of the reservoir (hydroelectric reservoirs 'supply' very large volumes of water). The allocated water supply volume for each use was also therefore requested in the questionnaire. It should be noted that these water volumes have been *allocated* to the relevant use (during design or subsequent operation review) and, depending on external factors such as annual precipitation, may not actually be required. Nevertheless, these data can provide a good indication of total resource potential for each use.

With the exception of Portugal, data concerning these variables was provided for very few reservoirs and it is therefore difficult to produce any meaningful regional comparisons.



### 3. Overview of environmental changes relating to lakes and reservoirs

In many ways, lakes and reservoirs are more vulnerable and sensitive to pollution than running waters or marine waters, since water volumes are not frequently renewed and lake morphology tends to lead to pollution accumulation. Lake water quality reflects pressures around the perimeter of the lake and, usually more significantly within the lake catchment, which may be extremely large and contain diverse potential sources of pollution, including:

- direct point sources, municipal and industrial effluents;
- diffuse agricultural sources, wash-off and soil erosion;
- diffuse urban sources, wash-off from city streets, from industrial areas, from horticultural activities;
- waste disposal sites of urban and industrial solid and liquid waste;
- riverine sources, inflow in solution or adsorbed onto particulate matter (or both);
- groundwater sources, aquifers polluted by point and diffuse sources which flow into rivers and into lake beds (bed seepage);
- atmospheric sources, direct wet and dry deposition to the lake surface amplified by erosional recycling of deposition on the catchment.

If lake water quality deteriorates, the flora and fauna may be affected and it may become unsuitable for certain uses such as drinking water supply. If water quality deteriorates in a reservoir, it may become unsuitable for its original purpose and costly measures may be required to combat the problem. It may also constitute a threat to the river system downstream.

In many European countries, it is reported that the most widespread important pollution is essentially caused by excessive nutrient input from waste water or agriculture. A second type of pollution is by chemical products, many of them toxic, such as phenols, dioxins, heavy metals, as well as hydrocarbons, radioactive substances. These are more difficult to remove than organic matter and nutrients in wastewater treatment and they also tend to accumulate in the foodchain. Solutions are therefore often more difficult to find. A third issue which affects many regions in northern Europe is acidification, where the pollution is often international and of a subtle nature, requiring major efforts to combat it.

In addition, other changes of the environment may affect lakes and reservoirs. Sedimentation can also affect reservoir usage, either because it can cause a significant reduction of the useful capacity of the reservoir, or because of its indirect effect on reservoir water quality. Lakes have

historically been affected by drainage activities, which are also described briefly in a later section.

The construction of a reservoir may cause certain impacts on the surrounding environment, including the dammed river. Artificialisation of lake shores may also cause impacts on the lake ecosystem. Some of these impacts are described in a later section of this report.

## 4. Eutrophication

### 4.1. Introduction

#### *4.1.1. Definitions*

Eutrophication is the enrichment of water by nutrients (especially nitrogen and phosphorus compounds, but also organic matter), causing an accelerated growth of algae and higher forms of plant life, to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of water concerned. In particular, the effects of eutrophication can render the water body unsuitable for uses such as public water supply and recreation, where a high standard of water quality is required.

In this report, we consider eutrophication as an imbalance in the trophogenic/tropholytic potential of any water system, including possible erratic manifestations of this phenomenon. In any eutrophic water body, nutrients tend to be used several times, especially those which are not exported out of the system. The residence time of nutrients (and the water residence time) are therefore key factors determining the trophic state.

#### *4.1.2. Eutrophication processes*

Three 'compartments' can be distinguished, generally corresponding to specific layers in the lake or reservoir, as follows.

##### **Productive layer**

The increase in the concentration of nutrients causes planktonic algae proliferation in the euphotic (surface layer) zone of lakes and reservoirs. The maximum nutrient load is therefore observed prior to the start of the photosynthesis period. Through photosynthesis in the upper layers, the oxygen and organic matter levels are affected in this way.

##### **Degradation layer**

In the hypolimnion (deeper thermal layers), where light does not reach, dissolved oxygen is consumed by the organism respiration during the stratification period, producing anoxic products. Organic matter produced in the upper layers is mineralised and settles to the bottom. Depending on the intensity of the eutrophication process, dissolved oxygen consumption usually begins during the summertime and can go on until the total depletion. The decrease in bottom layer oxygenation depends on the initial concentrations and the overturn frequency and can therefore require several years to recharge from previously low levels.

##### **Storage layer**

The phosphorus load is retained in the sediments and increases progressively (EEA, 1998). With falling oxygenation levels in the deep lake

layers (due to the mineralisation of the organic matter formed by photosynthesis in the upper layers), phosphorus is increasingly released and contaminates the neighbouring layers.

Consequences derived from the eutrophication process are in some cases the appearance of abnormal colours and bad smells, a degradation in fish diversity, changes in the composition of the populations of organisms (reduced biodiversity), and an increase in the cost in drinking water treatment plants.

## 4.2. Pressures leading to eutrophication

### ***4.2.1. Natural vs cultural eutrophication***

Considered in the context of geological timescales, natural lake basins are not permanent features of the landscape. They slowly fill in with sediment and respond to changes in their catchments in sensitive ways. Depending on climate and geology, the trophic state of natural lakes can evolve even in the absence of human activity.

In the UK, progressive oligotrophication would appear to be the usual long-term fate of natural lakes (Johnes, Moss & Phillips, 1994). Many British lakes were formed by glacial action and their bare catchments presented large surface areas for leaching. Palaeolimnological evidence suggests that lakes were initially rather fertile. As the climate warmed and vegetation developed, the supply of nutrients declined and lakes steadily decreased in fertility over several thousand years.

In contrast, progressive eutrophication can also be a natural tendency of lakes and reservoirs. Natural eutrophication can be the natural obsolescence process of the lake or reservoir that is extremely slow and irreversible. Natural eutrophication should therefore be distinguished from cultural eutrophication, which is due directly to human activities. Cultural eutrophication is more rapid than natural eutrophication, but it can be slowed down, or sometimes even reversed, by controlling the causes.

In this chapter, we focus on eutrophication caused by human activities, but it should be borne in mind that each lake and reservoir has its own natural reference state, according to its age, morphology, hydrology, geology and catchment nature.

In almost all cases, eutrophication is primarily caused by increased nutrient concentrations. However, the hydraulic residence time is one of the main factors controlling nutrient concentrations and eutrophication: flowing waters with short residence times are less prone to eutrophication than still waters with long residence times. The limiting nutrient in lakes is generally phosphorus, but in some cases, nitrogen can play an important role.

However a large number of other conditions are also important in many cases (Table 9).

The estimation of nutrient loads to a lake is not straightforward and requires a detailed catchment and sampling programme study. Data concerning nutrient loads are available for some lakes and reservoirs and their relationship to catchment area are presented in Figure 10. As can be observed in this figure, there is a very general and logical relationship between loads and catchment area – larger catchments have higher N and P loads, although there are a few catchments (bottom right corner of the graph) which with exceptionally low loads. However, there is significant variation in loads – often up to three orders of magnitude, reflecting the variable pressures on the catchment (population density, industrial activities, wastewater treatment possibilities, agricultural activities and practices, as well as natural variations due to geology and climate).

Vollenweider (1976) developed a phosphorus loading model based on a simple empirical relationship between phosphorus concentration in the lake, the hydraulic residence time and the phosphorus loads. The OECD study programme refined this model (OECD 1982) through a statistical study of a large number of lakes, expressing the relationship as:

$$[P]_{\lambda} = 1.55 \{ [P]_j / (1 + \sqrt{\tau_w}) \}^{0.82}$$

where:

$[P]_{\lambda}$  is the concentration of total phosphorus ( $\text{mg m}^{-3}$ )

$\tau_w$  is the hydraulic residence time (yr)

$[P]_j$  expresses the phosphorus loading ( $\text{mg m}^{-3}$ ) where:

$$[P]_j = L_p / q_s$$

and  $L_p$  is annual areal load of phosphorus ( $\text{mg m}^2 \text{yr}^{-1}$ )

$q_s$  is the annual depth of water received by the lake ( $\text{m yr}^{-1}$ )

However, the available data concerning phosphorus loads for this study (Figure 11) are too few to examine this relationship in detail.

#### **4.2.2. Eutrophication indicators**

Due to the complexity of the eutrophication process, which includes various physical, chemical and biological factors, it is important to take into account as large as possible number of parameters for the evaluation of the trophic state in the reservoirs. There are therefore many types of approach to indicators of trophic state.

Because of its complex and temporal nature and the difficulty of obtaining a satisfactory measurement of the biological response to nutrient increases, eutrophication is often assessed by indirect methods, such as nutrient concentrations. Although more sophisticated methods, such as algal

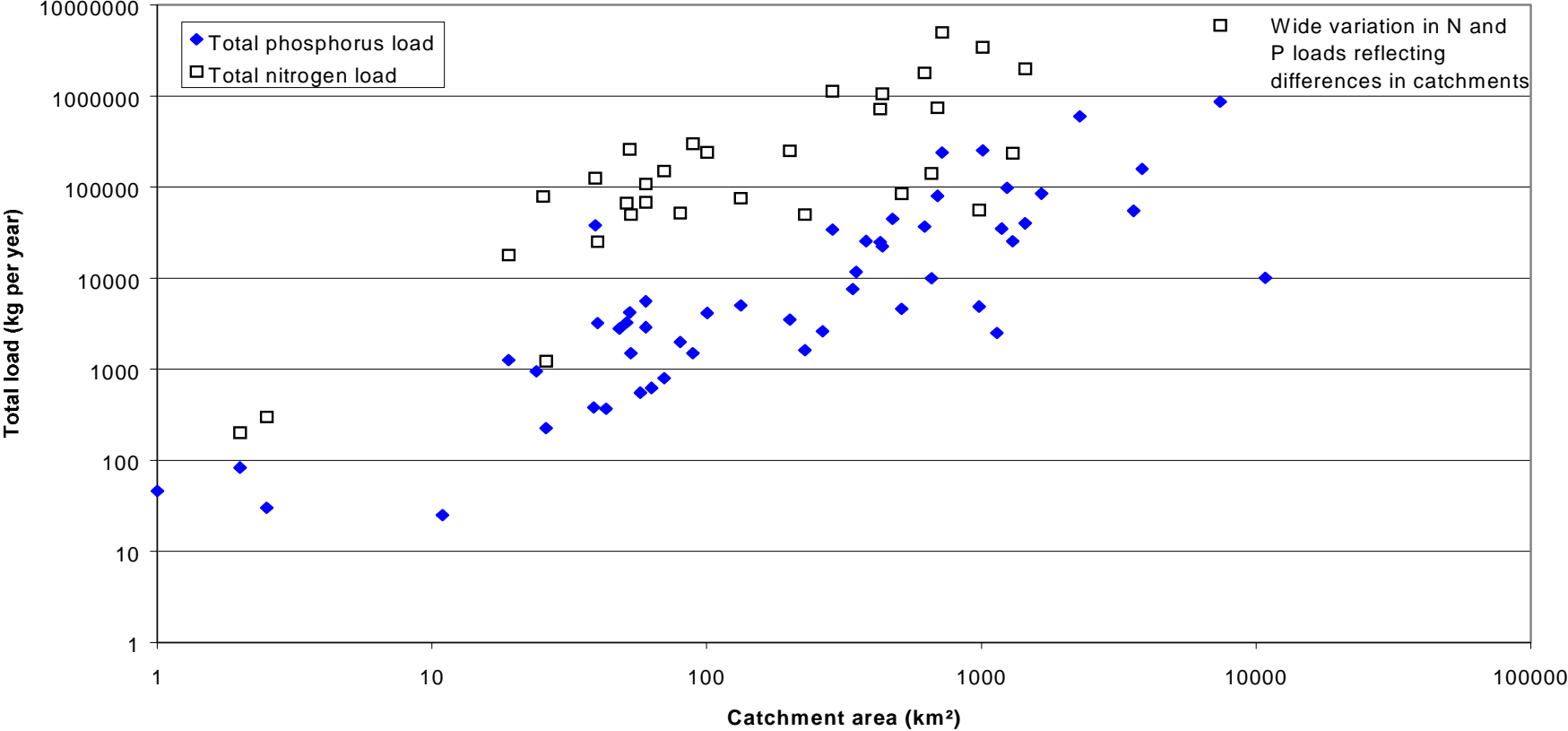
bioassays, have been developed and used in some countries, there is no 'standard' universal measurement of eutrophication in Europe.

The most widely used evaluation is based on the OECD study (OECD, 1982), which was developed using data from lakes and reservoirs from a range of geographic situations across the world. The most relevant variables were found to be the annual average/spring peak chlorophyll concentrations, Secchi disk (disappearance depth), annual average/spring peak total phosphorus and total nitrogen concentrations.

Table 9: Possible factors affecting trophic state

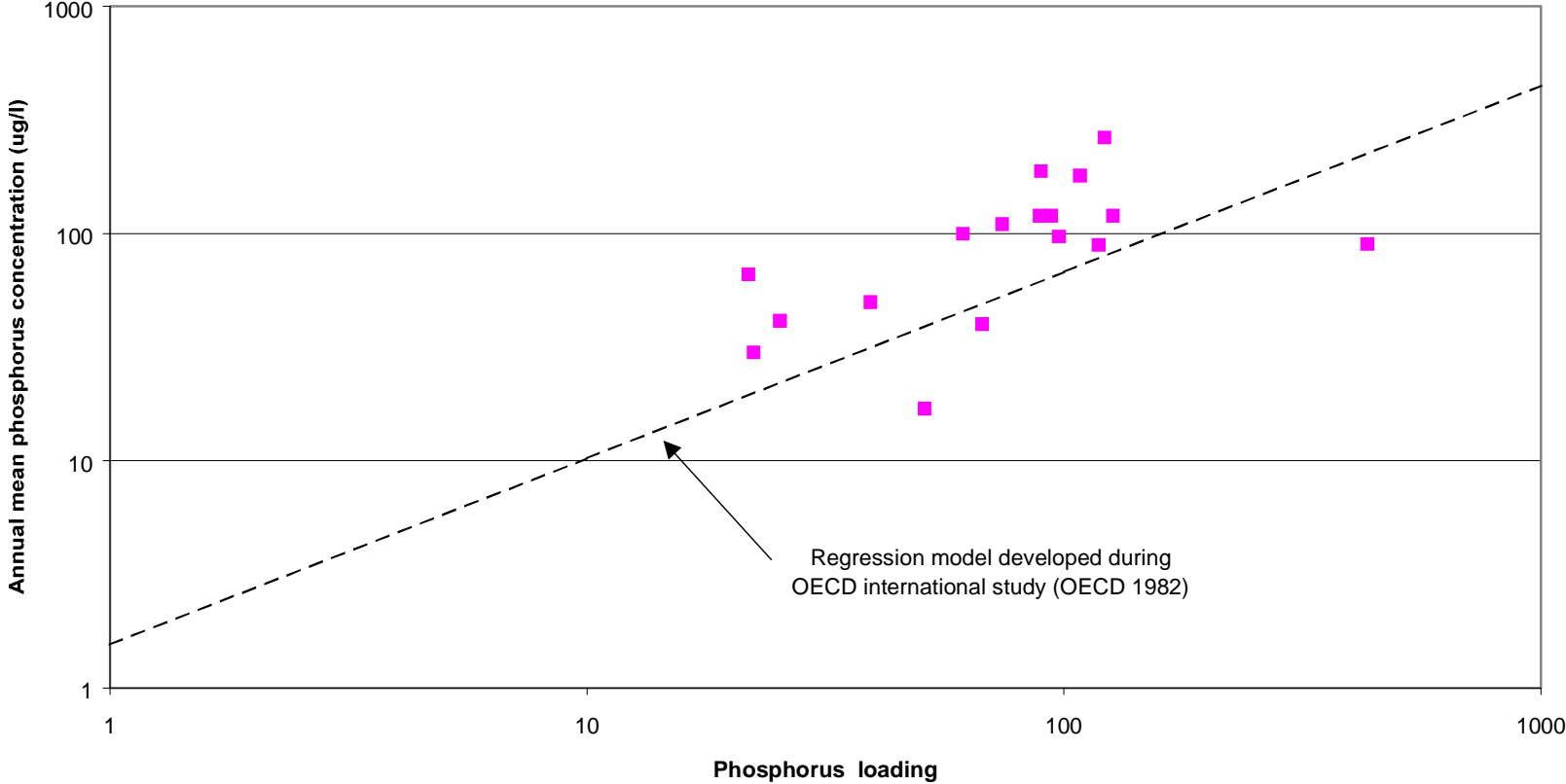
Type of condition	Condition	Factors affecting condition	Possible assessment variables
Chemical	Nutrient enrichment <ul style="list-style-type: none"> <li>phosphorus is the most common limiting nutrient</li> <li>nitrogen can be the limiting nutrient in some cases</li> <li>from urban, industrial and agricultural sources</li> <li>sediments may 'carry' nutrients</li> <li>presence of calcium reduces bio-available phosphorus</li> </ul>	Inflowing water quality	Average annual nutrient load Land use Catchment population Catchment area Precipitation
	Other chemical parameters <ul style="list-style-type: none"> <li>can inhibit algal growth</li> </ul>	Sedimentation Toxins	Average erosion rate in catchment Sedimentation rate in reservoir Geological rock types in catchment Qualitative assessment - presence of toxins?
Physical	Hydraulic regime	Volume of water body Water inflows Water outflows Water level variations	Hydraulic residence time Total annual inflows Total annual outflows
	Temperature profile	Climate Morphology of reservoir	Stratification regime
	Light availability	Turbidity (suspended solids)	Transparency (indicating light penetration)
Biological	Presence/Absence of algal grazers	Various environmental factors	

Figure 10: Relationship between catchment area and nutrient loads of lake/reservoir



Data source: most recent data available in ELDRED (updated 11/97).  
 Nitrogen data on 33 water bodies: Lac Léman, France (20 reservoirs), Germany (7 reservoirs), Finland (4 reservoirs), Luxembourg (1 reservoir).  
 Phosphorus data on 54 water bodies: Lac Léman, France (5 lakes, 24 reservoirs), Germany (10 reservoirs), Finland (4 reservoirs), Italy (6 reservoirs), Luxembourg (1 reservoir), Portugal (3 reservoirs)

Figure 11: Relationship between phosphorus loads and phosphorus concentrations



Data source: most recent data available in ELDRED (updated 11/97).  
 Phosphorus loading = annual areal phosphorus load ( $\text{mg}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ ) / (annual areal water loading ( $\text{m}\cdot\text{yr}^{-1}$ )  $\times$  (1 + hydraulic residence time<sup>-0.5</sup>))  
 Phosphorus concentration from most recent year available: Lac Léman, France (3 lakes, 9 reservoirs), Germany (4 reservoirs)



An alternative method is the Trophic State Index (TSI) (Carlson 1977), which is being used by INAG as part of their assessments of trophic state in Portuguese reservoirs (INAG 1996). There are two indexes which use measurements of biological parameters, chlorophyll a (chl a) and transparency (ds):

- $TSI_{chl\ a} = 9.81 \ln (chl\ a) + 30.6$
- $TSI_{ds} = 60 - 14.41 \ln (ds)$

Annual mean values of TSI indexes indicate eutrophic (>52), mesotrophic (45-52) or oligotrophic status (<45). These indexes are used in conjunction with information concerning annual fluctuations of chlorophyll and transparency to determine trophic state.

Full site-specific monitoring for eutrophication obviously includes many more variables than considered here: in addition to physical and chemical parameters such as conductivity, pH, temperature and oxygen, other parameters are also examined such as invertebrate indicators, macrophyte estimations, phytoplankton, zooplankton and fish population studies.

#### **4.2.3. Reference values**

Lakes have natural trophic states, against which impacts due to human activities should be compared. When using assessment criteria such as the above indicative limit values proposed by the OECD, it is necessary to take into account the likely natural phosphorus concentration. Some possible approaches are described below.

#### **Reference levels of phosphorus**

In the absence of site specific comparison values or in areas where normal pristine values are known, an absolute 'reference' value approach can be used.

Likely natural phosphorus concentrations can be estimated using the morphoedaphic index (MEI), which relates the concentration to the average depth and the conductivity or alkalinity. If we consider the difference between the OECD values (which define the trophic status) and probable natural concentrations (using the MEI), we can estimate the "excessive" concentration due to human activities, which can be subsequently adjusted to take into account water quality objectives.

This approach was described by Premazzi et al (1992) and a practical application (EEA 1998) indicated that "natural" phosphorus concentrations may vary between 3 and 25  $\mu\text{g l}^{-1}$ , depending upon the average depth and the conductivity or alkalinity. Shallow and alkaline lakes have potentially high natural phosphorus concentrations (for example up to 25  $\mu\text{g l}^{-1}$  for a lake with an average depth of 10 m and a high conductivity of 1000  $\mu\text{S cm}^{-1}$ ), which may make these water bodies very sensitive to any supplementary input, since they are likely to be naturally mesotrophic (EEA 1998).

### **Pristine reference situations**

Some data concerning the natural state of ‘pristine’ of lakes having oligotrophic status and unaffected by human activities are available (EEA 1998). In general, pristine lakes are characterised by a total phosphorus concentration of less than 25 µg P l<sup>-1</sup> (Table 10).

Table 10: Reference values of phosphorus in natural lakes (EEA 1998)

Site	Country	Number of lakes	Total P (µg l <sup>-1</sup> )
Sierra Nevada	ES	10	
Pyrenees	ES	102	~15
Tatra Mountains	CZ	10	5.7
Northern Apennines	IT	43	14
Southern Alps (Pennine-Leptine)	IT	50	19
Italian Alps	IT	320	<10 (85%)
Italian Alps Aosta valley	IT	100	
Reference-lakes, Sweden	SE	154	<15 (80%)
Forest lakes, Northern Sweden	SE	59	13.2
Forest lakes, Finland	FI	135	10
Black Forest Lakes	DE	6	

### **Baseline values**

An interesting study on possible ‘baseline’ states was carried out in England and Wales (Johnes *et al.* 1994). The baseline described in this study represents the pre-Second World War situation, before large-scale technology was introduced into agriculture. It was considered that, although agricultural impacts obviously existed before the second world war, the lake situation should better reflect the catchment nature and that this situation would reflect a more realistic objective than an absolute ‘pristine’ state. Using information concerning the pre-war Agricultural Censuses, geological databases, meteorological records and physical characteristics of the lake, regressions were used to determine an assumed pre-war baseline chemical state for each lake, against which present-day values could be compared.

Testing of this scheme using data from sometimes minimal sampling programmes suggested that nearly half of the 94 water bodies studied in England and Wales had experienced a significant change in eutrophication status (Johnes *et al.* 1994).

#### **4.2.4. Eutrophication classes**

Lakes and reservoirs are usually classified at several levels as (hyper)eutrophic, mesotrophic and (ultra)oligotrophic, according to the capacity of water body to produce a more or less abundant autotrophic biomass.

- Eutrophic lakes and reservoirs are characterised by having high concentrations of nutrients and high primary productivity. As a general

rule, they are shallow and turbid in summer due to phytoplankton and with dissolved oxygen concentration depletion near the bottom eventually leading to anoxia during the stratification period.

- Oligotrophic lakes and reservoirs have a low content in nutrients, they are less productive, more transparent, usually deeper and with high dissolved oxygen concentration in the hypolimnion.

Mesotrophic lakes and reservoirs are intermediate between eutrophic and oligotrophic.

Models such as those established by Vollenweider (1976) and Dillon & Rigler (1975) provide a relation between the phosphorus load and the biomass produced by photosynthesis. These models were in fact developed from observations concerning the biomass/phosphorus concentration relation and from the theory that phosphorus concentrations can be deduced from known phosphorus inputs. Even though the models are approximate, they enable us to define reasonable excessive nutrient loads for any particular lake.

Using the classification system in the table below developed from OECD (1982), the trophic state of reservoirs can be assigned as the probability for a given water body to belong to one of the five classes (ultra-oligotrophic, oligotrophic, mesotrophic, eutrophic and hypertrophic), according to the average annual total phosphorus concentration or the average annual total chlorophyll a concentration and according to a stochastic approach.

Table 11: Limit values proposed by the OECD for a trophic state classification system (OECD, 1982)

Trophic Level	Mean Chl.	Max. Chl	Total P	Mean Sec.	Min. Sec.
Ultraoligotrophic	< 1,0	< 2,5	< 4,0	> 12,0	> 6,0
Oligotrophic	< 2,5	< 8,0	< 10,0	> 6,0	> 3,0
Mesotrophic	2,5 - 8	8 - 25	10 - 35	6 - 3	3 - 1,5
Eutrophic	8 - 25	25 - 75	35 - 100	3 - 1,5	1,5 - 0,7
Hypertrophic	> 25	> 75	> 100	< 1,5	< 0,7

Mean Chl. = mean annual Chlorophyll concentration in epilimnion ( $\mu\text{g l}^{-1}$ )

Max. Chl. = peak annual Chlorophyll concentration in epilimnion ( $\mu\text{g l}^{-1}$ )

Total P = mean annual Total Phosphorus concentration ( $\mu\text{g l}^{-1}$ )

Mean Sec. = mean annual Secchi disk depth transparency (m)

Min. Sec. = minimum annual Secchi disk depth transparency (m)

#### **4.2.5. Data availability**

In anticipation of the data likely to be available across Europe, a simplified approach to eutrophication assessment was adopted in the questionnaire. A limited number of determinands, which are most commonly measured in lakes and reservoirs, were requested.

In all cases, annual average concentrations of total phosphorus, total nitrogen, chlorophyll a and Secchi disk transparency depth were requested. In the nutrients questionnaire (Dobris+3 water questionnaire), summer averages of these parameters were also requested. The major reservoir

questionnaire was more detailed and some additional parameters were requested. In addition, a qualitative assessment of the occurrence of eutrophication phenomena such as toxic algae, fish kills and sediment quality problems, was requested.

Lake and reservoir water quality monitoring is sometimes carried out on an irregular basis - for some lakes and reservoirs, the most recent data date back to the 1970's. For this reason, the most recent available data on each lake has been used to maximise the number of lakes included in the assessment. Historic data to show possible trends was also requested in the Dobris+3 questionnaire (e.g. 5 year intervals since 1975).

#### ***4.2.6. Assessment of status data provided by NFPs to ETC/IW***

Concentrations of annual mean total phosphorus for selected important lakes for the most recent year available are shown in Figure 12. It can be seen that the majority of these lakes has concentrations of total phosphorus over  $25 \mu\text{g l}^{-1}$  and in many cases, the concentration exceeds  $125 \mu\text{g l}^{-1}$ .

The N/P ratio for annual average values can indicate likely eutrophication and suggest which is the possible limiting nutrient in the system.

Figure 13 shows the general relation between N/P ratios and annual mean total phosphorus concentrations. Where the Redfield ratio (the assumed 'normal' algal growth N/P of around 8 to 12) is exceeded, lakes are generally P-limited and algal populations are characterised by diatoms and chlorophyceae. Lakes with higher phosphorus concentrations are however characterised by low N/P ratios and the probable excessive development of nuisance algae such as certain cyanobacteria, typical of eutrophic lakes.

Figure 14 integrates values according to several types of parameter to indicate the most likely trophic state for lakes and reservoirs in the ELDRED database. Despite the absence of data for many regions, the widespread nature of eutrophication can be observed.

### **Regional discussions**

The following discussions are based on contributions or literature review of general situations concerning eutrophication in various European countries. A special contribution to this report by CEDEX (Spain) describes in detail the particularly serious situation of eutrophication in Spanish reservoirs.

#### **Finland**

In the early 1990s, the eutrophication situation was observed to be worsening slowly in Finland. Although the load by industrial effluents and sewage has declined, the level of suspended matter and the increasing electrical conductivity indicate that the lakes are deteriorating. There were an exceptional number of algal blooms in Finnish inland water during the 1980's, which may be attributed to abnormally high levels of rain and

snowfall (causing increased leaching and run-off), as well as warmer than average summers (promoting algal growth).

### Norway

Water quality monitoring of reservoirs in Norway is reported to be limited because most reservoirs are located in remote unpolluted areas with practically no human activity in the catchments. The majority of reservoirs are understood to be considered oligotrophic.

Figure 12: Annual mean total phosphorus concentrations in a selection of European lakes and reservoirs. Data source: National Focal Points (replies to Dobris+3 questionnaire)

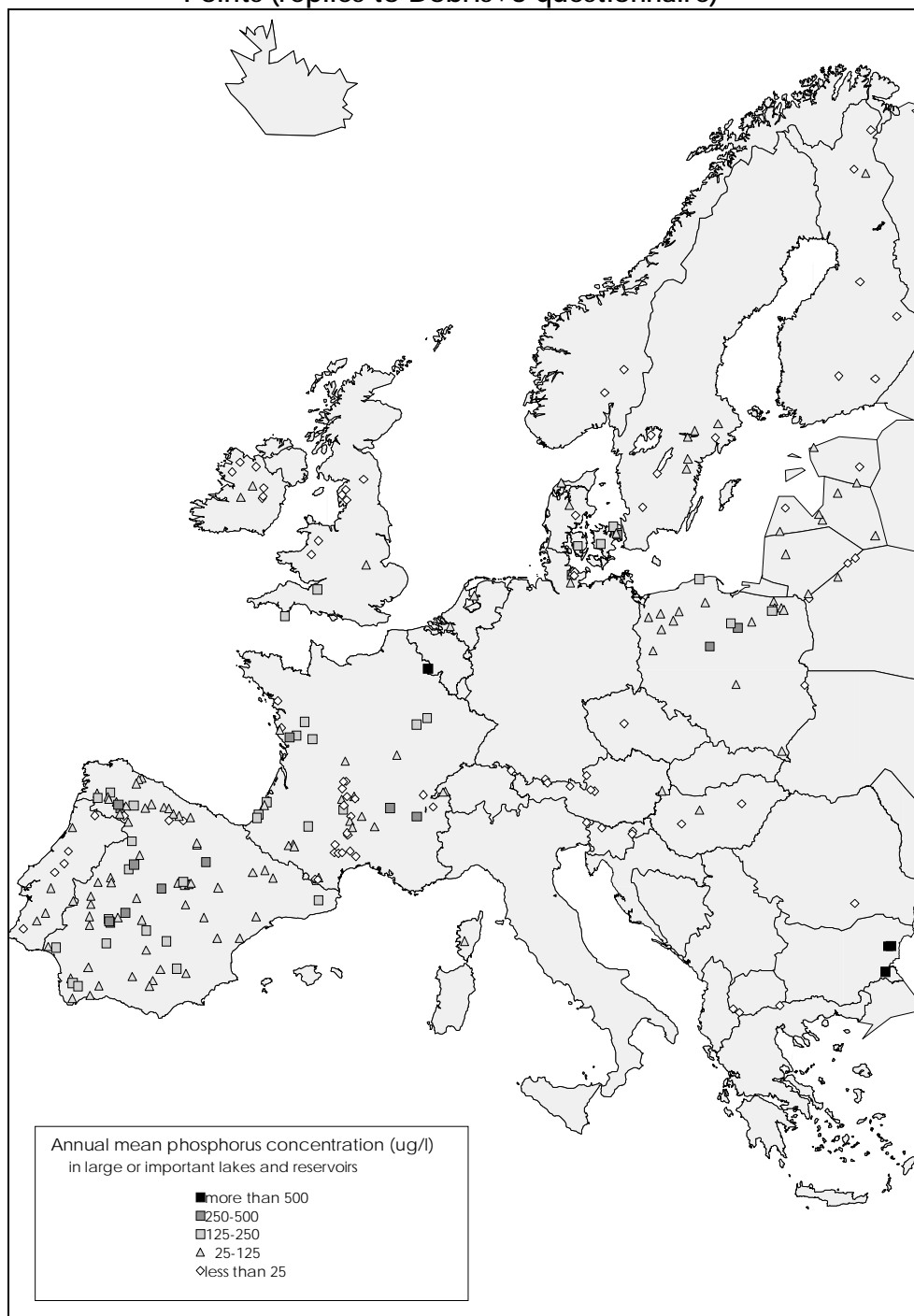


Figure 13: Nitrogen / phosphorus ratios in European lakes and reservoirs

Data source: available data in ELDRED, updated 11/97

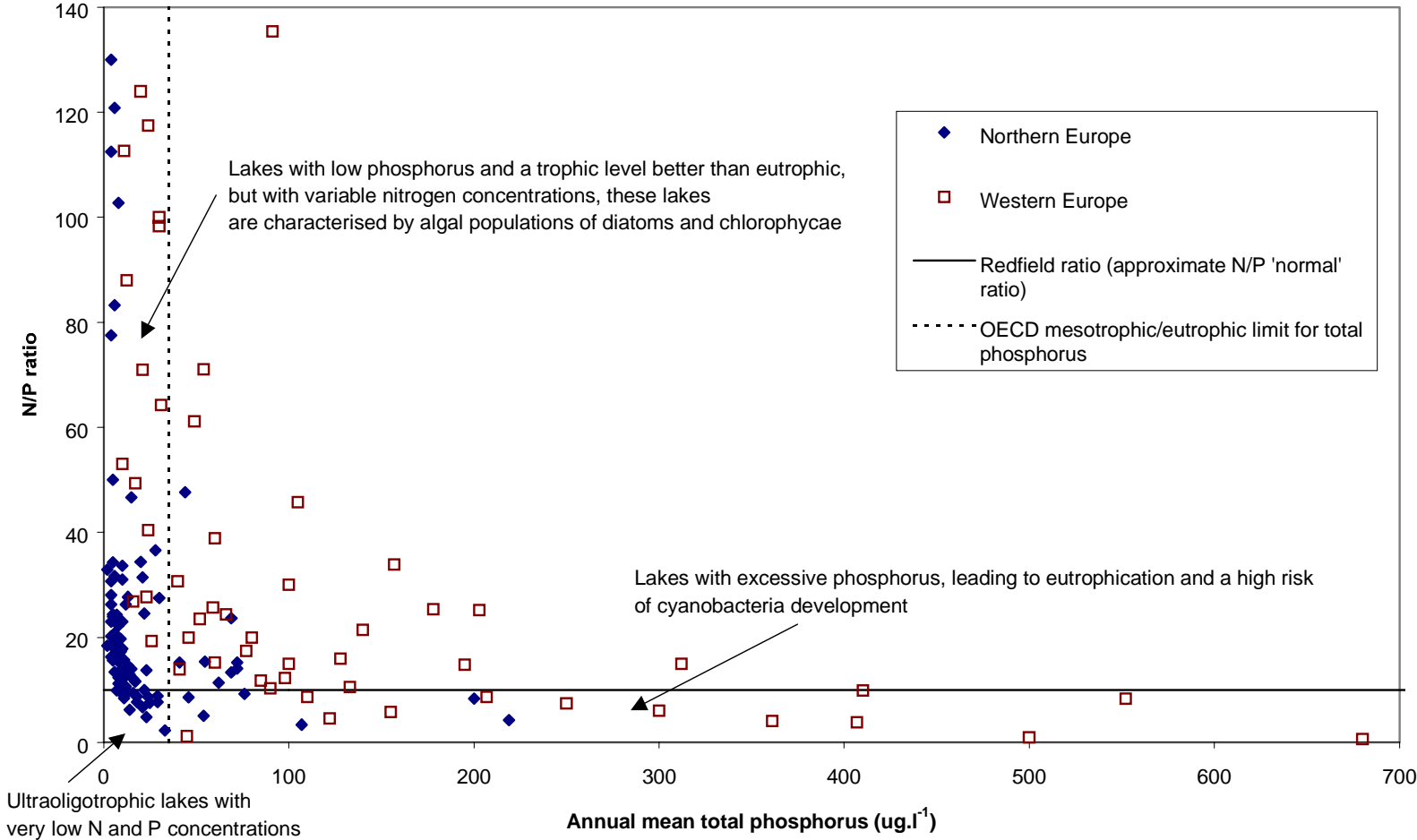
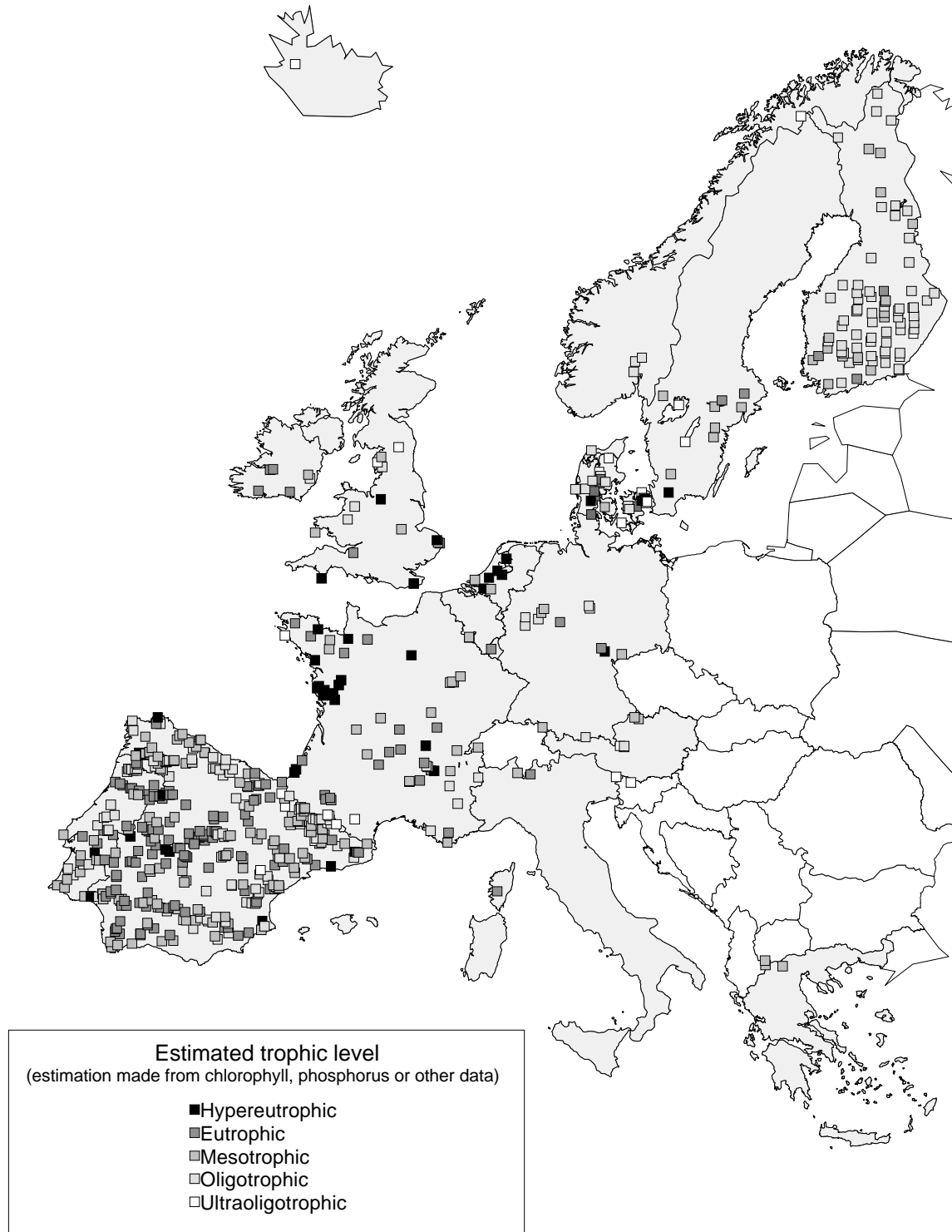


Figure 14: Estimated trophic state of lakes and reservoirs in ELDRED



Map includes all lakes and reservoirs for which appropriate data area available in ELDRED (11/98). Where available, information provided on trophic state, determined according to the OECD classification or other method (e.g. remote sensing survey) has been used. Where this classification has not been available, data concerning most recent summer chlorophyll a values or most recent annual mean total phosphorus values have been used.

### Ireland

Two large lakes in Ireland have been showing signs of increasing eutrophication over the past decades, believed to be mainly due to intensification of agriculture. Both Lough Derg (117 km<sup>2</sup>) and Lough Ree

(105 km<sup>2</sup>) in the Shannon watershed have shown progressive deterioration in water quality over the last twenty years (Bowman *et al.* 1993, Bowman 1996). Preliminary inspections in the early 1970s found moderate enrichment and the lakes were considered to be transitory between mesotrophic and eutrophic in the late 1970s/early 1980s. Studies during the 1980s and 1990s suggest a significant increase in the development of planktonic algae in Lough Derg - a key indication of eutrophication - and high concentrations of nutrients (average total phosphorus concentration in 1991-1992 of 43 µg l<sup>-1</sup>). Increased algal development was also observed in Lough Ree over the last decade. The deterioration in water quality has had an adverse impact on the beneficial uses of the lake and has led to concern about its future as a public amenity. The causes are increasing intensity of agricultural practices and increased levels of soil phosphorus. Increasing phosphorus concentrations have also been observed in Lough Conn (north and south lakes) in County Mayo, similarly believed to be due to intensification of agriculture.

### **Austria**

AWW reports that the main function of Austrian dams is hydropower production (more than 99% of Austria's drinking water supply is provided by groundwater resources). In general, there is a lot of data about water quantity, but dam operators do not carry out observations on water quality. A considerable number of dams are located in sparsely populated Alpine regions or along rivers, where water is stored for short periods of time only. In the lower parts of Austria, hydroelectricity reservoirs are also used for recreation purposes: AWW report that the short periods of water storage here as well, generally mean that eutrophication is not a problem.

### **France**

An extensive study of 95 natural lakes and 84 reservoirs used for public water supply carried out in France led the authors to estimate that approximately half of the water bodies located in low- or mid-altitude (less than 1000 m) are eutrophic (Meybeck *et al.* 1987). The principal cause was considered to be nutrient concentrations, often found to exceed the natural levels by a factor of ten. Data recently acquired on lakes and reservoirs in France would appear to indicate that this situation has not evolved significantly.

### **Italy**

A study of Lake Como (Chiaudani *et al.* 1993) in 1991-1992 indicated that the trophic condition of the lake has evolved positively in the previous ten years. After stable phosphorus concentrations of around 60 to 70 µg l<sup>-1</sup> during the 1970s, there was a marked decrease during the 1980s with an average annual decrease of 3 µg l<sup>-1</sup>. The western basin of the lake is now classed as being probably meso-eutrophic, while the south-eastern axis of the lake is probably mesotrophic. The natural trophic state of the lake, estimated using the MEI model, is considered to be oligotrophic (7.5 µg l<sup>-1</sup>), however a realistic long-term water quality objective of mesotrophy (corresponding to a phosphorus concentration of around 16 µg l<sup>-1</sup>) has



been proposed, taking into account the current loads and the possibilities to reduce them.

A comprehensive study of the water quality of Italian lakes and reservoirs, was reported in 1985 (Gaggino *et al.* 1985). Data relating to eutrophication status were available for a selection of 82 lakes and 55 reservoirs (including all the major Italian lakes), and led to the following conclusions.

- Phosphorus is the principal nutrient responsible for eutrophication, being the limiting factor in 85% of examined cases (7% of cases suggested that nitrogen was the limiting factor and 8% of cases had no particular limiting factor);
- Using the OECD classification according to phosphorus concentrations, 10% of the water bodies could be classed as being hypertrophic and 30% could be considered as eutrophic. Of the rest, 40% of lakes and reservoirs were mesotrophic and 18% were oligotrophic or ultraoligotrophic;
- Using data concerning catchment population and renewal times of the lakes, theoretical estimations of external phosphorus loads were made for 69 lakes and reservoirs. Comparison of these loads with “acceptable” loads calculated using the OECD relationships indicated that over 75% of these lakes and reservoirs were receiving loads greater than permissible for mesotrophic conditions, in some cases the estimated load was over 10 times higher;
- Of the lakes receiving higher than permissible loads, it was considered that approximately half could recover if loads were reduced - in particular, loads would be suitably reduced through the application of the 319/76 law which imposes a limit of 0.5 mg l<sup>-1</sup> for total phosphorus in wastewaters in lacustrine catchment areas.

In Sicily, a different study has thoroughly examined 31 water bodies (Calvo S *et al.* 1993). Data are treated according to a specific trophic index, not directly translatable to OECD 1982 trophic states. Nevertheless, a rough analysis suggests that 26 of these water bodies are created by large dams and that 1 (1 large) is oligomesotrophic, 4 (4 large) are mesotrophic, 21 (17 large) are meso-eutrophic (80% being more eutrophic than mesotrophic and 5 (4 large) are hypertrophic. Qualitative data available for Sardinia suggest that eutrophication of impoundments is also a major issue.

### **Portugal**

The most recent data provided by INAG (generally from 1990-1994) concerning the trophic state of 51 reservoirs indicates that 19 are eutrophic and 2 are hypertrophic. Many of these reservoirs are used for recreation purposes. A recent detailed study (INAG 1996) of trophic state of 9 reservoirs in northern Portugal indicates that 2 have an advanced eutrophic state (of which one continues clearly to be worsening), 3 are in an eutrophic state, 2 are mesotrophic (of which has a worsening trend), and only 1 is oligotrophic (and even here there seems to be a tendency towards eutrophication).

#### ***4.2.7. Eutrophication in lakes and reservoirs in Spain***

##### **Natural lakes**

Spain is a country with a great number of small natural water bodies and there are also some large lakes. Two natural lakes with considerable volumes are the lake of Sanabria, of glacier origin and fairly oligotrophic (Del Pozo, 1996) and the lake Bañolas, of karstic origin and also oligotrophic (Planas, 1973).

The rest of lakes and existing lagoons or ponds are mainly of smaller size, presenting a great diversity not only morphologic and genetic, but also functional. They show a wide range of trophic states, from the numerous ultraoligotrophic lakes in the mountains to the hypertrophic lakes in some endorheic basins (basins where the rivers do not reach the sea).

##### **Information about trophic state in Spanish reservoirs**

In general, trophic state and limnology has been studied more in reservoirs than in the natural lakes in Spain, especially when we consider the numbers studied - more than a thousand Spanish reservoirs have been studied, representing a very high percentage of the total volume of the inland water bodies in the country.

The parameters of most significance used to determine the trophic state in Spain are the concentration of chlorophyll a, the total phosphorus concentration and the Secchi disc transparency.

The evaluation of the trophic state in the Spanish reservoirs has been mainly based on these parameters. In the cases where the diagnoses by different parameters do not agree, preference has been given to the concentration of chlorophyll.

For the determination of the trophic degree of the Spanish reservoirs the information available since 1990 has been taken into account, as follows.

- Mainly the Limnological Surveys carried out effected by CEDEX (1990 - 1997).
- Information obtained from the Landsat Thematic Mapper imagery (TM sensor in the Landsat 5 satellite) through the remote sensing projects developed by CEDEX on whole water bodies in the Ebro (1990), Guadiana (1991), Tajo and Duero (1992) basins.
- With the purpose of updating all the existing information on eutrophication processes has been collected from various organisms or research centres. Amongst these, information has been provided by the EMASESA, Municipal Water Supply Company of Seville (1996), the Canal de Isabel II (1995-1996), Municipal Water Supply Company for Madrid Metropolitan Area, and Palma de Mallorca Waste Water Treatment Company (1996), the Mancomunidad de los Canales del Taibilla (1995), the Consorci Ter-Llobregat (1991), Iberdrola, Electrical Power Supply Company (1990 - 1996), the Granada University (1996), the University of Santiago (1996), the Confederaciones Hidrográficas (River Basin Authorities) of the North,

Duero, Guadiana, Guadalquivir, Júcar and Ebro, as well as the studies accomplished by the Local Government in Guipúzcoa (1993), the Consorcio de Aguas of Guipúzcoa (1995), the Water Supply Companies of Añarbe (1996) and Bilbao (1994).

- Exceptionally, in those reservoirs for which recent data are not available, studies effected by the Department of Ecology in the Barcelona University (1988) have been used.

#### **Assessment of trophic state in Spanish reservoirs**

In spite of the fact that the data are very disparate in time and the differences in the nutrients concentrations in wet and dry years are considerable, the reservoirs has been classified in five categories. For reservoirs studied by both remote sensing and limnological survey, if the trophic degree is not coincident, the survey result has been taken as valid, because the survey considered all the water column whilst the remote sensing refers only to the surface of the reservoir and to the moment when the images were taken.

The table below summarises the trophic state of the reservoirs by river basin. The total volume studied ( $49.684 \text{ hm}^3$ ) represents 92% of the total reservoir volume in Spain ( $53\,808 \text{ hm}^3$ ). This sample is judged to be sufficiently representative for the complete set of Spanish reservoirs.

Figure 15 demonstrates the volume of degraded water bodies, (eutrophic + hypertrophic) with respect to the total volumes in each basin (considering the reservoirs at top fill level). It appears that the reservoirs with the worst situation are those of the Tajo (68%), Internas Catalanas (67%), Galicia Costa (64%) and Duero (57%). This means that an estimated 48% of the total volume of the Spanish reservoirs is found in an advanced eutrophication state.

In considering the trophic level of reservoirs with a volume greater than  $10 \text{ hm}^3$  (Figure 16), it appears that most eutrophic reservoirs are located in the lower sections of the main rivers, downstream of the large urban areas, for example:

- in the Tajo, Castrejón, Azután, Valdecañas and José María de Oriol, due to the waste water from Madrid and Toledo;
- in the Duero San José reservoir, Villalcampo, Almendra, Aldeadávila and Saucelle which receive mainly the effluents from Valladolid, Zamora and Salamanca;
- in the Júcar basin, the reservoirs of Forata on the Magro river that receive the effluents from Requena and Utiel and Beniarrés in the Serpis river in the Alcoy zone.
- in the Guadalquivir basin, the Alcalá del Río, Cantillana, El Carpio and Marmolejo reservoirs are affected by catchments with population, agriculture and important cattle-raising.

The oligotrophic reservoirs, on the contrary, are located mainly on headwater rivers with low population density in the catchments.

Table 12: Percentages of each trophic state of the reservoirs grouped by big river basins

BASIN	RESERVOIR				TROPIC degree (n° of reservoirs)				
	N°	N°/%*	hm <sup>3</sup>	V/%*	U	O	M	E	H
NORTE I	28	53	2.986	98	0	4	12	10	2
NORTE II	15	56	523	94	0	1	12	2	0
NORTE III	9	28	109	89	0	5	4	0	0
GALICIA COSTA	6	27	620	90	0	2	2	2	0
DUERO	49	73	7.628	99	0	10	15	11	13
TAJO	117	59	10.998	99	1	10	27	53	26
GUADIANA I	45	50	7.881	93	0	17	16	11	1
GUADIANA II	25	69	644	94	0	18	6	1	0
GUADALQUIVIR	41	38	6.618	81	0	6	17	18	0
SUR	11	30	909	78	0	1	8	2	0
SEGURA	12	44	811	71	0	3	5	4	0
JÚCAR	22	47	2.845	85	0	4	7	6	5
EBRO	116	77	6.485	96	3	66	33	14	0
C.I.CATALANAS	7	50	616	89	0	2	1	3	1
BALEARES	2	100	11	100	0	0	2	0	0
TOTALS	505	49	49684	92	4	149	167	137	48

\* = Referred to the whole basin; UO = Ultraoligotrophic; O = Oligotrophic; M = Mesotrophic;

E = Eutrophic; H = Hypertrophic

N / % percentage of number of reservoirs studied to number of reservoirs existing in basin

V / % percentage of volume of reservoirs studied to volume of reservoirs existing in basin

Figure 15: Proportion of degraded water volumes in reservoirs in Spanish basins

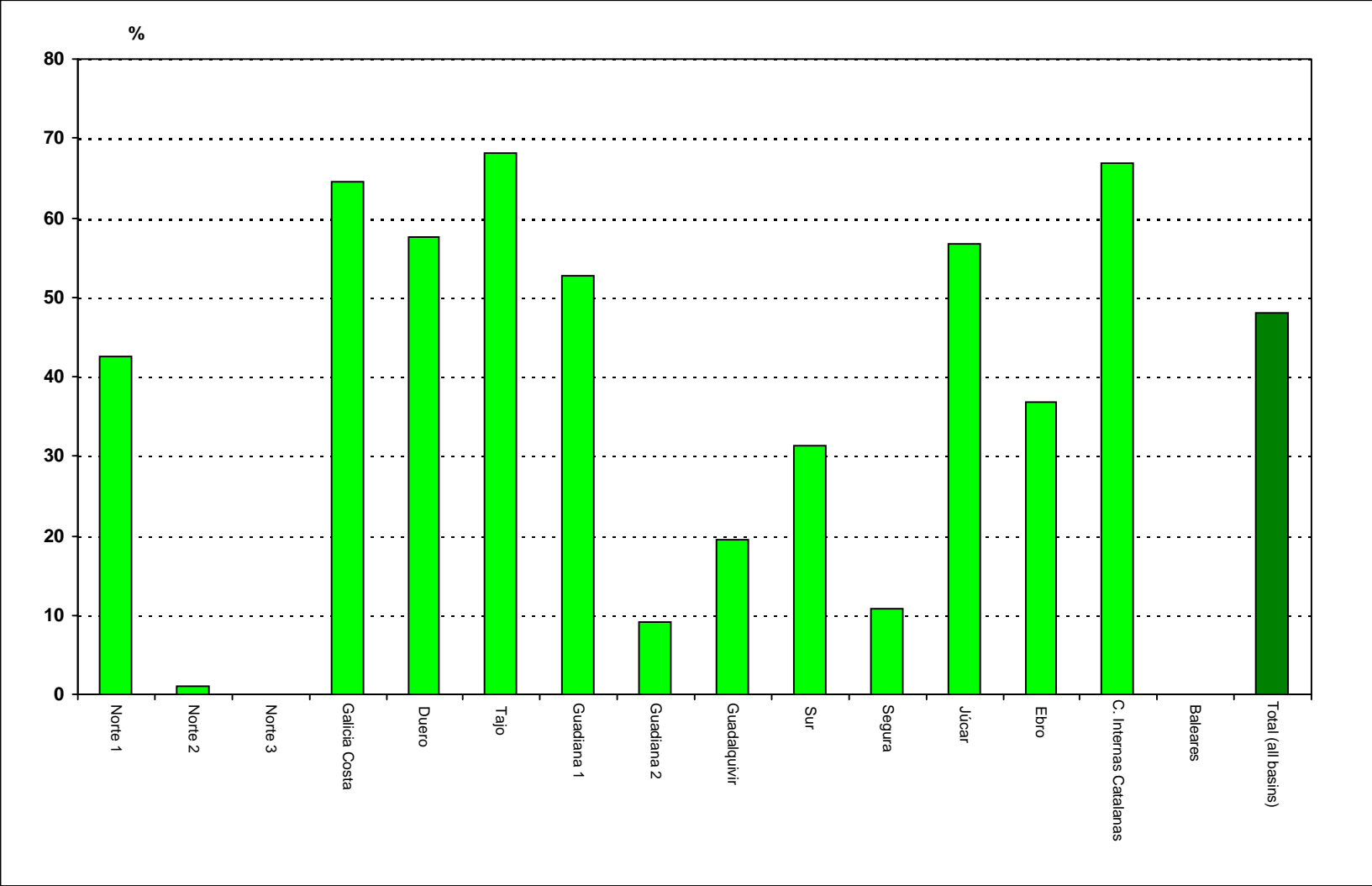
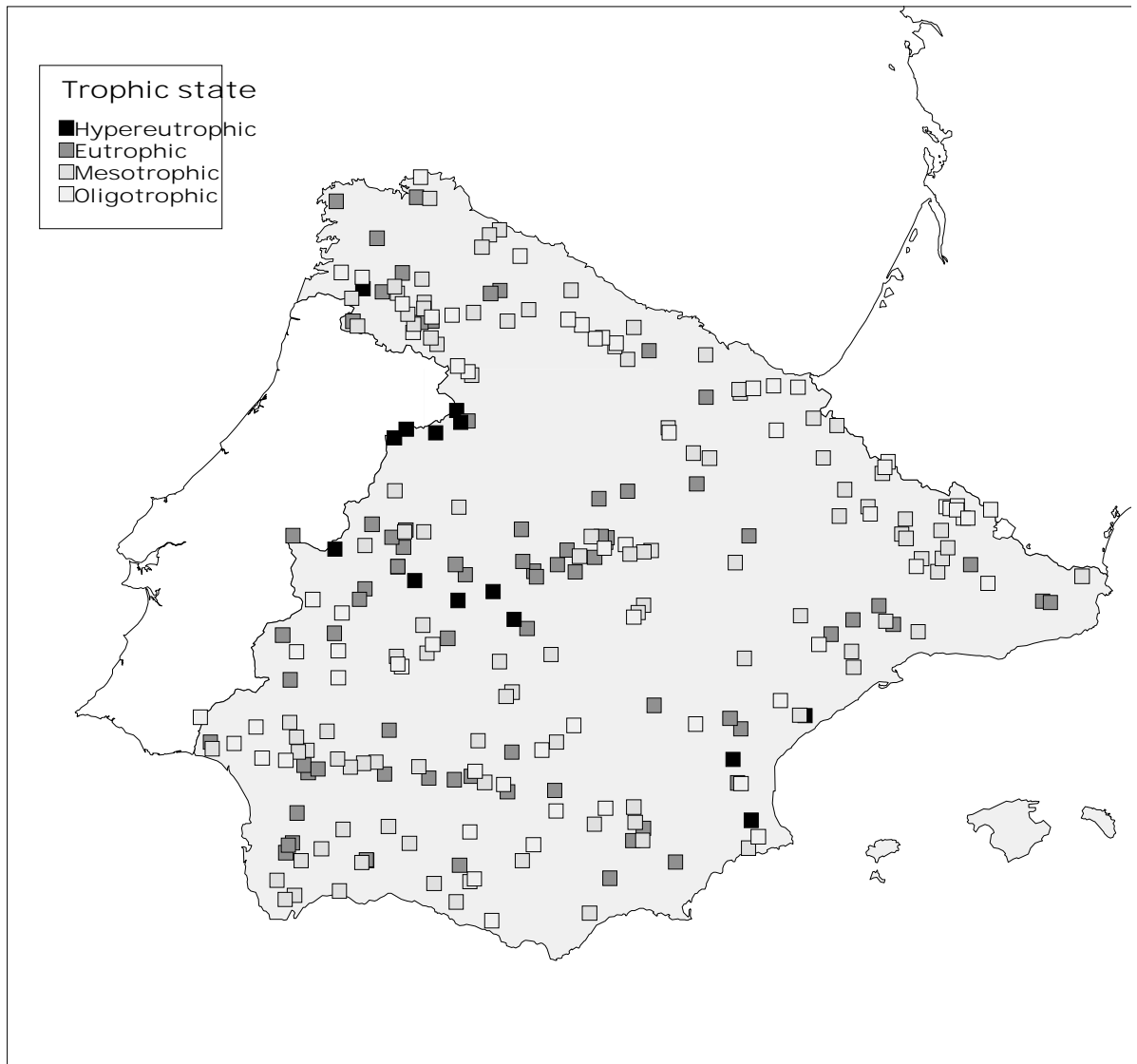


Figure 16: Trophic level of Spanish reservoirs (volumes greater than 10 hm<sup>3</sup>)



Source: CEDEX (for Ministry of Environment) 1997

### Comparison with water quality objectives

Though the figure of the 48% of the total reservoirs volume which is eutrophic could seem rather high, it should be put in the perspective of the water use required. The consideration of the eutrophic water as bad or oligotrophic waters as good, depends on the reservoir use and quality objectives have to be established according to the reservoir function. Thus a reservoir for water supply should have a water quality such that it could be treated with conventional methods at low cost. In fact, of the total volume of estimated degraded water (23.889 hm<sup>3</sup>), only 14% of total (3.344 hm<sup>3</sup>) is used to supply water.

Other criteria may be important for other uses. The water used for bathing should be free of planktonic undesirable organisms that can cause allergic skin reactions or other diseases. For waters intended for agricultural uses, i.e. irrigation, an excess of nutrients should not in principle be considered

as a problem, because it represent a free contribution of nutrients, though they can produce some secondary problems such as the enhanced growth of macrophytes in the irrigation channels.

The proportion of the volume of the water supply reservoirs (12.494 hm<sup>3</sup>) that is found in an acceptable state for use is 73%. It is observed that the proportion of the volume below the advisable levels is relatively low (27% of the total water supply volume is unsuitable for the desired use).

### **Trends in trophic state of Spanish reservoirs**

There are many studies related to the evolution of the trophic degree of Spanish reservoirs. The Ecology Department of the University of Barcelona (1990) has worked on an limnological evaluation of the state of the reservoirs. This compares the data from the first evaluation, in 1976 by the same Department, with the information taken in 1988 on the same reservoirs. In general terms, we observe an increase in the eutrophic level.

CEDEX studied over 60 reservoirs for the first time during the period (1973-1976) and repeated the study during 1986-1990. The results show that 54% of the reservoirs have increased in terms of eutrophication degree, 40% are found in the same state and only 6% have reduced in their trophic level (CEDEX, 1997).

The Consorcio de Aguas de Bilbao has carried out a study of the reservoirs in the Zadorra river system (1984-1994) and though at present are classified as mesotrophic, the trends of evolution is toward more eutrophic, mainly in Ullibarri-Gamboa and Urrunaga reservoirs.

### **Control strategies for Spanish reservoirs**

It is necessary to establish regulations to control eutrophication, according to the reservoir's purpose. The same degree of quality is not required for water supply of a population as for irrigation. For that reason, eutrophication control strategies should be directed to preserve in the best condition as possible the quality of the water to be used, mainly to cover the needs of the zones considered as sensitive (supply, bathing, etc.). These strategies should be based mainly on reducing the nutrient loads from the basin to the reservoir. If possible, the construction of the infrastructures and plants to improve the quality of rivers in Spain should be continued and increased in order to reduce the load of nutrients entering the reservoirs.

In general terms the most significant actions in Spain are as follows:

- improved wastewater treatment including phosphorus precipitation;
- reduction of phosphorus from main point sources;
- reduction of phosphorus from non-point sources;
- measures to control eutrophication effects in the water bodies.

The last category of measures to control eutrophication include macrophyte control in irrigation ponds using herbivorous fish as well as the

hypolimnetic oxygenation in anoxic reservoirs. Both practices have been developed by CEDEX in Spain during the last years, as follows:

- Fish introduction has as a goal the removal of aquatic weeds by biological methods in irrigation ponds, using the called green carp, grass carp or white samur (*Ctenopharyngodon idella*). These have been introduced with success from 1993 in El Ejido (Almería) and Fuente Alamo (Murcia).
- In the Pinilla reservoir (Madrid) (1995 & 1996), which is part of the Canal de Isabel II reservoir system, an hypolimnetic oxygenation system has been constructed and is operating. Liquid oxygen is used to reduce the problems due to iron and manganese present in the reservoir especially in the stratification period.
- Also in the Guadiana river basin the water authorities have operated aeration in the hypolimnion in Zújar reservoir (1994), and oxygenation systems in Zújar, Vicario and Alange reservoirs (1995), trying to reduce the anoxic conditions derived from the long dry period in the country.

#### ***4.2.8. Trend data***

For certain lakes, good historic data are available – some data have been presented in Figure 17 for selected large lakes. The graphs should only be interpreted in terms of the changes presented, as the lakes included are selected for their long time-series rather than for their representativity. The graph has been divided into three on the basis of initial phosphorus concentration.

These graphs suggest that the clean lakes have generally remained unchanged, intermediately polluted lakes shows diverse trends and the most polluted lakes have improved since the 1980s.

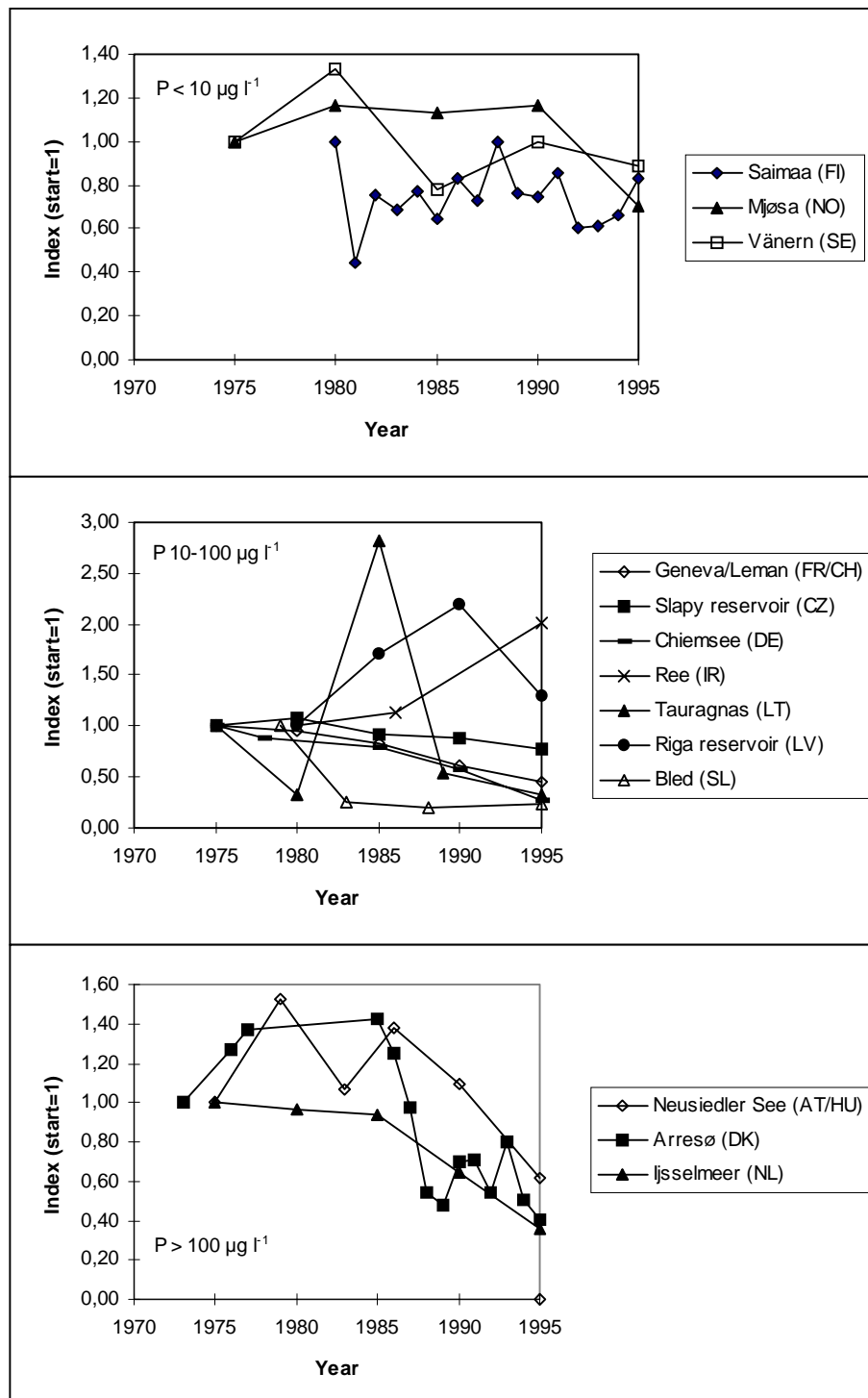
Certain lakes have been the subject of detailed studies and efficient action programmes to reduce nutrient loads in the catchment and several are showing signs of improvement. Overall improvements in wastewater treatment may have also improved the situation for some lakes in the 1980s and 1990s.

However, because of the inertia in still water systems and the accumulation effects of phosphorus in sediments, degradation may continue even if measures are taken to reduce pressures on the catchment. Some of these lakes will require several decades and strong preventive and curative measures for restoration.

Nevertheless, the state of European lakes and reservoirs is of concern, since the situation seems to be worsening in many other lakes with previously moderately or low pollution levels.



Figure 17: Temporal trends in selected European lakes with low, intermediate and high phosphorus concentrations



Unfortunately, the current general lack of good geographical and historical data makes regional comparisons at a European scale problematic and the currently available data are probably rather unrepresentative (data are generally more available for lakes having problems than those without problems).

### 4.3. Impacts due to eutrophication

#### **4.3.1. Impacts and water quality objectives**

Eutrophication can impact important ecological functions of still waters, as well as the possibilities for use of the water resource by humans. The significance of eutrophication impacts depends on the desired use of the lake or reservoir. Table 13 specifies the different types of uses of the water according to the trophic degree. The proposed trophic states do not take into account the downstream receiving water body.

#### **4.3.2. Ecological quality**

Eutrophication produces a shift in the biological structure of the lake or reservoir. A growing phytoplankton community feeds on the increased amounts of available nutrients and produces a turbid environment, which affects higher life forms, including certain fish species. The decaying phytoplankton, too abundant for the algal grazers to decompose, reduces dissolved oxygen concentrations, which may become too low to support fish and benthic invertebrates. The low dissolved oxygen also tends to enhance the release of additional phosphorus from the sediment, thereby increasing the available nutrient concentrations. Dissolved oxygen and pH in the surface layers often show significant daily variations, due to the response of the algal community to photic variations. Under these conditions, the lake/reservoir ecosystem changes drastically and generally experiences a significant reduction in bio-diversity.

Significant changes in population structure can be observed, for example in planktonic algae, macrophytes, benthic invertebrates and fish. In particular, effects of eutrophication on the fish population can lead to the development of species less sensitive to lake turbidity, low oxygen levels in water and sediment accumulation. In setting ecological quality objectives, it is important to take into account the type of lake under consideration, since two lakes with the same trophic level can have very different biotic capacities.

#### **4.3.3. Impacts affecting public water supply**

In addition to the impact on the reservoir ecosystem, the effects of eutrophication cause problems for many lake and reservoir uses. Public water supply is particularly sensitive to reservoir eutrophication, which may lead to the problems in the water treatment system such as the following (Meybeck *et al.* 1987):

- filter blockages in the water treatment system due to algae;
- undesirable tastes, odours and colour caused by algae;

- iron, manganese, ammonium, sulphur and carbon complexes, caused by hypolimnetic deoxygenation, which can cause problems in the treatment process and require elimination;
- seasonal and daily water quality variations, requiring frequent adjustment of the water treatment process (in particular, diurnal pH variations which cause problems in flocculation);
- formation of chlorophenols during chlorine disinfection due to phenolic substances liberated by cyanobacteria;
- increased chlorine requirements, formation of organochlorine compounds and a possible bacterial growth due to high dissolved organic matter content;
- presence of toxins liberated by certain cyanobacteria;
- pipe corrosion.

In France, the most common cause of failure to meet standards for public water supply reservoirs is associated with iron, manganese and ammonium concentrations, caused by deep anoxic waters (Meybeck *et al.* 1987). Diurnal pH variation and excess organic matter content also affect water treatment efficiency.

Colour is reported to be of concern for several British water companies (WRc pers. comm., 1995), although the introduction of costly ozonation treatment has greatly reduced this problem (in addition to reducing trihalomethane levels). There is evidence that colour in some reservoirs has increased over the past couple of decades, partly as a result of changed catchment management practices. In contrast to water supply companies, regulatory authorities are happy to maintain water colour at a 'natural' level, since it reduces light penetration and thus decreases the risk of algal bloom formation.

Table 13: Human use of water and trophic state

Indicated Use	TROPIC DEGREE	
	Required	Acceptable
Drinking water	Oligotrophic	Mesotrophic
Bathing/Swimming	Mesotrophic	Lightly eutrophic
Salmons hatchery	Oligotrophic	Mesotrophic
Cyprinids hatchery	-	Eutrophic
Cooling water	-	Lightly eutrophic
Aquatic sports	-	Eutrophic
Irrigation	-	Very eutrophic
Hydropower Plants	-	Very eutrophic (although in some cases, significant weed growth or sediments may cause problems for the turbines)

In the reservoir of Serones in Spain, on the river Voltoya (Ávila), a high manganese concentration exists, due partly to natural origin and partly to effects produced by the eutrophication process.

#### ***4.3.4. Impacts on hydroelectricity and irrigation uses***

Even in cases where the water quality is not a major concern, pipe and filter blockages can also be a problem for other reservoir uses, such as hydropower generation or irrigation. In addition, an accelerated rate of reservoir sedimentation associated with eutrophication has been observed in some cases, causing a reduction in the useful capacity of the reservoir.

#### ***4.3.5. Impacts on recreation in lakes and reservoirs***

Eutrophication may render the reservoir unsuitable for recreation due to the unpleasant appearance of water caused by high turbidity/low transparency, odours or algal masses. Furthermore the presence of toxic cyanobacteria may pose a health risk. During the summer of 1989, major blooms of toxic cyanobacteria were reported in many reservoirs in England, Finland, Norway and Sweden. This is believed to have been caused by a mild winter, high mid-summer temperatures and sunshine and a long period of stable weather in July. At Rutland Water (UK), several sheep and dogs died in 1989, most likely as a result of ingesting algal scum (NRA, 1990).

The required minimum transparency for safe bathing is 1 m. Figure 18 shows the annual mean transparency for lakes and reservoirs in several countries and also the differences between annual mean transparency and summer mean transparency. A significant loss of transparency in normally low turbidity lakes can indicate eutrophication (points above the +2 m loss line). Some lakes are in fact naturally turbid, showing medium to low annual values (1-4 m) and little difference in the summer (around 0 m difference). Some naturally turbid lakes can gain in transparency during the summer, possibly due to settling of particulate matter.

Undesirable fish species or fish kills caused by eutrophication pose obvious problems for other recreational pursuits, such as fishing.

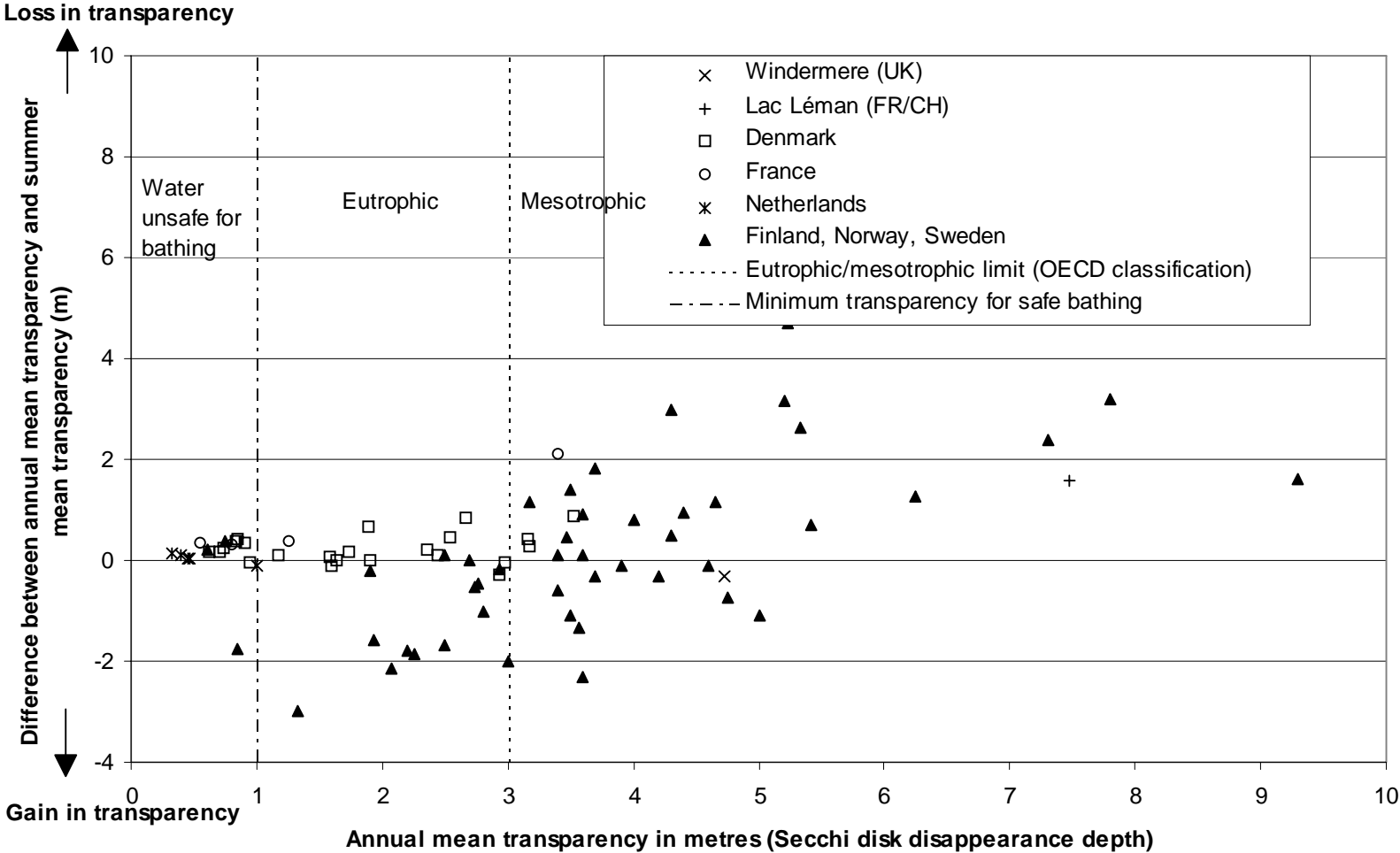
#### ***4.3.6. Available data***

The major reservoir questionnaire requested information concerning eutrophication impacts. The following tables provide an analysis of questionnaire responses concerning impacts in the reservoir. Data concerning downstream impacts from eutrophic reservoirs are presented in a later section of this chapter.

Problems due to algal blooms and/or potentially toxic cyanobacteria were reported in 21 Portuguese reservoirs. In addition, the occurrence of fish kills were reported in seven reservoirs. In Ireland, three reservoirs are

reported to have high levels of cyanobacteria: in one reservoir, problems related to toxic algae are reported.

Figure 18: Loss of amenity value in lakes and reservoirs



Comments about water quality problems in French reservoirs included oxygen deficits (9 reservoirs), suspended matter (2 reservoirs), elevated iron/manganese concentrations (2 reservoirs), nitrate concentrations (5 reservoirs), odour problems (2 reservoirs) and bacterial problems (2 reservoirs) for a total of some 250 returned questionnaires. In addition, fish kills were reported in 15 reservoirs, toxic algae in 4 reservoirs and problems related to sediment quality in 6 reservoirs. However, it is suspected that the small numbers of reservoirs described is a result of a lack of water quality monitoring.

#### 4.4. Control measures

Control measures may be preventative or curative. For water supply reservoirs, policies combining both types of measures have often been adopted in many countries. The questionnaire aimed to collect initial information concerning any specific prevention or curative measures implemented for each reservoir and a free text field was provided for this purpose.

Concern about the potential application of environmental economics to reservoirs is reported in the UK (WRc pers. comm., 1995). Some studies have indicated that it would be more cost-effective to abandon reservoir management techniques (such as aeration and phosphate stripping) and instead upgrade treatment facilities to deal with the resulting worse raw water quality.

##### ***4.4.1. Eutrophication prevention***

The principal preventive measures adopted in many European countries are as follows:

- increased wastewater treatment to reduce nutrients in effluents, possibly coupled with effluent diversion
- reduction of phosphorus used in detergents
- fertiliser application controls
- modelling of future reservoir conditions in order to optimise final reservoir location choice

The relative importance of different nutrient sources varies greatly, according to population, agricultural and industrial catchment densities. It is for this reason that prevention policies initiated in many European regions and countries differ greatly, as the examples below demonstrate.

Initial actions to control eutrophication in Swedish reservoirs and lakes in the 1970's were primarily external measures, including extensive wastewater treatment programmes and phosphorus content reduction or partial bans on household detergents (Forsberg, 1987). These actions produced many positive results, although there were also several disappointing cases where recovery was delayed, due in part to internal nutrient loading by sediments. More recently, a wide variety of internal

restoration measures have been undertaken on a lake-by-lake basis, with varying degrees of success.

In the Netherlands, it is estimated that the influx of nutrients via transboundary rivers exceeds the inland contribution (Van de Velde & Laane, 1990). In addition to extensive emission-orientated measures on a national basis, international action is, therefore, considered a very important aspect of eutrophication control in the Netherlands. As in other countries, delays in these measures taking effect is likely to be due to nutrient-rich sediments.

In France, control measures were initiated for many lakes and reservoirs in the 1970's, although some measures date back to the 1960's (Meybeck *et al.* 1987). However, the long residence times mean that many such catchment-orientated measures have a slow effect on the trophic states of these reservoirs. In France and particularly in the Loire-Bretagne basin, an agricultural nutrient reduction programme initiated in 1984 (CORPEN) places much emphasis on influencing agriculture practice by improving farmers awareness of the problem (Vinçonneau, 1992).

In Ireland, phosphorus removal for towns in the Shannon catchment has been recommended to improve water quality in the Ardnacrusa and Parteen Weir reservoirs. In France, the clearing of vegetation from the future reservoir area prior to flooding was mentioned as an important preventive measure for three reservoirs. Changes in land use or agricultural practice were also described in the catchments of 8 French reservoirs (information from project questionnaire responses).

The table below presents an analysis of responses to the Dobris+3 questionnaire and the major reservoir questionnaire which requested information on preventive measures. Responses for only 4 natural lakes and 24 reservoirs were received, but the results indicate that effort is generally concentrated on improving wastewater connections and treatment in the catchment.

Table 14: Preventive measures in European lakes and reservoirs

Prevention control measure	Number of lakes where this measure is being applied
Reduction of emissions from intensive livestock farming	6
Connections to sewage treatment plant	6
New wastewater treatment facilities	6
Upgrade of existing wastewater treatment facilities	6
Controls on land use in the catchment	5
Reduction of phosphorus loads from industry	5
Reduction of phosphorus loads from domestic detergents	4
Advice to farmers on fertiliser use	3
Regulations on fertiliser use	3
Deviation of wastewater discharges away from the lake	1
Other types of measures	5

NB Total number of water bodies for which information was available was 28 - more than one preventive measure may be applied at the same lake.

Data source: ELDRD 11/97.



#### **4.4.2. Curative methods**

Numerous types of restoration methods for lakes and reservoirs affected by eutrophication have been developed since the 1970's, some of which have proved more successful than others. The main types of measures reported in the literature are listed in the table below.

Responses from questionnaires indicate the following extent of curative measures being employed at 15 reservoirs and 2 natural lakes. The numbers of water bodies for which information is available is not sufficiently representative to provide a good overview of the extent of techniques.

Table 15: Curative measures applied in European lakes and reservoirs

Curative measure	Number of lakes where this measure is being applied
Aeration in the water body	4
Selective withdrawal of deep anoxic waters from reservoir	4
Chemical dosing (e.g. copper sulphate)	3
Installation of pre-dams	3
Dredging of sediments	3
Treatment of inflowing water	2
Water injection	2
Reservoir outlet management	2
Biomanipulation (e.g. Chinese carp)	1
Destratification of water body	1
Mixing of lake/reservoir layers	1
Other types of measure	2

NB Total number of water bodies for which information was available was 17 - more than one curative measure may be applied at the same lake.

Data source: ELDRED 11/97.

## 5. Acidification

### 5.1. Introduction

Surface water acidification has been extensively studied in lakes in many European regions, where 'acid rain' can affect pH levels and cause major ecological changes, in areas with base-poor geology. The effects are both direct (due to the effect of lowered pH on the phytoplankton community) and indirect (for example due to increase leaching of aluminium from soils leading to toxicological effects on fish).

The problem is characteristic of lakes in specific European regions which have soft water and are subjected to 'acid rain' (i.e. depositions enriched in sulphate and nitrogen oxides creating strong acids). Lake sensitivity is a reflection of sub-surface geology and the associated soils, which greatly determine the lake's acid buffering capacity. The buffering capacity of lakes located in non-carbonate terrains such as crystalline rocks or sandstones is rapidly exhausted. The extent and significance of acidification is the result of acid deposition on lakes of differing sensitivity.

Acidification in lakes has been observed in many northern European countries and is particularly extensive in southern Norway and Sweden (Kristensen & Hansen, 1994). Small high altitude lakes are generally found to be more affected than large lowland waters.

### 5.2. Indicators

The main indicators used to assess acidification (sensitivity and status) are as follows:

- acid neutralising capacity (ANC), which indicates the lake sensitivity to acidification (difference between certain base cations and strong acid anions);
- alkalinity (ALK), decreasing values indicate acidification;
- base cations (SBC),
- sulphate ion;
- nitrate ion;
- hydrogen ( $H^+$ ) ion;
- acidification index, a biological presence/absence indicator based on critical limits for different species (Fjellheim & Raddum 1990).

### 5.3. International assessment of freshwater lake status

The International Co-operative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes (ICP Waters) was designed to assess the degree and geographical extent of acidification on surface waters on a regional basis (Lückewille *et al.* 1997). During the last ten years

international emission reduction measures in Europe and North America have resulted in a decrease of atmospheric sulphur deposition of up to 50%. However, nitrogen deposition has stayed quite constant. The programme aims to correlate changes in acidic deposition with chemical and biological status of lakes and streams.

Careful and comparable sampling programmes have been carried out in the 1980s and 1990s in many European regions to examine the status and trends in surface water chemistry. Of the 75 sites described in the nine-year report in the EEA member countries, 35 are lake sampling sites and 40 are streams. Lake sites were as follows: Austria (3), Denmark (0), Finland (5), France (1), Germany (1), Ireland (3), Italy (3), Norway (3), Sweden (7), Netherlands (3) and UK (6). From these, it was possible to analyse trends at around 30 sites.

The main conclusions relate to both lakes and streams in general and were as follows (NIVA 1997), grouped according to large region (Nordic countries or other European countries).

- Reductions in sulphate deposition have led to decreasing sulphate concentrations at almost all sites and the decreases have been greater in the 1990s than in the 1980s. At some sites, the invertebrate fauna have also partly recovered.
- In Nordic countries (Norway, Sweden, Finland), ALK decreased in the 1980s (acidification) but increased in the 1990s (recovery). At many European sites (Italy, Germany, Netherlands, Denmark), ALK increased in the 1980s and this increase accelerated in the 1990s. Sites in the UK in the 1990s showed little change overall. With the regional recovery in ALK in the Nordic countries, SBC concentrations are no longer declining. The  $H^+$  observations are also consistent with these trends.
- Nitrate concentrations increased in Nordic countries and in European regions in the 1980s, but these increases have disappeared in the 1990s (with the exception of the UK where nitrate is still increasing). In some continental European areas, there is evidence of regional nitrate decline in the 1990s. Since there does not appear to have been a decrease in the deposition of nitrogen during this recent period, it is believed that other, possibly, temporary factors (possibly climate which could influence excess nitrate leaching) may be responsible for this hiatus in a what is thought to be a long term increasing trend.

A survey in 1995 compared estimated exceedances of the critical load for sulphur in different Nordic countries (Henriksen *et al.* 1997). A combination of high sulphur deposition and low critical loads results in the highest percentage of exceedance in Norway (the critical load for sulphur is exceeded in 27% of lakes). In Sweden and Finland, it is estimated that 9% of lakes have loads exceeding the critical load (corresponding to 6000 and 3000 lakes respectively).

## 5.4. Examples of strategies

### ***5.4.1. Long term responses***

The most significant long term actions towards reducing air pollution are the 1979 UN-ECE Geneva Convention on Long Range Transboundary Air Pollution, a multi-lateral treaty concerning air pollution and the EU 5<sup>th</sup> environmental action plan. These strategies concern target reductions in emissions of SO<sub>2</sub>, NO<sub>x</sub>, NH<sub>3</sub> and VOCs. Future EU strategy is being prepared which should integrate an effects-based (critical loads) and cost-effective approaches into defined targets.

### ***5.4.2. Lake liming in Sweden***

The severity of the acidification problem in Sweden has led the authorities to undertake curative measures, including a major lake liming programme.

It would appear that the worst acidification in Sweden occurred in the 1950s and 1960s when the sulphur fall-out increased significantly. In the late 1970s, about 25 000 of the 85 000 lakes in Sweden (over 1 ha) had such a low level of alkalinity that only resistant plants and animals could survive. Of these 25 000, it is estimated that man-made impacts account for changes in about 17 000 - the rest are more naturally acidic (Bernes & Grundsten 1992). Although 20% of lakes have been affected in terms of numbers, these are typically small lakes located in upstream areas and it is estimated that 10% of total lake area has been significantly affected by problems. Since the mid-1970s (when sulphur emissions were reduced) to the 1990s, the situation in southern and central Sweden has not changed significantly.

In an attempt to at least partly counteract the effects of acidification, almost 200 000 tonnes of lime are spread every year over Swedish lakes and rivers, representing the most extensive liming programme in the world. Between the 1970s and the early 1990s, in Sweden almost 6000 lakes were limed mostly through state funding. Larger lakes were the primary targets and so it was possible to restore half of the area that was acidified at the end of the 1970s. However, liming needs to be carried out regularly and the only long term solution is a reduction in acidic fall-out. In south-west Sweden trends of soils being increasingly saturated with nitrogen are observed, indicating continued acidification as nitric acid is leached out.

## 5.5. Acidification problems in reservoirs

Because of their large water volumes, major reservoirs are less likely to be affected by acidification than shallow lakes. Indeed, little evidence of problems caused by acidification to reservoir use can be found in the literature. The major reservoir questionnaire aimed to obtain an initial assessment of the situation, in order to ascertain whether reservoirs are susceptible to acidification. Responses on this subject were received from Portugal, France and Ireland. In Ireland, 3 out of the 7 reservoirs for which information was provided were reported to be susceptible to acidification

and in France, two reservoirs were reported to be susceptible to acidification (from a questionnaire return of 250 reservoirs).

## 6. Other types of water quality problems

### 6.1. Introduction

Because of their tendency to trap sediments and organic matter, lakes and reservoirs tend to accumulate pollutants such as heavy metals, pesticides and other organic compounds in certain areas. Such pollution, less well studied in reservoirs than in rivers, could pose serious problems to certain uses, particularly public water supply. In natural lakes, such pollution can also cause impacts to the ecosystem, through systematic accumulation of toxins through the foodchain. In addition, some natural sources of chemical compounds can mean that uses of lakes or reservoirs have to be limited.

Priority during the 1995-7 work programme was given to eutrophication issues, so data concerning concentrations of these types of pollutants have not been collected by questionnaire. Instead, a number of national overviews and case studies from the literature are presented to indicate the type of problems that do exist.

### 6.2. Problems due to natural chemical water quality

The natural water quality of a lake is determined by the geology of its catchment, the lake bed geology, the climate and the lake's morphological characteristics. Natural chemical water quality may pose problems for certain uses of lakes and reservoirs, particularly those uses with high water quality requirements such public water supply.

In Spain, there are many cases in which the water, due to salination processes from natural sources, produces some limitations for water uses. In the areas of evaporitic lithology, high salt content in river water is frequent. Examples are:

- the Guadalhorce reservoir (Málaga), in which are measured conductivity values of more than  $5.000 \mu\text{S cm}^{-1}$  (CEDEX, 1995),
- the Cuevas de Almanzora reservoir, with conductivity values about  $2.000 \mu\text{S cm}^{-1}$  (CEDEX, 1996).

The problems related to high degrees of mineralisation are mainly located in the reservoirs located in the Southeast and in the Eastern Spain (i.e. Alarcón reservoir, in the Júcar basin, and Mequinenza and Flix in the Ebro river basin).

## 6.3. Metal pollution

### ***6.3.1. Sources and types of metal pollution***

Pollution sources of metals include effluent discharges to water bodies in the catchment or directly to the lake and also atmospheric deposition on the catchment and the lake:

- prolonged discharge of effluents from industrial, urban or mining activities can cause significantly high heavy metal concentrations in some lakes;
- an important effect of acidification is that metal concentrations may become elevated in lakes and increasing trends in metal concentrations have been observed in many Nordic lakes.

Heavy metals enter the lake bound to sediment particles or dissolved in the inflowing water. Since a proportion of the metals entering the lake fall to the bottom attached to particles, the concentrations in sediments reflects the total loads of certain metals. Studies of metal concentrations in sediment profiles of lakes can reveal historic trends.

A number of case studies are given below to illustrate the types of problems that are encountered.

### ***6.3.2. Mining activities and Spanish reservoirs***

In Spain, a number of reservoirs show metal pollution problems related to mining activities, for example:

- the Eume reservoir (La Coruña) presents manganese problems.
- in the Sancho reservoir (Huelva) pollutants of mining origin have been detected, especially copper and iron.
- the Jándula reservoir (Andújar) presents very high levels of salinity and chemical pollution originating from mining industries of the Puertollano area.

### ***6.3.3. Heavy metals in Italian lakes***

A survey of Italian lakes in 1985 (Gaggino *et al.* 1985) indicated that, of the 65 lakes and reservoirs studied, two lakes gave cause for concern:

- Orta lake (Piemonte), where pH values were very low (pH 4) and the lake was polluted by copper at concentrations of  $50 \mu\text{g l}^{-1}$  which exceeded the toxicity threshold for living organisms;
- Annone lake (Lombardia), where extremely high iron concentrations ( $626 \mu\text{g l}^{-1}$ ) have been caused by industrial wastes.

#### **6.3.4. Heavy metals in acidic Finnish lakes**

In Finland, metal accumulation in lakes has clearly accelerated since the pre-industrial era - acidic lakes are the most affected because the low pH leads to higher dissolution of metals. Above-average concentrations of aluminium, manganese, zinc, lead, cadmium and mercury have been found in benthic organisms, plants and fish in acid lakes.

One particular problem is mercury, which originates from a number of point and diffuse sources (former use by the wood-processing and pulp industry, atmospheric releases from chlor-alkali plants and dressing of seed grain by the agricultural sector) (Wahlström *et al.* 1993). In a survey of 113 Finnish reservoirs, forest lakes and other lakes, small, new and severely regulated reservoirs were found to be the most polluted (Verdi *et al.* 1990).

It has been estimated that not a single lake in Finland has been spared the effects of air-borne mercury deposition. For this reason, it has been difficult to establish what natural concentrations should be in lakes and in fish. Fish in more than 3000 lakes contain mercury in excess of 1 mg kg<sup>-1</sup>, whilst the 'natural' concentration is believed to be 1 mg kg<sup>-1</sup>. Mercury persists in the environment for long periods, however concentrations in the worst-affected water bodies have been declining since the 1970s.

#### **6.3.5. Heavy metals in acidification-impacted Swedish lakes**

As mentioned above, acidification pollution can cause metal concentrations to rise in sensitive nutrient-poor lakes. In some cases, effects on the fauna in the lake can be demonstrated, but often it is difficult to determine what is the "natural" background level against which present levels should be compared. In southern and central Sweden, some 6 000 lakes are estimated to have zinc and cadmium concentrations at or in excess of the lowest known effect levels (Notter 1993). Around 40 000 lakes have mercury concentrations in pike above the set environmental goal of 0.5 mg kg<sup>-1</sup>.

Analyses of sediment show that the amount of metals entering lake waters has increased, particularly over the last 50 years (Notter 1993). A slight decrease in lead input has been observed in sediment collected in the 1980s, which is believed to be due to reduced emissions from road traffic. However, it was reported not possible to determine long term trends in water and biota owing to lack of data.

### **6.4. Persistent organic pollutants**

Persistent organic pollutants are organic compounds which are chemically and biologically stable and thus persist in the environment. They include such compounds as polyaromatic hydrocarbons (PAH), PAH derivatives, chlorobenzenes, polychlorinated dioxins/furans, chlorophenols, PCB, pesticides, detergents and many halogenated compounds.

Such compounds may have many different types of behaviour in the environment. In the aquatic environment, they often accumulate in the



sediment, which can later function as a dispersion source to water biota and the atmosphere (Alsberg *et al.* 1993). Since sediment is the food substrate for bottom-living organisms, which are in turn food for higher organisms, these compounds tend to reach higher concentrations as they accumulate in the food chain. In general the concentrations of most persistent organic compounds are elevated in the vicinities of the larger cities and industrialised areas.

Not only are many persistent organic pollutants difficult and costly to analyse and monitor, but the possible range of compounds is continually expanding. The effects on humans of these compounds are also difficult to establish.

In Sweden, studies of concentrations of persistent organic pollutants have included comparisons of concentrations in and around lakes (water, sediment and biota). At some lakes located downstream of recycled paper plants, concentrations of dioxins detected in the lakes sediments were higher than in sediments in the upstream or downstream river reaches, confirming the accumulation effect in lakes (Alsberg *et al.* 1993). Studies on fish and top level foodchain carnivores in lake environments, such as mink, have also clearly shown the bioaccumulation effects.

At Moulin Neuf reservoir, located in Finistère in France, it is reported that pesticides derived from agricultural practices in the catchment have led to elevated levels of atrazine and simazine, causing problems for the reservoir's primary use - public water supply. In addition to facilities installed to improve water treatment, an awareness programme amongst farmers in the catchment has been undertaken.

Diffuse pollution of remote lakes in Finland, by DDT (and also PCBs) which is now banned in Finland but brought by air currents from neighbouring countries, is believed likely to continue in the future (Wahlström *et al.* 1993).

## 6.5. Radioactivity

A synthesis of evaluations carried out concerning the impact of the Chernobyl accident on freshwater ecosystems was carried out in 1990 (four years after the accident) by the International Association of Radioecologists for DGXI (Foulquier *et al.* 1990). The radioactivity was directly related to the level of deposition which was essentially in wet form. Differences in levels were noted according to the distance from Chernobyl, the wind direction and rainfall. The most common detected radionuclides were iodine-131, tellurium-132, caesium-134/137, rubidium-103/106, silver-110 and also strontium. Very quickly, caesium 137 became dominant everywhere.

The peak in radioactivity in river water occurred very soon after the accident, but was of short duration due to dilution. In lakes however this

decay was much slower. The ideal storage location for radionuclides is sediment which accumulates in lakes.

Lake fish were variously affected by the caesium radioactivity, according to the lake's location and the fish's position in the food chain. Higher activity levels were found first in planktivorous species then in carnivorous species which have a slower accumulation process. The effective half-life is considerably slower than in rivers and can reach 3 years for trout in mountain lakes in Norway.

Some lakes and reservoirs are situated in areas with naturally elevated radioactivity levels. In some catchments, mining for uranium may affect levels in the lake – examples of reservoirs developed for use in conjunction with mines are found in the Massif Central in France.

#### 6.6. Bathing water quality

Lakes and reservoirs used for recreation are assigned a bathing water quality designation, according to Directive 76/160/EEC. Unfortunately, the overviews of data provided to the European Commission do not distinguish still water beaches from rivers, so it is difficult to produce an assessment of these results.

Extensive monitoring of pathogens is carried out in recreation lakes and reservoirs to determine their suitability for water sports. In public water supply reservoirs, since such monitoring is likely to be carried out after treatment, problems in the reservoir itself may be less apparent. Problems related to bacteria were reported in two French reservoirs (project questionnaire responses).

## 7. Sedimentation and drainage

### 7.1. Sedimentation issues in reservoirs

Unlike rivers which transport sediment, reservoirs trap a large proportion of the sediment influx, which can result in a significant reduction in useful capacity. Coarse sediments tend to be deposited close to the inflow location, whereas fine sediments are transported for a longer distance. Torrential inflows can produce density currents which transport silt to the dam foot. The rate of sedimentation depends on several factors (Duband, 1989):

- hydraulic residence time
- sediment loads from the catchment
- climatic conditions
- operating conditions, such as water level variations and bottom outlet use.

It is difficult to evaluate sediment loads, since there is no direct relation between river flow and the flux of suspended matter. Sedimentation is generally assessed by bathymetric surveys or by measurements during reservoir emptying.

There are very few data available concerning sedimentation on a European-wide scale. Overviews of the extent of sedimentation on other continents suggest that the capacity weighted average lifetime of reservoirs is 22 years (Mahmood 1987).

This figure has been determined from reservoirs located in very large, often highly erodable catchments in 6 continents and is likely to be very different in Europe, where spectacular examples of high sedimentation rates are less common. Approximate sediment yield figures for some important European rivers are between 83 (Danube), 111 (Rhône) and 214 (Po) tonnes per km<sup>2</sup> (Mahmood 1987), which compare with comparable North American and Asian example rivers (in terms of run-off and catchment area of 454 (Indus, Pakistan), 1167 (Copper, USA) and 500 (Susitna, USA) respectively).

The best way to minimise sediment input to a reservoir is to plan the location carefully and to take sediment control measures in the catchment (vegetation cover, afforestation, terracing etc.).

Sediment reduction in reservoirs is problematic. If the reservoir has a bottom outlet, sediment flushing (requiring near emptying of the reservoir) may be able to clear some of the stock, but this is not always possible due to the incoming and outgoing water volumes and possible downstream effects. Density currents can be used to transfer sediment-laden flow along the thalweg of the reservoir until it reaches the dam.

Other methods require mechanical excavation or suction dredging (Scheuerlein 1986).

## 7.2. Drainage issues in natural lakes

Although lakes are recognised as representing an important water resource, multitudes of small ponds and lakes can hinder land development because they may result in a lack of suitable agricultural or building land. Many such lakes have been drained, often as early as the 19th century when there was a large increase in population. This continued after the second world war, when many land reclamation schemes were launched. Often such schemes were subsidised by the state. In some cases, whole lakes have been emptied leading to the total loss of an aquatic habitat, but often the water level was simply lowered and the waterlogged land around the shores drained to allow use. Lowering the water level obviously has important effects on the lake morphology and thus on the lake's physical and chemical characteristics (more shallow, less water volume, invasion of plants such as rushes).

In Sweden, it is estimated that about 17 000 land reclamation schemes with government aid were carried out between 1881 and 1933 (Bernes & Grundsten, 1992). One long term effect has been a shortage of water in agricultural districts, probably caused by a combination of lake and wetland drainage, field drainage and irrigation, which tend to result in rapid surface water run-off. A detailed survey in Uppsala län indicated that 94 of the 368 existing in the 1940s are today totally overgrown, with others also on their way to becoming 'ex-lakes'.

Many drained lakes turned into sedge marsh or reed jungles, creating in some cases excellent bird habitats (Bernes & Grundsten, 1992). However if drainage continued, the newly-acquired bird paradise was reduced in size. A well-known example is Hornborgasjön in Västergötland, which did not have a particularly rich bird-life in its natural state. Three successive drainage schemes pre-1905 lead to a small reduction in open water surface, extensive shore 'jungle' and a rich bird population at the site. The fourth and fifth drainage schemes lead to almost no water being present in the lake by 1965 and the environment deteriorated for ducks, waders and other species. The lake is now one of the largest nature conservation projects in Sweden, with the aim of raising the water level by 85 cm and clearing the shore vegetation so that the lake regains its importance as a breeding location by the year 2000.

## 8. Environmental changes due to dam construction

### 8.1. Introduction

Although it is widely recognised that dams provide essential water and energy resources, they can also result in major environmental change, summarised in Table 16. The very presence of a new water body affects the valley's ecosystem: dams can create important migration barriers for fish and mammals. Artificial water flow regimes and associated variations in water quality are often observed to have marked effects on the downstream ecosystem. In the following sections, some of the possible environmental changes due to dam construction are discussed.

### 8.2. Environmental impact assessments (EIA)

The Directive (85/337/EEC) on environmental impact assessment includes dams (specified in Annex 2 as agricultural hydraulic projects, hydropower installations and structures intended to canalise or regulate rivers) as projects which *maybe* the subject of an environmental impact assessment (EIA). The application of the Directive to dam projects is thus optional.

Guidance or legislation concerning EIAs for dam construction projects has been in place in many European countries for some time. Many European countries have required studies at the pre-feasibility stage with some form of public participation in the planning process for major dam projects since the 1960s. For example, studies have been carried out in France for all hydropower plants with production capacities of greater than 500kW. Similarly, in Norway, all storage schemes and dams over 4 m have required EIAs (Anon., 1992).

Several aspects of EIA are of interest here:

- the type of project for which an EIA is required (e.g. size, project value, importance, location etc.)
- the stage in the project at which the EIA is carried out (e.g. pre-feasibility, feasibility, design)
- the extent of public consultation
- the type and significance of the impacts identified (e.g. water resources/quality, flow regime, fauna/flora, aesthetic, archaeological)
- the type of mitigation measures proposed (e.g. design, operational, location)

- the implementation and monitoring of the effects of mitigation measures

A world-wide survey on environmental management practice concerning dams found several examples of projects where important mitigation measures had been implemented (Anon., 1992), including the following:

- In Spain, dam design was modified in six examples, including height reduction in two cases.
- A restriction on the use of explosives is enforced during the bird nesting season in Spain.
- Examples of archaeological preservation include the removal of a Visigothic church from the Ricobaya site and a Romanesque church from the Riano site in Spain.
- In Germany, fifteen secondary reservoirs were created at the Große Dhunn reservoir scheme, eleven of which were solely for ecological reasons.
- In the UK, rare plants were relocated from the Cow Green dam site.

In several European countries, dams have been delayed or cancelled as a direct result of public participation in EIAs. Examples include four cancelled schemes in Spain (Anon., 1992), the Neger scheme in Germany and the Serre de la Fare dam in France.

As an initial approach, the questionnaire aimed to identify which dam projects had had an EIA completed prior to construction. This information would provide an overview of the extent of environmental impact studies and permit a more detailed assessment of selected dams in future studies. It should be noted that for older dams (constructed before the 1960s), it would appear that little information exists about any form of EIA that may have been carried out at the time of construction - the current operators may have maintained no records and impact assessment, if it existed, was, in any case, likely to have been incorporated into the general documentation for construction permits.

The responses, not necessarily very representative, indicate that:

- no EIAs were carried out for the 15 German reservoirs responding, nor for the 9 Irish reservoirs responding, nor for the 8 Austrian reservoirs responding, nor for the 7 Finnish reservoirs responding;
- in France, 24 of the 82 reservoirs for which responses were given had had EIAs, 51 had no EIA and for 7 the situation was not known;
- in Portugal, 8 out of the 87 reservoirs had had EIAs completed.

Old dams may, in some circumstances, be dismantled or functionally 'wiped out' for environmental reasons. In this case, an EIA may be conducted for these operations. Two examples currently exist in France: the St Etienne du Vigan dam and the Maison Rouge low head dam.

**Table 16: Environmental changes associated with dams**

Cause of Impact	Possible direct effects	Possible indirect effects
<b>Creation of the dam</b>	Creation of a major obstacle in the river	Barrier to migration for certain aquatic vertebrates, in particular fish.
	Associated construction work (noise, explosions, construction material temporary dumps, road construction, temporary channels)	Disruption of habitat (e.g. disturbance in the bird nesting season). Increased sediment erosion and temporary effects on river water quality.
	Population displacement	Population reduction in the vicinity of the reservoir
	Modification of landscape	Presence of new water body in landscape (particularly a semi-arid landscape). Cumulative effect on landscape of several dams in the same river basin. Presence of newly-built associated structures (turbine plants, treatment plants) Change in slope gradient - possible increased erosion Creation of a tourist attraction (for recreation). Seasonal population influx.
<b>Reservoir impoundment</b>	Flooding of land	Habitat destruction - possible loss of rare species Destruction of archaeological and historical features Decomposition of organic material, resulting in temporary eutrophication. Splitting of continuous forested areas in two belts Possible migration barrier for terrestrial fauna
<b>Presence of a permanent still water body</b>	Creation of a still water habitat	Change from riverine to lacustrine ecosystem Stratification of the water body, with associated changes to the ecosystem
	Creation of a micro-climate	Increased humidity and attenuated temperature changes upstream of the reservoir
	Rise in groundwater levels upstream of the reservoir	Possible flooding of land (waterlogging) and increased salinisation Changes in groundwater flow regime
	Effect on bedrock	Possible induced seismic activity (only in the largest impoundments)..
<b>Accumulation in the reservoir</b>	Water use	Change in downstream land use due to the availability of a new water resource (for example, for irrigation). Potential conflicting water demands.
	Sediment trapping	Sedimentation of the reservoir with associated water volume reduction. Reduction of particulate matter in downstream watercourse. Leaching of nutrients and other substances
	Nutrient enrichment, causing eutrophication	Evolution of ecosystem. Appearance of water detrimental to recreation uses - toxic algae Increased water treatment required for drinking water supply
	Atmospheric acidic deposition	Acidification of reservoir - low pH and effects on ecosystem
	Chemical pollution	Accumulation of pesticides, heavy metals and other micro-pollutants
	Biological pollution from human or animals	Possible presence of pathogens

Reservoir operating	Artificially-controlled flow discharges/compensating	Changes in downstream ecosystem due to artificial flow regime in the river (flood
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Cause of Impact	Possible direct effects	Possible indirect effects
rules	flows	attenuation, change in flood frequency, seasonal flow reversals, increased flow in dry season) Changes in downstream ecosystem due to modified water quality, which may be improved in relation to the water quality in the upstream river or worsened by de-oxygenation, manganese/iron deposits, gas supersaturation Changes in downstream ecosystem due to gradual or shock water temperature variations Possible impacts on downstream riverine fisheries Change in downstream river morphology Downstream riverbed degradation - effect on bridge piers or water intakes
	Periodic emptying	Impact on downstream ecosystem (sustained high discharge flows, water quality due to variations in a stratified reservoirs) Choice of emptying period may be limited with a narrow bottom outlet Possible clogging of downstream banks if no sediment management rules enforced.
	Water level variations in reservoir	Modification of shoreline ecosystem Effect on landscape of bare rock shoreline
Controls on upstream catchment	Legislation, regulation or education to reduce sedimentation or nutrient loads to upstream river	Changes in catchment land use. Alteration of fertiliser application practice Installation of wastewater treatment plants Improvement of upstream river water quality



### 8.3. Safety issues

Dam safety is an overriding concern both during construction and operation. Dam rupture can be induced by floods, structural failure or seismic events. Data from ICOLD indicate that there have been four large dam ruptures in European countries since 1980, three of which were caused by the malfunction of sluices during major floods (CEMAGREF, 1993).

In most countries, there is a national committee responsible for dam safety, reviewing dam construction applications for safety considerations and often co-ordinating or carrying out inspections of large dams on a regular basis. In France for example, reservoirs must by law be emptied every 10 years to allow a proper inspection of the dam wall. Most large dams incorporate safety observations systems in their design such as structural and hydraulic observation systems. Alert plans in the case of a disaster are drawn up including the probably area of flooding.

This aspect of risk to the human environment is not discussed in any more detail in this report.

### 8.4. Land use changes

The construction of a dam and the associated flooding of a large area of land can produce a number of significant changes in land use in and around the reservoir including:

- displacement of population
- loss of valuable land around the reservoir, such as forestry or agricultural land
- replacement of a riverine (or other) habitat by a permanent still water habitat
- creation of a micro-climate due to the presence of a large water body in the valley
- changes in land use due to control of nutrient loads in the catchment
- increased human presence due to the reservoir acting as a tourist attraction

No data concerning such land use changes, which are difficult to assess, were requested in the project questionnaire.

In a report on the environment in Sweden (Bernes & Grundsten, 1992), the National Environmental Protection Agency estimated that 70% of Sweden's rivers have already been exploited by dams, predominantly for hydropower production. Hydroelectric power has been identified as being responsible for the most extensive changes in the mountainous regions, where 73 200 ha of land have been flooded and 12 550 km of river have been dammed. Most of the Norrland rivers that have been exploited have been transformed into terraces of long river reservoirs separated by dams

with power stations. The large unexploited rivers are at present protected by the Natural Resources Act, however energy production targets established by the Swedish parliament meant that, in 1991, another 1.2 TWh in water power was needed. It is reported that several new projects are being planned, many of which are in conflict with nature conservation and outdoor recreation. Conservationists often accept the further exploitation of existing river systems, but oppose the exploitation of untouched rivers.

In Finland, although only 60% of the total harnessable hydropower energy was used being used in 1988, it was reported unlikely that production will be increased very much, mainly in order to preserve rapids in their natural condition and to prevent further destruction of natural landscapes (OECD, 1988). Fifty-three rivers have been protected by the Wild and Scenic Rivers Act.

### 8.5. Creation of migration barriers

Dams and reservoirs can act as important barriers for certain migratory fish and mammal species. Even a small structure such as a weir can present an insurmountable obstacle to a migrating fish when its height exceeds the maximum height that the fish can overcome.

In response to the observed adverse effects on the populations of migratory fish (including lamprey and eel juveniles) in many European rivers and the fishing lobby, many dams have been equipped with some type of fish 'pass' or 'ladder', intended to facilitate the passage of the fish from one side of the dam to the other. However, efficient fish ladders are complex to design, since they must take many diverse factors into account, including the fish species, its behaviour (in downstream and upstream directions), hydrological conditions, hydraulic conditions and topography. Fish ladders (sometimes elevators) are now widely known for their function in aiding the fish's migration upstream. However, downstream migrations are not yet satisfactorily addressed (except for juvenile salmon).

In general, a fish ladder acts to bring the migrating fish to a predetermined point, where it may then be encouraged or 'obliged' to pass upstream. The swimming capacity, endurance and jumping skills of the fish must all be considered in order to ensure that the water velocity and height differences in the fish ladder are optimised. The equipment should avoid stress, possible damage to the fish and minimise delays in the migration. Turbulence, light and noise may also affect the success of the fish ladder.

It has been observed that fish ladders are rarely totally successful: even the most efficient ones cause migratory delays (Larinier, 1987). Installation of new fish ladders was discontinued in Sweden and Finland in the 1950's (ICOLD, 1985). Instead, a large-scale programme for the artificial reproduction of salmon and sea trout was initiated, although it is

recognised that such a programme can only restore the population to a limited extent.

Migrating fish are also sensitive to river flow variations. Complex operating rules are often necessary to ensure that the downstream flow regime is suitable for migrating upstream fish. For example, at the Roadford dam in south-west Britain, salmon migrators were found to be highly sensitive to small summer floods, particularly in dry years (Lawson, Sambrook & Solomon, 1991). Proposed operating rules included the use of reservoir storage during critical environmental periods.

The questionnaire included a specific questions concerning dam equipment installed for migrating fish. The results indicated that, of 319 responses to this question, only 21 dams do have some type of fish pass. The break-down by country is follows: 1 out of 15 responses in Austria and in Germany, 9/94 in Portugal, 7/10 in Ireland, 3/165 in France, none of 7 reservoirs in Finland and the 11 reservoirs in Iceland possessed fish passes. Despite the major research effort dedicated to fish passes and although only incomplete data was obtained for this project, these figures would appear to indicate that very few large dams are actually equipped with any sort of fish ladder.

Because of their size, reservoirs can also represent migration barriers for non-fish species (such as mammals and amphibians). Such migrators may either follow the river or cross the valley, which may delay or impede the migration.

#### 8.6. Environmental changes upstream of the reservoir

The possibility of a micro-climate upstream of the reservoir has already been mentioned. The effects are likely to be more pronounced for reservoirs located in steep valleys in arid regions. Although the effects of micro-climates have been reported for several examples outside Europe (e.g. fruit tree planting upstream of certain Chinese reservoirs), the effects are less well-documented for European reservoirs.

The presence of a large water body can also induce a groundwater head rise when the upstream ground is in hydraulic continuity with the reservoir. In rural areas, this may adversely affect ground saturation/flooding, drainage systems, wetland habitats, tree growth and flood defences (Lloyd, 1994). In urban areas, additional effects may occur, including reduced foundation stability, dampness in buildings, pollutant mobilisation and problems with underground services. Such problems have been identified of being of particular potential concern in the case of several proposed low-crested estuarine barrages in Britain, which would be located close to urban centres.

In anticipation of the significant groundwater head rise, it was reported that the construction and operation of the proposed Vienna-Freudenau hydropower plant will be accompanied by the implementation of a detailed

groundwater management plan, covering an area of 25 km<sup>2</sup> in the city of Vienna (Hauck, 1991).

### 8.7. Environmental changes downstream of the reservoir

Reservoir operations can cause many changes in the downstream ecosystem. In comparing the unregulated river with the watercourse following damming, several effects of the dam may change the downstream ecosystem:

- artificial flow regime
- modifications or variations in water quality
- change or variations in water temperature
- periodic emptying of the reservoir

Different elements of the downstream ecosystem may be more or less affected in direct or indirect ways. Changes in riverbed morphology and water temperatures may affect benthic invertebrates. Water level variations affect the riverbank habitat, which are essential breeding grounds for many fish and bird species: for example, water level variations can leave young fish fatally trapped in rock pools. Mammals can also be affected: for example, it is reported that beavers' winter stores have been flushed away because of rapid variations in water level on the Fax River in Sweden (Nilsson & Dynesius, 1994).

In Finland, alterations in the river structure and water quality due to hydropower reservoir construction are reported to have caused a catastrophic reduction in animal diversity, in particular, many economic fish species have vanished from a number of rivers (OECD, 1988).

A large scale approach to this issue was used to assess the global environmental changes which would be induced by the Loire regulation programme after its completion (BETURE-SETAME/EPALA, 1990). Many scenarios of possible effects due to subtle changes in the hydraulic regime (flood frequency, low flow/flood period reversals, water level changes etc.) were analysed on a statistical basis. In many cases, impacts (positive and negative) were predicted at great distances downstream of the dam.

Such impacts on the ecosystem are very difficult to evaluate. Many studies have been carried out on a case-by-case basis in order to design improved operating rules. The most significant effects attributed to reservoir operations involve long-term hydrological/hydraulic simulation, which falls outside the scope of this report.

Responses to the questionnaire from Ireland indicated that much biological monitoring is carried out upstream and downstream of many reservoirs as part of the national biological monitoring programme. Fish stress due to low oxygen levels was reported downstream of one reservoir:

to counteract this problem, surface water is now mixed with hypolimnion water for discharges from this reservoir.

Downstream problems reported in France in the questionnaire responses include deoxygenation (3 reservoirs), oxide precipitation (1 reservoir), algal proliferations in the downstream reservoir (1 reservoir), minimum flow issues (1 reservoir) and the emptying of “ industrial muds ” (1 reservoir).

In some reservoirs, emptying is carried out on a regular basis, in order to reduce the sediment body present and carry out visual inspections of the dam. In addition to the continuous high flow discharge, the water quality in the downstream river is often adversely affected during emptying. In particular, the high levels of suspended matter, low dissolved oxygen, iron, manganese and ammonium levels can have a significant ‘shock’ impact on the downstream ecosystem.

Data concerning the emptying period and the duration of emptying were requested in the questionnaire. From an initial assessment of French reservoir emptying, it would appear that a significant number of French reservoir operators have no option but to carry out the obligatory 10-yearly emptying programme during the low flow season, when impacts by the released sediments on the downstream watercourse will be amplified. This is because the bottom outlet is too small so that total emptying is only possible when there are low inflows.

## 9. Conclusions

In the initial 1995-7 programme, the European Topic Centre on Inland Waters lakes and reservoirs study aimed to provide an overview of environmental conditions in major lakes and reservoirs in Europe. Data was collected through questionnaires to National Focal Points and added to a database that has been constructed based on information collected from about 3300 major European reservoirs over a number of years by the International Commission on Large Dams.

The results of the project are of interest for two reasons.

- The difficulties experienced by the National Focal Points in assembling the required information, due to important differences between national dam/reservoir monitoring programmes, serve to illustrate problems which may be encountered in the setting-up of the EEA monitoring networks for still waters.
- Although the lack of available information means that a complete picture cannot be drawn across Europe, the project has, nevertheless, been able to identify and provide some indication of the extent of the main issues concerning lakes and reservoirs and should serve as a framework upon which to base the future EEA monitoring programmes.

Bearing in mind the two points above, it is recommended that the future EEA still water information network should be based on a limited number of key priority variables and a limited number of still water bodies. This network should aim to obtain a representative view of the situation for the main issues described in this report.

In the long term, the requirement of the future Framework Directive on Water to include still waters in catchment plans may lead to information being more available concerning the pressures and state of these environments.

### **Information collection**

With significant exceptions, it is important to note that the availability of lake and reservoir data are limited and difficult to obtain. The guide density of 1 still water body per 1750 km<sup>2</sup> given in the Dobris+3 questionnaire and proposed for the EEA EURO-WATERNET was attained by only a small number of countries in the short time available to complete this questionnaire in 1997. Several countries did not respond at all to the lakes section of the Dobris+3 nutrients questionnaire.

For the major reservoirs questionnaire, only Portugal and Ireland were able to complete the questionnaires within the originally-proposed timescale (2 months). These two countries were able to provide almost all of the requested data in the format requested, since the information was already organised into national databases or because of previous comprehensive

surveys on a reduced set of reservoirs. Spain also provided essential data for all 905 of the Spanish ICOLD-listed reservoirs. Other countries replied after a longer period or with less data for major reservoirs, indicating various problems encountered, as follows:

- In France, Austria and Germany, the absence of a centralised survey organisation and the large number of independent dam owners required that a questionnaire survey be distributed internally within each country in order to respond to ETC/IW questionnaire (this was also the case in Luxembourg and the Netherlands).
- In Norway, information about dams and reservoirs is contained in a number of different databases which currently lack interfacing (although this is understood to be in development). The Norwegian Water Resources and Energy Administration (NVE) reports that the water quality monitoring programme is limited in Norway because most of the reservoirs are located in remote unpolluted areas (except for long range transboundary air pollution) with practically no human activity in the catchments.
- Italy and Finland were able to provide information about a limited number of selected or “ priority ” reservoirs, in Italy selected according to capacity criteria (the largest capacity reservoirs).
- Amongst the other countries with large numbers of dams (>100), it appears that the UK and Sweden are not able to provide data about their dams and reservoirs, nor carry out a validation of the initial data taken from the ICOLD World Register of Dams. In the UK, this is understood to be due to problems in accessing data held by the privatised water companies.
- Responses to the major reservoir questionnaire have not been received from several countries with small numbers of dams (Belgium and Greece).

### **Environmental issues**

The study indicates a wide range of environmental situations for lakes and reservoirs in Europe. Two main themes emerged: environmental problems affecting lakes and reservoirs ecosystems and uses, and impacts on the environment caused directly or indirectly by reservoirs.

- Eutrophication affects significant numbers of lakes and reservoirs across the whole of Europe and can render these water bodies unsuitable for human use, causing serious problems for public water supply, and impact the lake ecosystem. In most cases, phosphorus is the principal cause of eutrophication. Only in sparsely populated regions such as parts of the Nordic countries, Ireland and Scotland are there a high proportion of lakes with low phosphorus concentrations. Overall improvements in wastewater treatment may have also improved the situation for some lakes in the 1980s and 1990s. Certain lakes have been the subject of detailed studies and efficient action programmes to reduce nutrient loads in the catchment and several are showing signs

of improvement. Some of these lakes will require several decades and strong preventive and curative measures for restoration. Although the lack of data does not permit satisfactory conclusions, it would appear that the proportion of heavily polluted lakes has gradually decreased over the last few decades. However, the state of European lakes and reservoirs is still of concern, since the situation seems to be worsening in many other lakes with previously moderate or low pollution levels.

- The marked contrasts in reservoir use (and importance in terms of water resources management) across Europe reflect both geographical influences (water resource availability) and national energy policies (hydropower production). The numerous hydropower reservoirs often located in mountainous or Nordic countries can be distinguished from the generally smaller irrigation and public water supply reservoirs situated in lowland and southern regions, which tend to have longer renewal times. These latter reservoirs are more likely to be subject to higher nutrient loads and thus eutrophication.
- Acidification is a more regional issue, and some signs of improvement due to earlier atmospheric sulphur reductions are being observed.
- At specific reservoirs, sedimentation can be a significant problem with important long term impacts, requiring careful catchment management and drastic curative measures.
- Lakes and reservoirs ecosystems and uses are particularly sensitive to many types of water quality pollution because of their low water volume and their tendency to accumulate pollutants in water or in sediments. Occurrences of heavy metals, pesticides and other organic pollutants have been observed in several lakes and reservoirs.
- The 'encroachment' or 'artificialisation' effects on rivers and their ecosystems as a result of dam/reservoir construction and operations were also considered significant. Dams constructed in periods when environmental considerations were not foremost tend to lack facilities which would permit their operation in a more 'environmentally-friendly' way. Impacts on flow regime, temperature regime and water levels are particularly apparent in the case of the hydropower dams described above, since they are often located in remote sensitive mountainous regions. However, impacts have also been reported for other types of reservoir - for example impacts due to poor water quality during emptying operations or the creation of migration barriers for fish.



## References

- Alsberg T, Balk L, Nylund K, de Wit C, Bignert A, Olsson M, Odsjö T, 1993. Persistent organic pollutants in the environment. The environment in Sweden (MIST). Swedish Environmental Protection Agency.
- Anon, 1992. World Survey on Environmental Management Practice. Water Resour J no 174, 1-11.
- Belaud, Dauba & Lim 1993. Retenues et peuplements piscicoles. ENSAT. Adour Garonne no 56, p7-11. Agence de l'Eau Adour-Garonne, Toulouse.
- Bernes C & Grundsten C 1992. The Environment. Published by the National Atlas of Sweden. Theme manager: The National Environmental Protection Agency.
- BETURE-SETAME/EPALA 1990. Evaluation globale des effets du programme d'aménagement de la Loire sur l'environnement. EPALA, Orléans.
- Bowman JJ, McGarrigle ML, Clabby KJ, 1993. Lough Derg. An investigation of eutrophication and its causes. Environmental Research Unit, Dublin.
- Bowman JJ 1996. Lough Ree. An investigation of eutrophication and its causes. Environmental Protection Agency, Wexford.
- Calvo S, Barone R, Naselli Flores L, Fradà Orestano C, Dongarrà G, Lugaro A, Genchi G, 1993. Limnological studies on lakes and reservoirs of Sicily. Il Naturaliste Siciliano XVII, suppl.1993. 292pp.
- Carlson RE 1977. A trophic state index for lakes. Limnology and Oceanography 22 (2): 361-369.
- CEMAGREF, 1993. Sécurité de barrages en service. Session de formation continue de l'ENGREF, Montpellier.
- CEDEX, 1995 "Reconocimiento limnológico de los embalses de Guadalhorce y Conde de Guadalhorce" Madrid, Centro de Estudios y Experimentación de Obras Públicas.
- CEDEX, 1996 "Reconocimiento limnológico del embalse de Cuevas de Almanzora" Madrid, Centro de Estudios y Experimentación de Obras Públicas.
- CEDEX (for Ministry of Environment) 1997. Characterisation of Spanish reservoirs. Written contribution to ETC/IW report.
- Chabal JP, Pichavant P, Crouzet P, Levenq J, 1991. Impacts d'ensemble des aménagements à buts multiples: de la méthodologie au bilan. Proceedings of 17th ICOLD congress, Vienna 1991.

Chapman D (ed), 1996. Water quality assessments. Published on behalf of UNESCO, WHO and UNEP. Second edition. E&FN Spon, London.

Chiaudani G, Premazzi G, 1993. Il lago di Como. Condizioni ambientali attuali e modello di previsione dell'evoluzione delle qualità delle acque. Centro comune di ricerca. Comunità Europee – CCR Ispra. Università degli studi – Milano. Ministero dell'Ambiente – Roma. Ammonministrazione provinciale – Como. Comunità Europee, Luxembourg.

CLER 1997. Recensement des sites hydroélectriques de moins de 10 MW en France. Janvier 1997. Comité de Liaison Energies Renouvelables. Paris.

De Hoyos, C., 1996 "Limnología del Lago de Sanabria: variabilidad interanual del fitoplancton" Tesis doctoral. Salamanca. Universidad de Biología.

Dillon P, Rigler F, 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish. Res. Bd. Can. 31: 1771-1775.

Duband D, 1989. Consequences de la modification du regime d'écoulement à l'aval des retenues. In: Conference 'Ressources en eau en région montagneuse'.

European Environment Agency (EEA), 1996. Surface water quality monitoring. Topic Report 2, Inland Waters. EEA, Copenhagen.

European Environment Agency (EEA) 1996. Design of a freshwater monitoring network for the EEA area. Topic Report 10, Inland Waters. EEA, Copenhagen.

European Environment Agency (EEA), 1998. Excessive anthropogenic nutrients in European ecosystems. EEA Monograph 6. EEA, Copenhagen. (to be published)

EPA Sweden 1992. The Environment. National Atlas of Sweden.

EUROSTAT, 1995. Regions. Nomenclature of territorial unit for statistics. NUTS.

Fjellheim & Raddum 1990. Acid precipitation: biological monitoring of streams and lakes. Science tot. env. 96: 57-66.

Forsberg C, 1987. Eutrophication and Lake Restoration in Sweden: Theory and Practice. In: Balvay G (ed). Eutrophication and lake restoration, water quality and biological impacts. INRA, Thonon les Bains, France.

Foulquier L, Baudin-Jaulent Y, 1990. Impact radioécologique de l'accident de Tchernobyl sur les écosystèmes aquatiques continentaux. Contrat 88-ET-016. DGXI Environnement, Sécurité et Protection Civile. 1990.

Gaggino GF, Cappelletti E, Marchetti R, Calcagnini T, 1985. The water quality of Italian lakes. In: proceedings of lake pollution and recovery, European water pollution and control association, Rome, April 1985.

Hasler, AD, 1947 "Cultural Eutrophication is reversible". *Bio Science*, 19 (5) : 425-431.

Hauck HH, 1991. Groundwater management in the backwater reach of Freudenua Hydropower plant. In: Proceedings of 17th ICOLD congress, Vienna 1991. Question 64.

Henriksen A, Skjelkvåle BL, Mannio J, Wilander A, Jensen JP, Moiseenko T, Harriman R, Traaen TS, Fjeld E, Vuorenmaa J, Kortelainen P, Forsius M, 1997. Regional lake surveys 1995 in Finland, Norway, Sweden, Denmark, Russian Kola, Russian Karelia, Scotland and Wales – results. NIVA report 0-95001, serial no 3645-97, 41 pp.

Hutchinson GE, 1975. A treatise on limnology III. *Limnological Botany*. Wiley-Interscience, New York.

ICOLD, 1984/1988. World Register of Dams, published by the International Commission on Large Dams, (ICOLD), Paris. Complete register published in 1984, revision volume published in 1988.

ICOLD, 1985. Dams and the Environment: Notes on Regional Influences. International Commission on Large Dams (ICOLD). Bulletin n°50, 1985. Paris.

INAG 1996. 1° inventario do estado de qualidade da aguas doces superficiais. Ano hidrológico de 1994/1995. Ministério do Ambiente (Portugal).

Johnes P, Moss B, Phillips G, 1994. Lakes - classification and monitoring. A strategy for the classification of lakes. For the National Rivers Authority (NRA), R&D note 253. NRA Bristol.

Koussouris TS, Photis GD, Diapoulis AC, Bertahas IT, 1989. Water quality evaluation in lakes of Greece. In Watershed 89. Proceedings of the IAWPRC conference held in Guildford, UK 17-20 April 1989.

Kristensen P & Hansen HO (eds), 1994. European Rivers and Lakes. Assessment of their Environmental State. EEA Environmental Monograph 1.

Larinier M, 1987. Les passes à poisson: méthodes et techniques générales. CEMAGREF. Houille Blanche, 1987, No 1/2. Revue générale de l'Electricité, Paris.

Larre D, Bouni C, Laurans Y, 1990. Détermination pour la collectivité nationale des coûts et dommages de toutes sortes entraînés par

l'eutrophisation des eaux. Agences de l'eau, Organisation et environnement, Ministère de l'environnement (France).

Lawson JD, Sambrook HT, Solomon DJ, 1991. The Roadford Scheme: minimising environmental impact on affected catchments. *Water Env Man* 5, No 6.

Lloyd JW, 1994. Estuarine barrages and their influence on groundwater. *J Hydrol* 162, p247.

Luckewille A, Jeffries D, Johannessen M, Raddum G, Stoddard J, Traaen T, 1997. The nine year report: acidification of surface water in Europe and North America - long term developments (1980s and 1990s). International Co-operative Programme on Assessment and Monitoring of Acidification of Rivers and Lakes. Convention on Long-Range Transboundary Air Pollution. NIVA report serial no. 3637-97, 168 pp.

Mahmood K, 1987. Reservoir sedimentation: impact, extent and irrigation. World Bank, Washington 118p.

Meybeck M, Irlinger JP & Lunel S, 1987. L'eutrophisation en France: Origines, mécanismes et conséquences sur l'alimentation en eau potable. Fondation pour la qualité des eaux potables, France. Institut de Biogéochimie Marine, Ecole Normale Supérieure, Paris.

Nilsson C & Dynesius M, 1994. Ecological effects of river regulation on mammals and birds: a review. *Regulated rivers* Vol 9, 45-53.

Notter M (ed.) 1993. Metals and the environment. The environment in Sweden – status and trends (MIST). Swedish Environmental Protection Agency.

NRA, 1990. Toxic blue-green algae. Water Quality Series No 2.

OECD, 1982. Eutrophication of Waters. Monitoring, Assessment and Control.

OECD, 1988. Environmental Policies in Finland.

Planas D, 1973 "Composición, ciclo y productividad del fitoplancton del Lago de Bañolas" *Oecologia aquatica*, 1: 3-106

Pourriot R & Meybeck M (eds), 1995. *Limnologie Générale*. Masson, Paris.

Premazzi G. and Chiaudanni G. 1992: Current approaches to assess water quality in lakes pp 249-308, in *River water quality- assessment and control conf. Proceedings*, OPEC, Luxembourg.

Rothe J, 1991. Les ressources en eau dans le bassin Adour Garonne. Situation et perspectives. *Bull. Cons. Gen. GREF*, 1991, No 31, p41-53.

Ryding SO & Rast W (eds) 1989. The control of eutrophication of lakes and reservoirs. Man and the biosphere series, UNESCO, Paris.

Scheuerlein H 1986. Reservoir sedimentation. In: XIth world dredging congress, Brighton, UK, 4-7 March 1986.

Skjelvåle BL, Henriksen A, Faafang B, Fjeld E, Traaen T, Lien L, Lydersen E, Buan AK, 1997. Regional lakes survey in Norway – autumn 1995. A water survey of the water chemistry of 1500 lakes. NIVA report 3613-97. ISBN 82-577-3169-2, 73 pp.

Société Hydrotechnique de France, 1986. Les lacs de retenue et leur gestion. Dix neuvièmes journées de l'hydraulique, Paris 9-11 septembre 1986.

Thornton KW, Kennedy RH, Magoun AD & Saul GE, 1982. Reservoir water quality sampling design. Water Resour. Bull. 18: 471-80.

Travade F, Enderle MJ, Gras R, 1983. Retenues artificielles : gestion hydraulique et ressources piscicoles. In : Gestion piscicole des lacs et retenues artificielles. Actes du colloque national tenu au château de Baudnen (83630 Aups). 15-16 Novembre 1983. INRA, Paris.

UBA 1997. Response to EEA Dobris+3 questionnaire.

Van de Velde O & Laane WEM, 1990. The abatement of eutrophication of surface waters in the Netherlands. In: La gestion de l'eau, colloque européen, Paris, 4-6 décembre 1990.

Veltrop JA, 1991. Water, dams and hydropower in the coming decades. Water Res J No 9.

Verta & Matti, 1990. Mercury in Finnish forest lakes and reservoirs: anthropogenic contribution to the load and accumulation in fish. National Board of Waters and the Environment (Finland). Publication no 6, 1990.

Vinconneau JC, 1992. Lutte contre l'eutrophisation en France. Bull. Cons. Gen. GREF, 1992, N°33, p43-53.

Vollenweider R., 1976. Advances in defining critical levels for phosphorus in lake eutrophication. Mem. Ist. Ital. Idrobiol. 33: 53-83

Wahlström E, Hallanaro EL, Reinikainen T, 1993. State of the Finnish environment. Ministry of the Environment (Finland).

World Resources Institute, 1992. World Resources, 1992-1993. A guide to the global environment. Published by the World Resources Institute, in collaboration with United Nations Environment Programme and United Nations Development Programme.

WRc (pers comm.), 1995. Current issues concerning lakes and reservoirs in the UK. Written contribution to ETC/IW report.