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Development and validation of a global database of lakes, reservoirs and wetlands

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Abstract

Drawing upon a variety of existing maps, data and information, a new Global Lakes and Wetlands Database (GLWD) has been created. The combination of best available sources for lakes and wetlands on a global scale (1:1 to 1:3 million resolution), and the application of Geographic Information System (GIS) functionality enabled the generation of a database which focuses in three coordinated levels on (1) large lakes and reservoirs, (2) smaller water bodies, and (3) wetlands. Level 1 comprises the shoreline polygons of the 3067 largest lakes (surface area $\geq 50\ km^2$) and 654 largest reservoirs (storage capacity $\geq 0.5\ km^3$) worldwide, and offers extensive attribute data. Level 2 contains the shoreline polygons of approx. 250,000 smaller lakes, reservoirs and rivers (surface area $\geq 0.1\ km^2$), excluding all water bodies of level 1. Finally, level 3 represents lakes, reservoirs, rivers, and different wetland types in the form of a global raster map at 30-second resolution, including all water bodies of levels 1 and 2.

In a validation against documented data, GLWD proved to represent a comprehensive database of global lakes $\geq 1\ km^2$ and to provide a good representation of the maximum global wetland extent. GLWD-1 and GLWD-2 establish two global polygon maps to which existing lake registers, compilations or remote sensing data can be linked in order to allow for further analyses in a GIS environment. GLWD-3 may serve as an estimate of wetland extents for global hydrology and climatology models, or to identify large-scale wetland distributions and important wetland complexes.

Keywords: Lakes; Reservoirs; Wetlands; Global; Geographic Information System; Land cover maps

1. Introduction

It is estimated that today more than 8 million lakes larger than 1 ha (Meybeck, 1995), about 40,000 dams higher than 15 m (ICOLD, 1998) and some 800,000 smaller ones (McCully, 1996), and more than 10 million km^2 of wetlands (Finlayson and Davidson, 1999) exist worldwide. Due to their basic ability to retain, store, clean, and evenly provide water, as well as their distinct characteristics as still-water bodies, lakes, reservoirs and wetlands constitute essential components of the hydrological and biogeochemical water cycles, and influence many aspects of ecology, economy, and human welfare. Knowledge about

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the distributions of lakes, reservoirs and wetlands is therefore of great interest in many scientific disciplines. Besides their regional significance, global distributions are of particular interest for assessments of present and future water resources, for climate change modeling (global land surface parameterization, methane emissions), and for large-scale studies of the environment, biodiversity, health (spreading of water-borne diseases), and agricultural suitability (Dugan, 1993; Meybeck, 1995; Hagemann and Dümenil, 1997; Vörösmarty et al., 1997; Groombridge and Jenkins, 1998; Mitsch and Gosselink, 2000; Revenga et al., 2000; Sanderson, 2001; Wetzel, 2001).

Despite this importance, few comprehensive data sets exist which comprise information on location, extent and other basic characteristics of open water bodies and wetland areas on a global scale. Birkett and Mason (1995) found that quantity and quality of replies in their extensive search for global lake databases were poor, and very few authors have considered lake censuses on a global scale (Meybeck, 1995). A review of the Ramsar Wetlands Convention concluded that available data are too incomplete to provide a reliable estimate of the global extent of wetlands (Finlayson and Davidson, 1999).

As an alternative data source, recent developments in the field of remote sensing promise global land cover images in increasing quality and resolution, including the possibility to monitor spatio-temporal changes in lake and wetland extents. Based solely on the remotely received signal, however, the correct classification of an open water surface or a mixed vegetation area, say into ‘lake’, ‘reservoir’ or ‘temporarily flooded wetland’, is difficult. Misinterpretation of the signal may lead to errors, and the provided raster-cell representation hinders a clear identification of separate lake pools, individual wetland complexes or single components of braided river and lake systems.

Despite their individual limitations, the existing lake and wetland registers, maps and databases are unique and highly valuable sources of information, focusing on different geographic regions or aspects. The majority of currently available data sets can be grouped into two categories (compare Table 1).

(A) Databases, registers and inventories that focus on descriptive attributes (Table 1, Nos. 1–7). These data sets can provide extensive characterizations for individual lakes or wetlands. However, they generally tend to select only the largest or most important representatives, and they often lack detailed geo-referencing information. In a review, Birkett and Mason (1995) list 13 global and regional lake data sets, which partly include coordinate data, the largest of them comprising 1755 lakes. Since this review, some new databases were compiled, including up to 40,000 individual records (Ryanzhin et al., 2001), but all of them provide geo-referencing information only in terms of longitude/latitude point coordinates, rather than shoreline polygons.

(B) Analog or digital maps that show lakes, reservoirs and wetlands in their spatial extent. The digital maps include (i) polygon data sets of global hydrography, i.e. vectorized maps of river, lake and wetland outlines as derived from various source maps (Table 1, Nos. 8–11), and (ii) rasterized global land use or land cover characterizations as derived from remote sensing or other sources (Table 1, Nos. 12–17). Both type (i) and (ii) data provide information on extent and distribution of lakes and wetlands, but have limitations when individual attributes, e.g. name or ecological condition, are of interest. An important difference between type (i) and (ii) data sets is that remote sensing maps span only the most recent time period, while the polygon data are largely based on analog maps which were drawn from local observations and knowledge over a longer period of time. The polygon maps can thus be assumed to incorporate, at least to some extent, historic conditions and may tend towards representing lakes or wetlands as known in their maximum recorded extents.

This paper presents a new comprehensive database, which combines information of both categories A and B in a consistent manner. The compilation and linkage of attribute and geometric data of the different sources was realized within a Geographic Information System (GIS). The result is a Global Lakes and Wetlands Database (GLWD), organized in three levels: Level 1 comprises the shoreline polygons of the 3067 largest lakes (surface area $\geq 50\ km^2$) and 654 largest reservoirs (storage capacity $\geq 0.5\ km^3$) worldwide, and offers extensive attribute data. Level 2 contains the shoreline polygons of approx. 250,000 smaller lakes, reservoirs and rivers (surface area $\geq 0.1\ km^2$), excluding all water bodies of level 1.

Table 1
Overview of existing global and regional data sets of lakes, reservoirs and wetlands

No.	Name and citation	Geo-spatial characteristics	Attribute characteristics	Comments
1	MSSL Global Lakes Database – MGLD; Birkett and Mason (1995)	Global Point coordinates derived from satellite imagery and 1:1 million Operational Navigation Charts (ONC)	Comprises 1409 large natural lakes and reservoirs with surface areas $\geq$ 100 km^2 (approximately) Attributes include type, name, and area of lakes	MGLD focuses on identifying 'closed' (without significant outflow) vs. 'open' lakes; other attributes are derived from ONC maps and atlases (e.g. accuracy of lake surface area estimated at ±20%) Some errors are reported (Ryanzhin and Geller, 2001)
2	Data set of Large Reservoirs – LRs; Vörösmarty et al. (1997)	Global Point coordinates approximated on a global 0.5 x 0.5 degree grid	Comprises 713 large reservoirs with storage capacities $\geq$ 0.5 km^3 Attributes include dam name, dam height, storage capacity, and name of dammed river	LRs are largely based on ICOLD's World Register of Dams of 1988 (ICOLD, 1988), see No. 3 Dam names can be different to reservoir/lake names as provided in other sources
3	The World Register of Dams – WRD; ICOLD (1988, 1998)	Global No geo-referencing information (location only indicated by name of river and nearest city)	Comprises about 25,000 large dams (higher than 15m) Attributes include dam name, dam geometry, reservoir capacity, and purpose of dam	Apparently, ICOLD's World Register of Dams contains some significant errors, including order-of-magnitude errors (Leonard and Crouzet, 1999)
4	Survey of the State of World Lakes; ILEC (1988-1993, 2002)	Global Point coordinates	Comprises 752 lakes and reservoirs (Nov. 2002) Attributes include general information, physiographic, biological and socioeconomic data	Ongoing project to collect environmental and socio-economic data of important (significant for human beings) lakes and reservoirs around the world (ILEC, 2002) Available as 'Data Books of the World Lake Environments' and online database
5	Global Database and GIS WORLDLAKES; Ryanzhin et al. (2001)	Global Point coordinates	Currently comprises about 35,000 natural lakes, 5000 reservoirs, and 220 wetlands Attributes include geography, morphometry, hydrology, meteorology, chemistry, and biology	Extensive database and detailed lake characterizations of limnologically studied lakes (of any size) compiled from literature sources published in the last 40-50 years Not yet finalized and available
6	Ramsar Database – RDB; Wetlands International (2002)	Global Representative point coordinates	Currently comprises more than 1200 wetland sites Attributes, including site names, area, designation date and wetland characteristics	RDB contains information on wetlands designated as internationally important under the Ramsar Convention on Wetlands of 1971 (= Ramsar Sites) and is continually updated Also available as Ramsar List of site names, coordinates and areas only
7	Other global and regional wetland, lake and reservoir inventories and registers	Mostly regional In part with point coordinates	Various attributes Birkett and Mason (1995, their Table 1) list 13 lake data sets (10 global, 3 China); the largest comprises 1755, all others less than 500 lakes; except the data set of Herdendorf (1982), which comprises all global lakes > 500 km^2, none of them claims to be comprehensive	Examples include the African Dams Database of FAO (2001), the European Lakes, Dams and Reservoirs Database ELDRED (Leonard and Crouzet, 1999), or the United States National Inventory of Dams by the US Army Corps of Engineers
8	The Digital Chart of the World – DCW; ESRI (1993)	Global vector map 1:1 million resolution	Includes approx. 300,000 lake and wetland polygons, classified as 'permanent' and 'intermittent' water bodies, and 'wet sands'	Most comprehensive global vector data set, and best source of vector data for many areas of the world (Jaquet and Maliki, 1999), also known as VMAP-0; based on the US DMA (now NIMA) Operational Navigation Charts (ONC) whose information dates from between the 1970s to the 1990s (Birkett and Mason, 1995); no distinction between rivers, lakes and reservoirs; selected layers, including hydrographic features, are available online at http://www.maproom.psu.edu/dcw/

(*continued on next page*)

Table 1 (*continued*)

No.	Name and citation	Geo-spatial characteristics	Attribute characteristics	Comments
9	ArcWorld 1:3M data set; ESRI (1992)	Global vector map 1:3 million resolution	Includes 7283 polygons of open water bodies, classified as 'lakes', 'reservoirs', 'rivers', 'intermittent lakes', 'lagoons', and 'salt pans'	Coarser resolution than DCW (No. 8), but more detailed classification
10	Wetlands map of the World Conservation Monitoring Center – WCMC; Dugan (1993), WCMC (1993)	Global vector map Broadly based on 1:1 million maps and regional wetland directories prepared by IUCN (The World Conservation Union) and partners	Includes approx. 20,000 wetland and lake polygons, classified in 21 types (some of the classes, however, are indicating the same type with changing names for different continents)	WCMC's global wetlands map probably represents the most comprehensive and accurate vector map of the world's wetlands (Dugan, 1993). Compiled from a number of sources, however, quality and generalization of the wetland outlines vary considerably for different regions and continents. Although lakes are included, it was never intended to provide detailed lake information and there is no digital version which comprises all the lakes shown in the wetlands atlas (S. Blyth, WCMC, personal communication, 1999).
11	Other global and regional vectorized wetland, lake and reservoir maps and data sets	Mostly regional Various resolutions	Various attributes	Examples include the World Data Bank II (WDBII), ESRI's ArcAtlas (1:10 million resolution), the Mediterranean Wetlands Inventory (MedWet), the US National Wetlands Inventory of the Fish and Wildlife Service, or the hydrography layer of USGS National Atlas of the United States (USGS, 1999)
12	USGS Global Land Cover Characteristics database – GLCC; Loveland (1991), Loveland et al. (2000)	Global raster map Available in various resolutions, including 30 x 30 seconds (approx. 1 x 1 km)	Various classifications Available legends include 'IGBP Land Cover Classification' (Belward et al., 1999), 'USGS Land Use/Land Cover System (Anderson et al., 1976), 'Biosphere Atmosphere Transfer Scheme' (Dickinson et al., 1986), and 'Global Ecosystems' (Olson, 1994a, 1994b)	The GLCC database, derived from Advanced Very High Resolution Radiometry (AVHRR) is frequently applied and considered among the most convincing land cover products at a global 1-km spatial resolution (Strahler et al., 1999, Bright, 2002) Lakes (incl. reservoirs) and wetlands are represented in the IGBP legend as 'open water' and 'permanent wetlands'. The GLCC database in IGBP legend is also known as DISCover
13	MODIS (MODerate resolution Imaging Spectroradiometer) land cover product; Hodges et al. (2001)	Global raster map Available in various resolutions, including 30 x 30 seconds (approx. 1 x 1 km)	Various classifications Available legends include 'IGBP Land Cover Classification' (Belward et al., 1999), and water mask bit labels	The various land cover suites of the new MODIS data set are still in the process of quality assessment, but the first global 30-second (1-km) resolution maps recently became available Lakes (incl. reservoirs) and wetlands are represented in the IGBP legend as 'open water' and 'permanent wetlands'
14	Wetlands map of Mathews and Fung (1987)	Global raster map 1 x 1 degree resolution	Available classifications include major natural wetland types (both permanent and seasonal) and fractional wetland extent per cell	Matthews and Fung (1987) derived their database by integrating three independent global maps of vegetation, soil properties and inundation
15	Wetlands map of Cogley (1987, 1991, 1994)	Global raster map 1 x 1 degree resolution	Available classifications include major natural wetland types (both permanent and seasonal) and fractional wetland extent per cell	The wetlands data set assembled by Cogley (1987, 1991, 1994), which is included in the International Satellite Land Surface Climatology Project (ISLSCP), is based on 1:1 million terrain type maps
16	Wetlands map of Stillwell-Soller et al. (1995)	Global raster map 1 x 1 degree resolution (interpolated from 5 x 2.5 degree source map)	Available classifications include major natural wetland types (both permanent and seasonal) and fractional wetland extent per cell	Stillwell-Soller et al. (1995) updated an original 5 x 2.5 degree wetlands map of Aselmann and Crutzen (1989) and interpolated it to a 1 x 1 degree grid; update and corrections are limited to Alaska only
17	Other global and regional rasterized wetland, lake and reservoir maps and data sets	Mostly regional Various resolutions	Various attributes	Land cover maps are used in a wide range of environmental research and modeling applications and are available in different resolutions and classifications; examples include the European CORINE database, or FAO's AFRICOVER project

Finally, level 3 represents lakes, reservoirs, rivers, and different wetland types in the form of a global raster map at 30-second resolution, including all water bodies of levels 1 and 2.

The three levels of GLWD were originally developed to be applied in a global hydrological model in order to improve calculations of open water evaporation and lateral flow regimes (Alcamo et al., 2003; Döll et al., 2003). These objectives may have influenced some of the displayed characteristics of GLWD, e.g. some unmapped reservoirs were introduced as circular polygons in order to represent their evaporation surface. However, the generated database is believed to provide important information for the broader scientific community and to support a variety of applications.

2. Database generation

2.1. Definitions of lakes and wetlands

Lakes. There are various definitions of lakes, based on criteria like volume, surface area, depth, or presence of certain habitat types. For small lakes, lakes in floodplains or lakes adjacent to the sea, the distinction between slow-flowing rivers and lakes may be ambiguous (Leonard and Crouzet, 1999), there may be a continuum between lakes and wetlands (Meybeck, 1995), and a strict separation from the sea may be questionable. In the generation of GLWD we were restricted by the given classifications of the source data, which in some cases do not provide clear-cut criteria to support a correct identification. We therefore largely refer to lakes as permanent still-water bodies (lentic water bodies) without direct connection to the sea, but, in a compromise to account for the mixed classifications, we accepted saline lakes and lagoons (but not 'lagoon areas') as lakes, while excluding intermittent or ephemeral water bodies. For the global estimates of lake numbers and areas we assume a minimum size limit for lakes of 0.01 km^2 (1 ha); the GLWD database itself includes lakes ≥ 0.1 km^2. The term 'lake', if not stated otherwise, is used in this paper for both natural lakes and manmade reservoirs. The term 'reservoir' indicates that lakes are explicitly classified as manmade.

Wetlands. Wetland areas are commonly distinguished by the presence of standing water for some period during the growing season, either at the surface or within the root zone. Their clear definition is difficult, however, as they are by nature transitional between terrestrial and aquatic systems. A clear distinction of wetland types is additionally limited by a lack of standardization of terms such as 'bogs and fens' (peat-accumulating wetlands), 'marshes' (herbaceous, frequently inundated wetlands), or 'swamps' (forested wetlands) (Mitsch and Gosselink, 2000). At the Ramsar Convention, the International Union for the Conservation of Nature (IUCN, The World Conservation Union) adopted a wetland definition which includes areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or saline including areas of marine water, the depth of which at low tide does not exceed 6 m (Navid, 1989). The data used for the generation of GLWD generally follows this definition. We also include large rivers as wetlands (lotic wetlands) as we assume that only a river with adjacent wetlands (floodplain) is wide enough to appear as a polygon on the coarse-scale source maps.

2.2. Data sources

In the course of developing GLWD, different attribute and polygon data sources were investigated (Table 1). Each of them showed individual advantages and constraints. The three levels of GLWD were finally based on the combination of seven digital maps and attribute data sets (Table 2). Among these, the Digital Chart of the World (DCW) of ESRI (1993) is the most comprehensive global coverage of vectorized lake shorelines at a resolution of 1:1 million and thus served as the main source map for identifying lakes and reservoirs. A significant obstacle, however, of directly applying the drainage layer of DCW to identify individual water bodies is that no distinction is made between large rivers and lakes (or reservoirs). Where a large river (represented as surface polygon) drains into or out of a lake, DCW provides one seamless polygon only. Thus, in order to allow for the isolation of lakes, we visually inspected the entire global DCW coverage and intersected all assumed river–lake-polygons at probable locations of lake inflows or outlets. Various atlases and maps (foremost The Times Atlas of the World,

Table 2
Main data sources applied for generation of GLWD

Data set	No. in Table 1	Information included in generation of GLWD data set		
		Level 1	Level 2	Level 3
MGLD	1	Yes	No	Yes
LRs	2	Yes	No	Yes
WRD	3	Only to complete LRs	No	No
DCW	8	Class ‘Permanent’ $\geq 50\ km^2$	Class ‘Permanent’ $\geq 0.1\ km^2$	All classes $\geq 0.1\ km^2$
ArcWorld	9	‘Lakes’ $\geq 50\ km^2$, ‘Reservoirs’ $\geq 0.5\ km^3$	‘Lakes’ and ‘Reservoirs’ $\geq 0.1\ km^2$	All classes $\geq 0.1\ km^2$
WCMC wetlands map	10	‘Lakes’ $\geq 50\ km^2$, ‘Impoundments’ $\geq 0.5\ km^3$	‘Lakes’ and ‘Impoundments’ $\geq 0.1\ km^2$	All classes $\geq 0.1\ km^2$
GLCC in ‘Global Ecosystem’ classification	12	No	No	Class ‘Bog, Fen, Mire’

For data descriptions and references see Table 1.

Bartholomew Ltd, 1999) served as validation information in this process.

Besides the seven applied data sources (Table 2), other global or continental data sets of lakes and reservoirs were known at the time of constructing GLWD (compare Table 1) but were not included for various reasons. We did not incorporate the data sets listed in a review by Birkett and Mason (1995) as we consider them represented in the succeeding MGLD database. We also preferred MGLD over ILEC’s Survey of the State of the World Lakes database (ILEC, 1988–1993, 2002) because the latter, an ongoing project with currently about 750 entries, focuses less on size criteria rather than on lakes and reservoirs which are of importance for humans. In part, however, ILEC data is included in MGLD. Regional databases, like FAO’s database of African dams (FAO, 2001), the USGS lakes and reservoirs data set of the United States (USGS, 1999), or the ELDRED database of European lakes (Leonard and Crouzet, 1999) were not considered in order to avoid biased representation of different continents or countries. The World Register of Dams database, compiled by ICOLD (1998), does not list any coordinates, and given the risk of introducing significant errors we refrained from automated geo-referencing techniques (e.g. allocation via name of nearest city). Finally, the new extensive global database and GIS WORLDLAKE of Ryanzhin et al. (2001) was not available to us at the time of generating GLWD. Where possible, however, these additional data sets were applied for crosschecks, validation and correction of GLWD.

2.3. Generation of GLWD

Two main processes characterize the development of GLWD: (i) the generation of one single polygon map from three different sources; and (ii) the consolidation of the different attribute databases and their linkage to the respective polygons. The complexity of the first task is largely due to the various resolutions of the given data sets, their different level of shoreline generalization and their inherent inaccuracies.

Highly irregular shorelines, as found e.g. in Finland or Canada, generally make it difficult to distinguish separate lakes (Birkett and Mason, 1995). A high resolution map may divide a lake at narrow gorges into two or more pools, whereas a coarser map may generalize them in one combined lake polygon. If there is an additional slight offset in the polygon locations on the different source maps, such that the common overlap area of the multiple lake polygons is only partial, it is even more difficult to decide whether the intersecting polygons represent one or more individual lakes. Fully automated GIS algorithms cannot solve these problems, but rather tend to derive ‘best estimates’, e.g. by merging overlapping polygons into one combined object, by strictly favoring the higher resolution map, or by applying certain thresholds in their decisions.

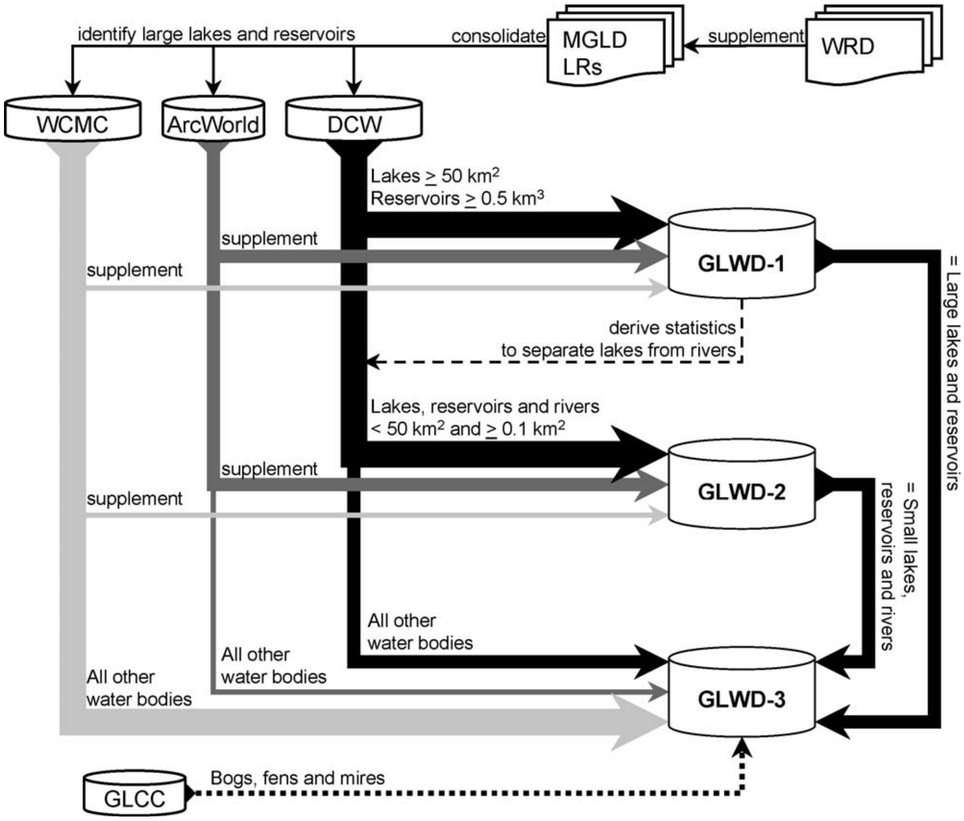

Fig. 1. Overview of GLWD database generation. Line widths indicate relative significance of data contributions, but are not proportional. For data descriptions and references see text and Table 1.

In the generation of GLWD, overlapping lake and river polygons were not merged (as this would methodically enlarge the original surface areas), but in each case a representative polygon was selected from one of the different source maps. In semi-automated procedures, the polygons of DCW were generally preferred over ArcWorld (due to DCW's higher resolution) and ArcWorld over WCMC (due to WCMC's lower consistency between continents). Additionally, extensive visual inspections and individual decisions were performed. Fig. 1 provides an overview of the generation of the three levels of GLWD, and the main processing steps are briefly outlined below.

2.3.1. Level 1 of GLWD

The first level of GLWD has been developed to provide a polygon data set of the world's largest lakes and reservoirs including detailed descriptive attributes. GLWD-1 comprises lakes and reservoirs which, according to the available source data (Table 2), fulfill at least one of the criteria 'lake area $\geq 50\ \text{km}^2$' or 'storage capacity $\geq 0.5\ \text{km}^3$'. The applied attribute data sets of MGLD (Birkett and Mason, 1995), LRs (Vörösmarty et al., 1997), and WRD (ICOLD, 1998) were first consolidated, crosschecked for errors and logical consistency, corrected, in a few cases updated with independent data (USGS, 1999; Ryanzhin and Geller, 2004), and finally linked to the identified polygons. Two equations were applied in order to complete missing reservoir data:

$$\text{Reservoir area} = 3.42 \times \frac{\text{Reservoir volume}}{\text{Dam height}} \tag{1}$$

$$\text{Reservoir volume (km}^3) = 0.009208 \times \text{Reservoir area (km}^2)^{1.114} \tag{2}$$

Eq. (1) was used to estimate reservoir surface areas from given volume data and dam heights. This equation was determined by a statistical regression analysis of 515 reservoirs with complete WRD data ($R^2 = 0.7$). It was applied for all reservoirs without documented surface areas. Eq. (2) is taken from Takeuchi (1997), who derived it by considering 7936 reservoirs worldwide. It was applied for all reservoirs without documented volume data. Due to Eq. (2), all reservoirs with a surface area ≥ 36.1 km^2 are included in GLWD-1, as their calculated storage capacity is larger than 0.5 km^3.

From the identified 3721 polygons of GLWD-1, 654 were attributed as reservoirs and 3067 as lakes, 1751 were assigned a name, and for various smaller subsets further descriptive attributes could be compiled, including the type of lakes (open/closed); the height and year of dam constructions; the name of dammed rivers; the nearest city to dams; and the main purpose of reservoirs. Additional information was derived for all polygons based on GIS supported analyses and overlaps of the shoreline polygons with other data sets. These attributes include the geometric calculation of surface areas; shoreline perimeters; center coordinates; as well as one or more assigned countries per water body (105 large international lakes and reservoirs were identified). Estimates of mean altitude and watershed areas were derived from an overlay with the HYDRO1k data set (USGS, 2000), a hydrologically enhanced digital elevation and watershed model in 1-km resolution. Finally, GLWD-1 includes a coarse estimate of average annual river flows into the lakes and reservoirs based on discharge calculations as provided by the global water model WaterGAP (Alcamo et al., 2003; Döll et al., 2003). Due to scaling issues and model inaccuracies, however, these estimates show a high degree of uncertainty and have to be interpreted with caution.

2.3.2. Level 2 of GLWD

The second level of GLWD has been developed to complement the large lakes and reservoirs of GLWD-1 such that GLWD-1 and GLWD-2 together provide a complete global polygon database of permanent lakes, reservoirs and rivers ≥ 0.1 km^2. Smaller objects in the source data (Table 2) were found to be increasingly erroneous. For the most part, GLWD-2 is composed of the remainder of permanent water bodies of DCW, comprising a total of approx. 250,000 polygons, and adds some few missing lakes and reservoirs from ArcWorld and WCMC.

As DCW does not distinguish rivers from lakes or reservoirs, we introduced this differentiation based on a GIS supported morphometrical analysis of the polygons' shape properties. After several tests with standard morphometrical form factors (Hutchinson, 1957; Håkanson, 1981), we defined a 'surface development' factor as the ratio of a water body's surface area to the area of the smallest circle that entirely encloses it:

$$\text{Surface development} = \frac{\text{Lake surface area}}{\text{Area of smallest enclosing circle}} \times 100\% \qquad (3)$$

A completely round water body has the highest possible surface development of 100%, and the stronger the deviation from the circular shape, the smaller the value. We presume in this approach that lakes and reservoirs tend to appear more compact and round in their overall shape than narrow, linear river polygons. We derived the surface development of all available shoreline polygons through GIS calculations. While 98.8% of GLWD-1 lakes and reservoirs show a surface development of more than 3%, typical river polygons of DCW are characterized by significantly smaller values. Based on this relation, we classified all water bodies of DCW with a surface development smaller than 3% as 'rivers', all others as 'lakes' (with some manual corrections).

Further attempts to distinguish lakes from reservoirs based on similar morphometrical form factors did not lead to statistically significant results, and we refrained from automatically classifying reservoirs in DCW. Thus, class 'lake' of GLWD-2 comprises both natural lakes and most manmade reservoirs, while only 168 polygons could be explicitly identified as reservoirs from the given source data.

2.3.3. Level 3 of GLWD

The objective of the third level of GLWD is to provide a global coverage of the maximum extent of

Table 3
Classification, extent and sources of wetlands as presented in GLWD-3

Id	Class	Original classes in source data	Global area		Sources of extent or of attribute
			10^3 km^2	%[a]	
1	Lake	'Lake' of GLWD-1 and GLWD-2	2428	1.8	α, β, γ, δ
2	Reservoir	'Reservoir' of GLWD-1 and GLWD-2	251	0.2	α, β, γ, δ, ε, ζ, η
3	River	'River' of GLWD-2	360	0.3	α, θ
4	Freshwater Marsh, Floodplain	'River' of β; 'Freshwater Marsh, Floodplain', 'Floodplain' of γ	2529	1.9	β, γ
5	Swamp Forest, Flooded Forest	'Swamp Forest, Flooded Forest' of γ	1165	0.9	γ
6	Coastal Wetland	'Lagoon' of β; 'Delta', 'Lagoon', 'Mangrove', 'Estuary', 'Coastal Wetland', 'Tidal Wetland' of γ	660	0.5	β, γ
7	Pan, Brackish/Saline Wetland	'Wet Sands' of α; 'Salt Pan' of β; 'Pan', 'Brackish Wetland', 'Salt Lake Area', 'Soda Lake Area' of γ	435	0.3	α, β, γ
8	Bog, Fen, Mire	'Bog, Fen, Mire' of ι	708	0.5	ι
9	Intermittent Wetland/Lake	'Intermittent' of α; 'Intermittent Lake' of β; 'Seasonal Wetland', 'Occasional Wetland' of γ	690	0.5	α, β, γ
10	50–100% Wetland	'50–100% Wetland' of γ	882–1764	0.7–1.3	γ
11	25–50% Wetland	'25–50% Wetland' of γ	790–1580	0.6–1.2	γ
12	Wetland Complex (0–25%)	'Wetland Complex' and 'Tank Region' of γ	0–228	0–0.2	γ
	Total lakes and reservoirs (classes 1 and 2)		2679	2.0	α, β, γ, δ, ε, ζ, η
	Total Wetlands (classes 3–12)		8219–10,119	6.2–7.6	α, β, γ, θ, ι

α: DCW (ESRI, 1993). β: ArcWorld (ESRI, 1992). γ: WCMC wetlands map (Dugan, 1993; WCMC, 1993). δ: MGLD (Birkett and Mason, 1995). ε: LRs (Vörösmarty et al., 1997). ζ: WRD (ICOLD, 1998). η: US National Atlas (USGS, 1999). θ: GIS analysis (shape morphology). ι: GLCC in 'Global Ecosystem' classification (Loveland, 1991; Loveland et al., 2000; Olson, 1994a,b).
[a] Total global land surface area (excluding Antarctica and glaciated Greenland) 133 million km^2.

lakes, reservoirs, rivers and wetland areas. For this purpose we overlaid all water bodies of GLWD-1 and GLWD-2 with the relevant wetland classes of DCW, ArcWorld and WCMC (Tables 2 and 3). Additionally, we supplemented one missing wetland type ('Bog, Fen, Mire') from remote sensing data.

In order to simplify the complex handling of multi-intersecting and overlapping polygon arrangements, we combined the source maps in raster format at 30-second resolution (approx. 1 km × 1 km at the equator). Conflicting classes of overlapping polygons were resolved by re-attributing the final coverage into a simplified classification scheme, applying priorities in the following order (compare classes of Table 3): lakes, reservoirs and rivers of GLWD-1 and GLWD-2 (classes 1–3); explicit wetland types of ArcWorld over WCMC and DCW (classes 4–7); inexplicit wetland types of DCW over ArcWorld and WCMC (classes 9–12).

In the resulting coverage, wetlands are present where a polygon exists in at least one of the source maps. This approach tends to reflect wetlands in their maximum extent, to which strong seasonal variations may apply. Three classes indicate only fractional wetland areas: '50–100% wetland', '25–50% wetland', and 'wetland complex'. The latter is a mix of different wetland types, for which we could not identify a clear spatial coverage ratio and suggest '0–25% wetland'.

3. Results, validation and discussion

3.1. GLWD Level 1

Level 1 of GLWD represents a digital global polygon map of the world's largest lakes and reservoirs. It contains 3721 water bodies, i.e. 3067 lakes with a surface area ≥ 50 km^2 and 654 reservoirs with a storage capacity $\geq 0.5\ km^3$. In total, the large lakes and reservoirs of GLWD-1 cover 1.9 million km^2 (including Caspian Sea) or 1.4% of the global land surface area (excluding Antarctica and glaciated Greenland).

In order to validate the completeness of GLWD-1, we compared it to various other data sets. Herdendorf (1982) lists 253 'great lakes' ($\geq 500\ km^2$) in his global compilation. This data is considered nearly comprehensive, apart from only one lake being missing (Meybeck, 1995). Of these lakes, 223 have been considered in MGLD (Birkett and Mason, 1995), and are thus captured in GLWD-1. In total, GLWD-1 encompasses 255 natural lakes and 109 reservoirs $\geq 500\ km^2$, and slightly more if a small deviation is allowed for the area limit. We thus consider GLWD-1 a virtually complete global polygon data set for 'great lakes' exceeding 500 km^2.

On a national level, we tested GLWD-1 against the hydrography map layer of the digital National Atlas of the United States (USGS, 1999), which includes lakes and reservoirs of the United States at a map scale of 1:2,000,000. The US National Atlas shows 329 large lakes and reservoirs fully within the boundaries of the United States (269 lakes $\geq 50\ km^2$ and 60 reservoirs $\geq 36.1\ km^2$, which according to Eq. (2) compares to a volume $\geq 0.5\ km^3$). GLWD-1 presents a total of 397 lakes and reservoirs in this size category, matching 283 of the National Atlas, while GLWD-2 covers another 35. The missing 11 water bodies of GLWD could be identified as intermittent lakes, lagoons and reservoirs. The higher total number of lakes and reservoirs in GLWD-1 is partly due to different interpretations of separated versus combined lake pools, including cases where groups of small lakes are lumped and thus appear as lakes $\geq 50\ km^2$. From the 283 common water bodies of National Atlas and GLWD-1, 69 lakes of the National Atlas were identified as reservoirs in GLWD-1, and 12 vice versa. For 22 water bodies the calculated polygon areas differed by more than 50%, 12 of which are marked as 'reservoir' in either data set. All other water bodies showed an average area difference of 11% for lakes, and 17% for reservoirs. In conclusion, GLWD-1 proved to provide a good overall coverage of large lakes and reservoirs for the United States. There are, however, some limitations and confusion in identified characteristics (type, pool connectivity) and, particularly for reservoirs, in actual size of the water bodies.

In order to evaluate the completeness of large reservoirs, we compared GLWD-1 to the FAO database of African Dams (FAO, 2001). The FAO data provides approximate point coordinates of 1056 dams for the African continent, of which 50 show an attributed volume of 0.5 km^3 or above. GLWD-1 identifies 37 of these dams, with another two matched by GLWD-2 (notably, 7 of the 11 missing dams are located in Nigeria and we could neither confirm location nor actual sizes from other independent sources). GLWD-1 lists 14 additional large reservoirs in Africa, of which six are documented in FAO's database with volumes $< 0.5\ km^3$ or unknown, the rest could not be identified. Based on these findings, a final judgment of the completeness of large reservoirs within GLWD-1 is difficult. In part, the general lack of reliable data for location and volumes of global reservoirs aggravates this uncertainty. Nevertheless, we believe that GLWD-1 provides an acceptable estimate of global and continental distributions of reservoirs, but we recommend re-evaluating GLWD reservoirs when assessing smaller scales.

The European Lakes, Dams and Reservoirs Database ELDRED (Leonard and Crouzet, 1999) shows a total of 95 large lakes and reservoirs ($\geq 100\ km^2$) for 13 countries (Austria, Denmark, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Spain, Sweden, United Kingdom). GLWD-1 includes 92 large water bodies in this size category (76 lakes and 16 reservoirs), and the largest differences in numbers for a single country are -3 for Finland and $+2$ for Sweden. GLWD-1 thus seems to adequately cover the largest lakes and reservoirs of Europe. When looking at reservoir volumes, however, GLWD-1 only includes a small and unevenly distributed fraction of maximum storage capacities per country. For the four dominating countries Spain, Norway, Sweden and Finland, with a total documented storage capacity of over 120 km^3 (Leonard and Crouzet, 1999), GLWD-1 only lists 51 km^3, even though it nearly reaches the full volume for Finland. This finding suggests that it is not legitimate to draw conclusions on country or continental storage capacities by looking at large reservoirs only.

3.2. GLWD Level 2

Level 2 of GLWD represents a digital global polygon map of approx 250,000 small lakes and reservoirs in the size range of 50–0.1 km^2. The lakes and reservoirs of GLWD-2 alone cover 0.8 million km^2. In combination with GLWD-1 they reach 2.7 million km^2, or 2.0% of the global land surface area (excluding Antarctica and glaciated Greenland). GLWD-2 additionally includes 1656 polygons classified as large rivers, which cover another 0.4 million km^2, or 0.3% of the global land surface. The attribute data of GLWD-2 comprise the geometric calculation of surface areas and shoreline perimeters as well as the coordinates of the polygons' center points. Only 168 small reservoirs are explicitly identified, while all others are classified as lakes.

In order to validate the completeness of GLWD-2, we tested it, in combination with GLWD-1, against independent data sets. Our main efforts concentrated on a comparison of GLWD-1/2 to an extensive global lake census conducted by Meybeck (1995), as well as to several other studies by various authors, at both global and regional scales (Table 4). As a first result, the representation of very small lakes in GLWD (0.1–1 km^2) only reaches 10% of the globally estimated 0.7–1.1 million (Meybeck, 1995) and is obviously far from complete. We thus refrain from a detailed investigation of this size class.

As for large lakes ≥ 100 km^2, i.e. GLWD-1 data only, the global coverage of 1452 lakes, totaling about 1.6 million km^2, is in very good agreement with documented values. In the size classes 1–10 and 10–100 km^2, GLWD presents more lakes and larger total areas than globally estimated by other authors. This may in part be due to generalization effects, i.e. groups of smaller lakes (including < 1 km^2) may have been lumped and introduced as larger ones. But considering that all documented global values for these size classes are largely based on extrapolations of few regional censuses, we believe that the actual count of lake polygons in GLWD indicates that recent global estimates are too low.

Most regional estimates of GLWD are in good or acceptable agreement with literature values. For India, GLWD values show a rather different breakdown of size classes, but a very similar limnicity (ratio of total lake area over total country area). As a possible explanation, in this case the literature values may group smaller lakes into large 'lake regions', while GLWD may consider them as single pools. The most significant underestimation of documented values in GLWD is observed for Scandinavia, where the country breakdown identifies Norway as the strongest outlier. However, considering that the documented lake numbers show 80% less lakes in Norway as compared to Sweden, but an even larger lake area, we are not confident in the reliability of this particular literature estimate. Finally, the values provided by Meybeck (1995) for USA may not include Alaska, although stated, as GLWD agrees well with estimates derived from the US National Atlas (USGS, 1999).

In conclusion, GLWD shows a very good global coverage of lakes ≥ 1 km^2 as compared to literature estimates. This result encouraged us to take further advantage of GLWD as being a fully georeferenced database, and to conduct spatial analyses for flexible units or regions. We investigated the latitudinal distribution of lakes and reservoirs as derived from GLWD (Fig. 2) and found the highest concentration of lakes clearly marked throughout all size classes in the de-glaciated areas between 50 and 70° North, including Alaska, Canada, Scandinavia and northern Russia. Lakes smaller than 10 km^2 tend to an even stronger accentuation of the northernmost peak than larger lakes. Lakes ≥ 10 km^2 show secondary peaks at about 30–35° North (including the lakes of the Tibetan Plateau and the lower Yangtze floodplain) and around the equator (including the Amazon and Congo floodplains and the African Rift Valley lakes). As for the floodplain lakes with fluvial origin, the concentration of larger lakes may be partly due to an interpretation of wide river stretches as lakes, while smaller lakes may not be explicitly distinguished from the braided river systems, may be lumped, or may be attributed as general floodplain (wetland) areas. Large reservoirs show their maximum numbers between 30 and 55° North, reflecting major dam constructions in the United States, southern Canada, Europe, Russia and China. Significant numbers of large reservoirs also exist between 30° North and 30° South, i.e. in South America, Africa and South-East Asia. Many of these reservoirs occur in regions with otherwise low concentrations of large lakes, suggesting that besides the alteration of the hydrologic regime they pose

Table 4
Global lake distribution of GLWD as compared to different authors

Country/Region	Size class (km^2)	Meybeck[a] (and others)			GLWD-1/2[b]		
		Number	Area (10^3 km^2)	Limnicity[c] (%)	Number	Area (10^3 km^2)	Limnicity[c] (%)
Former Soviet Union (1)	1–10	36,896 (36,660[d])	87.1 (86.5[d])		31,214	79.4	
	10–100	2360 (2373[d])	55.9 (55.2[d])	2.3	2668	64.3	1.7
	≥100	175 (181[d])	219.7[k] (184.8[d])		200	217.9	
Canada (2)	1–10	44,000[f]	114.0[f]		82,530	219.2	
	10–100	4500[f]	117.0[f]	8.4	7250	172.8	8.9
	≥100	561[f]	494.0		578	475.9	
USA (3)	1–10	3500[f] (8487[e])	9.1[f] (24.4[e])		11,378	29.3	
	10–100	450[f] (1103[e])	11.7[f] (29.4[e])	1.2	1320	33.5	1.8
	≥100	63 (151[e])	85.0 (108.7[e])		115	97.4	
Alaska	≥1	2200[f,j]		1.7	5696	34.2	2.5
India	1–10	130	0.5		1531	4.2	
	10–100	40	1.4	0.37	227	5.3	0.40
	≥100	19	9.9		9	2.8	
Argentina	1–10	1700[f]	4.4[f]		1307	3.7	
	10–100	166	4.5	0.88	161	4.6	0.69
	≥100	21	10.9		22	10.2	
Scandinavia (4)	1–10	8273 (7834[g])	21.5		6482	17.7	
	10–100	1087 (812[g])	28.2	9.4	775	19.1	5.9
	≥100	107 (77[g])	41.3		64	25.6	
Finland	≥1	2609	27.5[f]	9.4 (>9[g])	2168	24.1	7.4
Sweden	≥1	4370	31.7	8.55 (>9[g])	3331	29.7	6.9
Norway	≥1	657	34.9[f]	13.9	1825	8.6	2.9
France	≥1	100[j]		0.09	210	1.6	0.31
Great Britain	≥1	220[j]		1.0 (1[h])	317	1.4	0.75
Greece	≥1			(<0.5[g])	58	0.8	0.60
China (5)	1–10	2383	9.1		3314	9.6	
	10–100	341	12.3	0.88	655	19.3	0.83
	≥100	123	59.2		124	47.5	
Tibet	≥1	610[j]		2.0	741	24.0	2.1
Japan	≥1	100[j]		0.68	299	3.0	0.82
Indonesia	≥1	290[j]		0.32	531	6.9	0.37
North America (6)	1–10				95,203	252.3	
	10–100				8840	213.9	4.9
	≥100				734	594.1	
South America	1–10				6533	18.5	
	10–100				956	25.3	0.54
	≥100				111	50.6	
Europe (7)	1–10				15,057	41.2	
	10–100				1808	44.4	1.7
	≥100				143	81.0	

(*continued on next page*)

Table 4 (*continued*)

Country/Region	Size class (km^2)	Meybeck[a] (and others)			GLWD-1/2[b]		
		Number	Area (10^3 km^2)	Limnicity[c] (%)	Number	Area (10^3 km^2)	Limnicity[c] (%)
Africa	1–10				2641	7.9	
	10–100				504	12.7	0.75
	≥100				85	203.8	
Asia (8)	1–10				33,178	85.9	
	10–100				3446	87.2	1.9
	≥100				353	638.1	
Australia and Oceania (9)	1–10				1013	2.8	
	10–100				178	4.9	0.16
	≥100				21	5.1	
Global (10)	0.1–1	738,000–1,110,000[i]	192–288[i]		73,548	48.9	
	1–10	83,000–127,000[i]	216–323[i]		155,230	412.9	
	10–100	9440–12,300[i]	244–319[i]		15,916	392.8	
	≥100	1261–1523[i]	1624–1683[i]		1452	1573.4	
	Total ≥0.1	0.8–1.3 Mio[i]	2300–2600[i]	1.7–2.0	246,146	2428.1	1.8

(1) Excl. Caspian Sea. (2) Incl. Great Lakes except Michigan. (3) Incl. Alaska; Excl. Great Lakes except Michigan. (4) Norway, Sweden, Finland only. (5) Incl. Tibet. (6) Incl. Central America and the Caribbean; Excl. Greenland. (7) Incl. European part of former Soviet Union, Excl. Turkey. (8) Incl. Caspian Sea (378.1×10^3 km^2). (9) Australia, New Zealand, Melanesia, Micronesia, Polynesia. (10) Incl. Caspian Sea; Excl. Antarctica and glaciated Greenland.

[a] Meybeck (1995) compiled and estimated values based on censuses from various other authors.
[b] Countries and regions assigned via polygon centers.
[c] Ratio of total lake area over total area of country or region, includes all lakes ≥0.1 km^2.
[d] Gleick (1993), data based on Russian source.
[e] USGS (1999), there may be some reservoirs included (43 lakes ≥100 km^2 are identified as reservoirs in GLWD-1).
[f] Values estimated.
[g] Leonard and Crouzet (1999), including reservoirs, based on various authors.
[h] Leonard and Crouzet (1999), United Kingdom.
[i] Global values estimated with different approaches.
[j] Recalculated from lake densities and country areas as provided by Meybeck (1995).
[k] Aral sea area estimated to 68.000 km^2.

a significant change to the original environment in these areas.

Finally, we compared GLWD-1 and GLWD-2 to lake distributions as derived from remote sensing, i.e. the GLCC and MODIS land cover products (Table 1, Nos. 12 and 13). A suite of classification schemes (legends) is supplied with both databases. The different algorithms and methodologies, however, of supervised and unsupervised classification procedures have great influence on the quality of derived results. While theoretical accuracies of 70–90% for 1-km land cover types may be expected under optimal conditions (Strahler et al., 1999), comparisons for the United States indicate that, albeit good overall land cover reliability, many wetlands were recorded as open water bodies in GLCC (Bright, 2002). Also, when looking specifically at lake and wetland distributions, it is a critical issue that in the initial development of both GLCC and MODIS fixed land/water masks were applied (Strahler et al., 1999; Loveland et al., 2000: data documentation). This may bias an independent identification of wetlands versus open water bodies, i.e. lakes and rivers.

We obtained both original GLCC data (version 2, period April 1992 to March 1993) and MODIS data (MOD12Q1, 2000289, version 3, period Oct. 2000 to Oct. 2001) in 30-second resolution. From these source maps we derived GLCC and MODIS maps of

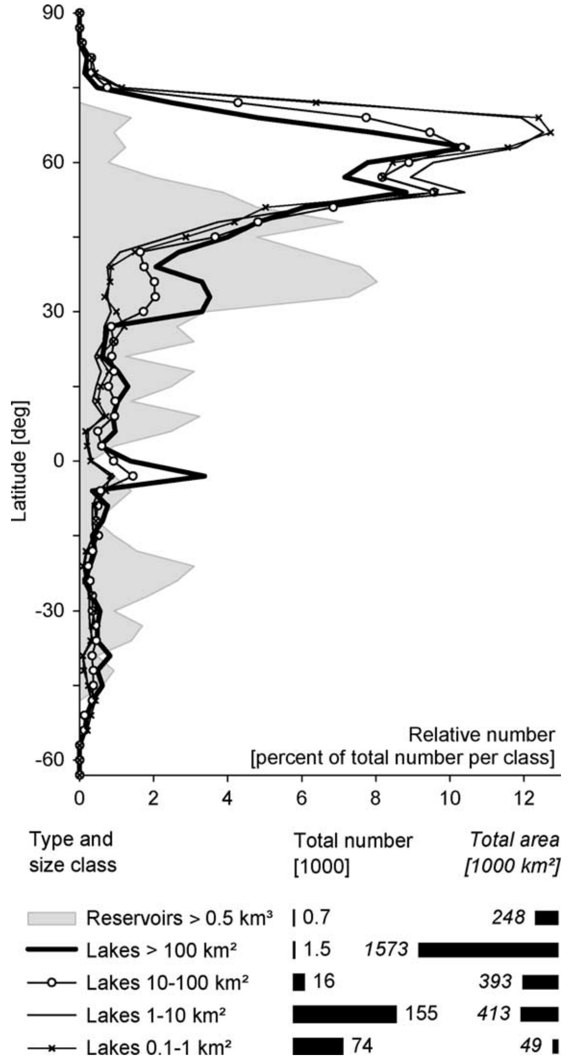

Fig. 2. Latitudinal distribution of global lake and reservoir numbers for different size classes according to GLWD. Relative numbers are aggregated in steps of 3° latitude. Total lake and reservoir areas per size class are provided for reference.

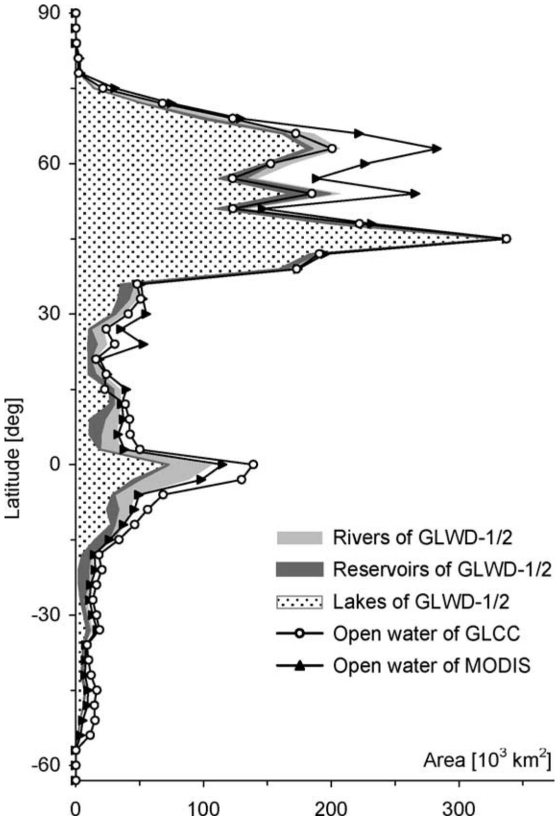

Fig. 3. Latitudinal distribution of global open water areas. Area values are aggregated in steps of 3° latitude. For data description and references see text and Table 1.

maximum 'open water' extents by flagging each cell as open water which is classified as such on at least one of the applied legends (as listed in Table 1).

The latitudinal distribution of lake areas (Fig. 3) reflects the general pattern of lake numbers as given in Fig. 2. An additional and most prominent peak occurs between 40 and 50° North, marking the dominating effect of the North American Great Lakes, and the Caspian and Aral Seas. Both GLCC and MODIS data show lake distributions which are mostly parallel to GLWD, with a tendency of generally higher values and some significant deviations. While the generally higher values as well as the difference around the equator can be attributed to open water surfaces classified as reservoirs and rivers in GLWD, MODIS data clearly exceeds the values of both GLWD and GLCC between 50 and 70° North. This discrepancy may indicate a large number of lakes smaller than the resolution limit of GLWD, or may be due to different interpretations of transition areas between wetlands and lakes (see also Section 3.3). As GLCC data matches GLWD very well in these latitudes, we believe that in general GLWD represents the global distribution of lake areas in good agreement with remote sensing data, but excludes very small lakes and ambiguous lake/wetland areas.

Some interesting statistical conclusions can be drawn from the integral size distribution of all global

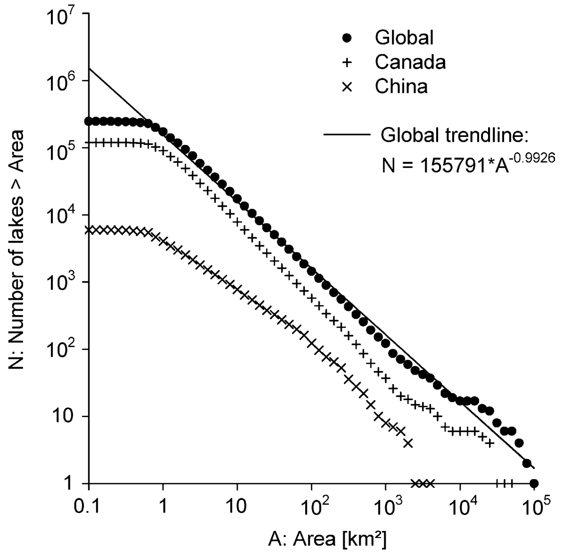

Fig. 4. Global and regional size distributions of lakes based on GLWD-1 and GLWD-2 data (no reservoirs). Values are calculated for equidistant area-intervals on logarithmic scale. Countries were assigned via lake centers.

lakes (total number N of lakes larger than area A). The most striking feature is the linearity of this distribution when drawn on a double logarithmic scale (Fig. 4). This indicates that the lake size distribution follows a power law in the form $N = xA^y$, an observation made already by various authors (Rapley et al., 1987; Wetzel, 1990; Birkett and Mason, 1995; Meybeck, 1995). If y is -1, the relationship becomes scale invariant, implying that, as with many other natural phenomena, the distribution of lakes and their sizes is fractal in form ('i.e. if one could make a copy of a random 10th of the world's surface and then magnify it so that its area was 10 times larger, its distribution of lake sizes would be statistically identical to that for the whole world', Birkett and Mason, 1995: p. 314). This is also reflected by an average tenfold increase of lake numbers from one logarithmic size class to the next smaller one (Table 4). Excluding lakes smaller than 1 km^2 (not complete) and limiting the analysis to a maximum of 100,000 km^2 (size of Caspian Sea is considered an outlier), we derived the global lake distribution as:

$$N = 155791 \times A^{-0.9926} \quad (4)$$

where N is the number of lakes > A, and A is the lake surface area in km^2.

If this distribution can be extrapolated to smaller lakes, the total number of lakes larger than 0.1 km^2 amounts to 1.5 million, and there would be 15.1 million lakes larger than 1 ha worldwide. Meybeck (1995), whose global estimates are significantly lower, notes that this distribution depends on the origin of lake areas and thus is not the same for different geomorphological regions and size classes. We can confirm his conclusions of a lower rise in the number of small lakes for dry and semiarid areas like China, while for formerly glaciated areas like Canada the increase of small lakes is slightly above the global average. When looking only at lakes smaller than 1000 km^2, the distribution of GLWD lakes would suggest an even steeper rise and thus a higher total number of small lakes than derived from Eq. (4). However, any extrapolation based on these findings has to be interpreted with caution. GLWD, as well as other estimates, may tend to underestimate the number of undocumented smaller lakes, as is obvious for lakes <1 km^2. To the contrary, it can be argued that through the effect of map generalization many very small (<1 km^2) water bodies may have been lumped and introduced as small lakes (≥ 1 km^2), thus overestimating the number of the latter in GLWD-2.

In order to estimate a global total number of lake areas, the lakes in classes 0.01–0.1 and 0.1–1 km^2 are approximated to have representative average areas per class. Tamrazyan (1974) estimated this average (geometric center) to be 2.4 times the lower class limit (i.e. 2.4 km^2 for the 1–10 km^2 class), while Meybeck (1995) suggests a factor of 2.6. We derived global average factors of 2.5 for the three classes of 10–10,000 km^2 (higher classes are dominated by outliers), and 2.7 for the class 1–10 km^2 of GLWD. Applying a value of 2.6 and Eq. (4) leads to an estimated lake area of 790,000 km^2 for the lakes of the two classes between 0.01 and 1 km^2. Together with the calculated GLWD lake area for lakes ≥ 1 km^2, we estimate the total global lake area at 3.2 million km^2, or 2.4% of the total global land surface area (excluding Antarctica and glaciated Greenland).

3.3. GLWD Level 3

Level 3 of GLWD represents a global raster map of lakes and wetlands (including reservoirs and rivers) at a spatial resolution of 30 seconds (Fig. 5). GLWD-3

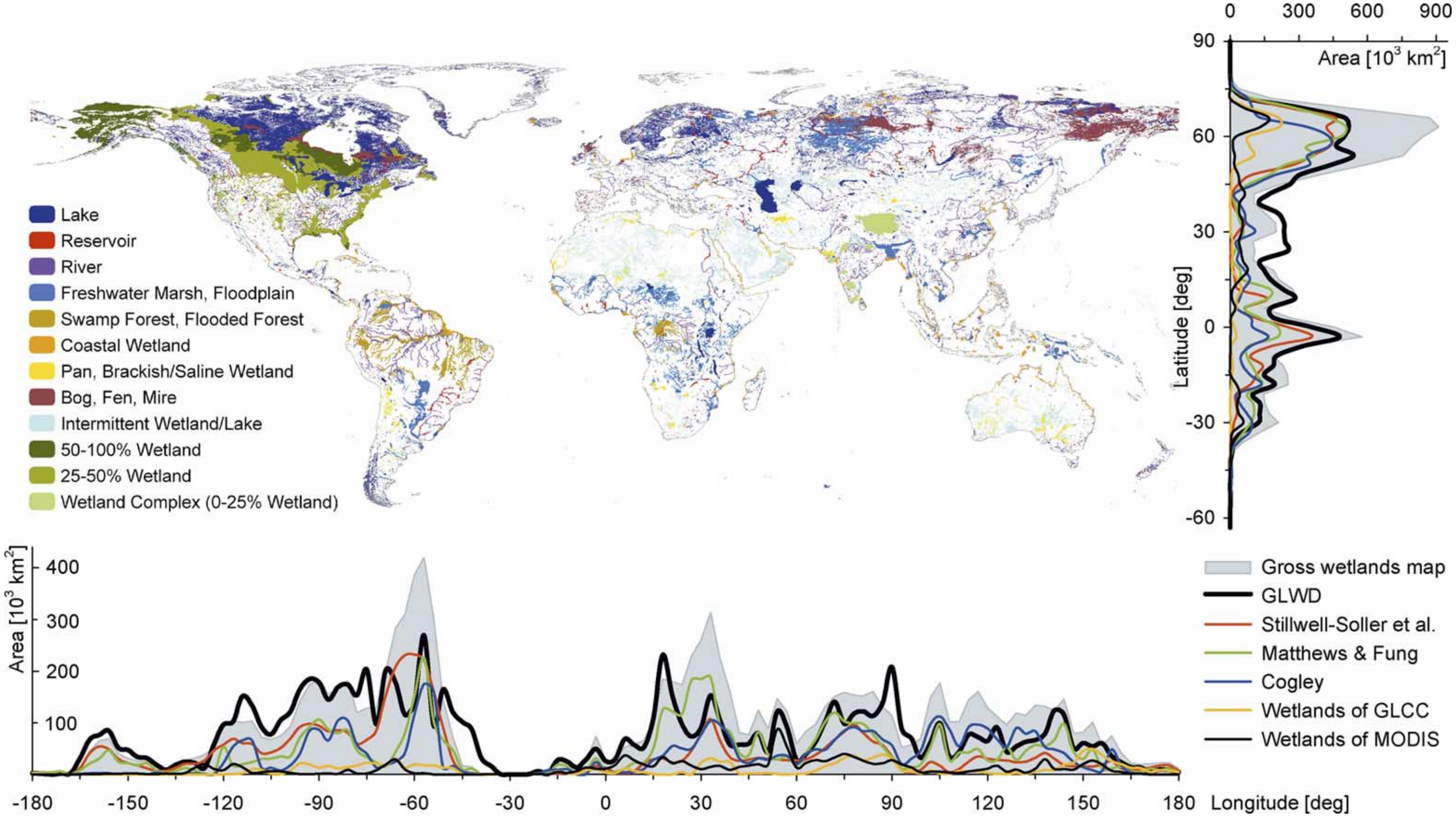

Fig. 5. Global wetlands map GLWD-3, with latitudinal and longitudinal distributions of global wetland areas. Area values are aggregated in steps of 3°. The three fractional wetland classes of GLWD-3 were calculated at their class centers (75, 37.5, and 12.5%). For data description and references see text and Table 1.

distinguishes 12 classes of lakes and wetlands, including the water bodies of GLWD-1, GLWD-2, and all further wetland areas as provided in the source maps. Without lakes and reservoirs of GLWD-1 and GLWD-2, the wetlands of GLWD-3 cover about 8.3–10.2 million km^2, depending on interpretation of fractional wetland classes, or 6.2–7.6% of the global land surface area (excluding Antarctica and glaciated Greenland).

The application of all described criteria and rules for the construction of GLWD-3 from multiple overlays of source data resulted in some complex structures with alternating wetland types (e.g. Lake Chad and surrounding wetlands). These areas have to be interpreted as a representative spatial distribution of different wetland types rather than a discrete localization of lakes, rivers and delimited wetlands. Wetland areas in arid or semiarid regions, in particular pans and intermittent wetlands, can represent dry river stretches or potential freshwater areas which only turn into actual wetlands more or less frequent. These occurrences depend on the presence of sufficient precipitation or inflow and may be extremely rare.

In order to validate the completeness of GLWD-3, we compared it to independent data sets. The GLCC and MODIS global land cover maps (see Table 1, Nos. 12 and 13, and GLCC and MODIS description in Section 3.2) include various classes of permanent wetlands. We derived GLCC and MODIS maps of 'permanent wetland' extents by flagging each cell as wetland which has not previously been identified as 'open water' (Section 3.2) and which is classified as wetland in at least one of the applied legends (as listed in Table 1).

Besides these two global land cover maps, which are not focused on wetland distributions, there are, to our knowledge, three global wetland maps available at 1° raster resolution (Table 1, Nos. 14–16). We applied the maps in their versions as total wetland fractions per cell. While the three 1° wetland maps have similar total wetland areas and overall distributions, significant differences occur in some areas. For this reason, Sanderson (2001) recommends the map of Stillwell-Soller et al. (1995) for global methane modeling, while Hagemann and Dümenil (1997) prefer the map of Matthews and Fung (1987) for global climate and hydrological modeling.

Darras et al. (1998) found in a comparison of the data sets of GLCC, Matthews and Fung (1987) and Cogley (1987, 1991, 1994) that large proportions of wetland areas described in the Ramsar Database (Wetlands International, 2002) are identified by neither of these maps. They conclude that existing global wetland inventories largely underestimate wetland areas and fail to identify a number of wetlands. In consequence, they propose a 'gross' inventory of wetlands in terms of a fusion of the four investigated data sources (including the Ramsar Database) by reclassifying each wetland pixel to the maximum wetland area identified in either source. To take this approach into account, we calculated a gross wetlands map from the five available wetland grids (the two land cover and three 1° wetland maps) by assigning maximum wetland fractions to each cell on a global 0.5° grid. For this purpose, the two land cover maps were aggregated and the three 1° wetland maps disaggregated (without interpolation). In order to allow for comparisons, we also obtained the most recent list of wetland sites from the Ramsar Database (Dec. 2002) and introduced the recorded wetlands as circle polygons at the given point locations in according size.

Table 5 and Fig. 5 provide an overview of global wetland distributions for various scales and regions according to the different data sets. In general, the latitudinal distribution of global wetlands largely parallels the distribution of lakes (Fig. 5 as compared to Figs. 2 and 3). The most striking result of comparing the different data sets, however, is the basic difference in their total global wetland areas, a result also found in the study of Darras et al. (1998). While the three 1° wetland maps agree at about 5 million km^2, GLWD-3 shows a nearly doubled extent of approx. 9 million km^2. The latitudinal distribution reveals that the major differences occur for the latitudes south of about 50° North.

The two land cover products show a generally much smaller total wetland extent of about 1 million km^2 globally. This can be largely attributed to their applied legends, which identify permanent wetland types only and no intermittent ones (Darras et al., 1998). Also, as observed in Section 3.2, GLCC and MODIS data seem to interpret some wetland areas as open water bodies. Thus, the remote sensing maps in their current classification schemes show only limited

Table 5
Global wetland distribution of GLWD as compared to different authors

Country/Region	Documented wetland extent	Matthews and Fung	Cogley	Stillwell-Soller et al.	GLCC	MODIS	Gross wetlands map[a]	GLWD-3
Niger Inland Delta[b]	15–17[c]; 20-30[d]	30	14	7	0	1	43	36
Zaire Swamps[b]	132–220[c]; 200[e]	100	69	30	0	0	139	184
Sudd Swamps[b]	16–31[d]; >30[e]	21	3	28	18	5	37	29
Okavango Delta[b]	10–18[c]; 16[e]	13	7	5	4	5	21	19
China, incl. Tibet	250[e,f]	93	378	27	5	76	495	311
Canada	1270[e]	681	757	1119	218	107	1814	1601
USA, lower 48	420[e]	197	80	173	8	25	373	733
Alaska	710[e]	197	13	243	0	8	328	456
Gran Pantanal[b]	140[e]	143	146	98	4	0	229	142
Amazon Wetlands[b]	300[e]	69	21	471	31	0	480	357
Ramsar sites	1059[g]	323	176	164	36	47	500	642
North America (1)	2400[e,h]; 2416[i,j]	1126	872	1542	248	153	2609	2866
South America	1208[k]	727	578	1365	80	58	2132	1594
Europe (2)		811	413	432	22	18	1195	260
Africa	1213–1247[i]	718	368	265	152	296	1431	1314
Asia		1688	2043	1183	587	659	3997	2856
Australia and Oceania (3)	>240[l]	188	67	8	1	108	342	275
Global (4)	8558[c]; 7000-9000[e]; 5600-9700[i,m]	5260	4340	4795	1093	1291	11,711	9167

All data sets (for descriptions see text and Table 1) were first aggregated/disaggregated to global 0.5° grids; countries and regions were then assigned via cell centers. The three fractional wetland classes of GLWD-3 were calculated at their class centers (75, 37.5, and 12.5%). All values in (10^3 km^2). (1) Incl. Central America and the Caribbean, excl. Greenland. (2) Incl. European part of former Soviet Union, excl. Turkey. (3) Australia, New Zealand, Melanesia, Micronesia, Polynesia. (4) Excl. Antarctica and glaciated Greenland.

[a] Derived as maximum wetland area per cell identified in either Matthews and Fung, Cogley, Stillwell-Soller et al., GLCC, or MODIS.
[b] Area derived as sum of all 0.5° cells at estimated location; the same cells were selected on all grids.
[c] Williams (1991).
[d] Whigham et al. (1993).
[e] Mitsch and Gosselink (2000).
[f] Natural wetlands only, another 375 of rice paddies, ponds, etc.
[g] Wetlands International (2002).
[h] USA and Canada only.
[i] Finlayson and Davidson (1999).
[j] No specification of included area.
[k] Finlayson and van der Valk (1995).
[l] Mitchell (1992), Australia only.
[m] The sum of individual regional estimates exceeds the global value and reaches 12,792.

value for estimating total global wetland extents, but can serve as a minimum baseline.

When comparing the derived wetland extents for Canada, Alaska and the lower 48 states of the USA (Table 5), the overall sum of 2.4 million km^2 as documented in literature is overestimated by more than 15% in GLWD-3, while the individual values for the three regions differ even more. We believe that the dominating fractional wetland classes in these areas, i.e. '25–50%' and '50–100%', which we fixed for the calculations at their respective class centers at 37.5 and 75%, respectively, are not well represented. The underestimation of Alaskan wetlands and overestimation for Canada and the lower 48 US states would significantly improve when assuming representative values of 25% (or even below the original limit at about 15%) and 100%, respectively. The latter value is supported by the observation that GLWD-3 shows only a global total of 0.7 million km^2 of bogs and fens (Table 3), while up to fivefold extents of northern boreal and subarctic peatlands are documented (Gorham, 1991). This larger extent would still be underestimated by GLWD-3 even if the entire '50–100%' class were considered '100% bogs and fens'. We also assume that strong local variations appear which are not adequately covered by the fractional classes.

Both in the latitudinal and longitudinal wetland distributions GLWD-3 is, for many regions, in good agreement with the gross wetlands map. Major differences occur for the northern latitudes between 50 and 70° North, as well as for about 60° West (Pantanal, Amazon wetlands) and 30° East (African Rift Valley, Sudd Swamps, Scandinavia), where the gross wetlands map exceeds the estimates of GLWD-3. The longitudinal differences seem to be largely influenced by trends of only one wetlands map each (Stillwell-Soller at al. at 60° West, Matthews and Fung at 30° East). For the northern latitudes, on the other hand, all three wetland maps agree with GLWD-3 in the overall magnitude of wetland extents, and only the gross map significantly exceeds these values. Looking at the calculated continental wetland extents (Table 5), we conclude that GLWD-3 may underestimate the wetland extent in particular for Scandinavia (Europe) and northern Russia (Asia), but we cannot ultimately verify which of the maps is more accurate. Overall, GLWD-3 shows the best agreement with documented values (Table 5) among all maps, both on a regional and global level, and covers most but not all Ramsar sites.

3.4. General limits of GLWD

Besides natural changes, freshwater systems have been altered by humans since historical times. The pace of change, however, accelerated markedly in the early 20th century. Although detailed figures are difficult to obtain, up to half of the world's wetlands are estimated to have been lost as land was drained and converted to agriculture and settlements, or filled for reasons of disease control (Dugan, 1993; UNDP et al., 2000). Because of drought or excessive diversion for agriculture, the surface areas and volumes of many lakes show strong decreases. Among the most prominent examples are Lake Chad in Africa's Sahel region, which shrunk by 75% in the last 30 years, and Central Asia's Aral Sea, once one of the largest lakes of the world, which lost three quarters of its volume and over 36,000 km^2 in surface area since 1960 (Revenga et al., 1998).

To take these often fast and ongoing alterations into account, the affected wetland and lake boundaries would need to be updated on an individual basis. For the generation of GLWD, we had no capacities to incorporate changes in a consistent manner, hence we decided to generally refrain from updating any of the given source data. This leaves some lakes and wetlands being represented in their historic instead of recent outlines.

The number of large dams (more than 15 m high) has increased nearly sevenfold since 1950, from about 5750 to more than 41,000 (ICOLD, 1998), and there is still a high number of large dams planned or under construction, particularly in the developing world (UNDP et al., 2000). The number of smaller dams is estimated at some 800,000 worldwide (McCully, 1996). GLWD-1 identifies only 654 large reservoirs, and GLWD-2 another 168 smaller ones. Although GLWD-2 data is supposed to include all unidentified reservoir polygons that were present on the source maps—foremost DCW's underlying ONC maps, whose information dates from the 1970s to 1990s (Birkett and Mason, 1995)—we assume that GLWD lacks a significant number of recently finished reservoirs.

4. Conclusions

Drawing upon a variety of existing maps, data and information, a new global lakes and wetlands database has been created. The combination of best available sources for lakes and wetlands on a global scale (1:1 to 1:3 million resolution), and the application of GIS functionality enabled the generation of a database which focuses in three coordinated levels on (1) large lakes and reservoirs, (2) smaller water bodies, and (3) wetlands.

Level 1 comprises the shoreline polygons of the 3067 largest lakes (area ≥ 50 km^2) and 654 largest reservoirs (storage capacity ≥ 0.5 km^3) worldwide, and includes extensive attribute data. Level 2 comprises the shoreline polygons of permanent open water bodies with a surface area ≥ 0.1 km^2, excluding the water bodies contained in GLWD-1. The approx. 250,000 polygons of GLWD-2 are attributed as lakes, reservoirs and rivers. Level 3 comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30-second resolution. For GLWD-3, the polygons of GLWD-1 and GLWD-2 were combined with additional information on the maximum extents and types of wetlands. Class 'lake' in both GLWD-2 and GLWD-3 also includes manmade reservoirs, as only the largest reservoirs have been distinguished from natural lakes. GLWD-2 and GLWD-3 do not provide detailed descriptive attributes such as names or volumes.

According to GLWD, lakes and reservoirs cover a total of approx. 2.7 million km^2 or 2.0% of the global land surface area (excluding Antarctica and glaciated Greenland), while wetlands are estimated to reach about 8–10 million km^2, or 6.2–7.6%. An extrapolation of GLWD data suggests that the total number of global lakes may reach or even exceed 1.5 million for lakes $\geq$10 ha, and 15 million for lakes $\geq$1 ha. With these numbers, lakes may cover about 3.2 million km^2, or 2.4% of the total global land surface.

In comparisons with other data sets, the polygon map of GLWD-1 has proven to be a virtually complete representation of great lakes $\geq$500 km^2, to provide a good coverage of large lakes $\geq$50 km^2, and to match the majority of large reservoirs $\geq$0.5 km^3. For the total of 3721 identified large lakes and reservoirs of GLWD-1, geometric attributes were derived, such as surface areas, average elevation, estimated watershed area, inflow, and location (coordinates and countries). For about half of them additional descriptive data could be compiled from various sources, including names of lakes and dammed rivers, storage capacities, and main reservoir purposes. The combination of GLWD-1 and GLWD-2, with approx. 250,000 open water bodies, generally confirms the results of an extensive global lake census by Meybeck (1995), which was based on extrapolations of regional data and estimates.

We believe that in combination GLWD-1 and GLWD-2, built largely from existing digital maps at resolutions of 1:1 to 1:3 million (ESRI, 1992, 1993), constitute a fairly complete database of global lakes $\geq$1 km^2 and represent the most comprehensive global vector database of lakes and reservoirs currently available. However, the results should not hide that besides original inaccuracies in the applied sources, the combination of different data sources may have introduced additional errors. For example, despite our efforts to correct the data, in some cases of GLWD-1 neither the geometric lake areas agree to documented values, nor do the different data sources agree with each other. We think that in most of these cases the surface polygons are accurate, but the assignment of lake attribute data or the data itself is incorrect. At large, GLWD-1 and GLWD-2 provide baseline maps to which existing lake registers, compilations or remote sensing data can be linked in order to combine both descriptive and geometric data in a GIS environment.

The GLWD-3 raster map of wetland areas, largely based on the wetlands map of the UNEP World Conservation Monitoring Centre (WCMC, 1993), provides a global overview of wetlands at a resolution between existing global wetland maps and the most recent remote sensing land cover products. For most regions, the amount of wetland areas in GLWD-3 exceeds the values of existing global maps, including remote sensing data, but is in good agreement with the extent of global and regional estimates as documented in literature. We thus believe that GLWD-3 provides a good representation of the maximum global wetland extent. The classification of GLWD-3 into 12 types of lakes and wetlands offers the possibility to assign temporal variability in wetland extents, i.e. floodplains may inundate and fall dry within an annual cycle, while forested swamps may be more permanent. Only one class of GLWD-3 is based on remote sensing data, keeping it a relatively independent reference for comparisons with land cover maps derived from satellite imagery. We want to emphasize, however, that we do not consider GLWD-3 a validated data set which, in particular, could replace groundtruthing efforts. Nevertheless, GLWD-3 may serve as an estimate of wetland extents for global hydrology and climatology models, or to identify large-scale wetland distributions and important wetland complexes, often in their historic extents, which then can be monitored at higher accuracy. In future, we hope that new remote sensing products, based on improved techniques and capabilities, will succeed GLWD-3.

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