T4

Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

GTOS 59

# WATER LEVEL

*Water level in lakes and reservoirs, water storage*

WMO UNESCO UNEP ICSU FAO

T4

ASSESSMENT OF THE STATUS
OF THE DEVELOPMENT OF THE STANDARDS FOR THE
TERRESTRIAL ESSENTIAL CLIMATE VARIABLES

# WATER LEVEL

*Water level in lakes and reservoirs, water storage*


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# List of Acronyms

| | |
|---|---|
| **CEOP** | Coordinated Enhanced Observing Period |
| **CESR** | Centre for Environmental Systems Research? |
| **CNES** | Centre National d'Etudes Spatiales |
| **DAAC** | Distributed Active Archive Center |
| **DFO** | Department of Fisheries and Oceans |
| **DMU** | De Montfort University |
| **EMAN** | Ecological Monitoring and Assessment Network |
| **ESA** | European Space Agency |
| **GCOS** | Global Climate Observing System |
| **GEMS** | Global Environment Monitoring Program |
| **GEO** | Group on Earth Observations |
| **GLAS** | Geoscience Laser Altimeter System |
| **GRDC** | Global Runoff Data Center |
| **GSFC** | Goddard Space Flight Center |
| **GTN-H** | Global Terrestrial Network for Hydrology |
| **GTN-R** | Global Terrestrial Network for River Discharge |
| **GTOS** | Global Terrestrial Observing System |
| **HARON** | Hydrological Applications and Runoff Network |
| **HYDROLARE** | International Data Centre on Hydrology of Lakes and Reservoirs |
| **ICES** | Ice, Cloud, and land Elevation Satellite |
| **ICOLD** | International Commission on Large Dams |
| **IGDR** | Interim Geophysical Data Record |
| **IGLD** | International Great Lakes Datum |
| **IGWCO** | Integrated Global Water Cycle Observations |
| **ISO** | International Organization for Standardization |
| **MSSL** | Mullard Space Science Laboratory |
| **NASA** | National Aeronautics and Space Administration |
| **RLA** | River Lake Altimetry product |
| **RLH** | River Lake Hydrology product |
| **SIRAL** | Synthetic Aperture Interferometric Radar Altimeter |
| **SUI** | State Hydrological Institute |
| **TOPC** | Terrestrial Observation Panel on Climate |
| **UN** | United Nations |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organization |
| **UNH** | United Health Group |
| **USDA/FAS** | United Nations Department of Agriculture's Foreign Agricultural Service |
| **UW** | University of Wisconsin |

| | |
|---|---|
| **WatER** | Water Elevation Recovery Missions |
| **WaterGAP** | Water – Global Assessment and Prognosis |
| **WCMC** | World Conservation Monitoring Centre |
| **WHYCOS** | World Hydrological Cycle Observing System |
| **WMO** | World Meteorological Organization |

# Executive Summary

Lakes level is a complex index of natural water exchange within their watersheds. Therefore, long-term level fluctuations in natural (unregulated) lakes also reflect climate changes occurring in the region. On the other hand, lake water storage, which depends on water level, is an easily available source of water for many sectors of economy such as agriculture, domestic and industrial water supply, hydropower, water transport and others.

The World Meteorological Organization's (WMO) International Glossary of Hydrology defines lakes as an inland body of water of considerable size while reservoirs are natural or man-made water bodies used for storage, regulation and control of water resources. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown (WMO-No.168, 1994). Hydrological information obtained by ground-based gauge instruments is limited due to the sparse distribution of gauge stations. An alternative is to use radar altimetry to measure surface water height of large lakes which has an accuracy of within two centimetres and is available in near-real time. Water level in lakes and reservoirs is measured in centimetres against the national reference plane or against some adopted plane (so called "zero" graph). Surface area of a lake or reservoir is measured in m2 or km2 depending on their size. Lake or reservoir storage (volume) is measured in m3 or km3 depending on their size.

Information relating to hydrological observing stations and to lake measurements are described in Volume III (Hydrology) of the Technical Regulations (WMO-No.49, 2006) and in the WMO Guide to hydrological practices (WMO-No.168, 1994). The sections on lake level specify the requirements in the establishment and operation of a hydrometric station for the measurement of stage. Stage, or water level, is the elevation of the water surface relative to a datum. Records of water level are obtained by systematic observations on a manual (non-recording) gauge, or from a recording gauge. It should be observed with a precision of one centimetre in general and to three millimetres at continuous-record gauging stations (WMO-49, WMO-168).

Several types of non-recording gauges for measuring stages are used in hydrometric practice: graduated vertical staff gauge, ramp or inclined gauge, wire-weight gauge installed on a structure above the stream, graduated rod, tape and wire or point gauges for measuring the distance to the water surface. The modern types of continuously recording stage gauges include: hydrostatic gauges, bubble gauges and non-contact gauges (radar and ultrasonic). The frequency of recording of water level is determined by the hydrological regime of the water body and by the purposes for collecting the data. A daily measurement of stage is usually sufficient in lakes and reservoirs for the purpose of calculating changes in storage.

Remote sensing can be used to measure a number of lake attributes including surface area and elevation but also location and lake name (calculated from Operational Navigational Charts, etc.). Although their primary objectives are ocean and ice studies, for more than 15 years satellite radar altimetry has been a successful technique for studying continental water bodies. The surface water level is measured within a terrestrial reference frame with a repeatability varying from 10 to 35 days depending on the orbit cycle of the satellite. A satellite radar altimeter is not an imaging device, but continuously records average surface ''spot'' heights as it transverses over the Earth's surface. The techniques are now well validated. Almost 150 lakes and reservoirs monthly level variations deduced from multi-satellite altimetry measurements are freely provided. Future missions like Cryosat-2, Altika and Sentinel-3 will be included in future processing.

## Recommendations

1. The existing methods and procedures for lakes and reservoir water level observations are well reflected in different technical documents of WMO, UNESCO and ISO, but it seems that there is a need to prepare a single standard document, for example an ISO Standard, taking as a base ISO/TR 11330:1997 (purely informative now).
2. The results of satellite water level measurements still contain substantial errors exceeding admissible limits. However this data enables the general assessment of seasonal and long-term water level trends. Further *in situ* validation of this data through ground networks and improvement of the technique of satellite water level measurements are necessary.
3. The International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE) should be made operational to allow the establishment of a global database of level observations on the world lakes and reservoirs for practical purposes and scientific analysis.
4. Implementation of advanced automated means of measuring water level (especially on lakes which were chosen as priority lakes in GTN-L*) are required to avoid subjectivity and errors unavoidable when using conventional methods.
5. Further analysis should be undertaken, through HYDROLARE, to ascertain the state of the world's lake and reservoir level observation methods and networks, taking into account the recommendations on the preparation of a special standard for water level of lakes and reservoirs.

*See Implementation Plan for the Global observing System for Climate in Support of UNFCCC – October 2004, GCOS-92 (WMO/TD Nº 1219 ).

http//www.wmo/int/pages/prog/**gcos/index.php**

# 1. Introduction

Having a certain inertness, lakes receive, transform and intensify climatic signals. The hydrologic characteristics of lakes (lake level and lake volume) are also important indicators of changes of climate. The analysis of temporal and spatial variability of lake level dynamics are therefore important contributions on global research of climate change.

Lake levels are a complex index of natural water exchange within their watersheds. Therefore, long-term level fluctuations in natural (unregulated) lakes also reflect climate changes occurring in the region. On the other hand, lake water storage, which depends on water level, is an easily available source of water for many sectors of the economy such as agriculture, domestic and industrial water supply, hydropower, water transport and others. Unlike river runoff, lake storage is known to be slowly renewable as it is formed during hundreds and thousands of years. Therefore, to ensure sustainable use, water use should not exceed the annually renewable volume (which is river inflow and precipitation minus evaporation). If water withdrawal regularly exceeds this volume lake storage and water levels will irreversibly drop. Great drainless lakes located in arid regions are the most sensitive to such a scenario. One of the most striking examples of this is the Aral Sea (lake by origin). In the 1970s and 1980s regular substantial irrigation water withdrawal from the inflowing Amu-Daria and Sir-Daria rivers resulted in the fast degradation of the Aral ecosystem. Since 1960 the level of the Aral has decreased by over 22.5 m, its storage has decreased by 9.6 times and the Aral region has been classified as area of ecological catastrophe.

Lake water level is also a complex index of water exchange in natural-technogenic system reservoir-river basin. The character of this water exchange depends not only on river flow but on the regime of runoff operating in the reservoir. The mode of the runoff operating (runoff redistribution) is determined by reservoir water storage relative to the annual river discharge at the dam site. If the volume of the reservoir is equal to or more than 20 percent of annual river discharge long-term runoff operating is possible. If the volume is less than 20 percent of annual river discharge only annual, seasonal, monthly or daily operating runoff may take place.

For reservoirs there are three typical operating levels: normal affluent, maximum controllable and minimum drawdown. Normal affluent level is the highest permissible operating level of a reservoir. Maximum controllable level is the highest level permissible during rare occurrence floods. The minimum drawdown level is the minimum level of operation without any damage to the reservoir ecosystem.

# 2. Definition and units of measure

The WMO International Glossary of Hydrology defines lakes as an inland body of water of considerable size while reservoirs are natural or man-made water bodies used for storage, regulation and control of water resources.

Water level is elevation of the free-water surface of a body of water relative to a datum level. Changes in water level of a lake or a reservoir are its absolute and relative fluctuations.

Absolute level fluctuations are changes in water level of a lake or reservoir caused by changes in its storage for a definite period of time.

Relative level fluctuations are, as a rule, short-term changes in the water level not associated with changes in the storage of water in a lake or reservoir and caused by dynamic factors such as wind and changes in the atmospheric pressure (surging, seiches). Relative level fluctuations in reservoirs may also be caused by non-regular work of hydroelectric complexes.

Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown (WMO-No.168, 1994). However, it is more feasible to locate them near the axis of equilibrium to smooth the influence of relative level fluctuations in computing changes in water storage of a lake or reservoir for the definite period of time (studies and reports in Hydrology, 31, UNESCO 1981).

Surface area of a lake or reservoir is the area of a lake or a reservoir relative to a specific water level.

Storage of a lake or a reservoir is volume of water accumulated in the basin at a specific water level. Lake or reservoir surface area and their storage at various water levels are determined from surveys and topographic-geodetic work. Based on these surveys, curves depicting surface area (area curve) and the volume of stored water (storage curve) against the water level are plotted (Hakanson, Lake morphometry). Storage curve is plotted based on the data from plotting the area curve. Firstly, individual volumes of water between two horizontals are determined and then successive summation is performed up to the horizontal line indicating the highest water level in the lake or reservoir.

### Measurement units

Water level in lakes and reservoirs is measured in centimetres against the national reference plane or against some adopted plane (so called “zero” graph). Surface area of a lake or reservoir is measured in m2 or km2 depending on their size. Lake or reservoir storage (volume) is measured in m3 or km3 depending on their size.

# 3. Existing measurement methods, protocols and standards

## 3.1 *In situ* measurement

### Measuring lake level

*Non-recording gauges*

Several types of non-recording gauges for measuring stage are used in hydrometric practice. The common types of gauges are:

(a) graduated vertical staff gauge;
(b) ramp or inclined gauge;
(c) wire-weight gauge installed on a structure above the stream; and
(d) graduated rod, tape, wire or point gauge for measuring the distance to the water surface.

*Recording gauges*

Many different types of continuously recording stage gauges are in use. They may be classified according to both mode of actuation and mode of recording.

A commonly used installation consists of a stilling well connected to the stream by pipes and a float in the stilling well connected to a wheel on a recorder by a beaded wire or perforated tape.

The modern means of measuring water level include:

- hydrostatic gauges,
- bubble gauges,
- non-contact gauges (radar and ultrasonic).

### Procedures for measurement of stage

*Establishment of gauge datum*
To avoid negative readings, the gauge should be set so that a reading of zero is below the lowest anticipated stage. The gauge datum should be checked annually by levels from local benchmarks. It is important to maintain the same gauge datum throughout the period of record. If feasible, the local gauge datum should be tied to a national or regional datum.

*Recording gauges*
The graphical (analogue), digital, electronic, or telemetering device recorder is set by reference to an auxiliary tape-float gauge or to a staff gauge located inside the stilling well. In addition, a staff, ramp or wire-weight gauge set to the same datum, is necessary to compare the water surface elevation in the stilling well with that of the river. For gauges with gas-purge systems and no stilling well, the staff, ramp, or wire weight gauge in the lake should serve as the reference gauge.

The operation of modern measuring methods are:

1. Hydrostatic gauges function through hydrostatic pressure on the height of the liquid over the pressure sensor. Hydrostatic pressure depends on the water temperature and the atmospheric pressure. Differential hydrostatic gauges are widely used in the hydrometric practices all over the world. They consist of a hollow tube which is opened to the atmosphere. Hydrostatic level gauges are the most common devices for measuring water bodies. The advantages are:
   - they are compact and relatively inexpensive to install;
   - they can be used for practically any range of level measurements (from 1 to more than 100 m), which is important for reservoirs were large fluctuations in water levels occur;
   - they can be used for level measurements even during winter freeze-up;
   - high accuracy of results;
   - low maintenance (it is recommended to check the gauge every six months).
2. Bubble gauges operate by measuring liquid pressure in the installer pressure unit point. It differs from the hydrostatic gauge as the pressure sensor is located on the shore (land) and is connected with the water surface through a hollow tube in which air is pumped at certain programmed time intervals. The absolute pressure sensor alternately detects air pressure in the hydrometric tube and the atmospheric pressure. Difference of these signals indicates water level. Operating temperature range and installation conditions make it possible to apply bubble gauges practically in all conditions. Bubble gauges are the most advanced and modern devices for measuring water level at automated sites.
3. Non-contact gauges measure water level remotely by contact sensors of two types: radar and ultrasonic. The sensor emits perpendicular to the water surface and uses the reflected signal to detect the distance (interference effect). The exact distance between the sensor and the water surface is computed by the processor. The device can be installed on a bracket or a bridge or other hydraulic objects above the water (Fig.1).

*Frequency of measurement*
The frequency of recording of water level is determined by the hydrological regime of the water body and by the purposes for collecting the data. A daily measurement of stage is usually sufficient in lakes and reservoirs for the purpose of computing changes in storage.

Fig.1 Variants of radar gauge installation

### WMO and ISO Standards

Information relating to hydrological observing stations and to lake measurements are described in the Volume III (Hydrology) of WMO Technical Regulations (WMO-No.49, 2006) and in the WMO Guide to hydrological practices (WMO-No.168, 1994). The sections on lake level specify the requirements for the establishment and operation of a hydrometric station for the measurement of stage. Gauges on lakes and reservoirs are normally located near their outlets, but sufficiently upstream to avoid the influence of drawdown. The precision of the observations should be one centimetre in general and to three millimetres at continuous-record gauging stations (WMO-49, WMO-168).

The ISO standards which are more closely related to lake measurements are Liquid Flow Measurement in Open Channels: Vocabulary and Symbols (in its Third edition) and the 1981 Liquid Flow Measurement in Open Channels. Part 1: Establishment and operation of a gauging station and Part 2: Determination of stage-discharge relation. However, the above mentioned standards cannot be used to measure *in situ* lake level observations such as lake level, lake area and lake storage relations

## 3.2 Satellite measurement

### Satellite derived products from Hydrolare

The Hydrolare data centre will include satellite radar altimetry data as the source of information for lake level time series deliveries. It is based on seven different satellites (Topex / Poseidon, Jason1&2, ERS2, GFO and Envisat). Historical time series will be provided as it is currently done on the Hydroweb data base (see below). Accuracy of radar altimetry for calculation of lake level depends on the size of the lake and the surrounding terrain. It goes from 2-3 centimetres of accuracy for the largest ones (like Lake Victoria for which validation of radar altimetry can be undertaken with *in situ* gauges) to up to 30-40 centimetres of accuracy for the smallest ones. Within the Hydrolare data centre, calibration/validation of products will be undertaken, by:

1. Comparison with limnigraph when they exist.
2. Field campaign at some dedicated sites (for example a cal/val site for altimetry has been set up in 2004 by the Legos on the Issykkul Lake and several campaigns have been organized since then to estimate altimetry accuracy for lake studies).

Products will be delivered on a monthly basis through an automatic system which is currently under development (current updating of products within Hydroweb is around six months to one year for more than 150 lakes).

## Satellite altimetry and imagery for lake monitoring, summary and principles

Remote sensing (satellite altimetry and monitoring of the area of lakes and reservoirs) has the potential to provide a number of lakes and reservoirs attributes, for example surface area, elevation, location and identification (lake name) calculated through Operational Navigational Charts maps, etc.; www.cpg.mssl.ucl.ac.uk/orgs/un/glaccd/html/mgld.html[1].

Although their primary objectives are ocean and ice studies, for more than 15 years satellite radar altimetry has been a successful technique for studying continental water bodies. In particular, the ability to remotely detect water surface level changes in lakes and inland seas has been demonstrated. The surface water level is measured within a terrestrial reference frame with a repeatability varying from 10 to 35 days depending on the orbit cycle of the satellite. A satellite radar altimeter is not an imaging device, but continuously records average surface ''spot'' heights as it transverses over the Earth's surface.

Operating at dual frequencies 13.6GHz (Ku Band: Jason T/P) and 5.3 GHz (C Band) or 13.6GHz 3.2 GHz (S Band: Envisat), each altimeter emits a series of microwave pulses towards the nadir direction that are examined in the time domain. By noting the two-way time delay between pulse emission and echo reception, the surface height is determined by the difference of the satellite orbit and the altimeter range measurement. Each returned height value is an average of all surface heights found within the footprint of the altimeter. The diameter of the footprint depends on the surface roughness, but can typically range between 200 m (for open pools of water in calm conditions) to a few kilometres (open

1 www.fao.org/DOCREP/005/AC666E/ac666e08.htm

| Satellite | Operation | Repeat Period |
|---|---|---|
| SEASAT | 1978 | 17 days |
| GEOSAT | 1986-1989 | 17 days |
| ERS-1 | 1991-1996 | 35 days (phases C+G) |
| T/P | 1992-2002 | 10 days |
| ERS-2 | 1995-2003 | 35 days |
| GFO | post 2001 | 17 days |
| ENVISAT | post 2002 | 35 days |
| JASON-1 JASON-2 | post 2002<br>post 2008 | 10 days |
| T/P(new orbit) | 2002-2005 | 10 days |

**Instrument Summary**

water with surface waves). Each satellite is placed in a specific repeat orbit, so after a certain number of days the same point (to within 1 km), on the Earth's surface is revisited. In this way, time series of surface height changes can be constructed for a particular location along the satellite ground track during the lifetime of the mission. There have been a number of altimetric satellite missions. Since 1993 for example, five are operating: T/P, Jason-1, Jason-2, ENVISAT and GFO.

Over the past five years the Legos has developed a web database (Hydroweb) containing time series over water levels of large rivers, lakes and wetlands at global scale. Almost 150 lakes and reservoirs monthly level variations deduced from multi-satellite altimetry measurements are freely provided. Potentially the number of lakes monitored could be significantly increased. Future missions such as Cryosat-2, Altika and Sentinel-3 will be included in future processing and will insure the continuity of the lake survey.

The current products (monthly water level and standard deviation for each lake) have been constantly compared to existing *in situ* data (for a group of 10 to 15 lakes) with a precision ranging from 3 cm (Lake Victoria) to 30-40 cm for very small lakes.

## Methodology of data productions

Lake levels are actually based on merged Topex/Poseidon, Jason-1 and 2, ERS2, ENVISAT and GFO data provided by ESA, NASA and CNES data centres (PODAAC and AVISO). The altimeter range measurements used for lakes consist of 1 Hz data for big lakes and 20 Hz data for smaller ones. All classical corrections (orbit, ionospheric and tropospheric corrections, polar and solid Earth tides) are applied. Depending on the size of the lake, the satellite data may be averaged over very long distances. It is thus necessary to correct for the slope of the geoid (or equivalently, the mean lake level). Because the reference geoid provided with the altimetry measurements (e.g. EGM96 for T/P data or GRACE models for more recent data) may not be accurate enough, we have computed a mean lake level, averaging over time the altimetry measurements themselves. The water levels are further referred to this "mean lake level". If different satellites cover the same lake, the lake level is computed in a three-step process. Each satellite data is processed independently. Potential radar instrument biases between different satellites are removed using T/P data as reference. Then lake levels from the different satellites are merged on a monthly basis (recall that the orbital cycles vary from ten days for T/P and Jason, to 17 days for GFO and 35 days for ERS and Envisat). Generally an increase precision is observed when multi-satellite processing is applied.

## Web databases

The Hydroweb Web site is hosted by CNES/Legos:
www.legos.obs-mip.fr/soa/hydrologie/hydroweb/

This Web database will be the core of HYDROLARE data centre for Remote Sensing data on lakes and reservoirs with additional information on surface variation for a number of lakes for which precise sets of satellite imagery (from MODIS, Landsat, ASAR, CBERS) have been processed.

Hydroweb provides lake level variations in time calculated from satellite radar altimetry. In addition the use of satellite images with adequate resolution (depending on the order magnitude of water extent variability) at different times, ranging from low to high water stage, it is possible to calculate a rating curve function which is simply the relation dh/dS, where dh is the variation of level, and dS is the variation of surface. Applying this rating curve function to all level data obtained from satellite radar altimetry will allow the calculation of the surface variation of the lakes over the time span of the altimetry data (ranging from 1-2 days for big lakes to one month for smaller ones). A prototype based on 20 lakes and reservoirs has been developed at Legos and will be extended to the whole database in the next months.

The U.S. Department of Agriculture's Foreign Agricultural Service (USDA-FAS), in cooperation with the National Aeronautics and Space Administration, and the University of Maryland, are routinely monitoring lake and reservoir height variations for approximately 50 lakes located around the world. This project is unique, being the first of its kind to utilize near-real time radar altimeter data over inland water bodies in an operational manner. Surface elevation products are produced via a semi-automated process and placed at this web site for USDA and public viewing. All targeted lakes and reservoirs are located within major agricultural regions around the world. Reservoir and Lake height variations may be viewed by placing the cursor on and clicking the continent of interest. Radar altimeter data from the NASA/CNES Topex/Poseidon and Jason-1 satellite missions. Time series of altimetric lake level Variations from the USDA Reservoir Database at www.pecad.fas.usda.gov/cropexplorer/global_reservoir

The European Space Agency (ESA) and De Montfort University (DMU -UK) developed a system to obtain an estimation of river and lake heights from both ERS and Envisat data. De Montfort University developed an automated system to produce two types of products called River Lake Hydrology product (RLH) and River Lake Altimetry product (RLA)[2].

ENVISAT-ERS Exploitation River and Lake Product Handbook describes the hydrology products derived from ERS-1/2 and Envisat satellite altimeter data.

The database developed by ESA (river and lakes) provides to users the level of lakes over the world from retracked envisat and ERS data for 13 big lakes in a NRT process. Only the most recent data (last two months) are directly available from the Web page. For historical altimetry retracking data, users need to apply directly to ESA.

http://earth.esa.int/riverandlake/

Advantages and Limitations of Satellite Radar Altimetry are shown in the site of USDA-FAS as follows:

*Advantages:*

- Day/night and all weather operation.
- Generally unhindered by vegetation or canopy cover.
- All determined surface heights are with respect to one common reference frame.
- Satellites are placed in repeat orbits (up to 1 km either side of a nominal ground track) enabling systematic monitoring of rivers, lakes, wetlands, inland seas and floodplains.
- Has the potential to contribute height information for any target beneath the satellite overpass, thus contributing information where traditional gauge (stage) data may be absent.
- Satellite altimetric instruments have been in continuous operation since 1991 and new missions are scheduled for the next decade. There is therefore the ability to monitor seasonal to interannual variations during the lifetime of these satellites.
- Techniques have been validated and results published in peer-reviewed journals.

*Limitations:*

- These instruments are primarily designed to operate over uniform surfaces such as oceans and ice-sheets. Highly undulating or complex topography may cause data loss or non-interpretation of data.
- Retrieved heights are an "average" of all topography within the instrument footprint. Such values are further averaged in the direction of the satellite

2 http://earth.esa.int/riverandlake/, ECV-T4-lake-ref-41-ENVISAT-ERS Exploitation River and Lake Product-Handbook_2_0.pdf

motion, giving, for example, one final height value every 580 m (TOPEX/POSEIDON) or 350 m (ERS) along the ground track. Altimetric values therefore differ from traditional gauge measurements which offer “spot” heights at specific locations.

- The height accuracy is dominated by knowledge of the satellite orbit, the altimetric range (distance between antenna and target), the geophysical range corrections and the size and type of the target.
- Unlike imaging instruments, altimeters only retrieve heights along a narrow swath determined by the instrument’s footprint size. The effective footprint diameter can vary depending on the nature of the target, and can potentially range from several hundred metres to many kilometres.
- Minimum target size is controlled by the instrument footprint size and the telemetry/data rates, and also on the surrounding topography and the target-tracking method used.
- The satellite orbit scenario and target size also determine the spatial and temporal coverage. Improved temporal coverage is gained at the expense of spatial coverage for a single satellite mission.
- Major wind events, heavy precipitation, tidal effects and the presence of ice will effect data quality and accuracy.

Despite those limitations the altimetry is a technique, which has a proven potential for hydrology science: the data are freely available for the whole planet, which for many remote areas is the only source of information. Moreover validation with ground-based gauge data gives some measure of the expected accuracy for a similar target type and size. Comparison of T/P and Jason results with gauge data for the Great Lakes, for example, show an accuracy ~3-5 cm rms (Shum *et al.*, 2003). Although this accuracy is reduced with smaller lakes the derived level variations are generally an order of magnitude higher than the total error budget. Ongoing research is examining the trade off between minimum target size observable and acceptable height accuracy for the various hydrological applications.

CryoSat-2, the next ESA radar altimetry mission, expected to launch in 2009 is designed to measure changing ice fields, but it will also contribute to monitoring water resources by acquiring samples of data from its new generation radar altimeter over inland water bodies upon request from scientists for experimental purposes.

CryoSat-2 will fly an enhanced radar altimeter instrument, called the Synthetic Aperture Interferometric Radar Altimeter (SIRAL) which will allow it to improve the resolution of the measurements by increasing the number of separate radar pulses it sends down to Earth every second from 1 800 to up to 17 800. The experiment will demonstrate the benefits of novel technologies to serve emerging science fields, such as hydrology, from space[3].

ENVISAT-ERS Exploitation River and Lake Product Handbook describes the hydrology products derived from ERS-1/2 and Envisat satellite altimeter data. The document contains five sections. In Section 2, the background of satellite altimetry is briefly described. Section 3 discusses the processing applied to these data to extract meaningful heights over inland water. In Section 4, the detailed product specification and formatting are defined. Section 5 contains information on the xml front end available for the general user hydrology product.

The University of Wisconsin (UW) has been active in pursuing the objectives of the IGWCO, including the launch of two initiatives:

- The Freshwater Color Coordination Group,
- The Multisensory Space-borne Monitoring of Global Large Lakes: Towards an Operational Assessment of Trends in Water Quantity and Quality.

3 http://www.earsc.org/web/template.php?page=individual&ID=208

The goals of this initiative are to:

- produce satellite-derived maps showing water level fluctuations over 40 large lakes worldwide;
- evaluate the ability of Ice, Cloud, and Land Elevation Satellite (ICES) / Geoscience Laser Altimeter System (GLAS) to provide accurate lake level measurements, for the same 40 lakes[4];
- use field observations from Global Environment Monitoring Program (GEMS) database and corrected satellite imagery to classify second set of lakes,
- derive basic operational algorithms;
- quantify remote sensing costs and data processing issues.

## 3.3 Summary of requirements and gaps

The following are required for improving lake level observations and filing data gaps:

- Analysis of national lake and reservoir water level observation networks need to be initiated for improving data exchange policy.
- Regular provision of water level data to HYDROLARE to allow the International Data Centre to become operational.
- Intercomparison and validation of *in situ* and satellite observational data for various lakes and reservoirs is required.
- Increase the use of the advanced water level measurement methods, especially for the 156 water bodies listed in the GCOS list, is highly recommended.

4 The NASA-sponsored Surface Water Working Group has established a framework for advancing satellite observations of river discharge and water storage changes which focuses on obtaining measurements of water surface height (stage), slope, and extent. Satellite laser altimetry provides a method to obtain these inland water parameters and contribute to global water balance monitoring.

# 4. Contributing networks and agencies

The proposed network will be the GCOS Baseline Lake Level/Area Network based on TOPC priority list (see www.wmo.int/pages/prog/gcos/index.php).

# 5. Available data

**International Data Centre on Hydrology of Lakes and Reservoirs**

The Agreement between the Federal Service for Hydrometeorology and Environmental Monitoring, the Russian Federation and the World Meteorological Organization on establishment of the International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE) was signed on 5 May 2008. HYDROLARE became operational on the 1 January 2009 and will be based in the State Hydrological Institute (SHI). SHI manages the hydrological network on lakes and reservoirs of the Russian Federation, which began in 1860, peaked in the 1980s at 493 stations, declined in the 1990s, and has now stabilized at 377 stations. Data and information on this network is archived electronically in hydrological yearbooks and includes lake levels, surface water temperatures, water temperature profiles, heat content, ice cover and thickness, snow depth, wind, water balance, waves and currents. HYDROLARE is being proposed to meet the need for global data on lakes and reservoirs. The amount of water stored in the world's 145 largest lakes is estimated as 168 000 km3. The overall objective of the proposed centre is to establish, develop and regularly update an international database on hydrological regime of lakes and reservoirs in order to:

- stimulate the development of a global monitoring system on lakes and reservoirs for rational use, preservation and management of global water resources;

- improve the knowledge of lateral fluxes transformation within lakes and reservoirs; and
- supply data for scientific and educational purposes, modelling, and the development of global and regional projects and programmes.

The first stage of developing HYDROLARE would consist of collecting, processing and distributing metadata and annually updated hydrometeorological observations for lakes and reservoirs including water levels, changes in water storage, inflow/outflow data, and ice conditions.

The GCOS/GTOS Terrestrial Observation Panel for Climate (TOPC) has identified an initial priority list of 156 lakes for which data on area, level and, if possible, freeze and break-up dates should be collected. The TOPC approach to monitoring is to focus primarily on closed-basin lakes but including major ephemeral lakes and a selection of the largest open lakes. The major consideration in the choice of sites is to ensure a representative sample of each type of lake (where present) in each region. Where multiple possibilities for monitoring exist, preference should be given to large lakes to facilitate the use of satellite observations. Secondary considerations in the choice of sites are: (a) water use, (b) relevance for other monitoring purposes (e.g. water quality, biodiversity, pollution), and (c) the existence of a longer-term, historic or palaeoclimatic record at the site.

The initial target of 156 lakes worldwide, ranging in size from 15 to 374 000 km2, will be of immediate benefit to climate modellers, though the inventory will have to gradually increase to the order of 500 lakes to ensure fully adequate regional coverage and sufficient sites to ensure replicability of the derived records. Lake level and area need to be measured ideally weekly or at least monthly, with a horizontal resolution of 10 m and a vertical resolution of at least 5 cm. These measurements would be made by national hydrological services and should be provided to a designated international data centre.

## International Lake Environment Committee (ILEC)

At present, coherent lake and reservoir data bases with global coverage do not exist, however pieces are available at various locations. The International Lake Environment Committee[5] maintains a database of lakes and reservoirs[6]; however this database does not contain time-series of relevant hydrological variables. Another lake database, the MSSL/WCMC/UN Global Lake and Catchment Conservation Database[7], was developed by Mullard Space Science Laboratory of the University College London as a prototype for remote sensing applications (Birkett and Mason, 1995). It includes over 1 400 lakes and reservoirs, but a very limited set of attributes (lake names, location, country, surface area and elevation estimated from Operational Navigational Charts maps, etc.).

## IGWCO Water Cycle Variable[8]: Streamflow and surface water storage (runoff)

The objective is the establishment of an integrated stream/lake/reservoir database, comprised of *in situ* and remotely-sensed capacity/flow monitoring in real time.

Given that water resource managers need timely and accurate information with respect to river flow and water storage in lakes and reservoirs to prevent,

5 ILEC, a non-governmental organisation established in 1986 in Japan, http://www.ilec.or.ip/e_ index.html
6 http://www.ilec.or.jp/database/index/idx-lakes.html
7 http://wwwcpg.mssl.ucl.ac.uk/orgs/un/glaccd/html/mgld.html
8 http://www.wmo.int/web/homs/igwco/reports/IGWCO_assessment_report.pdf

among other things, water-related disasters, the IGWCO has emphasized the development of a Global Runoff Monitoring Project. The objective of this initiative is to provide temporal observations and analyses of surface runoff and lake/reservoir storage variations and variability, by means of integrated *in situ* and remotely sensed real-time monitoring. In the year since it was first proposed, the project has expanded to include participants such as the ESA, GEO and GTN-H.

Participants include: GEO, GTN-H/GTN-R, ESA, De Monfort University, WHYCOS and WMO.

### International Commission on Large Dams

The International Commission on Large Dams (ICOLD) maintains a registry of dams (ICOLD, 1988). This database was originally published only in paper books, but recently became available electronically on CD-ROM. The ICOLD registry contains information on several thousand reservoirs, assembled from an engineering perspective. One criterion for including reservoirs in this registry was to have 15 m or higher construction, thus potentially leaving out many reservoirs in plain regions where several metres high dam construction might result in large inundation. While detailed information on the dam construction (purpose, height, length and volume of the construction, construction type, spillway capacity) are provided beside basic information on the reservoir itself (maximum capacity, reservoir surface area, etc.), but other essential information (including location, mean discharge through the reservoir) is missing. The only way to geographically identify these reservoirs is by the nearest city and river names that are provided as part of the database. Several attempts have been made to identify these dams on maps and correct the information (by UNH, GRDC, CESR). In related efforts, USGS developed a dam inventory for the US, and Russia maintains a database of national lakes and reservoirs.

The merging of the above-mentioned lake and reservoir data sets with the available digital maps could be a basis for a more detailed global lake/ reservoir database, but this work is not trivial and needs extensive manual effort. It was noted that at present no dynamic information is available on lakes and reservoirs (level changes, operation, etc.). Remote sensing (satellite altimetry, monitoring of the surface area) has the potential to solve this problem. NASA GSFC is working on using satellite altimetry (TOPEX/ POSEIDON, ERS-1) to measure lake and reservoir levels (Birkett, 1998). At the present time, global information on surface water storage in lakes, reservoirs and wetlands is inadequate in terms of coverage and time-series observation of changes in the storage volume at all scales. However, it was noted that higher resolution information available only in some regions is also important, given the regional nature of some hydrological issues.

### International Great Lakes Datum

International Great Lakes Datum (IGLD) is the reference system by which the Great Lakes-St. Lawrence River Basin water levels are measured. It consists of benchmarks at various locations on the lakes and St. Lawrence River that roughly coincide with sea level (all water levels are measured in feet or metres above this point). Movements in the earth's crust necessitate updating this datum every 25-30 years. The first IGLD was based upon measurements and bench marks that centred on the year 1955, and it was called IGLD (1955). The most recently updated datum uses calculations that centre on 1985, and it is called IGLD (1985). Measurements recorded in NGVD (1929) or IGLD (1955) need to be converted to IGLD (1985) measurements before they can be used in comparison situations9[9].

9 ECV-T4-lake-ref-37-International Great Lakes Datum 1985.pdf

## USDA Reservoir Database

Two altimetric datasets are currently being exploited:

1. TOPEX/POSEIDON (T/P). In its original orbit (1992-2002) this satellite operated with a ten-day repeat orbit, with global coverage extending to North/South latitude 66 degrees. Ten years of archived GDR data (from September 1992) are utilized. T/P datasets have been provided by AVISO/CNES (Version C) and the NASA Physical Oceanography DAAC at the Jet Propulsion Laboratory, California Institute of Technology.
2. JASON. As a follow-on mission to T/P, the Jason satellite was launched on 7 December 2001. This project utilizes the IGDR Jason data which is typically available within 3-4 days after satellite overpass. Like T/P, the Jason orbital repeatability is ten-days with the same global coverage. The Jason IGDR datasets are available via ftp. The aim is to provide time-series of water level variations for some of the world's largest lakes and reservoirs (>100 $km^2$) especially in important agricultural areas.

The main database products are graphs and associated information in tabular form. For the graphs, changes in water level are real but the y-scale is arbitrary (relative) and given in metres. The x-axis refers to time with intervals of several months. The blue symbol represents results from TOPEX (the NASA ALT or SSALT) altimeters, the red symbol denotes results from the Jason POSEIDON-2 altimeter. The Results Table gives heights, associated errors and date/time of the observation. Note that a geographical extent across the lake has been used to derive the time series - rather than a spot measurement which is more typical of a traditional gauge. A discussion on altimetric height accuracy can be found in the Accuracy+Validation section.

These lake products exist in the public domain. However, the following general acknowledgement of this database should be made if the information presented here is used for further scientific purposes and/or additional applications:

*Radar altimeter data from the NASA/CNES Topex/Poseidon and Jason-1 satellite missions. Time series of altimetric lake level variations from the USDA Reservoir Database at http://www.pecad.fas.usda.gov/cropexplorer/global_reservoir*

## Canadian Hydrographic Service[10]

Lakes and wetland areas are strongly driven by climatic conditions and also play a critical role in the cycling of carbon. Canada has 24 percent of the world's wetlands and these clearly need to be monitored. The country is also blessed with immense aquatic resources in its lakes (e.g. the Great Lakes, shared with the United States, contain approximately 18 percent of the world supply of fresh water). The Canadian Hydrographic Service, part of DFO, collects data for the Great Lakes and other large Canadian lakes and possesses records going back to 1918 while a number of smaller lakes have also been monitored for many years, for water management or research purposes. The Ecological Monitoring and Assessment Network (EMAN), discussed later in this report, is a link to many such research and monitoring sites in Canada[11].

10 http://www.ec.gc.ca/climate/CCAF-FACC/Science/nat2002/f49#f49
11 The Experimental Lakes Area (ELA) in western Ontario, the Turkey Lakes in southern Ontario, and Lake Kejimkujik in Nova Scotia are examples of such research initiatives that are useful in the assessment of ecosystem and aquatic impacts of climate change.

# 6. Conclusions

The existing methods for lakes water level observations are well developed and sufficient to obtain data accurate enough for further processing and analysis.

The results of satellite water level measurements still contain substantial errors exceeding admissible limits. However this data enables one to assess general seasonal and long-term water level trends. Further validation of this data through the lakes and reservoirs ground network and improvement of the technique of satellite water level measurements are necessary.

Making operational the International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE) will allow the development of a global database of level observations on the world lakes and reservoirs.

# 7. Recommendations

## 7.1 Standards and methods

1. The existing methods and procedures for lakes and reservoir water level observations are well reflected in different technical documents of WMO, UNESCO and ISO, but there is a need to prepare a single standard document, for example an ISO Standard, taking as a base ISO/TR 11330:1997 (purely informative now).
2. The results of satellite water level measurements still contain substantial errors exceeding admissible limits. However this data enables the general assessment of seasonal and long-term water level trends. Further *in situ* validation of this data through ground networks and improvement of the technique of satellite water level measurements are necessary.
3. The International Data Centre on Hydrology of Lakes and Reservoirs (HYDROLARE) should be made operational to allow the establishment of a global database of level observations on the world lakes and reservoirs for practical purposes and scientific analysis.
4. Implementation of advanced automated means of measuring water level (especially on lakes which were chosen as priority lakes in GTN-L) are required to avoid subjectivity and errors unavoidable when using conventional methods.
5. Further analysis should be undertaken, through HYDROLARE, to ascertain the state of the world's lake and reservoir level observation methods and networks, taking into account the recommendations on the preparation of a special standard for water level of lakes and reservoirs.

## 7.2 Additional recommendations

1. For lakes and reservoirs without storage and area curves, it is rather promising to develop a method of assessing volume changes within drawdown storage using satellite images for estimation of lake or reservoir surface area for a particular date.
2. It is necessary to continue comparative analysis of the results of *in situ* and satellite observations for various lakes and reservoirs in order to assess the effect of various factors on the accuracy of satellite water level measurements.
3. It is necessary to analyse the interdependence of lake and reservoir water level on other ECV variables and also on the elements of the abiotic and biotic regime.

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**156 Priority Lakes in Global Terrestrial Network Lakes**

| Name | Country |
|---|---|
| Abaya | Ethiopia |
| Abert | USA |
| Aibi | China |
| Alakol | Kazahkstan |
| Albert (Mobutu Sese Seko/Nyanza) | Zaire/Uganda |
| Amadeus | Australia |
| Aral Sea | Kazakhstan/Uzbekistan |
| Athabasca | Canada |
| Austin | Australia |
| Baghrash | China |
| Baikal | Russia |
| Balaton | Hungary |
| Balkhash | Kirgizstan (Kazakhstan!) |
| Bear | USA |
| Beysehir | Turkey |
| Biwa-Ko | Japan |
| Bodensee | Germany/Switzerland/Austria |
| Bogoria | Kenya |
| Boon Tsagaan Nuur | Mongolia |
| Bositeng-hu | China |
| Buhi | Philippines |
| Buyr | China/Mongolia |
| Caspian | Azerbaijan/Russia/Turkmenistan/Iran |
| Chad | Chad/Cameroon/Nigeria/Niger |
| Champlain | Canada/USA4 |
| Chany | Russia |
| Chienghai | China |
| Chilwa | Malawi/Mozambique |
| Colhue Huapi | Argentina |
| Crater | USA |
| Danau Toba | Indonesia |
| Daviumbu | Papua New Guinea |
| Dead Sea | Israel/Jordan |
| Descham bault | Canada |
| Diefenbaker | Canada |
| Dongling Hu | China |
| Eau Claire | Canada |
| Ebi | China |
| Egridir | Turkey |
| Ennadai | Canada |
| Erie | Canada/USA |
| Eskimo South | Canada |
| Eyre | Australia |
| Frobisher | Canada |
| Frome | Australia |
| Gairdner | Australia |
| Gatium | Panama |
| George | Uganda |
| Great Bear | Canada |
| Great Salt Lake | USA |
| Great Slave Lake | Canada |

| Name | Country |
|---|---|
| Hammer | Iraq |
| Har Us | Mongolia |
| Hubsugul | Mongolia |
| Hukun Hu (Hulun Nur) | China |
| Hungtze | China |
| Huron | Canada/USA |
| Hyargas Nuur (Khirgiz Nuur) | Mongolia |
| Ilmen | Russia |
| Inari | Finland |
| Issyk-Kul | Kirgizstan |
| Izabel | Guatemala |
| Junin | Peru |
| Kamilukuak | Canada |
| Kaminak | Canada |
| Kaoyu | China |
| Khanka | China/Russia |
| Khanku | China/Russia |
| Khovsgol Nuur (Hovsgul) | Mongolia |
| Kinneret (Sea of Galilee) | Israel |
| Kivu | Rwanda/Zaire |
| Koko Nor | China |
| Kootenay | Canada |
| Kulundinskoye | Russia |
| Kyoga (Kioga) | Uganda |
| Lac La Ronge | Canada |
| Lac Saint-Jean | Canada |
| Ladoga | Russia |
| Lago de Chapala | Mexico |
| Lago di Como | Italy |
| Lago di Garda | Italy |
| Laguna Salada Grande | Argentina |
| Leman (Geneva) | Switzerland/France |
| Lesser Slave | Canada |
| Lop Nor | China |
| Lough Derg | Ireland |
| Luang Sea | Thailand |
| Maggiore | Italy/Switzerland |
| Managua | Nicaragua |
| Manitoba | Canada |
| Mar Chiquita | Argentina |
| Maracaibo | Venezuela |
| Michigan | USA |
| Mono | USA |
| Naivasha | Kenya |
| Namu | China |
| Netilling | Canada |
| Neusiedlersee | Austria/Hungary |
| NgoringHu | China |
| Nicaragua | Nicaragua |
| Nipigon | Canada |
| Nyasa (Malawi) | Mozambique/Malawi/Tanzania |
| Ohrid | Macedonia |
| Okanagan | Canada |

| Name | Country |
|---|---|
| Onega | Russia |
| Ontario | Canada/USA |
| Oulu | Finland |
| Pajanne | Finland |
| Pangong | China/India |
| Patzcuaro | Mexico |
| Peipu | Estonia/Russia |
| Poyang Lake | China |
| Pyramid | USA |
| Qilin (Ziling) | China |
| Reindeer | Canada |
| Rotorua | NZ |
| Rudolf | Ethiopia/Kenya |
| Rukwa | Tanzania |
| Salton Sea | USA |
| Sandy | Canada |
| Sasykkol | Kazahkstan |
| Scutari | Albania |
| Seletytengiz | Kazahkstan |
| Seneca | USA |
| Sevan | Armenia |
| Shala | Ethiopia |
| Skadar | Albania |
| Superior | Canada/USA |
| Tahoe | USA |
| Tai-hu | China |
| Tanganyika | Tanzania/Zaire/Zambia/Burundi |
| Taymyr | Russia |
| Tengiz | Kazakhstan |
| Terinam | China |
| Titicaca | Peru/Bolivia |
| Torrens | Australia |
| Tuz | Turkey |
| Ulungur | China |
| Urmia | Iran |
| Uvs Nuur | Mongolia |
| Valencia | Venezuela |
| Van | Turkey |
| Vanern | Sweden |
| Vattern | Sweden |
| Victoria | Tanzania/Uganda/Kenya |
| Volvi | Greece |
| Wei-shan | China |
| Wigry | Poland |
| Windermere | UK |
| Winnipeg | Canada |
| Winnipegosis | Canada |
| Xototlan (Managua) | Nicaragua |
| Yamdrok | China |
| Ziway | Ethiopia |
| Zug | Switzerland |
| Zurichsee | Switzerland |

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