



## **GEO Inland and Nearshore Coastal Water Quality Remote Sensing Workshop**

27 - 29 March 2007, Geneva, Switzerland

**Final Report  
December 2007**

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### Acknowledgements

The organizing committee wishes to thank the GEO Secretariat for their hosting of this workshop, the writing teams for their creative thought and recommendations and the participants for their exceptional work, taking time and effort and incurring the expense to attend this important forum to collectively chart the future of this science. The contents of this report reflect the opinions of the workshop participants, the writing teams and/or the organizing committee, and do not constitute a statement of policy, decision, or position on behalf of their respective organizations or GEO. For questions pertaining to this report or inquiries regarding the GEO water quality tasks, please contact:

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## **Executive Summary**

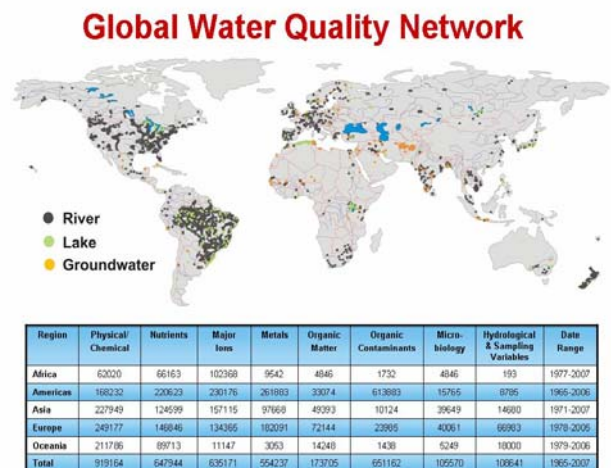
Having and maintaining suitable water quality is critical to sustain life on our planet. Monitoring of water quality using remote sensing, in conjunction with strategic *in situ* sampling can play a crucial role in determining the current status of water quality conditions and helps anticipate, mitigate and even avoid future water catastrophes. The GEO Remote Sensing of Water Quality Workshop helped identify issues, gaps, solutions and recommendations to expand our capability and capacity to utilize remote sensing technology. A major outcome of the workshop was a series of recommendations, addressing a number of far-ranging facets of this emerging remote sensing application. Key recommendations focused on continuity of existing satellites, development of new and improved sensor/platform technology, algorithm development and calibration/validation activities, improvements in data accessibility, education, and capacity building through new demonstration project initiatives, and the formation of a scientific group dedicated to inland and coastal water quality remote sensing. It is hoped that this workshop is the beginnings of a coordinated effort to future advance of this technology. It is important to emphasize the need for strong linkages between the entities that produce the data and the end users, for this relationship will ultimately determine the success of these tools for future water resource management.

## Introduction

As precipitation falls on the Earth's continents, the resultant runoff entrains a variety of dissolved and particulate substances, of both natural and anthropogenic origin. These land-based materials, together with those produced or deposited directly within the aquatic environment (e.g. algal blooms, spills) collectively contribute to inland and nearshore coastal water quality. Inland and coastal areas are of a particular concern as the majority of the world's population lives in these riparian and coastal areas. In addition, half of the Earth's available freshwater is already appropriated. Concurrent with an increase in freshwater demand, the supply of "clean" water continues to dwindle as a result of contamination from pollutants. This contamination, from municipal and industrial discharges and non-point source runoff affects coastal receiving waters, inland water bodies and groundwater. Additional issues include: increased sedimentation that can adversely affect fisheries, shellfish, plant life and coral reefs; large influxes of nutrients that can potentially lead to harmful algal blooms, decreased dissolved oxygen and hypoxia in coastal areas; and water-borne pathogens. Every year, over 2 billion people suffer from water-borne illnesses and water-related diseases account for 5 million deaths. Further, more than one-fifth of the world's people do not have access to safe drinking water and one-half of the world's population does not have adequate sanitation. Therefore, water quality monitoring is critical to the future health of the human population as well as the health of the ecosystem by determining the current status of water quality conditions and helps anticipate, and hopefully avoids, future water catastrophes. Given the large number of global issues directly or indirectly linked to water resources, or more specifically here water quality, this priority area has been identified by GEO as one of the key societal benefit areas and seeks advances in earth observation capabilities.

Water quality monitoring and assessment can be grouped into two approaches; 1) *in situ* collected by field staff; 2) Earth observation (EO) or remotely sensed based on satellite, airborne or ground-based sensors. These approaches, sometimes in concert, can address water quality at local, regional and global scales. However, many water quality monitoring programs are deficient. For example many countries lack the technical, institutional, financial resources and infrastructure, and sometimes, the political stability to conduct proper water quality assessments on a long-term basis. One international example with respect to global-scale *in situ* monitoring is the United Nations Environment Programme (UNEP) archives freshwater quality data from national and international cooperators around the world in their Global Environmental Monitoring System (GEMS).

*In situ* methods can be both time consuming and locally expensive, so EO is an emerging capability that can greatly bolster traditional *in situ* methods. However, the field is relatively new, especially in its application to water quality in inland and coastal regions. So EO offers a potentially promising alternative for scientists and managers in assessing large numbers of water bodies in an economical and timely fashion if further scientific advances are made in this area. These areas of advancement include:



UNEP GEMS global network of monitoring stations

- Inland and coastal waters are a complex mixture of constituents, the composition of which varies across water bodies, regions and globally. Unlike open-ocean surface waters, which are generally clear and typically contain only low concentrations of phytoplankton, inland and coastal waters contain a myriad of both dissolved and particulate matter. Techniques need to account for and separate these constituents.
- Inland and coastal waters can exhibit significantly heterogeneous patterns of water quality. These patterns, and associated processes and phenomena, are frequently dynamic, short-lived and small-scale. They may be missed by satellites with inadequate spatial and/or temporal observing capabilities.
- Small water bodies (lakes) are irregularly distributed across the terrestrial landscape, often representing only a few pixels in a satellite image, and will have a number of “edge” pixels that are contaminated by the brighter land signal.
- EO generally only represents surface conditions; also, it can be difficult to relate what the satellites can actually “see” (e.g. ocean color) to those properties that are of primary interest to a manager or decision-maker (e.g. bacteria, toxins).
- EO has attempted to quantify a number of water quality parameters, with varying degrees of success and utilization. These include biological, biogeochemical and ecological parameters such as chlorophyll concentration, turbidity/suspended solids concentration, dissolved organic matter, water clarity, macrophyte surveys, slick and spill detection and underlying geophysical parameters such as surface temperature, winds, currents and waves, bathymetry and flooded area. The broad suite of “ocean color” parameters (e.g. chlorophyll), as well as temperature, currently represent the primary areas of user interest in addition to scientific research and development activities. However, there needs to be a stronger focus on the requirements of inland and coastal waters as these have specific requirements that may not be addressed by global (primarily open-ocean) datasets and approaches.

These shortcomings and issues provided the impetus for organizing an international workshop to provide a forum to collectively address these problems and formulate a path forward for this science.

### **The GEO Workshop**

The first GEO Inland and Nearshore Coastal Water Quality Remote Sensing Workshop was held in Geneva, Switzerland, on 27-29 March 2007. This seminal gathering of experts from around the world was hosted by the GEO Secretariat and co-chaired by representatives from GEO and the Integrated Global Observing Strategy Partnership (IGOS-P) Integrated Global Water Cycle Observation (IGWCO). The workshop was endorsed by GEO as a part of their activities on water resources and water quality initiated in 2006 (Work task WA-06-01). The workshop was attended by 55 participants representing a diversity of backgrounds, expertise and regions of the world with a total of 26 countries being represented.

### **Goal**

The workshop goal was to bring together EO data providers and expert users to improve our ability and capacity to remotely assess and monitor inland and nearshore coastal water quality. This was viewed as a forum for a diverse group, from data providers to end users, to collaboratively chart a course for the future of this emerging science.

### **Objectives**

The workshop objectives were to (1) assess existing and planned EO capabilities; (2) identify gaps relative to user needs in the acquisition, processing, distribution and utilization of remotely sensed data, derived products for water quality research and applications; (3) formulate solutions to address potential gaps and other related challenges.

### **Outcomes**

The workshop participants defined six major issues that were subsequently addressed during the workshop. These six issues are:

1. Satellite sensors for inland and nearshore coastal water quality applications
2. Calibration and validation requirements
3. Data acquisition and distribution
4. Data processing and product development
5. Developing countries needs in earth observation and *in situ* monitoring, and management of inland and near coastal water quality
6. What Earth observation can deliver vs. what should be delivered

At the conclusion of the workshop, writing teams were formed to draft the six sections of this report covering these corresponding topics. For each of these topics, the writing teams were asked to report the workshop's findings with respect to **gaps and issues**, **solution and priorities** and **recommendations**. Furthermore, the report covers short-term priorities for improving capacity and utilization for water quality assessment and monitoring, as well as formulating short and long term strategies to identify, enable and implement enhanced capabilities. The audience for these "issue briefs" is meant to include data providers, GEO members and participating organizations. The following sections address the six topics listed above.



## **Satellite Sensors for Inland and Nearshore Coastal Water Quality Applications**

### **Background**

Synoptic, multi-sensor satellite data products and imagery have become increasingly valuable tools for the assessment of water quality in inland and nearshore coastal waters. Significant research and development activities and related user-driven applied efforts are underway in both developed and developing nations to generate products and information of interest for managers and decision-makers.

Underlying these efforts are the data streams generated by a suite or virtual constellation of international satellite sensors providing water color information at different spatial and temporal resolutions. Moderate spatial resolution data are provided by a number of sensors (e.g. MERIS, MODIS, OCM and SeaWiFS), as are high resolution imagery (e.g. ASTER, IKONOS, Landsat, and SPOT). This color information is supplemented by physical measurements made by other satellite sensors such as synthetic aperture radar (e.g. Envisat/ASAR, ALOS/PALSAR and RADARSAT), thermal measurements (e.g. ASTER, AVHRR, MODIS, AATSR) and ocean vector winds (e.g. QuikSCAT, ASCAT). A promising future envisions opportunities to combine remote observations and hydrodynamic/ecological models to promote synergy, and deliver meaningful products to better understand water quality and related processes.

### **Needs, Issues and Gaps**

Users require timely and accurate data at regular intervals over sustained periods for their particular region that adequately resolve the processes, phenomena and characteristics of interest for regional and local water quality monitoring and management. The IGOS Coastal Theme Report (IGOS, 2006) provides a thorough overview of user needs, requirements and gaps from a coastal as well as a satellite perspective. Overall, satellite ocean/land color observations were identified as having the greatest value utility for water quality applications, but a host of supporting geophysical observations is strongly desired, e.g., surface temperature, roughness, and land cover.

Aside from the issues of calibration/validation (Cal/Val, see Issue #2) and data access (Issue #3), a key concern amongst users is ensuring the continuity of the data both from *in situ* and satellite sources. These are measurements and systems that have already proven valuable, particularly moderate resolution ocean color imagery (e.g. MERIS and MODIS,) and high spatial resolution imagery (e.g. ASTER and Landsat). That being said, existing and planned satellite observing capabilities generally provide inadequate spatial, temporal and/or spectral resolution of important biological and geophysical parameters for inland and nearshore coastal water quality applications, with some key measurements not made at all from space (e.g. estimates of river discharge). As such, there is a compelling need for new and improved observations that can help address water quality needs in these regions, recognizing that tradeoffs will be necessary in order to accommodate the diverse and challenging user requirements.

In terms of satellite water color observations, hyperspectral ultraviolet/visible (UV/VIS) to shortwave infrared (SWIR) (0.35-2.4  $\mu\text{m}$ ; 5-10 nm channels continuous through at least 1.1  $\mu\text{m}$ ) data



are considered ideal and represent the observing system goal to be achieved. Enhanced multispectral data, as described below, satisfies the threshold requirement for water quality efforts. Overall, there is a compelling need for broad spectral coverage (extending from the UV through near-infrared, NIR, with SWIR bands to support improved atmospheric correction), twenty or more narrow (~5-10 nm) spectral bands, and the highest possible signal-to-noise ratio (SNR) to support accurate and robust aquatic-related product development. In this regard, “land” sensors as presently configured have significant limitations in terms of (potential) use for inland and nearshore coastal water quality applications. These aquatic requirements should be considered as one of the key drivers in the anticipated development of future dual-use high-resolution land/aquatic missions.

In terms of the space and time observing “tradespace”, current sensors provide either high spatial resolution but low temporal resolution or high temporal resolution but low spatial resolution. In order to adequately observe inland waters and the land-sea interface, a spatial resolution of 10 m or better and ideally weekly or better repeats is desirable. In dynamic nearshore coastal waters, high frequency temporal revisits (goal of 1 hour) are the principal driver, coupled with moderate (~ 100-300 m) spatial resolution and good offshore (e.g. EEZ) coverage. Suitable *in situ* measures for cal/val of these observations are likewise a compelling need (see Issue #2).

Regarding geophysical observations, thermal observations (e.g. Sea Surface Temperature, SST) are widely utilized by this user community. Continuity of existing capabilities is needed for both global-scale synoptic measurements (e.g. AVHRR, MODIS), as well as high resolution local thermal observations such as provided by ASTER and Landsat. Of particular concern is a lack of any thermal bands on the recently announced Landsat Continuity Mission, which means when current instruments fail there will be no high spatial resolution thermal data; both ASTER and Landsat are well beyond their planned operational lifetimes.

Scatterometry data are potentially useful for assessing the fate and transport of pollutants and pathogens amongst other uses. However, surface vector wind fields from QuikSCAT and others are relatively coarse in space (and time), making them somewhat marginal for use in inland and coastal waters. Next generation scatterometers should have greater utility for water quality applications given anticipated improvements in resolution (e.g. 1-5 km spatial resolution). SAR-derived high-resolution wind fields can potentially provide additional regional support (see below).

The workshop participants also expressed interest in satellite altimetry measurements. However, as was the case with scatterometry, existing altimetric measurements are too coarse for most water quality applications. New and improved satellite altimetric measurements, particularly to extend precision sea level measurements into coastal regions as well as provide estimates of river discharge and storage of water in lakes, wetlands and reservoirs, along with necessary *in situ* measures are of significant value to the water quality community; examples exist in the research community, but need to be developed further for routine operations/applications.

Surface roughness observations from synthetic aperture radar (SAR), ideally multi-band/polarization, can be used to detect and monitor pollution hazards such as runoff and spills, as well as characterize small-scale wind fields, coastal and inland emergent vegetation flooded area and other characteristics. Generally speaking, the spatial resolution afforded by existing SAR sensors is more than adequate; temporal revisits, data access and continuity are significant issues, but hopefully are to be addressed in a coordinated manner by CEOS agencies over the short- and long-term. Interferometer SAR utilizes multiple images of the same location and infers change such as

inundation, vegetation loss/gain, dome building geophysics and other phenomena that make it valuable for analyses.

Novel upcoming measurements such as salinity are of interest to this user community, provided they are at the appropriate spatial and temporal resolution (e.g. next generation SMOS/Aquarius heritage). Finally, there is interest in potential future availability of space-based LIDAR measurements, particularly to provide improved characterizations of aerosol fields (significant need for the atmospheric correction of ocean color data).

## **Solutions and Priorities**

### *Continuity*

The inland and nearshore coastal water quality user communities make extensive use of existing global satellite observations. Their continued availability in a routine and sustained mode is necessary to support ongoing monitoring and decision-making from both a near-real time and climatological perspective. As indicated earlier, satellite water color observations were identified by the workshop as having the greatest general utility for water quality applications, and thus represent a priority need for continuity. These existing color sensors and associated programs can be categorized by spatial resolution. They are:

- Moderate resolution global water color continuity (e.g. MERIS and MODIS) for synoptic context and climatology. Associated with these sensors are specific needs including: at least two sensors in orbit at any one time (e.g. ideally AM & PM); facilitation of greater access/distribution of regional moderate resolution data; the continued inclusion of fluorescence and SWIR bands (the latter for improved atmospheric corrections); need for merged/blended products to address data dropouts along the coast.
- High resolution land/optical imager continuity (e.g. ASTER, Hyperion and Landsat/LDCM). Needs include thermal bands as well as water optical bands (e.g. blue sensitive) bands.
- Fine resolution optical imagery (e.g. IKONOS, SPOT and QuickBird class). Specific needs include greater accessibility to these datasets.

Additional sensor continuity in other electromagnetic regions includes:

- SAR continuity. The present coverage/access is inadequate, so a constellation is needed with widely available data.
- Global and regional surface temperature continuity (e.g. AVHRR, GOES and MODIS) for synoptic context and climatology. There is a need for multiple low Earth orbit (LEO) satellites complemented by geostationary orbits for intensive regional looks. Additionally, there is a sustained need for merged/blended products to address data dropouts along the coastal areas.
- Global ocean vector wind continuity (e.g. ASCAT and QuikSCAT). There is a need for improved spatial resolution and a constellation to provide improved temporal coverage.

### *New and Improved Capabilities (research and development needed)*

As previously indicated, existing satellite observations generally provide inadequate spatial, temporal and/or spectral resolution of important biological and geophysical parameters for inland

and nearshore coastal applications. Research and technology development efforts are needed to implement new missions/sensors that can adequately address these requirements.

- The top two priorities are for nested local and regional aquatic imagers:
  - High resolution *local* aquatic imaging mission(s) in low Earth orbit, with a goal of 10m or better ground resolution and ideally weekly or better repeats, with pointing capabilities and/or a constellation of imagers utilized to provide more frequent looks than currently available through existing high resolution sensors; potential partnership opportunities with the terrestrial observing community;
  - Constellation of *regional* geostationary ocean color imagers to provide regional high frequency temporal revisits. Goal of 1 hour for revisiting dynamic events, moderate (~100-300 m) spatial resolution and good offshore (e.g. EEZ) coverage of coastal regions ~ globally. Potential partnership opportunities with the atmospheric/regional air pollution communities;
  - Hyperspectral capabilities are desired for each of the above, with a minimum of twenty (or greater), narrow (~5-10 nm) spectral bands covering a broad spectral range extending from the UV (0.35 $\mu$ m) through NIR (1.1  $\mu$ m) with discrete SWIR bands also needed to support improved atmospheric corrections and thermal bands desirable for physical dynamics; high signal-to-noise ratio (SNR) is a crucial need for aquatic (versus land) applications.
- Other desired geophysical measurement capabilities include:
  - High resolution/improved coverage altimetry for lake, wetland and reservoir storage, river discharge, nearshore sea level, bathymetry and others (e.g. SWOT and WatER mission concepts).
  - Salinity at an adequate spatial resolution for coastal applications (potential for next generation SMOS/Aquarius heritage instruments).
  - Surface currents from space as a global coverage; especially for developing countries where shore-based HF radar is likely to be prohibitively expensive.
  - LIDAR aerosol column profiles for improved atmospheric corrections; other space based or airborne active measurements (e.g. particle profiles, bathymetry, shoreline position and topography).

## Recommendations

### *Short-Term*

- Water Quality Community: Should become active in future mission concept studies and scoping efforts, with guidance and advisement to be provided by the water quality remote sensing working group (or community of practice) to be formed as a result of this workshop.

- GEO: Help communicate water quality observing requirements associated with this workshop to space agencies and other relevant partners, and identify appropriate individuals and mechanisms for follow-up (including facilitating the following recommendation).
- CEOS: Insert/address aquatic requirements in current/upcoming mission concept studies and scoping efforts; particularly for future high resolution land imagers (especially hyperspectral designs) - make these requirements part of the mission trade space.
- CEOS and/or IOCCG: Conduct ocean color geostationary constellation scoping study – need to plan/implement these geostationary observations in a coordinated manner across multiple regions/basins to provide adequate coverage; explore and identify platforms of opportunity in addition to “free flyers” to facilitate build-out of this constellation.

*Long-Term*

- GEO: Continue to gather evolving user requirements for inland and nearshore coastal waters and reconcile planned measurement capability with user requirements.
- CEOS: Ensure continuity of existing sensors/capabilities of priority need for water quality use as articulated above; multispectral ocean/land color observations are heavily utilized and thus represent a particularly important continuity need.
- CEOS: Develop and implement new and improved inland and nearshore coastal capabilities as identified earlier; particular priorities are for local and regional aquatic imagers with high SNR and improved temporal and spatial resolution.
- CEOS: Plan for and facilitate the transition of existing (as well as planned/future) research and developmental missions for use with water quality assessments and applications into sustained operations in support of user needs (i.e. management and decision-making as well as for research).

## Calibration and Validation Requirements

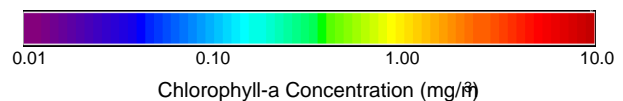
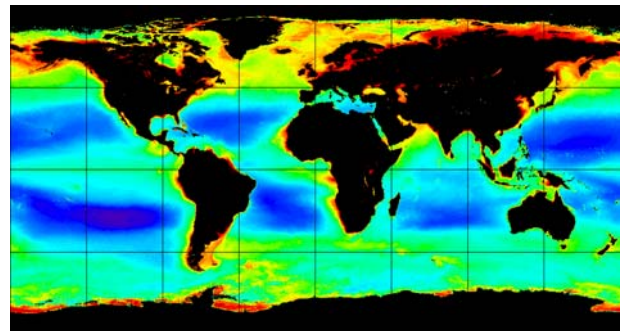
### Background

Calibration and validation (cal/val) are key components for satellite remote sensing of inland and nearshore coastal optical, biological and biogeochemical properties that contribute to water quality. EO of aquatic properties from satellite sensors places very stringent requirements on the sensor's radiometric calibration in the visible spectral region due to significantly low (<10%) water contributions measured by the satellite sensors. In addition to the required pre-launch sensor characterization and radiometer calibration, the on-orbit sensor vicarious calibration is necessary to produce accurate satellite-derived ocean property data. Therefore, the *in situ* vicarious calibration facilities such as the Marine Optical Buoy (MOBY) and BOUSSOLE are essential. MOBY has been used for the on-orbit vicarious calibration of various ocean color sensors for the last 10 years. However, after more than a decade, MOBY is aging and is in need of replacement with a modern system.

A robust and collaborated validation system within the international aquatic science community is important. The validation program serves the functions of product quality assurance, algorithm performance validation and the development and refinement of algorithms. This also assures the satellite-derived products meet scientific requirements for research and applications. In addition, a robust *in situ* database such as the SeaBASS is also needed. SeaBASS has collated and consolidated all NASA funded *in situ* data sets, and made them available to the general scientific community. The SIMBIOS project (1997-2003) was a good example of serving the ocean community for cal/val and involved international scientists in various activities including instrument characterization and evaluation, calibration “round-robin”, *in situ* data collection with standardized protocols, data processing and archiving. However, there has been a significant decrease in the amount of *in situ* data collection in recent years due to a number of factors including the cost of collecting *in situ* data.

A recent development is the SeaWiFS Photometer Revision for Incident Surface Measurement (SeaPRISM) that has demonstrated a capability for supporting validation activities in coastal waters. As integrated into the Aerosol Robotic Network

(AERONET), SeaPRISM data have been processed and made available by AERONET.



Example of SeaWiFS Chlorophyll Concentration product (SeaWiFS Project NASA/GSFC).

## Issues and Gaps

There are various issues and gaps listed here (not in particular order as listed), but the consensus was that the most crucial point was to build coordinated international partnerships including all GEO participant countries working together to address these issues.

- Build international partnerships for cal/val activities.
- Continued support for vicarious calibration facilities and emphasize the need for published documentation on instrument characterization, data acquisition procedures and measurement accuracies.
- Continued *in situ* data collection, in particular in inland and coastal regions.
- A data sharing mechanism for cal/val needs to be built under GEO international partnerships encouraging data sharing and data exchanging for research and applications. NASA has a relatively open data sharing policy (e.g. SeaBASS), while it is not necessarily easy nor clear on how to get data from other organizations.
- Data acquisition protocols: The NASA SIMBIOS project had extensive and detailed protocols published for measurements of various ocean and atmospheric physical, optical and biological parameters. These protocols (with subsequent revisions) have served good guidance documents for scientists worldwide to make good quality *in situ* measurements. The protocols need to be continuously re-visited and revised, taking consideration of the particular requirements for inland and coastal waters.
- Data processing protocols: Similarly, there is a need to continuously re-visit and revise (if necessary) the data processing protocols; in particular the ones dealing with the radiometric data.
- Instrument calibration comparison among various groups: Under GEO international partnerships, we need to support instrument calibration round-robin activities.
- Training and capacity building remain crucial needs.

## Solutions and Priorities

GEO can play an important role in encouraging its member countries to actively participate in calibration and validation activities.

- Under GEO, build international partnerships for aquatic cal/val activities. A group functioning similar to the previous NASA SIMBIOS project would be really helpful.
- GEO needs to continue to push for various agencies to support the *in situ* data acquisition for cal/val and the development of regional ecosystem models.
- GEO needs to encourage various agencies to provide support for maintenance of a vicarious calibration facility (or facilities) and *in situ* monitoring.
- GEO needs to encourage the expansion of networks such as SeaPRISM (in AERONET) for the product validation and water quality monitoring, particularly for sites located in inland and coastal regions. Studies are needed for the identification of optimal sites.
- GEO needs to work out a mechanism for data sharing and data exchange among various international participants.
- GEO needs to have a group of experts or communities of practice to continuously re-visit various measurement and data processing protocols.

- GEO should support training sessions, in particular, in the developing countries and facilitate capacity building.

## **Recommendations**

### *Short-Term*

- As appropriate within its power and purview, GEO should contact various agencies and bodies to encourage continued support for cal/val activities and *in situ* monitoring.
- In cooperation with other organizations (e.g. IOCCG), GEO can build the international partnerships within its member countries for cal/val activities (e.g. a group of international experts or community of practice). Issues to be discussed include instrument calibration, data processing, data accuracy, data sharing, protocols etc.
- In cooperation with other organizations, GEO should fund training sessions for EO, particularly, in the developing countries as a form of capacity building.

### *Long-Term*

In addition to the short term items mentioned above, GEO needs to develop an effective strategy on how to influence and coordinate decision-making in the various agencies and bodies in support of broader community efforts such as this.

## Data Acquisition and Distribution

### Background

The impact of a new satellite sensor for inland or coastal water studies of a research or operational nature is dependent upon the ability of users to access data in a timely fashion with appropriate quality. Operational water quality management frequently requires the most rapid access to data to enable a decision to be made in a timely manner. Longer-term climatological studies require access to well calibrated and validated data sets, particularly if derived from a series of similar sensors on separate platforms (such as MODIS on Terra or Aqua) or different sensors on different platforms (e.g. AVHRR and MODIS). Space agencies appear to consider the ground segment as an “add-on” to the mission. This frequently leads to problems with data access and slower than expected exploitation of new datasets. These problems have been particularly acute with the ATSR (Along-Track Scanning Radiometer) series of sensors.

### Issues

Issues concern the technical access to data in terms of processing level, speed of access and quality where these factors may be in tension. Others include bureaucratic issues such as initial access and limitations on use or redistribution. On the technical side, speed of access is important for users monitoring harmful algal blooms and water quality or guiding *in situ* sampling: data should be available within a few hours from collection on the satellite. For such applications, arguably, speed is more important than best accuracy (i.e. waiting for ancillary data to be available for atmospheric correction or the best possible geolocation). Conversely, assimilation into numerical models typically requires the highest quality data (and knowledge of errors) to ensure accurate nowcasts or forecasts. For climatological studies, delayed-mode, re-processed data are required raising issues of long-term calibration and continuity between satellite missions. For some users lower level data (i.e. level 1 prior to atmospheric correction) are required for the application of regional algorithms.

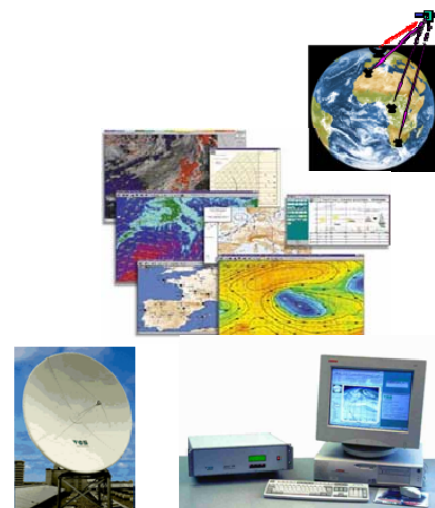
Bureaucratic issues include gaining authorization to access to the data: for example, applying for ESA MERIS data is considered to be difficult. While the procedure is not too difficult (though more so than NASA MODIS data) access to MERIS full resolution (FR) data (where available) still requires ordering of individual scenes subsequent to reception leading to delivery delays of weeks or months. Restrictions on the re-distribution of data are particularly relevant; notably for commercial high resolution data sources.

It is important to note that aquatic studies are frequently multitemporal in nature, requiring many images from the same area over extended periods. This requirement often goes against data distribution policies and tools that are based on a user requesting a few scenes of an area rather than many scenes of a much smaller area. Ground data systems may provide tools to subset out data or “push” data to the user. As a result, users may require huge storage systems and must download large quantities of data, often discarding 95 percent of the data prior to analyzing the data from the smaller area they are focused on, as well as preventing internet download in countries with poor infrastructure. The lack of these tools leads to a tremendous waste of resources which is a major concern for developing countries.



## Gaps

Some satellites do not have direct broadcast (DB) capability that would enable users to receive and process their own data and some DB data are encrypted. Some data suppliers restrict re-distribution of data. Access to high resolution data can be expensive, especially if a time series is needed. These issues are understandable for commercial satellites, but less so for instruments from publicly-funded agencies. Data are often only available in non-specific formats that mean specialized software is needed for viewing or analysis. Data access and distribution is a particular problem for developing-countries with poor communications infrastructure; both to overseas and within the country. The cost of X-band reception stations (needed for high data volume downloads) can also be a problem specifically for developing countries, but even where a station exists the lack of a local network infrastructure prevents transfer of data from the receiving station to end users.



Overviews of GEONETCast concept  
(credit: EUMETSAT)

## Solutions and Priorities

Satellite agencies should be encouraged, through user representations, to give more consideration to the ground segment to ensure rapid access to processed data, to provide direct broadcast capability and to avoid data encryption. These issues are high priority for new satellite missions addressing inland and coastal waters and need to be established early on in the system development. Poor network access, notably for developing countries, could be addressed through novel communications technologies such as GEONETCast, a system supported by GEO, that uses communications satellites to transmit data to end users who only need to purchase a low cost receiver. Of particular value is that multiple data providers can feed data into GEONETCast so users don't have to set up multiple subscriptions with different agencies. The initiative is a priority for funding through European Commission Framework 7 programme and a project called DevCoCast (GEONETCast for developing countries) is currently under negotiation with the aim of providing, *inter alia*, satellite ocean colour and SST data to countries in Africa, South America and Asia. A similar concept is the ESA DDS used to transmit MERIS data to users, with relatively inexpensive reception stations. Other novel approaches include downloads of small images to mobile phones or podcasts. These should be complemented with internet based portals that provide low volume (~100 Kbyte) mapped products, or possibly streaming technology, to supplement the 100 Mbyte raw or unmapped level 2 data, and expanded as internet infrastructure improves. The ChloroGIN system follows this approach (<http://www.npm.ac.uk/rsg/projects/chlorogin/>). Data could be provided in Google Earth or OGC-compliant formats (such as being developed in the EC FP6 InterRisk project) for easy viewing by non specialist coastal zone managers. The InterRisk system aims at interoperability of data suppliers (e.g. NASA or ESA) and data types (in situ, satellite or models) with web-based visualization. Improvements to direct reception capability coupled with capacity building and maintenance in developing countries is also needed. ChloroGIN is an appropriate model where "centres of excellence" can undertake data processing by using a local algorithm and local distribution in a local language. ChloroGIN also promotes the dual approach of satellite and *in situ* data gathering.

## **Recommendations**

### *Short-Term (<2 years)*

- Raw data should be released within minutes of reception and processed products within 1-2 hours; NRT metadata should provide information on accuracy (or errors); faster access is needed to ancillary data to improve accuracy of NRT data; mark the words “near real time data” on the image as well as in the metadata.
- MERIS FR data should be made available in NRT through the rolling archive.
- Encourage or support use of GEONETCast and ESA DDS to improve data distribution, particularly for developing countries.
- Server-side options could be implemented such as spectral or spatial sub-setting on demand to reduce data transmission size.
- Data could be provided more through GoogleEarth or interoperable (OGC compliant) systems.

### *Short- and Long-Term*

- Satellite agencies should continue with appropriate cal/val procedures for data products.
- Data should be provided in agreed formats, and data networks should be more interoperable. Open formats should be utilized and open source software encouraged for multiple platforms. Vendors with proprietary processing software should be expected to provide data in a recognized format.
- Capacity building and maintenance should be encouraged and supported in developing countries with the aim of improving infrastructure and building centers of excellence or networks e.g. following the ChloroGIN model.

### *Long-Term*

- Satellite agencies should make their data freely available via direct broadcast, unencrypted without restriction on redistribution.
- More consideration should be given to the ground segment when constructing new satellite-based systems.

## **Data processing and product development**

### **Background**

In this section, the discussion on defining requirements and recommendations for data processing and product development was synthesized. The comments are provided both with respect to EO aspects and those pertaining to *in situ* datasets; however the focus will be mainly on the satellite aspects, as most of the details relating to *in situ* datasets were addressed in the cal/val (Issue #2) section of the report.

The optical complexity of inland and coastal waters, and the strong temporal and spatial dynamics of these regions, largely dictates the overarching themes addressed in this section. These themes, which will be detailed in the subsequent sections below, include: open standards and flexible processing code/software; interoperable publicly accessible datasets for algorithm development for both atmospheric and in-water constituents; standardized data formats and resources to advance state of the art in implementing algorithm at the regional scale and ensuring the data are publicly available. It is important to recognize that a large proportion of the proposed topics in the following sections are common to both inland and coastal water bodies. These commonalities are largely dictated by their optical complexity and in the need for extensive and standardized in-water and atmospheric datasets to define algorithms. Furthermore the remote sensing processing and algorithm requirements discussed here specifically focus on optical remote sensing datasets, and their associated products. It is well understood that there is an important need for ancillary data in these regions provided by other EO technologies such as SAR and altimetry for river discharge estimates. These will undoubtedly play an important role in ultimately providing an integrated water quality assessment system.

### **Issues**

There are a number of fundamental issues relating to the use of optical remote sensing data in inland and coastal waters that need to be addressed to enable applications to make use of the full potential of these datasets. In many cases these issues are common to optical remote sensing over any water body (including the open ocean), but are often amplified in inland and coastal waters by their specific morphological and dynamic characteristics. The issues include:

- The need for standardized community based open-source radiative transfer (atmospheric and water) models.
- The need for standardized algorithmic methods to be well documented and user-adaptable.
- The need for interoperable data formats, taking into consideration not only preferences/ideals of the remote sensing specialist but those of potential end users as well.
- The re-processing of standard base level products by space agencies, i.e. water leaving radiances as a fundamental requirement to guarantee the highest quantitative accuracy of the derived products.
- There is a user requirement voiced on many occasions, and not currently fulfilled, that entities responsible for deriving core and derived products should be responsible for

providing compatible error estimates (including its spatial variability) with all products provided.

- There is a great need for *in situ* measurements to foster cal/val, assessment of accuracy of products, and overall characterization of processes that are under study. This can be met with in-water and atmospheric datasets to define algorithms.
- There are investment requirements for research and development on specific topics to advance the state-of-the-art including, but not restricted to: atmospheric correction development for inland and coastal waters (including the use of SWIR bands), cloud edge and adjacency correction algorithms and the assimilation of the derived product in physical and/or ecological models.
- Finally, there is a major issue in the development of tools for the integration of the derived products into an accessible user interface e.g. a Google Earth® for water!

### **Gaps, Solutions and Priorities**

In considering the broad issues identified above, a summary of existing gaps and deficiencies is provided, both in the existing infrastructure and in the algorithms and processing chains available for the quantitative use of optical remote sensing for water quality applications in coastal and inland waters. These gaps are listed under the main themes identified above:

- It is acknowledged that the open source software (SeaDAS) provided by NASA for processing SeaWiFS and MODIS has had an extremely positive effect on the community. It would be likewise desirable that analogous open software is available from ESA for MERIS, as well as from other emerging space agencies (e.g. CNSA, INPE, ISRO and JAXA).
- There are wide ranges of “look-up tables” (LUT) used to define atmospheric and in-water constituent properties in the different code. Where possible, these should be consistent or at least well documented through perpetually updated ATBDs.
- Space agencies continue to use different data-formats to store both core and derived-products. Particularly for inland and coastal waters, with a wide variety of users having a broad range of computing backgrounds, consistent and user-friendly data formats need to be agreed upon.
- There is a lack of atmospheric measurements made in parallel with in-situ measurements; these are fundamental in refining algorithms for these regions.
- There is need for a consensus building exercise (perhaps proposed IOCCG WG) on regional algorithms and method to merge these back into homogenous products.
- The EO community is still slow in not providing pixel based error estimates that are a fundamental requirement from the user community.
- Although there have been recent efforts to investigate the merging of multiple datasets for open ocean applications this needs now to be considered also for inland and coastal water bodies to ensure long-term climate data records in these regions.
- There is no coordination of research needs for algorithm requirements (considering topics such as atmospheric correction in turbid waters, both high scattering and very high absorbing, adjacency effects and regional semi-analytical algorithms).
- The capacity building initiatives at present are insufficient to ensure adequate use of optical remote sensing for water quality application in less-developed countries.
- For these developing regions and in general, there are inadequately user-friendly interfaces to the data (webmap servers, Google Ocean)

## Recommendations

### *Both Short-Term and Long-Term*

In synthesizing the above described issues, subsequently refined in a list of identified gaps the following concrete recommendations are highlighted for aspects relating to the processing and algorithm development requirements.

- An open modular processing software for “Inland and Coastal Colour” datasets (SeaDAS-type) where space agencies can introduce new modules for new sensors as they become available.
- A coordination activity to standardize LUT consistency across sensors (e.g. atmospheric LUTs).
- An international activity/entity to ensure that inland and coastal algorithmic requirements (e.g. SWIR wavelength atmospheric correction, adjacency effects, optical parameter assignment in semi-analytical models) are taken into consideration for present and future missions. This should include developments for envisaged future remote sensing capabilities (e.g. high-spatial resolution hyperspectral and geostationary hyperspectral imaging). These wavelengths are particularly valuable for evaluations of inland and coastal wetlands and riparian areas.
- A working group (through IOCCG) to explore methods for regional algorithm implementation including their integration into seamless products.
- A further activity (related to 3 and 4) to define protocols/methods for providing pixel based uncertainty estimates for core and derived products.
- A consensus building exercise led by the space agencies to standardize data and metadata formats that are compatible with end user requirements.
- Better harmonization of quality control and accessibility of *in situ* data (atmospheric and in-water) for algorithm parameterization purposes (i.e. an internationally sanctioned and supported SeaBASS extended to include inland and coastal waters).
- Resources to advance state of the art research on algorithm development issue specific to inland and coastal waters. Including capacity building funds to propagate this know-how to less-developed regions.
- User led activity to define appropriate tools for access to products for water quality assessment with a focus on new web-based technologies.

## **Developing countries needs in Earth Observation and *in situ* monitoring and management of inland and near coastal water quality**

### **Background**

The GEO Task WA-07-01 (global water quality monitoring) represents a teaming of efforts by international organizations, institutions and scientists from GEO member countries concerned by the cross-cutting theme of water quality in large inland and nearshore coastal zone environments. The aim is reinforcing integrated global observational capacities in water quality based on EO and *in situ* monitoring.

Developing countries play an important role as key shareholders of large tracks of coastline, large estuarine areas as well as vital inland ecosystems. There is therefore a need to address specific issues and needs, particular in developing nations, in order to better articulate their role and participation in this field and in the GEO process in general. During the meeting, a special session paid attention to developing countries issues and their particular needs concerning EO and *in situ* monitoring of water quality in freshwater and coastal zones, and capacity building.

### **Issues and Gaps**

The following generic issues were raised and gaps identified:

- Most developing countries are characterized by a lack of a sustained long-term local infrastructure in both human capacity and physical operational EO and *in situ* observing systems.
- A strong fragmentation of mandates among institutions and administrations dealing with multiple aspects of water quality leading to poorly coordinated actions and efforts.
- Poor recognition and awareness of the societal importance, cross-cutting impact of water quality issues in a country's social and economic development, leading to lower priority in fund allocations. As a consequence, long term observation or *in situ* monitoring programs are usually defunct of operational budget and staff.

In relation to the use of *in situ* and EO monitoring for water quality, the following issues and gaps were identified:

- Lack of data sharing interests and standardized exchange mechanisms (data protocols, database standards, data quality controls) between institutions, departments and countries (e.g. sharing freshwater resources).
- Compared to temperate regions, there is far less knowledge on the adequacy of retrieval algorithms in tropical waters (e.g. complex mixtures of particulate and dissolved substances with optical properties other than phytoplankton or its breakdown products);
- The cost of hyperspectral optical satellite or airborne data as well as the equipment for *in situ* measurements needed for monitoring water quality parameters is prohibitive for many lesser developed countries;

## Solutions and Priorities

- Foster free accessibility to satellite data suitable for monitoring inland and coastal water quality in developing countries;
- Use local scientific communities to identify the feasibility and applicability of EO combined with *in situ* monitoring for solving their water quality issues;
- Facilitate coordination and collaboration between member countries in the field of water quality monitoring strategies, set-up of in-country and coastal monitoring networks;
- Support national and regional capacity building initiatives, comprising education and training and local permanent infrastructure building, to collect, analyze, use and disseminate data;
- Make use of recognized international training institutes and universities, involved in space sciences, environmental sciences and GEO/GEOSS information technology, and employ their alumni networks to establish partnerships;
- Use the scientific capacities not only of developed, but also of developing countries;
- Support efforts to ensure that training and capacity building activities are made jointly with local institutions and linked to their existing research priorities and capacities.

## Recommendations

### *Short-term*

Recommendations that could be realized in the short term as fast-track initiatives are:

- Inventory of the demand for EO products in relation to water quality in developing countries, and establish the points of contacts in the GEO member countries in relation to the water quality theme (e.g. start from UNEP GEMS focal points).
- Include elements of the inland and coastal water quality issue in the GEO presentation for the ministerial level GEO Earth Observation Summits (November, 2007 and others) and later GEO Plenary meetings.
- Launch capacity building initiatives in some developing countries with active involvement of graduate students and researchers from developed country universities.
- Support the development of e-learning and distance learning in EO and *in situ* measurements and analysis for water quality, using freeware and open source domain software tools (e.g. BEAM/Visat, BILKO, ILWIS, SeaDAS, SPRING etc.);
- Support actions geared towards cross-platform usability (LINUX/UNIX and Windows) of current software for water quality and ocean color satellite data processing.
- Use and organize international field measurement campaigns (also as capacity building segments) in developing countries and/or foster active participation of developing countries in international cal/val campaigns.
- Initiate awareness building and extension in EO for water quality at secondary and post-secondary school level (e.g. the GLOBE project for teaching teachers and children *in situ* environmental monitoring).
- Support ICT initiatives to promote EO-derived water quality maps in e.g. Google Earth or similar web-based global services.
- Facilitate and conduct pilot projects in countries faced with emergency water quality problems.

### *Long-term*

These recommendations fit into the long-term strategies of GEO, in line with the GEO 10-year Implementation Plan.

- Use GEO as an umbrella organization for creating a global partnership between developing nations and the international global observing science community in the field of water quality EO;
- Use GEO to promote fund raising (e.g. donor conference) for establishing long term programs of regular water quality monitoring in data scarce or poorly studied areas in developing countries.
- Support developing countries for instrumentation needed for *in situ* cal/val operations and EO data acquisition.
- Other issues of relevance noted were that GEO should actively support initiatives for upgrading the spatial resolution of the currently available global water quality (ocean color) sensors.

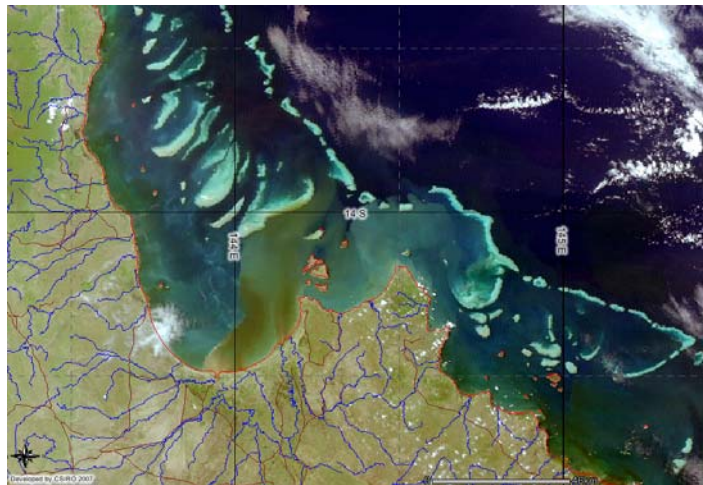


## What remote sensing can deliver vs. what should be delivered

### Background and Issues

The EO applications need to be split into two areas: one is inland water remote sensing and the other is coastal waters remote sensing including estuaries and bays, although the coastal scientific community can nurture the inland waters community and vice versa.

Inland water remote sensing has always been a local concern or regional activity. Consequently, the inland water remote sensing community has never been able to organize themselves such as the ocean remote sensing community. Examples of known freshwater remote sensing applications are in the USA (Wisconsin Lakes and the Great Lakes); in Europe (Finnish lakes, Swedish Lakes, Estonian Lakes, Lake Constance, Dutch Lakes etc.). However, these examples are localized and apply a variety of approaches (empirical through to analytical) and sensors. Consequently, no standard approach exists and the use of results by managers is limited.



MODIS image of river plume entering the Great Barrier Reef after significant rainfall, 9 Feb 07 (CSIRO)

Coastal remote sensing does have programmes which shows improved collaboration among agencies at the national (e.g. US) and international (European Union e.g. MarCoast) level. Further, satellite sensors such as MERIS, MODIS and SeaWiFS are more suitable for coastal remote sensing than for inland water remote sensing. Indeed MERIS was the first semi-operational satellite sensor to specifically include spectral characteristics suitable for coastal and other case II waters. However, the spatial resolution of the imagery still prevents the use of these satellites for monitoring spatially dynamic coastal environments. The coastal remote sensing community is better organised along national scales in some countries (e.g. USA), but generally aligned internationally in Europe for effective remote sensing applications. The IGOS Coastal Theme has had a very positive role in getting this community together. This is a first good step into creating a global community of practice.

### Issues and Gaps

The operational use of satellite imagery for monitoring water quality of inland and coastal waters is presently limited. In these application areas, problems arise due to a lack of suitable sensors: in the case of using available ocean colour sensors, the standard algorithms based on limited number of spectral bands are usually inaccurate to invalid in inland and many coastal waters as they cannot discriminate the three optically active water quality components of algal pigments, coloured

dissolved organic matter or total suspended matter. Additionally, the spatial resolution of ocean colour sensors is inadequate for inland and coastal areas that need more detail than the 1 km scale (for the 300 m pixels) and at the 3 km scale (for the 1 km pixels). Finally, these sensors do not have the required high signal to noise ratio at short wavelengths. On the positive side these sensors do give relatively high temporal resolution.

If one uses land remote sensor instruments the repetition time becomes too long, the spectral bands are inadequate (except for experimental hyperspectral sensors). If the spatial resolution is high enough (e.g., Quickbird and IKONOS) the costs become (too) high for operational use. Monitoring chlorophyll especially becomes a problematic. Similarly to ocean colour satellites, these sensors do not have the required signal to noise ratio at short wavelengths.

Problems also arise due to the lack of accurate quantification of remotely measurable optical water constituents and their relationship with water quality indicators. Together, lack of appropriate satellite, lack of models that take into account the variability of these waters, and built relationships between information derived from satellites and water quality indicators, and lack of robust atmospheric correction models prevents water quality managers to use satellite information for decision-making purposes. Thus water quality managers are not enthused to commit to remote sensing for any of their information needs, thereby causing a vicious circle. Also, the lack of long term guarantees of delivery of suitable types of remote sensing data is a core issue that halts acceptance.

## **Solutions and Priorities**

Suitably designed sensors with appropriate spatial and temporal resolution must first become available. Additionally, standardization of approaches that deliver well known and validated products is needed. Indeed, the setting of standards is a crucial activity before national and international water quality bodies will certify information from EO. Broad acceptance will only happen if the end-user community is involved in the development of the methods, protocols and deliverables.

Proposed new sophisticated land sensors could play an important role in the EO of inland and coastal water quality if their specifications were to be slightly modified to have either more spectral bands or more blue spectral bands and a higher signal-to-noise ratio (See Issue #1 section). This enhancement of an existing planned mission would potentially be much more cost-effective than developing and launching dedicated inland or coastal water sensors. Similarly, if ocean colour sensors could also have a 50, 100 or 200m mode they would be so much more applicable.

## **Recommendations**

### *Short Term*

- Create a Global Remote Sensing of Inland and Coastal Waters Community of Practice (CP), or join a related CP.
- Establish minimum level of monitoring requirements that are reachable by many technologies and approaches.

- Establish two demonstration projects in each hemisphere, involving the pioneers of the water quality management that want/need to embrace what this technology can offer.
- Develop programs to promote adoption of valid remote sensing derived information.
- Use experimental hyperspectral satellite sensors (e.g. CHRIS\_PROBA, Hyperion and new future ones) in combination with airborne systems and ocean coastal sensors to demonstrate the added value for water quality managers.
- Develop a scientific consensus on algorithms for analysis of chlorophyll, cyanobacterial pigments, non-algal particulate matter, coloured dissolved organic matter, vertical attenuation coefficients of light, transparency, turbidity, potentially harmful algal blooms and related variables.
- Fund and publish studies that look at time series statistics to establish baselines, seasonality, trends, extreme events etc.
- Consider opportunities on the development of early warning systems with related EO system activities.
- Work on the assimilation of EO derived water quality information into biogeochemical and hydrodynamic models in order to achieve better, predictive solutions.

### *Long Term*

- Establish a global freshwater and coastal water watch program.
- Analyze long term datasets of water characteristics to provide an informational clearinghouse for disputes of water diversions and fate, and what quality was evident. This may be facilitated by building reference databases.
- Show environmental management examples of success and failure so as to build confidence in EO approaches.
- Full integration of watershed remote sensing and data assimilation with receiving river, estuarine, coastal and ocean data and models.
- GEO can provide an important role in the process of synthesizing more complex remote sensing data products with biogeochemical and hydrodynamic models as they become more sophisticated, and perhaps harder to combine and integrate.
- Improved capacity building including training staff, building and increasing investments, coordination, and providing geographic equity (developing world to developed world equity).

## Appendix 1. Glossary of Acronyms

AERONET	Aerosol Robotic Network
Agua	Earth observations satellite
ASAR	Advanced Synthetic Aperture Radar (ESA)
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced very high resolution radiometer
BEAM/Visat	Open source domain software tool
BILKO	Open source domain software tool
Cal/val	Calibration and validation
CEOS	Committee on Earth Observation Satellites
CHRIS_PROBA	Compact High Resolution Imaging Spectrometer Project for On-Board Autonomy
ChloroGIN	Chlorophyll Global Integrated Network
DDS	Data Dissemination System
EC FP	European Commission Framework Programme
EEZ	Exclusive Economic Zone
ESA	European Space Agency
GEO	Group on Earth Observation
GEOS	Global Earth Observation System of Systems
GEONETCast	A global network of satellite based data dissemination systems
GEMS	Global Environment Monitoring Program
GEO	Group on Earth Observations
GEOS	Global Earth Observation System of Systems
GLOBE	Global Learning and Observations to Benefit the Environment
IGOS-P	Integrated Global Observing Strategy-Partnership
INPE	Instituto Nacional de Pesquisas Espaciais (Brazil)
InterRisk	Interoperable GMES services for environmental risk management in marine and coastal areas
IOCCG	International Ocean Color Coordinating group
IKONOS	Satellite-based imagery acquisition systems
ILWIS	Open source domain software tool
ISRO	Indian Space Research Organisation
JAXA	Japan Aerospace Exploration Agency
Landsat	Land imaging series of satellites and sensors
LEO	Low Earth orbit
MarCoast	Marine & Coastal Environmental Information Services
MERIS	Medium Resolution Imaging Spectrometer
MOBY	Marine Optical Buoy
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NIR	Near infrared
OCM	Ocean Colour Monitor
OGC	Open Geospatial Consortium
QuikSCAT	Quick scatterometer for seawind measurements
Radar	Microwave imaging radar

RADARSAT	Canadian Radar Satellite
SAR	Synthetic Aperture Radar
SeaBASS	SeaWiFS bio-optical archive and storage system
SeaDAS	Open source domain software tool
Sea PRISM	SeaWiFS Photometer Revision for Incident Surface Measurements
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIMBIOS	Sensor intercomparison and merger for biological and interdisciplinary oceanic studies
SMOS	Soil moisture and ocean salinity Earth explorer
SPOT	Satellite Earth Observation System by Centre National d'Etudes Spatiales
SPRING	Open source domain software tool
SST	Sea Surface Temperature
SWIR	Short wavelength infrared
Terra	Earth observations satellite
UNEP	United Nations Environmental Program
UNIX	Open source domain software tool

## Appendix 2.

### Selected links to relevant web pages and documents

Coastal Theme Report of the Integrated Global Observing Strategy (IGOS) Partnership  
[http://www.igospartners.org/docs/theme\\_reports/IGOS%20COASTAL%20REPORT%20midrez.pdf](http://www.igospartners.org/docs/theme_reports/IGOS%20COASTAL%20REPORT%20midrez.pdf)  
[http://cryos.ssec.wisc.edu/docs/theme\\_reports/Coastal\\_Theme\\_Report.pdf](http://cryos.ssec.wisc.edu/docs/theme_reports/Coastal_Theme_Report.pdf)

GEO website documents from the water quality workshop  
<http://www.earthobservations.org/meetings/workshops/Inland/Inland05.html>

International Ocean-Colour Coordinating Group. Contains an excellent report on remote sensing of optically complex water (report no.3)  
<http://www.ioccg.org/>

IGOS Integrated Global Water Cycle Observations (IGWCO) Theme information and report  
<http://www.gewex.org/igosreport.htm>

ESA Tiger Initiative  
<http://www.tiger.esa.int/>

International Institute for Geo-Information Science and Earth Observation  
<http://www.itc.nl/research/policy/spearhead5/su.asp>

Commonwealth Scientific and Industrial Research Organisation. Remote sensing group  
<http://www.clw.csiro.au/research/sensing/remote/>

University of Wisconsin Remote Sensing Water Clarity Project  
<http://www.lakesat.org/>

Global Ocean Observing System  
<http://www.ioc-goos.org/>

South America Antares Project  
<http://home.antares.ws/>

ChloroGIN Africa Project  
<http://www.npm.ac.uk/rsg/projects/chlorogin/>

Remote Sensing of Water Resources at University of Minnesota  
<http://water.umn.edu/>

NOAA Coastal Services Center  
<http://www.csc.noaa.gov/crs/cwq/demo.html>

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