United States
Environmental Protection
Agency

Office of Water
(4503F)

EPA841-B-99-006
December 1999

EPA

Remotely Monitoring Water Resources: An EPA/NASA Workshop

Acknowledgments

This document was compiled for the U.S. Environmental Protection Agency's Office of Water with partial support under Purchase Order No. 9W-0492-NATX to Dr. Theodore A. Endreny (now with SUNY College of Environmental Science and Forestry) and Contract No. 68-C7-0018 to Tetra Tech, Inc. from the EPA Office of Wetlands, Oceans and Watersheds AWPD Watershed Branch, and with partial support under Contract No. 68-C5-0065 to Lockheed Martin Environmental Services from the EPA Environmental Photographic Interpretation Center, National Exposure Research Laboratory. The EPA Project Officer was Douglas J. Norton.

Notice

Where to obtain copies

Single copies can be ordered for free by calling 1-800-490-9198 and requesting document number EPA841-B-99-006, "Remotely monitoring water resources: an EPA/NASA workshop." The document in full is also found on the Internet at ***http://www.epa.gov/owow/watershed/wacademy/its.html***

This report should be cited as:

U.S. Environmental Protection Agency. 1999. ***Remotely monitoring water resources: an EPA/NASA workshop***. EPA841-B-99-006. Office of Water (4503F), United States Environmental Protection Agency, Washington, DC. 101 pp.

FOREWORD

In December, 1996, the U. S. Environmental Protection Agency (EPA) and the National Aeronautics and Space Administration (NASA) brought together scientists and managers from both agencies and their collaborating research organizations to discuss the potential applications of existing and developmental remote sensing technologies to water resources monitoring. The workshop planners crafted the following statement to explain the workshop's aims and guide its participants:

WORKSHOP STATEMENT OF PURPOSE

Monitoring the condition or health of the environment is essential to its proper stewardship and management. Under the Clean Water Act, water resources are monitored by states and other jurisdictions, but current programs are unable to monitor all their watersheds, water bodies, and point- and non-point pollution sources. In reality, the majority of U.S. water bodies are not monitored regularly, and even more are not monitored as well as resource managers would like. This is both a financial and technical problem, as many monitoring methods are not cost-effective or technologically efficient enough for monitoring all water bodies of interest.

The rapid advancement of new technologies, such as remote sensing, may someday provide methods for monitoring more water quality parameters, in more water bodies, with improved accuracy, or with reduced per-unit costs. To actively improve the status of monitoring science, however, monitoring professionals must learn about emerging technologies as well as those available now, and researchers who develop these technologies must learn the needs of their clientele. In order to focus and accelerate research and applications of advanced technologies in water resources monitoring, the U.S. Environmental Protection Agency (EPA) and the National Aeronautics and Space Administration (NASA) are convening a workshop to discuss and match monitoring needs with the appropriate advanced technologies. The purpose of this workshop is to expose technical and management personnel of both agencies to (1) NASA's remote sensing science and technology, and (2) EPA's water resources monitoring requirements and data bases. The goal of the workshop is mutual education, and the opportunity to explore future collaboration in water monitoring/remote sensing research and applications.

Three years later, this workshop's findings continue to be relevant to water resources monitoring and management. The challenges facing local, state and federal water monitoring programs basically remain the same. The opportunities for NASA and its collaborating researchers to apply remote sensing technologies to water resources monitoring are still significant. Moreover, NASA's Mission to Planet Earth program, now called Earth Science Enterprise, is considerably closer to applying new remote technologies in 1999 than three years ago, and some of the collaborations suggested at the workshop are already taking place. Accordingly the EPA Office of Water has published this workshop report, with minor updates, to share its useful findings with water resource managers and researchers.

Workshop Co-Chairs

EPA Research & Development	EPA Office of Water	NASA Headquarters
Stephen A. Lingle US EPA (8101) 401 M Street SW Washington, DC 20460 Phone: 202-260-2619 Fax: 202-260-4524 **lingle.stephen@epa.gov**	Douglas J. Norton US EPA (4503F) 401 M Street SW Washington, DC 20460 Phone: 202-260-7017 Fax: 202-260-7024 **norton.douglas@epa.gov**	Alexander J. Tuyahov NASA HQ Code YS 300 E Street SW Washington, DC 20546 Phone: 202-358-0250 Fax: 202-358-3098 **atuyahov@hq.nasa.gov**

Discussion Group Co-Chairs

Watersheds, Lakes and Rivers	Wetlands	Groundwater	Oceans and Estuaries
EPA: Barry Burgan NASA: Ted Engman	EPA: Peter Stokely NASA: Vic Klemas	EPA: Joe D'Lugosz NASA: James Arnold	EPA: Joe Hall NASA: James Yoder

Workshop Planning Group

Individual	Agency
James Arnold	NASA Headquarters
Barry Burgan	EPA Office of Water
Joe D'Lugosz	EPA Region 5
Ted Engman	NASA Goddard Space Flight Center
Murray Felsher	Associated Technical Consultants
David Friedman	EPA Office of Research and Development
Don Garofalo	EPA Office of Research and Development
Joe Hall	EPA Office of Water
Anthony Janetos	NASA Headquarters
Vic Klemas	University of Delaware
Steven Lingle	EPA Office of Research and Development
Tom Mace	EPA Office of Information Resources Management
Doug Norton	EPA Office of Water
Gary Shelton	NASA Headquarters
Peter Stokley	EPA Region 3
Alex Tuyahov	NASA Headquarters
Ming Ying Wei	NASA Headquarters
James Yoder	NASA Headquarters

TABLE OF CONTENTS

LIST OF TABLES

EXECUTIVE SUMMARY

The *EPA / NASA Workshop on Water Monitoring, Remote Sensing and Advanced Technologies* of December 1996 was held to identify NASA remote sensors and advanced technologies that could assist EPA and its local and state partners in monitoring the condition of the nation's water resources. Workshop findings and recommendations generated by EPA and NASA personnel are still timely and relevant today. This workshop report summarizes, with minor updates, the water resources monitoring applications of remote sensing instruments that were identified during the 1996 workshop.

Prior to attending the workshop, participants were provided a background paper that outlined the EPA's water resources monitoring mission and identified science areas that might benefit from remote sensing and advanced technologies. At the workshop, EPA personnel emphasized agency needs for high spatial and temporal resolution monitoring instruments that enable national assessment, as well as instruments that would improve monitoring efficiency and accuracy at local scales. NASA personnel provided a tutorial to introduce the Earth Science Enterprise mission and other relevant technologies. Joint EPA and NASA moderators then guided the 74 workshop participants in breakout session discussions that were organized into four principal water resource areas: watersheds, rivers, and lakes; wetlands; groundwater; and estuaries and oceans. Each breakout session identified possible applications of existing and future remote sensing and advanced technologies to water resources monitoring needs.

Common themes in the workshop findings included: decentralizing EPA and NASA interactions with regional offices; increasing training in remote sensing; facilitating technology transfer; ensuring data standardization and consistency; developing pilot projects that demonstrate remote sensing applications; and coordinating the simultaneous collection of *in-situ* and remotely sensed data. Monitoring areas in which remote sensing showed the greatest promise included: assessment of non-point source pollution; determination of flooding and waterbody extent; aquatic habitat classification and health assessment; riparian habitat classification and health assessment; land use / land cover mapping; detection and measurement of suspended sediment, temperature, and algal blooms; and temporal profiling of vegetation greenness.

The specific recommendations from each breakout session identify the monitoring needs and applicable technologies, point to gaps in current technologies, and then conclude by identifying emerging technologies that are under development or in planning. This report serves both as a reference for identifying current applications of remote sensing in water resources monitoring and as a guide to better understanding how such advanced technologies may partner with water resources monitoring missions.

SECTION 1

INTRODUCTION

The _EPA / NASA Workshop on Water Monitoring, Remote Sensing and Advanced Technologies_ was held on the 11th and 12th of December 1996 in Washington, DC. U.S. Environmental Protection Agency (EPA) and National Aeronautics and Space Administration (NASA) employees comprised the majority of workshop participants (Table 1.1), but a small number of other agencies, states and academic institutions were also represented. A complete listing of the workshop participants can be found in Appendix C.

Table 1.1: Summary of Participating Agencies and Institutions.

AGENCY	Number of Attendees
EPA/Research	13
EPA/Water	9
EPA Regions	9
EPA Other Offices	3
NASA	14
NASA Academic/Investigation	20
State / Academic	2
Other Agencies	4
Total Attendance	**74**

Workshop Structure

This workshop was designed jointly by EPA and NASA to initiate inter-agency discussions on the topic of monitoring water resources with remote sensing and other advanced technologies. The *Workshop Statement of Purpose* is provided in the Foreword, located on page *iii* of this report.

The workshop took place over the course of two days and was structured to maximize the time spent on identifying technologically advanced and appropriate approaches to water resource monitoring. The entire workshop agenda is presented in Appendix A. Workshop participants were sent a background white paper (see Section 3) that summarized EPA's Clean Water Act mandate and the shortcomings of current monitoring programs, and identified how NASA advanced technologies such as remote sensing might assist EPA in meeting their mandate.

The first part of the workshop provided tutorials in EPA water resources monitoring needs and NASA remote sensing instruments, thereby orienting the participants toward relating the two agencies' activities. The remainder of the workshop was then dedicated to identifying remote sensing and advanced technologies that might be applied to EPA's specific water resource monitoring needs. These discussions occurred within Breakout Sessions that were co-moderated by EPA and NASA scientists.

Water Resource Types Considered

Four separate water resource categories were used to structure discussions on monitoring needs and potential remote sensing and advanced technology applications. The four water resource categories included: ***watersheds, lakes, and rivers; wetlands; groundwater; and estuaries and oceans***. These resources are briefly described below in terms of their distribution, their volume relative to the global supply of water, and their residence time (the amount of time necessary for water to move through the water body of interest), which are all factors that influence the utility of monitoring with remote sensing or other advanced technologies.

Watersheds, Lakes and Rivers

Water bodies in this category -- lakes, rivers and streams -- are the principal inland surface water bodies; watersheds are their surrounding drainage areas. Rivers (taken to mean all rivers and streams of any size in this workshop) contain approximately 0.2 % of all available fresh water resources; there are over 3 million miles of rivers and streams in the US. Lakes and reservoirs, which are usually grouped in the same category, contain approximately 3.0 % of available fresh water resources. Residence times are highly variable according to water body size. About 40 % of these freshwater bodies do not fully meet state water quality standards.

Watersheds, which encompass the land area and subsurface aquifers draining into a body of water, often also include groundwater, soil moisture, biospheric water, and atmospheric water that contribute to the rivers and lakes. In some areas, and during some seasons, snow and glaciers contribute additional sources of water. Soil contains approximately 1.7 % of available fresh water, which has a residence time of 2 weeks to 1 year. Atmospheric water is approximately 0.2 % of all fresh water and has a residence time of 1.3 weeks. Watershed characteristics such as soils, surficial geology, and land use/land cover, and processes such as runoff quality and quantity and pollutant transport, groundwater recharge, and erosion/deposition of sediment, often affect the quality and quantity of lake and river water resources.

Wetlands

Wetlands are a diverse group of surface water resources that are typically found at the interfaces of terrestrial and aquatic ecosystems. They are defined and delineated by the presence of characteristic saturated soil types and water tolerant plant species, and distinct periods of near-surface saturation or surface inundation. Wetlands are often attributed with beneficial functions such as stream flow moderation (including flood control as well as base flow maintenance during drought), shoreline stabilization, sediment trapping and nutrient retention, and wildlife habitat. Wetlands comprise approximately 6 % of the earth's total land area; over half of the wetland area in the US has been lost since colonial times, concurrent with an undetermined amount of degradation or loss of beneficial wetland functions.

Groundwater

Groundwater resources are subsurface water reserves that are held in saturated soils and geologic formations. Groundwater reserves interact with unsaturated soils, wetlands, rivers, and lakes, and depending on the surface topography or the hydrologic regime, these interactions can result in a gain or loss of surface waters from place to place and time to time. Groundwater that is readily retrievable for drinking water comprises approximately 97% of all freshwater supplies (approximately $9.9 \times 10^6 km^3$) and has a residence time that ranges from 2 weeks to 10,000 years. In the United States, ground water provides 50% of all drinking water (90% in rural areas), 25% of industrial water and 34% of agricultural irrigation. As human population increases competition for fresh water, particularly ground water in arid and semi-arid lands, will likely become more intense. Degradation of groundwater resources is not thoroughly documented in national monitoring reports, but the monitoring and reporting of ground water quality is increasing significantly. Impairment of groundwater often occurs from infiltration of surface contaminants, or migration of pollutants from uncontrolled burial or landfilling sites. Loss of groundwater is often due to overutilization or reduction in the ability to recharge aquifers.

Oceans and Estuaries

Near-coastal ocean waters and estuaries are the focus of EPA's coastal programs. Estuaries are located at the interface of fresh and saline waters, often defined by the tidally influenced zone at the mouth of a river entering the ocean. Oceans and estuaries comprise over 97% of all water on the earth and evaporation from these reserves produces the fresh water which later precipitates over land to recharge rivers, lakes, wetlands, and groundwater supplies. Residence times vary with size. Burgeoning coastal populations are creating a greater need for monitoring coastal water quality to detect emerging water resource problems as early as possible.

* * * * *

These four resource types inevitably have some overlap. Certain characteristics of the ***watersheds, lakes and rivers*** category in particular are held in common with the other three categories: 1) the fact that virtually all water bodies have watersheds; 2) the surface and subsurface water exchanges among rivers, lakes, wetlands, estuaries, oceans and groundwater; and 3) the wetland types that are physically similar to or co-located with lake littoral areas and riparian areas of streams and rivers. Therefore, the report discusses all watershed implications for all water body types under the ***watersheds, lakes and rivers*** heading, and also identifies areas where monitoring needs of one category of water resource are transferrable to the other categories.

Remote Sensing Technologies Considered

A host of environmental remote sensing instruments have been developed and launched into orbit by NASA and other international space agencies since the 1970s. New and improved technologies are continually developed by these agencies, and due to legislation signed in the 1990's, private companies are now also developing and launching environmental sensing technologies into earth's orbit. In this section, several basic premises common to many remote sensing technologies are introduced.

Materials on the earth's surface, such as water, soil, and plant chlorophyll, have a unique atomic structure that reflects a predictable and often unique amount of radiation at each interval along the electromagnetic spectrum. A material's unique reflectance curve is often referred to as its spectral signature. Electromagnetic radiation, arriving from the sun or sent by a remote sensor, can range from the very short wavelength gamma rays and x-rays to the visible and near infrared and onto the longer microwave and radio. Only certain parts of the electromagnetic spectrum are useful for certain remote sensing applications. For example, at some wavelengths the material of interest may not reflect any unique signature, while at other intervals the material may display a very unique signature but atmospheric gasses might trap the signal and prohibit its detection by the sensor.

Electromagnetic Sensors

Electromagnetic sensors are not capable of detecting and measuring all spectra, and instead are designed to measure across a discrete range of the entire electromagnetic spectrum. Using the physical relations of electromagnetic theory along with extensive laboratory and field tests scientists have successfully identified the specific spectra or combinations of spectra most strongly emitted from, and unique to, the environmental resources of interest (e.g. water, suspended sediment or chlorophyll). Sensors commonly used in environmental remote sensing include those designed for gamma radiation, visible radiation, infrared radiation, thermal radiation, and microwave radiation. Remote sensing instruments are often categorized by the electromagnetic sensor's radiometric resolution, spatial resolution, and temporal resolution.

Radiometric Resolution

Radiometric resolution refers to the band-size or spectral range of the electromagnetic sample received by the remote sensor. Many multi-band remote sensing platforms that sample in the visible spectrum are designed to retrieve signals at red, green, and blue wavelengths, which corresponds to spectral ranges from approximately 0.45 to 0.55 for red, 0.55 to 0.65 for green, and 0.65 to 0.75 for blue. If a single sensor is used to sample at this resolution the sensor is considered broad band, while hyper-spectral sensors are capable of resolving multiple wavelengths within each of these bands.

Spatial Resolution

Spatial resolution refers to the horizontal length scale resolved by each individual electromagnetic sensor pixel aboard the platform. Remote sensing platforms typically have a fixed spatial resolution, and current technologies use resolutions that range from 1-m to over 1-km length scales. During data retrieval events remote sensing platforms will sample an entire scene that is composed of an array of pixel areas, resulting in an entire ground swath area of 100s to 10,000s of km^2 at the same point in time.

Temporal Resolution

Temporal resolution refers to the frequency at which the remote sensing platform revisits the same point in space. Geostationary remote sensing platforms are in high orbits (10,000s of km) that position them above the same general area and can therefore retrieve duplicate images at sub-hourly temporal resolutions. Sun-synchronous platforms are in lower (600 to 1000 km), semi-polar, orbits that typically result in temporal resolutions measured in the 10's of days after the platform has circled the entire earth. More advanced sun-synchronous platforms are sometimes designed with tilting sensors that allow the platform to retrieve duplicate coverage by using a different 'look' angle. These platforms can achieve temporal resolutions that are hourly to daily.

SECTION 2

GENERAL FINDINGS AND RECOMMENDATIONS

General findings and recommendations identified by the participants of the *EPA/NASA Workshop on Water Monitoring, Remote Sensing, and Advanced Technologies* are presented in this section. Although the workshop utilized four water resource types to organize the discussion of which NASA remote sensing instruments might assist EPA in performing monitoring needs, this section presents findings that were major and/or common across all water resource types. Table 2.1 provides a summary of the general findings and recommendations of the workshop participants. Then, several technical applications areas with potential for collaboration among EPA and NASA are discussed.

Table 2.1. Common Themes in Research Findings and Recommendations.

Decentralize NASA and EPA Accessibility
Decentralize NASA and EPA outreach and application missions to make remotely sensed data more accessible to national, regional, state and local users.
Increase Remote Sensing Education
Increase instruction in the use of remotely sensed data in order to encourage and direct the proper use of the data products.
Facilitate Technology Transfer
Facilitate data use by providing descriptions of data capabilities and limitations as well as guidelines on how to manage the large volumes of data that high spatial and temporal resolution remote sensing makes available.
Ensure Data Standardization and Consistency
Ensure that all remotely sensed data are measured dependably by creating data standards. Increase the amount of raw data that can be processed or used in environmental modeling or monitoring applications by developing data consistency standards.
Develop Pilot Projects
Develop pilot projects that demonstrate the use of new technologies. As data revenues increase additional funding should be allocated to data collection and processing.
Coordinate In-situ and Remotely Sensed Data
Coordinate remotely sensed data collection with *in situ* data collection to authenticate classification procedures and develop new empirical relationships.

Technical Applications with Potential for EPA/NASA Partnership

Workshop participants also identified science initiatives that could be implemented into existing EPA and NASA monitoring and remote sensing programs. These workshop findings are described according to their ***action type*** (institutional, application, or general), ***status*** (operational or developmental), and ***applicability*** (mainly what types of water resources it applies to).

NON-POINT SOURCE POTENTIAL FROM LAND COVER / LAND USE

At a range of spatial scales, classification levels, and spatial resolutions, land use can be identified as having the potential to be a cause or an origin of non-point source (NPS) pollution loading. The linking of land use type with pollution loading potential is frequently applied but always ready for improved technical assessment methods and wider, more consistent application. One relatively simple NPS prediction model is the Export Coefficient Model that uses areal estimates of land cover class types together with empirically derived nutrient export coefficients from those land classes to estimate total basin NPS pollution loading at annual time steps. This model can be parameterized using a single input of land cover / land use from multi-spectral sensors (MSS) in the visible and near-infrared wavelength. More recent studies have coupled continuous distributions of terrain elevation with land cover classes to rank the watershed areas with the greatest NPS loading potential. These studies used remotely sensed terrain data to compute the upslope contributing area and downslope dispersal area for each land area and then ranked the likelihood that a critical amount of runoff both entered that land parcel and traveled from the land parcel to the adjacent waterbody.

- ***Action type***: Application
- ***Status:*** Operational
- ***Applicability***: All watersheds and waterbodies

FLOODING AND WATERBODY EXTENT

One of the most operational uses of remote sensing is detection of flooding and waterbody extent. The water-land interface is critical information for determining human health and safety risks, assessing threats to water quality, and estimating the extent and volume of water resources. The detection of these interfaces is limited by sensor resolution and sensor response functions. Generally, airborne sensors are used when the timing of data retrieval is critical or high spatial resolution is required (usually over limited areas), while spaceborne sensors provide more frequent although coarser monitoring options. Appropriate sensors include MSS of visible and thermal wavelengths as well as microwave radar sensors for overcast conditions. High-resolution satellite sensors can resolve lakes and ponds greater than 1 ha in area (e.g. 30-m length scales), while coarser scale 1-km sensors can create large boundary errors in detecting waterbody boundaries.

- ***Action Type***: Application
- ***Status***: Operational
- ***Applicability:*** Streams, lakes, wetlands, watersheds, estuaries

MODELING RUNOFF, DETENTION TIME, AND FLOW

Land surface characteristics influence runoff, infiltration, detention time, and resultant in-stream flow dynamics. Runoff quantity, as a result, is a critical parameter affecting dilution of pollutants and directly linked to the risk of poor water quality conditions. Remote sensing of parameters linked to effects on runoff and flow can feed an entire family of watershed-based models that are useful in predicting water quality and quantity. Improved accuracy and availability of remotely sensed data that parameterize runoff models would be extremely useful across all spatial scales. A recent need for these spatially distributed data sets is in Total Maximum Daily Load- (TMDL) related watershed modeling. TMDL-related modeling attempts to estimate the relative contributions of all point and non-point sources of a given pollutant in the watershed, in planning for reducing their total loads to ensure that a water quality standard is met. Some watershed models may ultimately require daily time step data inputs at resolutions that capture NPS pollution loading processes. Model input data types might include land cover classes, leaf area index and associated evapotranspiration indices, impervious surface mapping, and various topographical parameters such as drainage networks, estimates of runoff contributing areas, and pollutant transport dispersal areas.

- ***Action Type***: Application
- ***Status***: Operational to Near Operational (varies)
- ***Applicability***: All types of watershed and waterbodies

INTEGRATION OF *IN SITU* AND REMOTELY SENSED MEASUREMENTS

Models need both *in situ* and remotely sensed measurements to achieve accurate parameterization and produce reliable results. The two data types, *in situ* and remotely sensed, represent mutually supporting data points that can synergistically operate to both reduce costs and increase reliability of the derived information. Models that utilize remote sensing data to test hypothesis regarding watershed processes can provide *a priori* information to guide the placement of *in situ* monitoring stations and indicate whether the data are representative. While the coupling of *in situ* and remotely sensed measurements has traditionally occurred during calibration and validation of remote sensing instruments, a continued coordination of the two activities is necessary to ensure accuracy during the entire lifetime of the equipment. Furthermore, the coordination of the two sampling techniques allows for a spatial extension or scaling of the *in situ* data across the domain of the remotely sensed data. An example of this coordinated sampling is seen in the combined use of rain gauges with radar microwave precipitation analysis, where the radar provides comprehensive spatial coverage and the rain gauges indicate measurement bias and error.

- ***Action Type***:
  - Institutional - create multi-disciplinary science working groups;
  - General: EPA works frequently at the 8-digit Hydrologic Unit Code (HUC) basin scale, but many monitoring activities span local- to national-scale issues;
  - Application: Focus on non-point source & watershed levels – local to national.
- ***Status***: Operational for some non-point and watershed levels
- ***Applicability***: All areas

AQUATIC HABITAT CLASSIFICATION AND HEALTH

EPA's watershed programs have a fundamental need for general indicators of aquatic and terrestrial habitat condition and classification. Habitat can be assumed here to mean aquatic habitats, riparian habitats, and upland habitats through the watershed. Water resources management relies upon timely and spatially representative sampling of habitat to guide management decisions. Many of the indicators currently used are limited to *in situ* monitoring, however remote sensing can provide rapid and spatially extensive estimates of land cover biomass, vegetation class, and some types of habitat change, as well as measurements of aquatic temperature, chlorophyll concentrations, and sediment load for larger bodies of water. No single indicator or index will serve to represent all aspects of aquatic ecosystem health, however a variety of indicators sampled from visible, near infrared, and thermal sensors, together with microwave radar sensors, are capable of measuring components of habitat class and health. Research that develops relations between habitat and remotely sensed parameters is in need of continued funding. Developing and utilizing habitat indicators is a high priority need for EPA's Index of Watershed Indicators (IWI) and other projects. A team from both agencies might be able to offer assistance in the development of such indicators and how to measure them from imagery and ancillary data on the 8-digit HUC watershed scale.

- ***Action Type***: Application
- ***Status***: Research to Near-Operational
- ***Applicability:*** All waterbodies and watersheds

RIPARIAN AREA CLASSIFICATION AND HEALTH

Riparian areas are the buffers joining the aquatic ecosystem with the adjacent terrestrial ecosystem, and are periodically likely to experience various stages of saturation or flooding. In many areas, riparian zones have been cleared of natural cover and replaced with crops or lawns, left as bare earth, or converted to impervious surfaces and development. Intact riparian areas that have vegetative cover may provide numerous beneficial functions for people as well as aquatic and terrestrial environments. For terrestrial ecosystems, these riparian areas mitigate the impact of overbank flooding and erosion, and for the aquatic ecosystem the buffer areas provide organic matter, shade, and 'buffering' capacity against surface and subsurface pollutants travelling from toward the stream. Remote sensing instruments that operate at high spatial resolutions are capable of detecting riparian buffer presence or absence but are unable to detect micro-topographic or vegetative features that may strongly influence the ability of the area to filter suspended pollutants. Desirable riparian zone widths are related to stream size, so spatial resolution requirements vary with stream size, from 1-m sensors zones along smaller perennial streams to 30-m resolution sensors along larger rivers. Measurements relating to riparian zone structure, integrity, and contiguity would be useful nationally or regionally, however most assessments of riparian zone structure or condition have only been done in scattered locations. A national indicator of riparian zone condition would have immense value if able to be applied on 8-digit Hydrologic Unit Code (HUC) watersheds.

- ***Action Type***: Application
- ***Status***:
  - Operational at the local scale;
  - Near-Operational at regional to national scales.
- ***Applicability***: Watersheds, lakes, rivers, streams, wetlands, estuaries

AREAL EXTENT OF IMPERVIOUS SURFACES

Urbanization traditionally replaces a significant percentage of a watershed's soil surface and vegetation with concrete, rooftops and altered drainage systems. These changes to the landscape result in a change in the speed, volume and quality of infiltration and runoff, sometimes significantly altering streamflow volume, flooding frequency, and water quality. Information on the extent of impervious cover for various parts of the watershed is extremely valuable for identifying and ranking NPS problems, modeling storm flow dynamics, siting detention basins, and developing watershed management remedies. Some indexes of impervious area have been developed for different densities of residential development and urban downtown environments. Remote sensors of visible and near infrared can distinguish between impervious non-impervious areas and thereby help managers estimate the watershed response to precipitation events. Although remote sensing instruments can assist in estimating the percentage of precipitation that does not infiltrate, the technologies are currently unable to provide estimates of the complex urban drainage networks of street drains and culverts. The use of Geographical Information Systems (GIS) is recommended to integrate *in situ* and remotely sensed measurements as input into runoff prediction models.

- ***Action Type***: Application
- ***Status***: Operational (local and regional scale) and Research
- ***Applicability***: Watershed

WATER QUALITY: CLARITY AND COLOR

In situ measurement of water quality parameters such as clarity and color are relatively straight forward and represent the water properties such as chlorophyll, total suspended solids (TSS), total organic phosphorous, specific conductance, dissolved organic carbon (DOC), selected minerals, and water pH. Remote sensing of water clarity and color is feasible with visible and near infrared sensors, but the sensor measurements must be calibrated with *in situ* measurements. Required field measurements should contain representative sampling of the range of conditions typically present within a resource and throughout a given monitoring period. For deeper waters the remote sensing instruments are limited to the upper water column due to the rapid adsorption and scattering of visible light by water. Detection of clarity and color is performed best on water bodies that that exceed the spatial resolution of the sensor by a factor of 10 (e.g. 1.25-ha per 30 m Landsat pixel). Operational instruments include MSS on aircraft (resolution 1 to 20-m) and satellites (resolution 30-m to 1-km) and non-imaging airborne laser fluorosensors. Available experimental instruments include airborne hyperspectral with experimental satellite hyperspectral instruments being available within 2 years. It is recommended that techniques are developed to use Secchi measurement for rough calibration of sensor clarity measurements.

- ***Action Type***: Institutional - requires coordination between field crews (remote and local) for overflights and calibration. Requires moderately sophisticated equipment and expert knowledge of water variables over the survey area to interpret results.
- ***Status***:
  - Operational at a regional scale for MSS - limited by available satellite overflights and cloud cover;
  - Near-Operational (3 to 5 years) for Hyperspectral applications at the local level;
  - Near-Operational for laser fluorosensor at the local level;
  - Theoretical status for combination of fluorosensor under-flights with satellite overpass to reduce field sampling required.
- ***Applicability***: Lakes, rivers and estuaries

WATER SURFACE TEMPERATURE

Currently EPA is collecting *in situ* temperature measurements via ground truth and automatic gauges in numerous streams, rivers, and lakes. Remote sensing instruments have also been used. For example, NASA, EPA (at Las Vegas, Nevada), other government agencies, and certain commercial industries have performed thermal surveys on local, regional and national scales. Helicopter, fixed wing (low and high altitude) aircraft and satellites have each been used to retrieve these thermal measurements and there exists a range of spatial resolutions for the various thermal sensors. Helicopter and low altitude aircraft provide 1 to 3-m resolution data, small jets provide 3 to 10-m resolution data, high altitude planes (e.g., the ER-2) provide 20-m resolution data, and satellites (e.g. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Landsat 5 and 7) can provide 60 to 120-m resolution data of thermal aquatic condition.

- ***Action Type***: Applications - need national standard
- ***Status***:
  - Operational locally via aircraft for 0.2° C measurements; operational regionally via satellite on larger bodies of water at 1.0° C;
  - Near-operational satellites (e.g. ASTER) will improve to 90-m resolution at 0.5° C resolution.
- ***Applicability***: Streams and rivers

TEMPORAL PROFILING OF VEGETATION GREENNESS

Vegetation biomass and leaf area indices (LAI) are useful parameters for determining some aspects of watershed health, stressors and water resource condition. Tracking the changes in vegetation along time is also critical for drawing associations between changes in water resource condition and changes in watershed condition. Combinations of visible and near infrared remote sensing measurements are used to estimate vegetation health. One popular indicator of LAI and biomass is the normalized difference vegetation index (NDVI), which is calculated from a variety of sensors, including the Landsat MSS and Advanced Very High Resolution Radiometer (AVHRR) satellite imagery. Repeated NDVI analyses, like the biweekly NDVI maps produced since 1990 by the U.S. Geological Survey (USGS), make it possible to track seasonal greenness changes and comparisons year to year. Analysis could reveal wet to dry year differences and significant land cover changes (e.g. fire, harvest, development and disease). When NDVI data sets are regularly created at national scales then it becomes possible to separate anomalous seasonal or annual fluctuations from more significant trends in the composition and vigor of watershed vegetation.

- ***Action Type***: Application
- ***Status***: Operational to Near-Operational
- ***Applicability***: Watershed

SECTION 3

BACKGROUND: EPA MONITORING NEEDS, NASA MONITORING TECHNOLOGIES

A Natural Partnership: EPA & NASA Missions

The individual EPA and NASA science missions share common themes and contain research components that may be addressed by pooling skills and resources from the two agencies. Just as EPA is mandated to work with states, tribes and others to monitor and protect the nation's water resources, NASA is mandated to develop and test environmental remote sensing instruments. The coupling of these science missions provides EPA and its partners with technologically advanced tools to monitor water resources and provides NASA with an application that tests remote sensing capabilities and provides *in situ* calibration and validation measurements.

Managing the nation's water resources requires that the EPA and the states maintain strong monitoring programs. Monitoring, with both *in situ* and remote sensing technology, provides the agency with useful data for tracking resource status and trends. Monitoring data that enable EPA and its partners to develop appropriate water resources management strategies include information that illuminates associative relationships between water resource condition and anthropogenic or natural stressors. Not only should monitoring include some information that is consistent at the national scale and includes stressor as well as response data, but there must also be data at spatial and temporal resolutions that capture the impairment processes. In summary, the nation's water resources monitoring programs especially need data with any of the attributes listed in Table 3.1.

Table 3.1. Particularly Useful Attributes for Remotely Sensed Water Resources Monitoring Data.

National spatial coverage
High spatial resolution
Short temporal resolution
Representative of ecosystem condition, stressors and responses

EPA's WATER MONITORING MISSION TUTORIAL

Prior to attending the December, 1996 *EPA/NASA Workshop on Water Monitoring, Remote Sensing, and Advanced Technologies*, participants were sent the paper, ***Needed Improvements in Aquatic Ecosystem Monitoring Methods: A Discussion Paper for the EPA/NASA Workshop on Water Monitoring and Advanced Technologies***. This white paper presented an outline of the nation's efforts to monitor water resources puirsuant to the federal Clean Water Act and then identified the shortcomings in monitoring technologies that limit monitoring capabilities. At the EPA/NASA Workshop, Elizabeth Fellows and Douglas Norton of the EPA Office of Water provided a Water Monitoring Mission Tutorial that summarized the White Paper contents in two short presentations (see **Appendix A** for the Workshop Agenda). Rather than summarize the EPA Tutorial, a full and updated copy of the White Paper is provided in the pages below.

1999 Editor's Note: *The following document was written and circulated to all participants during November 1996 in advance of the workshop. It served as a problem statement describing the challenges faced in water resources monitoring programs by EPA and its partners from state, tribal and local water programs. This paper set the scene for the workshop and enabled NASA and its research community to prepare for the dialogue on using advanced technologies to help meet these water resources monitoring and management needs. Minor changes have been made to reflect program name changes and revised national statistics.*

Needed Improvements in Aquatic Ecosystem Monitoring Methods: A Discussion Paper for the EPA/NASA Workshop on Water Monitoring and Advanced Technologies, December 11-12, 1996, Washington, DC.

Douglas J. Norton

USEPA Office of Water

Monitoring the condition of our environment is essential to its proper stewardship and management. States and other jurisdictions have water resources monitoring programs, but most of these are unable to monitor all of their watersheds, water bodies, and point- and non-point pollution sources. In reality, the majority of U.S. water bodies are not monitored regularly and even more are not monitored as well as resource managers would like. This is both a financial and technical problem, as many monitoring methods are not suitably cost-effective or efficient for characterizing water resources condition in a meaningful time frame across all water bodies of interest.

The rapid advancement of new technologies such as remote sensing may some day provide methods for monitoring more water quality parameters, in more water bodies, with improved accuracy, or with reduced per-unit costs. To actively improve the status of monitoring science, however, monitoring professionals must learn about emerging technologies or those available now, and researchers who develop these technologies must learn the needs of their clientele. In order to focus and accelerate research and applications of advanced technologies in monitoring, the U. S. Environmental Protection Agency (EPA) and the National Aeronautics and Space Administration (NASA) are convening a workshop to discuss and match monitoring needs with the appropriate advanced technologies.

This paper provides summary background information for workshop participants about water monitoring responsibilities and information needs, in order to help NASA participants understand where and how their technologies may be useful. The paper covers relevant water law and monitoring programs, their unique challenges and common water quality problems, and some of the types of solutions that advanced technologies may offer. Also provided are summarized monitoring needs and recommendations.

Determining Monitoring Programs' Needs

In developing this paper, we contacted several EPA regional and state monitoring program staff and managers to gain insight into some of the specific problems they encounter with monitoring, and the ways they'd like to be helped with these problems. Their insights have provided the structure and the substance of this paper, and are the basis for our conclusions and recommendations for the workshop.

Each monitoring professional was asked the following four questions:

1. what are the most prominent water quality problems in your area and in what kind of water bodies are they occurring?

2. which of these are not well monitored and why?

3. if you could reinvent water monitoring what would you ideally like to be able to measure?

4. what are your ideas of "condition" in watersheds and water bodies?

This effort achieved reasonably good national coverage. Monitoring staff from 9 of 10 EPA regions responded, as did personnel from two states and two other federal agencies.

The Clean Water Act and Monitoring: an Overview

The EPA has a dual mission that includes the protection of both the environment and of human health and welfare. The Clean Water Act, which is the primary federal statute related to the protection of aquatic resources, is one of EPA's main statutory authorities. The stated goal of the Act is, "to restore and maintain the chemical, physical and biological integrity of the Nation's waters." The ultimate intent of the law is to attain and maintain a level of aquatic ecosystem integrity that will sustain human uses and ecosystem functions. Over the years, the Clean Water Act has evolved from its narrow origins in water pollution control and end-of-the-pipe discharge limits to a watershed-oriented statute that supports holistic environmental management within watershed boundaries.

Under the Clean Water Act, EPA administers several different programs dedicated to maintaining and improving the Nation's waters. The Act is predominantly state-implemented under federal oversight, with most of the Act's programs and activities carried out in concert with states, American Indian tribes, other federal agencies, local governments, private organizations and citizens. The Clean Water Act therefore is not only among the federal government's most powerful statutory tools for protecting aquatic systems, but also provides structure for forming multiple governmental and private partnerships to pursue Clean Water Act goals. One part of this cooperative structure pertains to water monitoring programs and the use of monitoring data to generate national reports on water quality.

Section 305(b) of the Clean Water Act requires that states and other jurisdictions submit water quality assessment reports every 2 years. The ***National Water Quality Inventory Report to Congress***, often also called the 305(b) Report, characterizes water quality, describes widespread water quality problems of national significance, and describes various programs implemented to restore and protect U.S. waters. The 305(b) Report summarizes the monitoring information submitted by states, territories, tribes and other jurisdictions, and as such it reflects their water quality issues and concerns, not just those of EPA. The states and others survey their waters by determining if their waters attain the water quality standards they established. Water quality standards consist of beneficial uses, numeric and narrative criteria for supporting each use, and an antidegradation provision. Their reporting summarizes monitoring results in terms of relative levels of beneficial use support; readers are referred to ***The Quality of Our Nation's Water: 1996*** (USEPA 1998) for a more detailed discussion of the 305(b) program and summary monitoring results aggregated by jurisdiction and by water body type.

The Clean Water Act allows states and others to set their own standards but requires that all beneficial uses and their criteria comply with the goals of the Act. At a minimum, beneficial uses must provide for "the protection and propagation of fish, shellfish and wildlife" and provide for "recreation in and on the water" (i.e., the fishable and swimmable goals of the Act), where attainable. The Act prohibits designating waste transport or waste assimilation as a beneficial use, as some states did prior to 1972.

The most common form of monitoring in support of the Clean Water Act is water quality monitoring, defined by the Interagency Task Force on Monitoring as "an integrated activity for evaluating the physical, chemical, and biological characteristics of water in relation to human health, ecological conditions, and designated water uses." It consists of data collection and sample analysis performed using accepted protocols and quality control procedures, and also includes subsequent analysis of the body of data to support decision making. A variety of jurisdictions, industries and private groups monitor a combination of chemical, physical and biological parameters throughout the country:

- **Chemical data** measure concentrations of pollutants and other chemical conditions that influence aquatic life, such as pH or dissolved oxygen. Chemical parameters may be analyzed in water samples, fish tissue samples, or sediment samples.

- **Physical data** include measurements of temperature, turbidity, and solids in the water column.

- **Biological data** measure the health of aquatic communities, and include counts of aquatic species that indicate healthy conditions.

- **Habitat and other ancillary data** help interpret the above monitoring data.

Monitoring agencies and groups vary the parameters, sampling frequency, and sampling site selection to meet program objectives and funding constraints. Sampling may occur at regular or irregular intervals or in one-time surveys. It is important to note that states and other jurisdictions do not use identical methods because they favor flexibility to accommodate variability among their waters, and therefore data are of limited consistency or comparability.

Data gathered during 1994 and 1995 were compiled to generate the 1996 305(b) report. Summary figures are presented in Table 3.2 below.

Table 3.2: Relative Proportions of Surveyed Waterbodies Meeting Designated Uses, 1996 (from USEPA, 1998)

Water Body Type	Total Surveyed (%)	Good – Fully Supporting (%)	Good but Threatened (%)	Impaired for One or More Use (%)	Not Attainable (%)	Type of Impairments
Rivers/ Streams	19%	56%	8%	36%	<1%	siltation, nutrients, bacteria, metals, O2 depletion, pesticides, habitat alteration, susp. solids, metals
Lakes, Ponds, Reservoirs	40%	51%	10%	39%	<1%	nutrients, metals, siltation, O_2 depletion, noxious aquatic plants, susp. solids, toxics
Estuaries	72%	58%	4%	38%	<1%	nutrients, bacteria, toxics, O_2 depletion, oil & grease, salinity, habitat alteration
Ground - water (40 states reporting, limited data)	X	X	X	X	X	nitrates, metals, volatile and semivolatile organic compounds
Wetlands (9 states reporting, limited data)	X	X	X	X	X	sediment/siltation, nutrients, filling and draining, pesticides, flow alteration, habitat alteration, salinity/TSS/chlorides, metals

How and Why Monitoring Falls Short

Well over half of US water bodies are not monitored and assessed in each biennial 305(b) report, and many of the waters that are reported on have less monitoring data (not enough relevant parameters, too few locations, too infrequent measurements, or inferior measurement methods) than desirable to be indicative of ecosystem condition and ambient water quality. The universal reason for this is that the cost and effort to monitor all waters with conventional methods far exceeds state and local resources to do so even with federal assistance. Below are some common shortcomings of water monitoring and the type of technological solutions that may help to address each problem (see also Table 3.3):

- **Too infrequent measurements.** Some water quality parameters change yearly, seasonally, daily or even hourly. Elevated temperatures, for example, occur and do their damage in very brief and irregularly occurring episodes. Infrequent monitoring can miss episodic impairments or misinterpret direction of water quality trends. *Possible solutions:* Continuous recorders may capture the episodic impairments; remote transponders may be used to signal onset of a condition needing onsite measurements.
- **Sampling limitations.** Some water quality parameters vary spatially over fairly short distances. Variability with depth, or with channel morphology (e.g., riffles, glides, pools, rapids, eddies) can produce different results in, for example, contaminated sediments. Limited budgets also often result in very few samples representing tens or hundreds of river miles. The magnitude of problems may be over- or under-estimated, or missed entirely. Other sampling problems are also common. Sample locations are often not documented accurately, and samples may not be timed appropriately to allow adequate evaluation of possible confounding factors. *Possible solutions:* greater sample size or the use of methods that enable synoptic coverage of a water body; more attention to sampling design; a strong locational data policy requiring GPS use.
- **Too few parameters measured.** Land uses in the watershed often prompt monitoring programs to test specific water bodies for specific pollutants or impairments, but there may be other, more subtle problems. Yet blind monitoring for every possible concern is not feasible. *Possible solutions:* As direct measurement of every possible stressor is improbable, the likely solution is to monitor broadly by using well-chosen indicators associated with groups of water quality problems, then looking closer on fewer, specific locations of concern.
- **Data and measurement quality limitations.** Limited accuracy or precision of some monitoring methods and data stands as an obstacle to broader use and limits the significance of monitoring results. Also, data are often not collected in or translated into electronic formats that can be easily loaded into fully relational databases and GIS software. Data are thrown away by agencies because "no longer needed", rather than given to a central data repository. *Possible*

solutions: Methods refinement may improve existing monitoring tools that had been marginally useful; improved information management and coordination among programs could reduce waste of older data.

- **Absence of any monitoring.** 83 percent of the total number of perennial rivers and streams, for example, were not monitored at all in the 2-year 1994 reporting period. Assuming consistent progress, and given this 2-year reporting cycle and approximately 1/6 of the resource monitored per cycle, complete coverage would take 12 years, change detection 24 years, and the earliest 3-point trend detection 36 years. This is too long to provide meaningful data for management action based on monitoring insights. *Possible solutions:* changing the 2-year reporting cycle for 305(b) to a 5-year cycle, might allow for comprehensive coverage of state waters over a five-year period. This change, coupled with changes in monitoring design and the possible uses of synoptic-coverage technologies such as remote sensing, should bring improvements. To improve cost-per-unit-area, monitoring programs could employ large-area analysis methods for initial screening, coordinated data sharing, and better probability-based sampling designs to stretch the monitoring dollar.

- **Insufficient analysis of probable causes of impairment.** A given water body may have nutrient problems revealed by monitoring, but no knowledge of the probable cause of the problem. This is a common concern relative to the more complex nonpoint source pollution problems. *Possible solutions:* Accumulate evidence of and quantify the dose/response relationships evident between stressors in the watershed and impairments in the water body. Develop new models that simulate these relationships and strengthen existing model assumptions with better data.

- **Insufficient translation into management guidance.** Also stemming from the lack of understanding of probable causes is the inability to step beyond monitoring to selecting and implementing control measures. *Possible solutions:* As above, managers need to draw from a science base of dose/response relationships between stressors and effects and understanding of thresholds at which impacts occur, in order to focus management actions on the problem at hand. Models, ranging in scope from specific dose/response relationships to whole watershed processes, may help to evaluate the effects of different options for action.

- **Delays in data availability.** The length of time required to analyze monitoring data is a problem in the case of some common impairments. For example, bacterial testing requires an incubation period that in effect allows swimmers continued exposure to pathogens and possible harm while the results of testing are awaited. *Possible solutions:* Increasingly, real-time or near-real-time results are desired. Telemetry provides one option for accessing data that are measured by in situ sensors and communicated to a manager's computer system remotely via communications satellite, cellular phone, or even telephone lines. In addition, however, more and better in situ or remote sensors are needed to measure more water quality parameters.

Table 3.3: Monitoring Shortcomings, Monitoring Needs, and Technologies that may Improve Monitoring.

Water Resource Monitoring Shortcomings:
Too infrequent measurements, sampling limitations, too few parameters measured, data and measurement quality limitations, absence of any monitoring, insufficient analysis of probable causes of impairment, insufficient translation into management guidance, delays in data availability.
Water Resource Monitoring Needs:
Improved temporal coverage, improved spatial coverage, improved accuracy of measurements, real-time results, less expensive monitoring techniques.
Technologies that May Improve Monitoring:
Improved in-stream/in situ sensors, remote sensing of environment, satellite telemetry from in situ sensors in water bodies, cellular phone technology from sensors in water bodies, telephone line hookups to sensors in water bodies, improved modeling used in conjunction with the above, improved use of indirect (e.g., indicator) vs. direct measurement, improved laboratory analyses, better computer software for data management, central data repositories serving local, state and federal programs, increased use of laptops in the field, improved spatial location data (GPS), increased training of staff in new monitoring techniques.

New Directions in EPA Water Monitoring

In order to draw conclusions about environmental conditions, water monitoring programs have long been oriented toward measuring single, or sets of closely related water quality parameters, such as pH, dissolved oxygen, temperature, or concentration of a given pollutant, at selected locations. These types of measurements will continue to be essential to water monitoring. In addition to these, however, there is increasing attention to the concept of the watershed's or water body's overall condition. Approaches to measuring condition, although still not fully accepted into practice, would provide the benefits of a big-picture complement to the more narrow and parameter-specific measurements of traditional monitoring programs.

To begin addressing watershed condition, EPA published a national water indicators report (USEPA 1996) and characterized the nation's watersheds using many of the key indicators (USEPA 1997).

In June 1996, EPA and its cooperators published the report, ***Environmental Indicators of Water Quality in the United States***. The report's 18 indicators focus on the condition of the environment and the stressors that impact water resources. EPA intended to use indicators as the basis of how it measures improvements in water quality throughout the country. The indicators will be used to measure progress toward national goals of clean water and safe drinking water, and the objectives of human and ecosystem health, meeting the designated uses that states set for their waters in their water quality standards, preserving and improving ambient conditions, and reducing or preventing pollution loadings and other stressors. They do not measure the administrative actions taken in response to environmental problems; this is left up to the management strategies of the involved organizations.

These indicators were refined and published with a geographic basis in a document entitled the ***Index of Watershed Indicators*** in November, 1997. The EPA Office of Water's Index of Watershed Indicators used indicators to analyze watersheds throughout the nation based on the 2,150 eight digit Hydrologic Unit Codes (http://water.usgs.gov/GIS/huc.html), which average approximately 1,700 square miles in area, to initially characterize condition and vulnerability. The IWI is now entirely based on the World Wide Web, and has been updated four times since initial publication. The URL is **http://www.epa.gov/IWI/.**

A summary of the IWI indicators appears in Table 3.4. The data quality of all of the indicators is considered variable, but the quality of the data used has been well documented. These are categorized into indicators of condition and indicators of vulnerability. A new category of indicators, those showing program responses (e.g., the type of program and support funding) will be added. Efforts to improve nationally consistent data sources for key indicators are underway. The category of indicators describing program responses will be added to the IWI in future updates.

Table 3.4: Summary of indicators used in the Index of Watershed Indicators (IWI).

Index of Watershed Indicators (IWI) Condition Indicators
1). Designated Use Attainment - The percent of assessed water bodies meeting or not meeting the designated uses set by States and Tribes in their water quality standards, and number or percent of unassessed water bodies.
2). Fish Consumption Advisories - Waters that are subject to State-issued fish consumption advisories. Advisories issued by States include restricted consumption (generally restrictions on the number of meals over a period of time or the fish weight consumed over a period of time) and no consumption of fish.
3). Drinking Water Quality Impacts – Populations served by CWS that are in violation of national health-based drinking water standards for contaminants that are source-related (i.e. inorganic

chemicals, volatile organic chemical, synthetic organics, and radio-nuclides), have treatment in place beyond conventional treatment to address source water quality problems, or use surface water sources that are unfiltered and are in violation of the SWTR.

4). Monitored Water Quality - Toxic Pollutants – Ambient water quality data from STORET showing percent violations over a 6 year period of the following contaminants compared with reference levels: cadmium (1.1 ug/l), copper (12 ug/l), lead (3.2 ug/l) and mercury (0.12 ug/l).

5). Monitored Water Quality - Conventional Pollutants - Ambient water quality data from STORET showing percent violations over a 6 year period of the following contaminants compared with national criteria levels: ammonia (0.89 mg/l), BOD (7 mg/l), nitrogen (10 mg/l), phosphorous (0.1 mg/l), and suspended sediment (500 mg/l) (called "residue" in STORET).

6). Wetlands Loss - Wetland loss rates from 1982 to 1992 for individual states; State rate assigned to cataloguing units (derived from 6-digit accounting unit level).

7). Contaminated Sediment - Data from sediment sampling sites that indicate a high probability (or potential for risk) to human health and the environment, including some sites with supporting fish tissue residue values added. Where sediment contamination problems were identified, the station is identified as Tier 1; where more serious problems were identified, the station is classified as Tier 2.

Index of Watershed Indicators (IWI): Vulnerability Indicators

1). Aquatic Species at Risk - Watershed with high occurrences of species at risk, presented either compared to occurrences within the entire state or within the nation as a whole.

2). Discharge Loads Above Permitted Discharge Limits - Toxic Pollutants - Loading over the discharge limits set in each individual NPDES permit for the group of toxic pollutants (e.g., mercury, lead, cadmium, and copper) contained in permit limits. Loads for the contaminants will be combined.

3). Discharge Loads Above Permitted Discharge Limits – Conventional Pollutants - Loading over the discharge limits set in each individual NPDES permit for the group of conventional pollutants (e.g., ammonia, BOD, nitrogen, phosphorous, and suspended solids) contained in permit limits. Loads for the contaminants will be combined into one total.

4). Non-point Source Impact Potential – Urban Impervious Surfaces - Percent of imperviousness using established relationships between imperviousness and housing density. Housing density was aggregated to the block group and assigned to cataloging units. Information is collected on a probabilistic basis.

5). Non-point Source Impact Potential – Agriculture – This indicator provides a perspective on the threat to the condition of the aquatic system from non-point source pollution from agricultural activities. The NPS Impact Composite consists of: 1) nitrogen leaching index; 2) sediment delivery to streams; and 3) a pesticide leaching index.

6). Population Change - Population growth rate in each watershed. This indicator assigns scores based on whether population has remained stable or decreased, increased from 0-5%, or increased more than 5%.

7). Hydromodification - Stream miles impounded by dams and other man-made structures.

8). Estuarine Pollution Susceptibility - This indicator uses assessments by NOAA of an estuary's susceptibility to pollution as defined by its relative ability to concentrate dissolved and particulate pollutants. An index based on physical, land use, nutrient sources, and nutrient loading data for all estuaries of the contiguous United States.

Discussion and Recommendations for Improving Water Resources Monitoring through Use of Advanced Technologies

Monitoring provides valuable information for environmental stewardship, but as an applied tool of environmental stewardship it does not yet live up to its potential. In a time of such rapid technological advancement, we may soon have greater expectations of technology and of monitoring. Our dialogue with regional and state monitoring personnel, as well as a number of other current activities that have investigated ways to improve monitoring, point to many good suggestions to guide future action:

- Cost-effectiveness, or more simply cost, usually drives monitoring programs' choices of measurement techniques. If a method is too expensive, it will not be widely used. Funds for monitoring programs are not likely to change even with availability of improved methods if those methods are costly. On the other hand, improved speed, low maintenance or large area of coverage can improve the per-unit cost.

- Monitoring programs may achieve better coverage in the future if they focus on measuring fewer, more meaningful parameters rather than striving to measure every possible parameter of concern. Long and short term measurement strategies deserve consideration; long term measurements should cover fewer, more consistently applied and carefully targeted parameters. Short term measurements may differ over time, as problems and the state of knowledge change. Choices are of paramount importance to depict water body condition and the influence of multiple stressors.

- A broad variety of advanced monitoring technologies should be explored to improve water resources monitoring. This should include not only the full array of remote sensing technologies available from aircraft or satellite platforms, but also telemetry using communications satellites, cellular phone technology, and conventional phone lines. Furthermore, additional methods for real-time in situ identification, quantification, and temporal and spatial profiling of individual chemicals in the water column should be explored.

- Advances in modeling in conjunction with these technologies should also be emphasized and fostered using real-life problems in impaired water bodies; there are so many impaired water bodies available for advanced study that it is difficult to fathom not using more of these sites for applied research or graduate training. The most effective basis for such studies would need to include simultaneous characterization of stressors, exposure pathways, receptors, and effects.

• Matching technologies to monitoring information needs should not be confined to efforts to use these technologies to measure specific pollutants. Measurements of ecological responses in the water body, status and changes in the stressors themselves, and a wide variety of physical, chemical or biological indicators can also be closely related to environmental health and public welfare. A growing emphasis on finding measures of watershed and aquatic ecosystem condition and function, not just conventional measures of common pollutants, is reflected in many monitoring programs. In addition, cross-media pathways such as airborne sources of water pollutants remain important.

• Chemical and physical measurements continue to be of concern, particularly as related to point source discharges. A growing interest in biological measures of watershed and water body condition is now emerging among water resources managers, and this includes aquatic and shore lands habitat. Successful development of indicators in these areas would need to be supported by a strong scientific basis for the selection and interpretation of these indicators as well as by accurate and precise measurement techniques.

• National-scale indicators, despite their desirability as rapid, easy to measure and widely applicable measurement endpoints, are not magic bullets. Specific and quantitative physical, biological, and chemical metrics will continue to play a crucial role in evaluating water and watershed condition for the indefinite future. As such, water monitoring will continue to need the very specific as well as the very general environmental measurements.

References

USEPA. 1996. Environmental Indicators of Water Quality in the United States. EPA841-R-96-002.Office of Water (4503F), USEPA, Washington, DC. 25 pp.

USEPA. 1997. Index of Watershed Indicators. EPA841-R-97-010. Office of Water (4503F), USEPA, Washington, DC. 56 pp.

USEPA. 1998. The Quality of Our Nation's Water: 1996. Executive Summary of the National Water Quality Inventory: 1996 Report to Congress. EPA841-R-97-008. Office of Water (4503F), USEPA, Washington, DC. 521 pp.

Notice

This paper has not been peer or administratively reviewed by the U. S. Environmental Protection Agency and should not be construed to represent EPA policy. Use of trade names does not constitute endorsement for use.

NASA's REMOTE SENSING MISSION TUTORIAL

EPA/NASA Workshop participants were not provided with an equally detailed "White Paper" on the NASA earth resource science mission. Instead, it was understood that the NASA earth resource science mission included components that supported the EPA water resource monitoring needs. NASA's Ghassem Asrar provided workshop participants a brief sketch of this overlap, in the form of a Remote Sensing Tutorial.

NASA's Tutorial presentation followed upon the EPA Tutorial. NASA's science mission includes, among other things, the development and testing of advanced technologies and remote sensing devices for the advancement of earth and environmental science.

1999 Editor's Note: *At the time of the conference NASA had named its earth science mission, "Mission to Planet Earth". The mission has been renamed is now entitled, "Earth Science Enterprise" (ESE). A summary of the goals and objectives of the NASA's ESE Mission is provided in this summary of Ghassem Asrar's Tutorial.*

Tutorial Presentation

Mission to Planet Earth: Enabling Earth System Science Research and Education in the 21st Century, December 11, 1996, Washington, DC.

Ghassem Asrar

NASA EOS

During the 1980's ambitious plans were laid out for the beginning of a new era in earth studies. Presidential Initiatives in the 1990's created the U.S. Global Change Research Program, including as its largest component, Earth Science Enterprise (ESE), led by the National Aeronautics and Space Administration (NASA). NASA's Earth Science Enterprise efforts are aimed at improving our understanding of the earth as a system, and our ability to assess and predict the environmental, social and economic impacts of natural and human-influenced processes. The overall goal is to establish the scientific basis for national and international policy-making in response to changes in the earth system.

Over the last several decades, an increasing pace of scientific advancement in earth studies has coincided with increasing public awareness of the global and regional aspects of environmental issues. Changes in the earth's climate over time have been documented by evidence from such sources as tree rings, gases trapped in the polar ice caps, glacial landforms, and stratification in ocean sediments and in rocks. Today, scientists' track processes of global change, and possibly climate change, in real time.

The Earth Science Enterprise is primarily focused on obtaining global observations from spaceborne instruments and to model the earth as a system. As such, attention has not traditionally focused on the monitoring of water and watershed properties at the scales used by EPA to assess water resource health. Instead, NASA's integrated, comprehensive, and sustained Earth Science Enterprise program has documented the earth system on a global scale that supports focused and exploratory studies of the physical, chemical, biological, and social processes that influence the earth system. Despite these apparent discrepancies in spatial scale, the science and technology develop by NASA's ESE can assist and contribute to EPA's hydrological science initiatives and water resource monitoring programs.

NASA recognizes that improvements over current capabilities in the range, detail, and frequency of remote sensing observations are also needed to develop and test integrated, conceptual and predictive models of the earth. It is the opportunity to work with EPA in the monitoring and modeling of water resource health that addresses these needed research initiatives.

NASA has defined three major tasks for success in the Earth Science Enterprise, and they correspond to improving observations, data and information systems, and science.

1) Developing integrated observational systems based from spacecraft, aircraft, unpiloted airborne vehicles, and on the ground and at sea.

2) Building a comprehensive data and information system to make data useful and readily available.

3) Training the next generation of scientists and supporting them to analyze the data collected, to build models of the earth system, and to provide interpretations that will improve our understanding and predictive capabilities.

The scientific knowledge gained from this initiative will enable an assessment of the impacts of climate variations on agricultural, industrial and societal activities at the global, continental, regional and local levels in 21st Century.

Phase I of the Earth Science Enterprise is well underway, with each of the three above tasks integrated within a series of flight missions. Phase II began in 1997 with the coordination of these tasks within the Earth Observing System (EOS) Program. In addition, Phase II of the Earth Science Enterprise will continue to support smaller, unique observation projects and focused scientific investigations that require specific platforms or time lines that cannot be achieved by the EOS or by other national and international programs. Phase III will begin in 2000 and will benefit from scientific knowledge gained and technological advancements achieved during Phases I and II.

Earth Science Enterprise Components

NASA's Earth Science Enterprise's (ESE) technical science component is primarily part of the Earth Observing System (EOS) mission, which is primarily administered through NASA's Headquarters, Goddard Space Flight Center, Jet Propulsion Laboratory, and Stennis Space Center. Table 3.5 highlights four major components of the ESE.

NASA continually updates information on the status of each of the ESE and EOS projects. Interested readers are encouraged to visit the NASA ESE World Wide Web site at http://www.earth.nasa.gov to obtain current and additional data or information on any of the ESE program components.

Table 3.5: Four Key NASA Earth Science Enterprise Missions.

Earth Observing System – Atmospheric Physics and Land Surface Processes
Goddard Space Flight Center coordinated long term observations of climate, terrestrial and marine ecosystems to understand earth as a unified system. Stennis Space Center is also coordinating an Earth System Science initiative to study coastal ecosystems.
Earth Observing System – Physical Oceanography
Jet Propulsion Laboratory coordinated long term observations of ocean ecosystems to understand earth as a unified system.
Earth Probes
Jet Propulsion Laboratory and Goddard Space Flight Center coordinated, specific, highly focused missions in earth science research to complement EOS.
Commercial Remote Sensing
Stennis Space Center coordinated outreach to commercial industry to ensure U.S. companies maintain their technological and business leadership.

SECTION 4

WORKSHOP FINDINGS

Workshop findings are presented within this section according to breakout session type. Four water resource categories were used to organize the breakout sessions into groups that focused on unique monitoring needs and challenges. These four resource groups were:

- Watersheds, Rivers and Lakes
- Wetlands
- Groundwater
- Estuaries and Oceans

For each breakout session the findings were organized into areas of: ***Needs and Applicable Technologies, Gaps in Current Technologies, and Emerging Technologies*** to address components of current and future monitoring missions.

Breakout Sessions

Breakout sessions were organized so that EPA and NASA personnel could exchange insights with each other on EPA monitoring needs and appropriate NASA and other advanced technologies. Prior to entering into the breakout sessions all participants had been updated on the general needs of EPA water resource monitoring. EPA personnel in each breakout session were then able to focus on monitoring needs specific to their water resource type. NASA personnel were able to generate a list of satellite, aircraft and stationary remote sensing devices, along with a description of their characteristics and limitations. NASA personnel were also able to clarify the capabilities of remote sensing systems, as well as their operational status, data availability, and the nature of remote sensing computer analysis algorithms. Ideas for specific monitoring application / instrument pairings appeared during the discussion.

The breakout sessions concentrated in identifying the remote sensing needs of the EPA that could be addressed by current and emerging NASA technologies. The discussions centered on which technologies NASA had developed that currently matched EPA needs. Dialogue was also held on what gaps existed between current technologies and EPA needs. Finally, a dialog was held to define possible joint efforts between the EPA and NASA that could be undertaken to further advance technology and address the data needs of the EPA and its partners in water resources monitoring.

WATERSHEDS, RIVERS AND LAKES

Introduction to Watersheds, Rivers and Lakes Monitoring

The Environmental Protection Agency's monitoring activities in rivers and lakes are mandated under the CWA and implemented primarily through delegation to states and tribes, who submit monitoring reports to EPA biennially for the National Water Quality Inventory Report to Congress (often called "the 305b report"). State reporting indicates that there is more monitoring of lakes and rivers than of any other water body type. However, less than 20% of all rivers are assessed in a typical 2-year monitoring period. Within lakes, rivers and their watersheds, non-point source (NPS) pollution is the major challenge because the formerly greater point source pollution problems are now mostly under more effective controls. The importance of NPS pollution is closely linked to activities in the watershed in a vast number of cases, and thus watershed monitoring is an essential part of the need for understanding and managing the sources of lake and river degradation. The most commonly reported impairments of lakes and streams are caused by (in order from the most frequent): sediments, pathogens, nutrients, metals, dissolved oxygen depletion, habitat or flow alteration, pH, elevated water temperature, pesticides, mercury, inorganics, ammonia, toxic organics, and chlorine.

In most monitoring areas remote sensing technology cannot make a direct, quantitative measurement of the chosen water quality parameter (e.g., suspended sediment concentration in mg L^{-1} or ppm, the concentration of nitrate nitrogen in mg L^{-1}, etc.). Scientists with only remote measurements have instead had to rely upon empirical relationships between surrogate indicators and the parameters of interest to monitor these water bodies. Some of these methods have been relatively successful as long as field calibration and measurement limits are observed. Thermal pollution is an exception, however, because the thermal sensors in satellite and airborne platforms can directly measure the temperature of the water resource at the surface. In contrast, remote sensing of watershed characteristics associated with stress on water bodies has been more limited. Success in this area has been limited to activities such as land use/land cover analysis along with specific measurements of human activity (such as amount of impervious surface, or linear measurement of denuded vs. intact riparian woodlands). Monitoring watershed changes is therefore a very broad applications area of proven potential.

Breakout Session Findings

The purpose of the watersheds, lakes, and rivers Breakout Session was to: 1) identify matches between current technology and watershed, lakes, and rivers management and monitoring requirements, 2) examine EPA needs that could be satisfied using NASA technology, 3) identify gaps between EPA's needs and NASA's current technology, 4) examine ways to solve EPA's needs with existing or planned future technology provided by NASA, and 5) identify a joint effort project which could be used to advance the means by which EPA handles wetland management issues. The final goal of the Breakout Session was to report these findings and make recommendations. Because watersheds are the geographical unit defining the boundary of all water resources, the workshop organizers recognized that the findings of this Breakout Session were potentially applicable to the three other resource Breakout Session groups (wetlands, groundwater and estuaries/oceans). Therefore, the watershed findings listed in this session should be considered relevant to all the Breakout Sessions that follow.

PRECIPITATION ANALYSIS

Needs and Applicable Technologies

By measuring precipitation water resource managers are able to predict the inputs or loading to such resources as rivers, lakes, wetlands, groundwater, estuaries, and oceans. Precipitation data not only provides an estimate of resource inputs and therefore information on possible droughts and floods, but precipitation data also enables calculations of residence times and water quality. Given the importance of precipitation data and the limitations of rain gauges for measuring spatially distributed rainfall, scientists are utilizing remote sensing to quantify precipitation input across large areas.

Satellites using visible, near-infrared, and thermal sensors are capable of estimating the spatial extent and movement of potentially rain-producing clouds, but the precipitation below the clouds goes undetected by the above electromagnetic bands. Useful cloud data are obtained from the polar orbiting NOAA (National Oceanic and Atmospheric Association) satellites and the geostationary GOES (Geostationary Operational Environmental Satellites) satellites. Visible, near-infrared, and thermal sensors are capable of indexing clouds based on cloud type and tracking the life history of various clouds by using a combination of visible and thermal sensor types across daylight and darkness periods. GOES Infrared images are useful for predicting heavy precipitation and flashfloods at temporal resolutions between 5 and 60 min and at spatial resolutions of 4 km.

Ground based radar remote sensing using microwave sensors does penetrate through clouds and allow for accurate estimates of precipitation intensities and volumes across large areas. The Weather Service operates more than 120 NEXRAD (Next Generation Radar) WSR-88D (Weather Surveillance Radar – Doppler) stations capable of retrieving measurements in 1 to 4-km spatial resolutions at 5 to 60-minute intervals within a region with a radius of approximately 225-km. These measurements are based on principles of microwave scattering and attenuation of the WSR-88D signal by raindrops, hail, snow, and other 'hydro-meteors'.

Gaps in Current Technologies

Earth orbiting satellites operating in the visible bands are incapable of penetrating the cloud tops and imaging the actual precipitation. Ground based microwave radar is incapable of imaging low-level precipitation without increasing the probability of radar striking the ground and generating 'anomalous' propagation signals. By not directly measuring low-level scattering the WSR-88D often underestimates total precipitation.

Current technologies are not capable of measuring dry and wet deposition of nutrients and other chemical constituents that impact water quality. The problem of acid rain is an example of where a measurement of rainfall quantity is not adequate for an understanding of water resource condition. Sensors are needed that can distinguish atmospheric and precipitation concentrations of common aggravating pollutants.

Emerging Technologies

TRMM (Tropical Rainfall Measuring Mission) is part of the EOS program and is a joint U.S. – Japanese satellite operated by NASA and launched in November of 1997 with a nominal lifetime of 3-years. TRMM objectives are to measure precipitation and evaporation in tropical areas, which extend into the southern part of the U.S. (Texas, Florida, etc.). The TRMM Microwave Imager (TMI) instrument has a horizontal spatial resolution ranging from 4.4 to 45-km and is capable of retrieving precipitation measurements at 1-km vertical increments within the entire troposphere, including the low-level areas missed by WSR-88D.

SNOW COVER AND PACK DEPTH

Needs and Applicable Technologies

Snowfall during a precipitation event does not directly recharge water resources such as rivers, lakes, wetlands, groundwater, estuaries, and oceans. Instead, snowfall often accumulates to a certain pack depth during the snow season and then during the snowmelt, it ultimately recharges water resources. Nearly all regions of the electromagnetic spectrum provide useful information about snowpack, but no single area provides highly accurate information on snowpack areal extent, its water equivalent, and its physical condition. By estimating the extent, depth, and snow water equivalent or density of snow, predictions can be made of the volume of water held within a watershed's snowpack.

Low-elevation aircraft carrying gamma-radiation detectors can measure the natural gamma radiation from the soil, and this is empirically related to an average snow water equivalent. The NOAA operational gamma-radiation program covers more than 1400 flight lines annually in the U.S. and Canada. Snow surface albedo, which is used to map extent, can be identified using satellite visible and thermal bands from instruments such as Landsat ETM.

Gaps in Current Technologies

Although depth, extent, and snow water equivalent can be roughly estimated with multi-frequency passive microwave sensors, most critical snowmelt areas still use *in situ* measurements to calibrate and validate remotely sensed estimates of depth and density.

A major gap in the current technology is the inability of sensors to measure snowpack chemistry, particularly nitrate concentrations. During the spring thaw when the snow is finally converted to liquid water the accumulated nitrogen is released to recharges the rivers, lakes, and other resources. More sophisticated sensors may be able to some day determine how much nitrogen will be released by the snowpack.

Emerging Technologies

Microwave remote sensing offers the greatest potential for measurement of snowpack extent, depth, and water equivalent. The Special Sensor Microwave Imager (SS/MI) is an U.S. instrument with horizontal spatial resolutions ranging from 14 to 70 km depending on the microwave frequency. The capabilities of this instrument of predicting snowmelt volume and timing are currently being demonstrated and examined.

Radarsat is a Canadian Space Agency microwave sensor that is currently used to estimate snowpack extent and depth. New snowpack analysis techniques from these Radarsat remotely sensed products are under development.

EVAPOTRANSPIRATION FROM LAND AND PLANTS

Needs and Applicable Technologies

Evaporation across entire field plots or watersheds is not readily measured directly by *in-situ* or remote devices. Instead this component of the hydrological cycle is often estimated by taking the difference in precipitation, runoff, and changes in soil moisture. Although remote sensing does have the potential to make indirect measurements of watershed and atmospheric properties, evapotranspiration is estimated by using empirical relationships between sources (e.g. plants or land) and sinks (e.g. the atmosphere), or on the closure of energy and water balance models.

Plant based transpiration can be estimated using imagery of land cover, which is available with AVHRR sensors. Land based evaporation can be estimated with imagery of soil moisture and canopy areas (e.g. direct evaporation from canopy areas that intercepted precipitation) given there are additional measurements of surface winds or temperatures. Thermal infrared measurements are capable of providing the necessary surface temperature estimates.

Microwave sensors are useful for measuring soil moisture states, which are used to estimate the partitioning of incoming radiation into its latent and sensible components. Energy balance methods partition incoming radiation into latent heat, sensible heat and ground heat flux. The latent heat, which goes into evaporating water, is coupled with water balance methods that partition rainfall into runoff, changes in soil moisture, and evapotranspiration. Remote sensing can estimate incoming solar radiation by observing cloud cover with geostationary satellites (e.g. GOES).

Gaps in Current Technologies

There are no current technologies that can directly measure evapotranspiration. There has also been little progress made in the measurement of atmospheric parameters such as near surface winds, temperatures, and water vapor gradients, all of which help to estimate evapotranspiration.

Emerging Technologies

Visible and near-infrared sensors (e.g. Landsat ETM, AVHRR) that measure plant biomass and LAI have helped to parameterize empirical evapotranspiration equations. Thermal measurements have also been used to estimate regional scale evapotranspiration rates due to the localized cooling effect caused by the evaporative process, which converts energy into a latent heat form.

There are currently numerous studies conducted jointly with NASA and the U.S. Department of Agriculture – Agricultural Research Service on using microwave Synthetic Aperture Radar (SAR) technology to estimate soil moisture and boundary layer conditions and parameterize energy balance models of evaporation.

WATER QUANTITY: RUNOFF, FLOODING AND WATERBODY EXTENT

Needs and Applicable Technologies

Remote sensing techniques cannot measure runoff volume or rates directly, but visible, near-infrared, and thermal sensors can image runoff extent, flooding extent, and waterbody extent. Multi-spectral scanning (MSS) is one form of technology available for such measurements. Although MSS was the sensor aboard Landsat 1 – 5 that provided

79-m resolution imaging, the same visible and near-infrared scanning technology is available in other sensors. Landsat 4 and 5, for example, carried the Thematic Mapper (TM) that was a 30-m mechanically scanned imaging radiometer. Landsat 7 carries a MSS type instrument known as the Enhanced Thematic Mapper (ETM), while the European SPOT satellite carries a visible-infrared sensor push-broom technology with no mechanical scanning. Data from Landsat ETM, along with microwave, hyperspectral, and aerial photography are all functional technologies for estimating runoff, flooding, and waterbody extent.

Estimates of land cover and land use provide insight on how the precipitation inputs are partitioned between infiltration and runoff. Many runoff and flooding studies, therefore, use remotely sensed imagery of land cover to classify the watershed areas as: 1) impervious and that would not allow for infiltration, 2) susceptible to erosion, and 3) likely to serve as a water detention area or facilitate evapotranspiration. Topographic data, in the form of digital elevation models (DEM), are also used to chart likely runoff pathways and river networks. Both visible and microwave sensor stereopair data are used to generate these maps using photogrammetric or interferometric techniques.

Gaps in Current Technologies

Although empirical models are available for estimating peak discharge and low-flow discharge given estimates of rainfall, waterbody extent, and land cover type, the models are not tested nor robust to spatial scaling and changes in land cover complexity. As such, the current technology is inadequate for providing real-time and accurate estimates of flow rates and volumes. Landsat ETM and AVHRR remote sensing images in the visible are blocked by cloud cover, and when clouds are present then waterbody extent must be measured using alternative portions of the electromagnetic spectrum, such as microwave sensors.

Emerging Technologies

Stage-discharge relations that are calibrated estimates of discharge given flow height are currently measured with *in situ* devices. Hence, flow height can be used to estimate flow rates and volumes. Radar altimeters that identify water stage, and with Doppler technologies water velocity, are currently planned for estimation of discharge measurements on larger (> 250m) rivers. The Shuttle Imaging Radar (SIR) and SAR are both new tools for imaging flood extent during all-weather conditions, day and night.

A new technology is NASA's Sea-viewing Wide Field of view Sensor (SeaWiFS) which is capable of providing 1 to 4-km resolution images of land – water interfaces for demarcating boundaries and estimating waterbody extent.

WATER QUALITY

Needs and Current Technologies

Water quality in rivers, lakes, and other water resources is typically monitored *in situ* for pollution that may arrive from point or NPS. Watershed managers are increasingly using the TMDL approach to quantifying water resource condition and watershed compliance with CWA guidelines. The TMDL approach encourages managers to map all NPS and point source loads to see if the total load exceeds the healthy limit that the water resource can receive. In cases where loading needs to decrease, the TMDL approach encourages creative spatial and temporal arrangements that attempt to maximize load reduction while minimizing the cost of that abatement strategy. These TMDL scenarios require spatially distributed data sets from remote sensing platforms as well as computer models or GIS technologies.

Empirical relationships between remotely sensed data and water quality are being developed that should allow for more use of remote sensing for monitoring water quality. As the causes of water quality problems in locations with similar geology, climate, etc., are better understood, these remote-sensing relationships hold the key to effectively monitoring higher percentages of the U. S. watersheds. Once a relationship between reflectance and water quality is empirically established, remotely sensed data can be used as input to extrapolating the information between the *in situ* locations to give a complete description of the quality of the water body. Regional characterizations of water quality will also be very effective in identifying problem water bodies and potential "hot spots" for future sampling or attention.

Remote sensing instruments that utilize these empirical relationships are currently in use. Chlorophyll in the upper water column is sensed using MSS, ETM, laser fluoro-spectrography and hyperspectral imaging. Each of these methods detects the presence of chlorophyll in plants, and the hyperspectral technique can distinguish between different types of pigments in addition to chlorophyll. Suspended solids, particulate matter, water clarity and turbidity can all be detected with MSS, ETM, aerial photography and hyperspectral sensors. Fluorescences in terrestrial plants can be detected with fluorosensors, and point discharges from pipes or barges can be detected with MSS, ETM, hyperspectral, aerial photography.

Direct measurement of thermal water pollution is the only 'direct' measurement of a water pollution constituent available with remote sensing technology. Sensors capable of thermal detection include the Landsat-7 ETM thermal infrared band at 60-m resolution.

Gaps in Current Technologies

Contaminants within the water column determine how much incoming radiation is adsorbed and scattered. The empirical relationships that equate the presence of a thermal, algae, or sediment type pollutant with a certain adsorption signature are primarily in the visible, near-infrared, and thermal wavelengths. Because clouds and darkness block these wavelengths, their use is limited to monitoring water quality during blue-sky conditions. Another gap in the technology is the spatial and temporal resolution of images, which are usually retrieved at a 30-m to 1.1-km horizontal resolution and range from 2 to 16 days for repeat imagery.

Remote sensing technology has not been developed to detect or measure dissolved oxygen, basal oxygen demand, nitrogen and phosphorous nutrients, pathogen counts, ammonia concentrations, and chemical constituents such as cadmium, copper, lead, mercury, phenols, and total residual chloride. These water quality parameters are important indicators of water quality and future remote sensing developments should attempt to estimate their presence.

Emerging Technologies

There is active development of computer models and geographical information systems (GIS) packages that provide quantitative and automated methods for analyzing the large quantities of remotely sensed spatial data. The spatial analysis tools that help organize the remotely sensed data so that interactions between land cover / land use and the intersecting soil types, topography, and water resources are an emerging area that will need to undergo additional advances to handle the increasing volumes of spatial data.

The most frequently used hyperspectral sensor is AVIRIS. NASA's Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS) has 224 spectral channels ranging from the visible to the infrared region of the electromagnetic spectrum. AVIRIS is truly a hyperspectral technology that is capable of monitoring water resources at high spectral resolutions when flown in high-altitude aircraft. New empirical relationships between various water constituents and the spectral signatures detected by AVIRIS are under development.

SOIL MOISTURE

Needs and Current Technologies

Soil moisture is an important part of the water balance and is useful for understanding the partitioning of rainfall into infiltration and runoff, as well as for estimating watershed evaporation. Soil moisture also determines the chemistry of the watershed, as is the case for redox reactions that go toward reduction in saturated soils and toward oxidation in aerated soils. Soil moisture has traditionally been monitored using *in situ* devices, most recently using a time domain reflectrometry technique that is based on the dielectric properties of water and the soil medium. This dielectric technique can also be used by passive and active microwave remote sensing instruments that can detect the difference in emissivity between dry and moist soils. The SIR and SAR instruments are active measurement tools while Radarsat is a passive measurement tool for detecting soil moisture.

Soil moisture can also be inferred from measurements of a soil's thermal inertia. Daytime and night-time thermal infra-red measurements of soil temperature can be combined to deduce the thermal inertia and empirically relate this to the soil moisture.

Gaps in Current Technologies

Passive microwave devices with longer wavelengths provide greater penetration through covering vegetation and deeper measurements into the soil, however these measurements are limited to a coarse spatial resolution. Active microwave sensors using SAR measurements overcome this spatial resolution limitation. Although microwave signals can pass through vegetation the vegetation does create interference and cause a decrease in the signal to noise ratio that in turn decreases the sensitivity of the microwave sensor to changes in soil moisture.

Emerging Technologies

A variety of SAR devices have been flown aboard the space shuttle and high altitude aircraft for research studies that examine soil moisture distributions and evolution. NASA and the U.S. Department of Agriculture have flown numerous longer (L band) and shorter (C band) microwave SAR and SIR missions in the Southern Great Plains to better understand soil moisture measurement techniques. Many findings from these studies are regularly being presented in hydrology and atmospheric science journals.

LAND USE / LAND COVER

Needs and Current Technologies

Land use / land cover data are fundamental to most watershed studies since they represent the watershed's surface layer, an area responsible for determining both the rate and fate of runoff. For most water resource managers, the most critical components of the terrestrial ecosystem involve riparian areas, impervious surfaces, and edge habitat. Each of these land cover types plays a dominant role in abating or aggravating water pollution. In distributed watershed management modeling the use of riparian areas and impervious areas would play an important role in determining whether the watershed was in compliance with TMDL requirements. Measurement of aquatic habitat would be useful in determining the sensitivity of the resource to future stresses.

Visible and near infrared remote sensing instruments (e.g. Landsat ETM, SPOT, and the AVHRR) are the most commonly used devices for imaging land cover / land use data. *In situ* data that are within the same area sampled by the remote sensor provide a data set for performing training and later classification of the spectral imagery. After classification the land cover / land use data product should be checked for classification accuracy by using a separate set of field data not used in training and from a representative section of the watershed.

Vegetation is generally sampled in the visible and near-infrared regions of the electromagnetic spectrum. Reflectance rises sharply at the red edge, which is between these two areas in the spectrum. Vegetation health and biomass is estimated by taking the ratio of visible and near-infrared wavelength, thereby enhancing this red edge effect. A typical measure of biomass or leaf area index is the NDVI or the normalized vegetation difference index, however other index methods exist to identify vegetation health and biomass, including the transformed vegetation index, the perpendicular vegetation index, and the weighted difference vegetation index.

Gaps in Current Technologies

Current remote sensing instruments are limited to coarse spatial resolutions with a high temporal resolution (e.g. AVHRR provides 1.1-km resolution images twice daily) or to fine spatial resolutions with a coarse temporal resolution (e.g. Landsat ETM images the same 30-m area every 16-days). Cloud cover blocks both of these wavelengths and the technology of land use mapping is therefore extremely dependent on conditions where fair weather coincides with fly-over and imaging dates.

Emerging Technologies

New commercial satellites are currently capable of retrieving visible and near-infrared images at much high temporal and spatial resolutions than the existing Landsat and SPOT sensors. These new data sets will allow for highly detailed studies that examine the interaction of land use / land cover with changes in water quality.

The NASA the SeaWiFS aboard the SeaStar satellite, although designed for ocean color viewing, is obtaining visible and near infrared images of the earth's land cover and processed vegetation index products at 1 to 4-km resolution. These images are posted on the Internet as a free product for scientific study. The availability of these images should encourage new developments in land cover science.

The NASA AVIRIS is flown as a hyperspectral airborne instrument. This instrument is providing high radiometric resolution images of mineral and vegetation properties that will potentially lead to new empirical relationships between land cover health, classification, and remote sensing.

NASA is also flying a Light Detecting And Ranging (LIDAR) laser to measure the total biomass between the canopy crown and the earth's surface soil layer. The LIDAR instrument is capable of a very high vertical accuracy that will enable a precise measurement of the entire terrestrial biomass.

TOPOGRAPHY AND TERRAIN ANALYSIS

Needs and Current Technologies

Topographic data describes the shape of the watershed terrain and is called a DEM when it is stored as a raster matrix of elevation values. DEM data are used to identify probable surface runoff pathways toward rivers and lakes, determine watershed areas likely to serve as groundwater recharge or discharge areas, as well as identify watershed areas most susceptible to erosion and deposition processes. In addition to delineation drainage networks, watershed boundaries, and slope aspects and angles, DEM data are used to compute topographic indices that predict the spatial distribution saturation likelihood.

Two remote sensing techniques are currently used to generate DEMs. The most common technique uses two different look angles from visible sensors (e.g. Landsat ETM or SPOT) for the same area and then estimates an elevation by using photogrammetric techniques that derive estimates of stereo-correlation within the stereopair of images. The other technique is called interferometry, which is a process that uses two or more SAR images from different look angles and isolates phase differences to compute elevation. The SAR-derived DEM's are becoming increasingly popular.

Gaps in Current Technologies

DEM 30 and 90-m data sets for the U.S. were derived from high altitude photographs by the USGS. The generation of high-resolution satellite derived DEMs is constrained to isolated research watersheds and study areas due to the high cost of each satellite scene. GTOPO30, the only global DEM, is a 30-arc second product (approximately 1-km pixels) that was derived from a variety of national elevation maps, each with varying vertical accuracy limits. It is critical that new DEM data sets are derived from the current generation of government and commercial satellites.

Emerging Technologies

Several new technologies are either operational or scheduled for launch that will advance the current limitations of DEM data. The Shuttle Radar Topography Mission (SRTM) is a SAR microwave device that will fly in 2000 aboard NASA's space shuttle and use interferometric techniques to derive a 30 and 100-m resolution DEM for all land areas on the earth. Another mission is the ASTER is a NASA – Japanese sensor scheduled for launch in 1999 as part of EOS that will provide 15-m stereopair products for DEM generation for the entire globe.

NASA's LIDAR laser altimeter instrument will be flown as a special shuttle instrument capable of distinguishing the true earth surface from the false canopy surface measured by multi-spectral sensors such as Landsat ETM and SPOT.

WETLANDS

Introduction to Wetlands Monitoring

The Environmental Protection Agency's activities in wetland area protection are mandated under the Clean Water Act and administered through the EPA office of Oceans, Wetlands, and Watersheds. EPA's wetlands program has some activity on local as well as regional and national scales, and each of these scales has different implications for the possible use of remote sensing instruments.

At local scales, EPA plays a major role in the process of evaluating CWA section 404 permits required of individual projects that propose to fill wetlands. To support this activity, good detection and mapping of individual wetlands' boundaries are of paramount importance. Further, evaluating permit applications considers effects on wetland functions, and may consider landscape-scale issues such as proximity to other wetlands, or amount of wetlands in the watershed where the permit applicant is located. Wetland functions include soil retention, soil generation, pollution trapping, and flood mitigation.

In some cases, EPA is involved in enforcement actions that may include disputes over wetland boundaries, loss of acreage, or loss of function. Through the Advance Identification process, wetlands or wetland complexes of unusual value or high threat may be labeled as potentially suitable or unsuitable for filling permits, and remote analysis of their areal extent and/or functions and other attributes (e.g. extent of exotic vegetation, or drainage patterns) can contribute.

At regional and national scales, EPA's wetland program is attentive to large-area trends in wetlands acreage loss or gain, as well as any widespread degradation or loss of function. Regional and national patterns often influence the program's priorities as well as the permitting decisions on a local scale (e.g., a decision to deny or modify a permit due to significant threats regionally to the type of wetland involved).

The predominant regional and national-scale issues of wetlands influence the outreach and information transfer components of the wetland program. Thus, comprehensive mapping of wetland extent, mapping of change in area over seasonal time steps, and analysis of overall condition or function of wetlands are of high importance in setting program direction. These monitoring activities differ from local-scale activities in their impact on spatial resolution limits, areal coverage, classification detail, and cost that remote technologies would need to provide.

Breakout Session Findings

The purpose of the wetlands breakout session was to: 1) identify matches between current technology and wetlands management and monitoring requirements, 2) examine EPA needs that could be satisfied using NASA technology, 3) identify gaps between EPA's needs and NASA's current technology, 4) examine ways to solve EPA's needs with existing or planned future technology provided by NASA, and 5) identify a joint effort project which could be used to advance the means by which EPA handles wetland management issues. The final goal of the Breakout Session was to report these findings and make recommendations. Although watersheds were discussed in the above breakout session, the geographical unit defining the boundary of all water resources is a watershed, and therefore the workshop organizers consider the findings of the watersheds breakout session potentially applicable to this wetlands session.

WETLANDS MAPPING, INVENTORY AND BOUNDARY DELINEATION

Needs and Applicable Technologies

Wetlands mapping, inventory, and delineation of boundaries are necessary procedures for a national wetlands protection program. National Wetland Inventory (NWI) maps, a product derived from high altitude aerial photos and produced at 1:24,000 scale, are an important tool for wetland management. NWI maps are limiting in their usefulness, however, if there are major land cover changes between image collection and image use or map use. Satellite images are typically less expensive per unit area of coverage and therefore permit more frequent repeat coverage. However, accuracies in identifying wetlands through satellite image processing have been low, especially for wetlands a few acres or less in size. Consistent accuracy and available repeat coverage is needed in order for scientists to update wetlands location and extent, as well as establish association and possibly causation between changes in wetland extent or structure and observed changes in watershed condition. Wetland managers need wetland inventories just as they need indicators of wetland condition changes and trends, processes that require regular sampling of the area across time.

Remote sensing applications that can accomplish some forms of broad-scale wetlands mapping include the use of satellite-borne MSS such as Landsat ETM and SPOT, airborne MSS, and aerial photography. These technologies, combined with improved algorithms and classification techniques that use computer software to spectrally identify types of wetlands, were identified for potential use.

Microwave remote sensing with SAR is considered an active sensor technique for measuring soil moisture values. If the soil moisture temporal patterns indicate a period of saturation then the area is more readily classified as fitting formal wetland definitions.

Gaps in the Current Technologies

Current wetland databases and maps are not sufficient in accuracy or resolution for detailed wetland studies. This gap is largely economic due to the cost of obtaining and processing high-resolution data over large areas. When remotely sensed data are combined with field observation data, the accuracy of the information on wetland function or health can reach as high as 90% or better, which meets or exceeds the accuracy needed for most wetland studies.

Data errors exist in the current NWI data, due to a variety of factors including change over time. One option to improve accuracy is to overlay high-resolution MSS (Landsat or SPOT) technology to identify and improve upon areas where the NWI data are unclear. Pilot tests of this method should be reviewed for their suitability for NWI updating.

Microwave radar remote sensing, both passive and active sensors, can provide additional information for wetland mapping. Higher spatial resolution is obtained with the active SAR device, but this is still primarily an airborne sensor and not available for continued monitoring. The cost of covering the entire U.S. is considered too expensive so this technology is still limited to research areas.

Forested wetlands present a unique challenge for identification of wetland boundaries and functional attributes. The challenge is created when the forest canopies completely obscure the soil moisture condition as well as any understory vegetation that is indicative of wetland habitat. The use of vegetation penetrating radar may help to delineate wetland boundaries under closed canopies. A combination of the use of microwave radar with the NWI data maps may provide a well-balanced approach to delineating the wetland areas, but cost per unit area must be assessed to determine feasibility of application within limited budgets.

Emerging Technologies

In order to close some of the gaps between wetland management needs and available technology, the problems of spatial and temporal resolution and map coverage need to be addressed. Technicians need to better determine exactly what level of data resolution is needed to identify wetland boundaries and develop maps of wetland changes across time.

Incorporation of spatial map data and global positioning system (GPS) data points (especially in the wetland permitting process) can improve the accuracy of remotely sensed data. Use of new high-resolution sensors and advanced processing technologies (sub-pixel analysis) to map intrusive species, edge effects and support enforcement and large scale studies are all areas that need to be examined as a means of closing gaps between management needs and available technology.

High accuracy DEMs, when combined with land cover maps, provide a good data source for examining whether wetland location coincides with topographic depressions that accumulate water. LIDAR altimeters can provide very precise measurements of the terrain surface that assist in this wetland verification technique.

Several technologies have been identified as possible solutions in improving the mapping of wetland land cover and land use. These emerging techniques include the use of high-resolution satellite MSS, multi-temporal analysis, sub-pixel analysis techniques, fuzzy logic classification, and hyper-spectral scanners for soil and vegetation analysis.

CHANGE ANALYSIS OF WETLAND EXTENT

Needs and Applicable Technologies

Change analysis is an important technique for assessing wetland habitats. Multi-spectral scanners such as Landsat ETM, SPOT and airborne MSS provide advanced technologies that can support analysis of wetland change.

Problems in wetland change analysis exist due to inconsistent data, lack of data, or too infrequent collection of data. To achieve better detection of wetland change, the lag time between updates should be shortened. It may be necessary in some wetlands complexes to sample seasonally to capture the hydroperiod defining that wetland hydrological regime. Regular images taken with MSS on Landsat ETM and SPOT satellites, airborne MSS, together with digitized aerial photographs will improve the ability to analyze change. SAR can also be used to reveal important information on wetland change in soil moisture cycles.

Gaps in the Current Technologies

Change analysis is hampered by the coarse spatial and temporal resolution of satellite images, resulting either in overly coarse or temporally limiting databases that provide little insight to wetland change. Further problems exist in change detection due to the quality of existing remotely sensed data. Cloud conditions, for example, that obstruct a satellite fly-over create data holes that hamper otherwise effective change detection algorithms. This repetitive lack of data collection due to cloudy conditions makes wetland change analysis much more difficult. Change detection is also challenged by the lack of resources available to perform the data analysis.

Emerging Technologies

Change analysis would benefit from the creation of improved baseline data. Costs could be constrained by focusing on "hot spots", thereby limiting the aerial extent of change analysis to more manageable areas. The inclusion of advanced detection techniques and the use of GIS should help provide a better understanding of environmental limits, such as the tidal cycle, on wetland extent. SAR should be considered as a means to overcome cloud cover obstruction.

NUISANCE SPECIES AND EDGE EFFECTS

Needs and Applicable Technologies

Nuisance species and edge effects in wetlands are important indicators of wetland condition and outlook for the future. Monitoring for these wetland properties requires more spatially and spectrally detailed sensors than those used for simply mapping the wetland boundary, and identification of specific species is not yet achievable with current remote sensing tools.

These monitoring tasks are best performed with high-resolution remote sensing tools. Mapping of nuisance species and mapping of edge effects in ecotones is being done through the use of aerial photography and airborne MSS remote sensing. The multi-spectral data is then combined with data digitized from the aerial photos into GIS databases to improve the spatial accuracy of boundary locations for the species.

Gaps in the Current Technologies

The current remotely sensed satellite images lack the spatial resolution to accurately identify boundaries of invasive species encroachment. Airborne MSS, which can provide sub-meter resolution, can better address the spatial resolution needs related to mapping intrusive species than satellite data. The improved spatial resolution improves the accuracy of vegetation classification of nuisance species.

Emerging Technologies

New high-resolution spatial and spectral sensors, such as NASA's AVIRIS together with advanced processing technology, such as sub-pixel analysis, are emerging as refined ways to map intrusive species, edge effects, and support implementation of large scale studies.

STRUCTURAL AND FUNCTIONAL ASSESSMENT AND TREND ANALYSIS

Needs and Applicable Technologies

Land cover indicators of wetland health and function are needed in order to identify troubled and stressed wetland areas that require immediate management attention. Structural and functional wetland assessment, combined with the use of trend analysis, provides the scientist with better tools to manage wetland areas.

Productivity and health trends in wetland areas require scientists to ask questions regarding wetland hydrology, the production of biomass, species diversification, wetland sustainability, and habitat mapping. All of these factors can be examined using data remotely sensed from Landsat ETM, SPOT, or airborne MSS.

Structural degradation can also be detected through remote sensing. Structural degradation data sensed remotely should be combined with functional degradation data determined by other techniques such as field-testing. Additional tools for structural and functional assessment are long-term historic aircraft imagery and aerial photography. Modeling should test hypothesis regarding the role of wetland physical controls on wetland function as well as identify the best remotely sensed indicators for identifying the presence of those wetland functions.

Gaps in the Current Technologies

Modeling wetland productivity, diversity, sustainability and habitat structure is hampered by inadequate data resolution in both the spatial and spectral region. Data on structural degradation is either not available or not consistent enough for detailed modeling.

Water salinity and temperature data should be included in trend analysis routines that are exploring the possibility of wetland degradation. Wetlands are ecologically sensitive systems that might die back with small changes in soil water temperature and salinity. These two indicators of functional assessment are readily detected with *in situ* techniques and there is a definite need to calibrate thermal infrared and microwave SAR sensors to detect the same chemical and physical wetland features.

Emerging Technologies

Airborne electromagnetic profiling and other techniques for wetland structural assessment and bathymetric mapping should be examined for incorporation into watershed models. The use of laser fluorosensing should be considered as a means for determining habitat stress.

New technologies that also hold promise for improving structural and functional assessment are hyperspectral scanners such as NASA's AVIRIS, new high temporal resolution sensors such as NASA's SeaWiFS, and improved computational and analysis algorithms for identifying habitat health.

INUNDATION AND SOIL MOISTURE IN SATURATED WETLANDS

Needs and Applicable Technologies

Detection of inundation and soil moisture can serve at least three distinct purposes for wetland resource monitoring. First, this monitoring can demonstrate a distinct period of saturation (e.g., the hydroperiod) that indicates compliance with formal wetland definitions. Second, the inundation can indicate which zones are most likely redox zones or areas of increased chemical activity. Third, inundation can help to define the boundaries of the wetland. The reader is referred to the above **Watershed, Rivers, and Lakes** breakout session to learn more about remote sensing microwave technologies for detecting soil saturation.

Monitoring in wetlands in visible bands is limited by canopy and cloud cover obstruction, while microwave bands are capable of passing through these obstacles. SAR and radar altimeters are the current tools used in data collection for modeling applications. SAR data can be very valuable in detecting saturation and flooding across the wetland landscape, however the satellite based instruments have a coarse temporal and spatial resolution while the airborne instruments are limited to infrequent and expensive flights.

Landsat ETM thermal bands can provide and alternative tool for measuring thermal inertia and the extent of water in wetland areas and marshes.

Gaps in the Current Technologies

Wetland hydrologic and vegetative change across seasons, along with the frequency and periodicity of inundation, are very important variables that need to be mapped with future remote sensing missions and devices. Another important variable is variation of soil moisture.

Emerging Technologies

Recent experiments with SAR and radar altimeters have provided good results in the mapping of wetland inundation and identification of saturated areas. The estimation of areas of inundation using high-resolution DEMs together with overlays of vegetative maps may be a technique for improving mapping accuracy.

SALINITY IN SOIL AND WATER

Needs and Applicable Technologies

Salinity concentrations and gradients of wetland soil and water is a critical indicator of wetland function and health. Depending on the wetland type, either coastal or inland, different salinity gradients are considered normal. Changes in the salinity in both directions during tidal fluctuations may occur naturally in coastal wetlands, however changes in salinity in inland wetlands are likely indicative of ecosystem stress and severe disruption. SAR and airborne microwave radiometry are the current remote sensing sources of data for salinity modeling.

Gaps in the Current Technologies

The reliability of microwave remote sensing collection techniques is still uncertain. There are a variety of experimental missions and a great need for demonstrating the ability of the equipment to detect salinity gradients. Due to issues of data reliability microwave data do not currently support many modeling needs.

Emerging Technologies

Investigation of improved airborne microwave radiometers that are more capable of detecting salinity signals should be examined and field-tested.

GROUNDWATER

Introduction to Groundwater Monitoring

Ground water within the U.S. Environmental Protection Agency is addressed in the Office of Ground Water and Drinking Water. EPA's Office of Ground Water and Drinking Water (OGWDW) programs include Wellhead Protection, Sole Source Aquifer Protection, Underground Injection Control and the Comprehensive State Groundwater Protection program. The Office of Research and Development (ORD) is the primary research arm supporting the program offices and the environmental community. ORD cooperates with other federal and state agencies and conducts a major grants program to promote independent research in critical areas.

All groundwater regulation and research supervised under EPA has traditionally focused on point and non-point sources of contamination to groundwater resources. EPA sub-offices and divisions develop policy and conduct research in the area of aquifer protection, source water protection, underground injection control, wellhead protection and underground storage tanks. Technical guidance for groundwater remedial technologies have been established as well as measurement and monitoring methodologies for operational and closed facilities.

EPA has cooperated with outside organizations such as the American Society for Testing and Materials to produce a compendium of agency consensus standards. Continuing in this cooperative mode the EPA sees a benefit to collaborate with NASA scientists and engineers to further strengthen and improve upon groundwater protection monitoring and modeling. Remote sensing instruments offer the potential to improve upon traditional characterizations and monitoring techniques used by the EPA.

Monitoring of both saturated and unsaturated groundwater resources can benefit from advances in remote sensing and other technologies. Near surface and unsaturated monitoring might include locating groundwater inflow, the finding and monitoring movement of contaminated sediments, and measuring organic compounds. Saturated zone needs are focused on better determination of fractures (including subsurface) and real-time potentiometric surface measurements.

Groundwater, unlike the other water resources discussed in this workshop, is typically not visible above the ground surface. Monitoring techniques that use visible and near infrared sensors may not be as advantageous to groundwater management as application of new technologies in other areas of geophysical research, such as advanced electrical and acoustic sensing devices. NASA's development of advanced geophysical devices for exploration of other planets, such as the Mars Explorer mission, may provide spin-off technologies that benefit characterization of earth's groundwater resources.

Breakout Session Findings

The purpose of the groundwater breakout session was to: 1) identify matches between current technology and groundwater management and monitoring requirements, 2) examine EPA needs that could be satisfied using NASA technology, 3) identify gaps between EPA's needs and NASA's current technology, 4) examine ways to solve EPA's needs with existing or planned future technology provided by NASA, and 5) identify a joint effort project which could be used to advance the means by which EPA handles wetland management issues. The final goal of the Breakout session was to report these findings and make recommendations. Although watersheds were discussed in the above Breakout session, groundwater recharge and discharge areas are contained within a watershed (e.g. lakes and rivers), and therefore the workshop organizers consider the findings of the watersheds Breakout session potentially applicable to this groundwater session.

AQUIFER DELINEATION

Needs and Applicable Technologies

Aquifer delineation is critical to quantifying the volume of subsurface water reserves available for human development and utilization. Inaccurate estimates of the aquifer extent can lead to 'mining' of water resources that is characterized by withdrawal rates exceeding aquifer recharge. Delineation of aquifers can also help to identify areas of recharge and discharge within the watershed overlying the aquifer.

Hyperspectral imaging for delineation of vegetation types and their seasonal and moisture-controlled changes is a technology that can help in defining aquifer boundaries. Phreatic aquifers with near surface watertables can be detected with microwave SAR devices that measure changes in dielectric properties between the grain and water components of the soil medium.

MSS data, such as Landsat ETM imagery, as well as active and passive radar data, can provide information as the extent of geological and geomorphologic terrain features. These data collection techniques help to characterize the larger bounding features of the aquifer and possibly help scientists extend point source surface measurements to larger geographic scales.

Gaps in Current Technologies

Groundwater monitoring data obtained from satellite sources is typically considered too coarse in spatial resolution to solve standard monitoring needs. The frequency of the data collection also limits detection of changes in the surface features as the respond to groundwater and subsurface fluctuations.

Emerging Technologies

Advances in the availability of hyperspectral data along with increased spatial and temporal resolution of microwave remote sensing data will help to characterize the plant and soil moisture properties associated with *in situ* delineate aquifers. These empirical studies will help to provide baseline measurements from which to track changes in surface aquifer extent across time.

The use of SAR interferometry to detect phase shifts caused by the change in mass of subsurface aquifers may be a new technology that can assist hydro-geologists define aquifer boundaries.

AQUIFER CHANGE DETECTION

Needs and Applicable Technologies

Changes in the surface characteristics of aquifer plant communities can indicate a change in the hydrologic properties of the underlying aquifer. Current remote sensing instruments in the visible and near infrared bands on Landsat ETM, SPOT, and the AVHRR are capable of detecting changes in vegetation greenness that could indicate changes in aquifer water levels.

Microwave radar remote sensing of soil moisture can provide the same information about aquifer surface conditions but at coarser spatial resolutions than the Landsat and SPOT 30 and 10/20-m resolution visible bands.

Gaps in the Current Technologies

The current technologies are not capable of penetrating beneath the ground to detect changes in the deeper portions of the aquifer.

Emerging Technologies

The SAR interferometry technologies discussed in the previous Breakout session finding are applicable to this finding as well. It is possible that detection of aquifer phase shifts could reveal information about aquifer changes in location and volume.

DETERMINATION OF RECHARGE AND DISCHARGE ZONES

Needs and Applicable Technologies

Aquifer recharge zones typically extend across 85 to 95% of the aquifer surface area, while some recharge areas provide inflow to regional flow networks and others supply more local subsurface flow networks. Understanding the recharge of the aquifer is critical to computing sustainable pumping rates for aquifer development and utilization. Mapping the location of recharge zones relative to the distribution of surface contaminants provides and indication of the risk that pollutants will enter groundwater reserves. Visible features used by hydro-geologists to detect recharge zones include local and more regional topographic high points and areas of fractures and fault zones.

Discharge zones are often identified as areas of topographic lows, often coinciding with streams, lakes, and wetlands as well as areas with unusually lush vegetation compared with surrounding patterns in the landscape.

Remote sensing instruments that utilize visible wavelengths can detect drainage and associated vegetation patterns, as well as surface features related to fractures and fault lines. These features can serve in mapping and monitoring groundwater recharge and discharge zones. Remote sensing instruments that operate in the thermal region of the spectrum can provide information on soil moisture and compaction and technologies that operate in the microwave can also be used to estimate soil moisture. Microwave sensors (i.e. Radar) can also be used to map land surface elevations, as well as providing some canopy penetration in forested areas.

Gaps in the Current Technologies

More sophisticated technologies that penetrate below the ground surface to detect changes in saturation, rock density, or the thermal signature of water, are technologies that would help hydro-geologists better characterize recharge and discharge zones.

Emerging Technologies

NASA's AVIRIS is a hyperspectral technology that is capable of detecting slight changes in mineral properties and plant characteristics. Development of empirically based techniques for using AVIRIS and other hyperspectral sensors to identify the influence of discharge zones is recommended for additional investigation. Additionally, Interferometric Synthetic Aperture Radar and scanning LIDAR instruments are technologies that can potentially provide detailed digital elevation models. The limitations of these technologies need to be explored in a variety of landscape types.

ACID MINE DRAINAGE DELINEATION

Needs and Applicable Technologies

Acid mine drainage is a contaminant that can endanger surface and subsurface water quality. Delineation of acid drainage from mines is of prime importance to many regions of the nation where open pit mining occurred. Larger mines and their drainage areas can be viewed in remotely sensed AVHRR 1-km data, while higher resolution Landsat (e.g. 30-m) and SPOT (e.g. 10/20-m) imagery are needed to analyze smaller mines that may reside within complex terrain. Re-visitation rates of approximately two weeks after major meteorological events are optimal to make contributions to EPA's acid mine drainage monitoring program.

Gaps in the Current Technologies

Current remote sensing instruments do not allow for a comprehensive detection of the many chemical contaminants, mineral precursors to acid mine drainage, and the gradients of chemical concentrations found in mine drainage areas. Characterization of the topography surrounding and within the mine area is another problem. The current spatial resolution of most airborne and space borne sensor systems is inadequate to resolve the effects that occur in the smaller streams that usually occur adjacent to the mines.

Emerging Technologies

Hyperspectral remote sensing instruments, such as the AVIRIS, and Multispectral Thermal instruments, such as the Thermal Infrared Multispectral Scanner (TIMS) and the MODIS (Moderate Resolution Imaging Spectrometer) - ASTER simulator (MASTER) have the potential to discriminate between a variety of chemical constituents and mineral precursors and better detect the high risk from the benign minerals and waters that are also distributed about the mine area as well as having the potential to detect vegetation effects at very early stages of damage. These airborne systems have space borne equivalents as part of the Earth Observing System (i.e. MODIS, ASTER, and EO-1's Hyperion). Interferometric Radar and Topographic LIDAR systems may also be available from air borne and space borne platforms to characterize topography for risk assessment and management.

SALINITY MAPPING

Needs and Applicable Technologies

Salinization of soil and water may jeopardize both environment health and agricultural productivity. Salinization can occur within an aquifer due to evaporation drawing dissolved minerals and salts toward the surface and due to groundwater pumping accidentally drawing adjacent salt-water reserves into the aquifer.

Microwave SAR instruments have been used as a screening tool to identify areas where *in situ* research is needed to investigate the risk of salinization.

Gaps in the Current Technologies

Remote sensing instruments are currently unable to detect areas were salt-water intrusion into freshwater aquifers is occurring. These subsurface measurements require knowledge of pumping rates, aquifer draw down, and the proximity of bounding salt-water aquifers.

Emerging Technologies

Development of airborne electromagnetic and magnetometer capabilities to detect salinization impacts should be focused on relatively small, cost-effective studies that use a combination of spaceborne, airborne, and surface remote sensing. These studies should help to develop the use of advanced technologies for ground water applications.

GROUNDWATER SUBSIDENCE

Needs and Applicable Technologies

Groundwater subsidence describes the lowering of ground-surface elevations due to changes in the potentiometric pressure of the underlying aquifer. When groundwater withdrawal rates exceed recharge rates subsidence has an increased potential to occur. Remote sensing instruments may not be capable of gauging the imbalance of pumping and recharge rates, however the use of high-precision altimeters, such as the LIDAR laser altimeter, together with GPS technology can help to monitor changes in ground elevation.

Gaps in the Current Technologies

The working groups identified no gaps in current technologies, but instead noted the lack of application.

Emerging Technologies

Microwave SAR interferometry and LIDAR laser altimeters are both capable of detecting terrain elevation. The SAR interferometry technology is not as precise as the LIDAR laser altimeter and initial detection of subsidence will likely be clearer on the LIDAR systems. For larger areas, however, the SAR interferometer will provide a more cost-effective measurement technique.

DETECTION OF POTENTIOMETRIC SURFACE

Needs and Applicable Technologies

A fundamental parameter for hydro-geological monitoring and modeling is the aquifer potentiometric surface. These spatially distributed measurements of aquifer pressure indicate the flow path directions and help to detect areas of recharge and discharge. Both surface and subsurface aquifers have a potentiometric surface, and the shape of the watertable defines the surface aquifer's potentiometric surface.

In situ measurements with wells and piezometers are traditionally the measurement technique of choice for potentiometric mapping. Advances in remote sensing instruments have not provided any practical tools for monitoring potentiometric surfaces. NASA may develop other advanced geophysical techniques, however, that help in the monitoring of this fundamental aquifer property.

Gaps in the Current Technologies

There is a need to investigate potentiometric surface mapping applications for the advanced geophysical technologies developed by NASA and other technology based industries.

Emerging Technologies

No existing technologies were identified as likely candidate geophysical tools for advancing remote sensing of potentiometric surfaces.

OTHER GROUNDWATER MONITORING NEEDS

The Groundwater Breakout session created an additional list of monitoring needs that could benefit from remote sensing or advances in geophysical detection methods. These monitoring needs were for near surface water resources that were either monitored near the surface (Table 4.1) or below the surface (Table 4.2).

Table 4.1. Monitoring Needs for Near Surface Measurements

Locate Groundwater Inflow in Waterbodies:
Current technologies cannot accurately define zones of groundwater inflow in harbors, bays, estuaries, riparian zones.
Monitoring Sediment Capping:
The Army Core of Engineers uses capping as the major means of isolating contaminated sediments. There is currently no reliable method to monitor advection through the cap.
Seepage Meters:
Current design is ad/hoc. There is a need to develop a system for real-time monitoring of flow and collection of samples. Could also be used for riparian zones.
Monitoring of Organic Compounds:
New containment strategies require better methods for location and measurement of biodegradation.
Real-time Measurements & Monitoring:
Need research and development for real-time monitoring, this includes development of sensors and placement methods such as moles.
Geophysical Surveys:
Enhance the quality of seismic surveys, both reflection and refraction.

Table 4.2. Monitoring Needs for Below Surface Measurements

Enhanced Determination of the Potentiometric Surface:
Wells and piezometers measurements are not a cost-effective method of accurately determining head relationships over large distances. Need better application of geophysical methods.
Push Technology Needs to Achieve Greater Depths:
Monitoring penetration depth could possibly be enhanced by combining rotary and vibratory methods with push methods.
Real-time Measurements and Monitoring:
Need research and development for real-time monitoring, including development of sensors and placement methods such as moles.
Horizontal Wells:
Develop horizontal emplacement to monitor areas under containment fractured rock.
3-D Geophysics:
Assess the cost:benefit ratio of further technologies in 3-D geophysical monitoring and development.

ESTUARIES AND OCEANS

Introduction to Estuaries and Oceans Monitoring

Some of the most important applications of satellite and airborne remote sensing are in data extrapolation and modeling, the planning of field sampling, and the ability to put data from local studies into a regional perspective. The EPA Office of Oceans, Wetlands, and Watersheds is involved in using large ocean and estuary data sets to monitor and manage the earth's ocean ecosystem.

Most EPA data comes from *in situ* and point measurements. For ocean resources, however, that is not a practical sampling technique. Given the vast spatial scales that describe the earth's ocean it is critical to use remotely sensed measurement techniques together with *in situ* measurements so that monitoring can occur across a greater percentage of the ocean's expanse. *In situ* data help to calibrate remotely sensed data, detect sampling bias, and develop empirical equations that equate remotely sensed measurements with water parameters of interest.

Although NASA satellite and aircraft instruments appear to operate at coarse spatial scales compared to landscape heterogeneity, the relatively homogeneous surface of the ocean makes the NASA technologies a very appropriate monitoring design. The sensors are incapable of detecting ocean properties at great depths, however, future hyperspectral sensors may be useful for characterizing submerged aquatic vegetation such as macro-algae and sea grasses.

Breakout Session Findings

The purpose of the estuaries and oceans Breakout session was to: 1) identify matches between current technology and estuaries and oceans management and monitoring requirements, 2) examine EPA needs that could be satisfied using NASA technology, 3) identify gaps between EPA's needs and NASA's current technology, 4) examine ways to solve EPA's needs with existing or planned future technology provided by NASA, and 5) identify a joint effort project which could be used to advance the means by which EPA handles wetland management issues. The final goal of the Breakout session was to report these findings and make recommendations. Although watersheds were discussed in the above Breakout session, the watershed and its rivers and lakes are the hydrological resources draining into estuaries and oceans, and therefore the workshop organizers consider the findings of the watersheds Breakout session potentially applicable to this estuaries and oceans session.

WATERSHED IMPACTS ON ESTUARY WATER QUALITY

Needs and Applicable Technologies

The combined effect of upslope watershed activities on downstream water quality has not been regularly studied. EPA, NASA (through the Earth Science Enterprise), and other agency research programs, however, are pursuing research activities that are well distributed within the watershed area, from headwater regions to the estuary and ocean receiving waters. Coordinating the data storage from these multiple research projects will allow for integrated assessment of watershed impacts on estuary and ocean water quality.

One the specific problem involves the effect of combined sewer overflows on downstream water quality. During precipitation events, raw sewage is dumped directly into the estuaries from many coastal communities. These effects could be estimated through the use of the appropriate remotely sensed data such as hyperspectral, high resolution MSS, and laser fluorosensors.

Remote sensing systems may also be useful for determining the effects of natural disasters such as hurricanes and floods on estuaries and coastal waters. Products developed to study the global ocean may be too coarse for coastal applications, however raw satellite data can often be processed and optimized for coastal applications.

Gaps in the Current Technologies

Integrated and regional watershed monitoring programs that address both baseline and trend data are needed. Statistically based monitoring programs that are well designed to isolate the impact of watershed changes on water quality impacts can provide useful information for designing pollution abatement devices. Estuary sampling should try to isolate water and sediment quality, animal tissue samples, and air quality as a function of watershed changes that are detectable with advanced monitoring methods.

Emerging Technologies

NASA investigators are using new fluorometric techniques that should enhance monitoring of estuarine chemistry. Hyperspectral remotely sensed data from instruments such as the AVIRIS offers an alternative technology that promises to better identify and characterize the chemical signals of contaminants and other components of estuaries.

NASA's SeaWiFS that is carried by the SeaStar satellite is capable of retrieving 1 to 4-km resolution images of estuary and ocean temperature along with upslope watershed vegetation indices. The data from the SeaWiFS sensor is made available to the general public over the Internet within one-day after image capture. This is an emerging technology that will likely advance integrated estuary and wetland analysis.

LARGE ESTUARIES AND COASTAL WATERS

Needs and Applicable Technologies

Ocean color data is a standard monitoring product that indicates the presence of photosynthetically active pigments such as chlorophyll-a. By tracking intensities and changes in ocean color, scientists are capable of estimating the biological productivity of the ocean. MSS measure biological productivity in ocean, estuaries and coastal areas.

Gaps in the Current Technologies

Ocean color analysis must distinguish between surface reflectance caused by photosynthetically active pigments and reflectance caused by suspended sediments and DOC. Because the suspended sediments and DOC are usually recorded in coastal waters it is not a significant limitation that the remote sensor has trouble distinguishing between these two sources of color.

Emerging Technologies

The Ocean Color and Temperature Scanner (OCTS) on the ADEOS-1 (Advanced Earth Observing Satellite) spacecraft has been collecting ocean color data over the US coastal waters since November 13, 1996. The National Oceanic and Atmospheric Administration has recently begun distributing real-time data products based on imagery from this satellite through its Coast Watch nodes. These data products are available for research purposes and for government, including state and local operations. OCTS collects data over the US coastal waters (including the Great Lakes) once every two days. Standard collection products, with a resolution of 0.8 km (pixel size) include: phytoplankton chlorophyll; water clarity indices; sea surface temperature; dissolved organic matter estimates; and suspended sediment estimates.

TURBID COASTAL WATERS

Needs and Applicable Technologies

Turbid waters are more challenging for remote sensing and traditional monitoring due to the turbulence created by the severe wave and wind action. Oceans are continually moving due to storms and currents, however, and advanced technologies need to monitor the condition of the ocean and estuary waters under a variety of conditions.

Gaps in the Current Technologies

As mentioned above, MSS operating in the narrow visible band used for ocean color sampling are incapable of readily distinguishing between sediment and DOC reflectance and chlorophyll reflectance. Because turbid waters stir up bottom sediments, the suspended sediment and DOC reflectance measurements are typically of turbid waters. Therefore, combined with measurements of wave height and spectra, reflectance spectra can be assigned to either chlorophyll or sediment and DOC sources.

Emerging Technologies

The OCTS, which holds great promise in large estuary and coastal water applications, has not been as effective for turbid coastal areas. The algorithms for calculating chlorophyll and other products do not yet work as well in coastal waters as they do offshore. Therefore, one has to be very careful how these products are interpreted for estuarine and coastal waters.

NASA's SeaWiFS is capable of retrieving 1 to 4-km resolution images of estuary and ocean temperature and reflectance data. These data from the SeaWiFS sensor are regularly made available and is an emerging technology that should advance turbid water analysis..

OCEAN AND ESTUARIES - GENERAL PROGRAM

Needs and Applicable Technologies

Estuary and ocean boundary delineation is important for resource management and monitoring. The use of high spatial resolution data along with higher spectral resolution MSS or hyperspectral data will improve modeling of riparian zones, coastal boundaries, and species habitats.

Digital elevation data of the water surface are important for detection of ocean currents and waves. High-resolution DEMs provide needed data for these monitoring activities.

Change analysis is fundamental to a complete estuary and ocean monitoring program. Databases must account for temporal (seasonal) change as part of standard estuary analysis. Maintaining a high accuracy of baseline data is critical for effective change analysis modeling, while development of historical databases also becomes important for longer-term studies. These databases need to be maintained with metadata that clearly describes data capture and manipulation procedures and then and ultimately stored in a location where they can be easily accessed.

Gaps in the Current Technologies

The current DEM maps are too coarse in resolution for many monitoring application, while the emerging technologies discussed in the **Watersheds, Rivers, and Lakes** breakout session are likely to advance the science of DEM analysis. The use of both radar altimeter and LIDAR laser altimeter data should improve the spatial resolution of the elevation data collected.

The ERS-1 and Radarsat Satellites with radar imagers, altimeters, and scatterometers, can be used for studying ocean dynamics, such as waves, currents and fronts. The use of these attributes can lead to better understanding of the global climate, pollutant movement, coastal processes and physical oceanography.

Small aircraft sensors such as MSS, video cameras, thermal infrared, and microwave radiometers have the attributes of high spatial resolution and are multi-spectral. The above sensors are likely applicable to the advanced study of coastal-estuarine processes and can remotely monitor properties such as ocean color, temperature, salinity, features, plumes, fronts and. These attributes allow for monitoring of tidal effects, plankton blooms, and pollutant dynamics.

The European Space Agency ERS-2 and the ADEOS-2 NASA Scatterometer (NSCAT) sensors that are presently operational and measure wind velocities over the ocean. The footprint of these sensors is 15-km or greater, which constrains their use in coastal, estuarine and Great Lakes monitoring.

Emerging Technologies

Color scanners such as SeaWiFS, OCTS, Landsat-7, hyperspectral scanners, and the AVHRR, for sea surface temperature, provide scientists with additional tools for water quality monitoring. Aircraft tools include hyperspectral imagers such as the AVIRIS, which flies at high altitude on sophisticated aircraft, and smaller hyperspectral imagers, that can fly on low altitude aircraft which are relatively inexpensive to operate.

Better algorithm techniques are being developed for these emerging technologies to more accurately identify ground items according to their spectral signature.

SeaWiFS successfully launched into orbit in 1997. Data are available from NASA for research purposes and direct real-time reception of data is available for commercial and government purposes. It is possible to purchase a license to receive these data from Orbital Sciences Corporation. This satellite collects information about ocean color, chlorophyll, temperature, dissolved organic compounds, pollutants, etc. Its applications range from studying ocean productivity, fisheries management and pollution control to marine biology. Some of the problems that are inherent to this system involve the need for calibration of the collected data. Algorithms need further development to overcome problems with atmospheric correction. Another data sensing problem is in the lack of days in which remote sensing can take place due to cloud cover.

NASA's MODIS is an advanced NASA ocean color scanner scheduled for launch in 1999 on the EOS-Terra platform.

APPENDIX A

WORKSHOP AGENDA

December 11, 1996

7:30-8:15am Registration

8:15-8:45am Welcome and Introductory Remarks

- Dr. Nancy G. Maynard, Deputy Director, Science Division, NASA's Office of *Mission to Planet Earth* (OMTPE)
- Dr. Joe Alexander, Deputy Assistant Administrator for Science, EPA's Office of Research and Development (OR&D)
- Dana Minerva, EPA's Deputy Assistant Administrator of Water

8:45-10:15am **EPA's Water Monitoring Mission Tutorial**

- Elizabeth Fellows, Chief, Monitoring Branch, "EPA's Water Monitoring Mission"
- Douglas Norton, Watershed Branch, "EPA's Water Monitoring Needs"

10:15-10:30am Break

10:30-12:00pm **NASA' Remote Sensing Tutorial**

- Dr Ghassem Asrar, Earth Observing System (EOS) Chief Scientist, "Mission to Planet Earth Program"
- Dr. Ramapriyan, Earth Science Data Information System (ESDIS), "Earth Observing System Data Information System (ESDIS)"

12:00-1:45pm Lunch

- Luncheon Speaker: Dr. Charles G. Groat, Director, Center for Environmental Resource Management, University of Texas at El Paso.

1:45-2:00pm Breakout Panel Instructions; Douglas Norton, Watershed Branch.

2:00-5:00pm Joint EPA/NASA Breakout Panels (w/working break)

1) Wetlands (Co-Moderators: Dr. Vic Klemas-NASA and Peter Stokley-EPA)

2) Watersheds, Lakes, Rivers (Co-Moderators: Barry Burgan-EPA and Dr. Ted Engman-NASA)

5:30-7:00pm Reception

December 12, 1996

8:00-11:30am Joint EPA / NASA Breakout Panels (w/working Break)

1) Oceans and Estuaries (Co-Moderators: Dr. James Yoder-NASA and Joe Hall-EPA)

2) Groundwater (Co-Moderators: Joe D'Lugosz-EPA and Dr. James Arnold-NASA)

11:30-1:00pm Box Lunch

1:00-1:30pm EPA/NASA Summary Findings and Recommendations-Wetlands Panel

1:30-2:00pm EPA/NASA Summary Findings and Recommendations-Watersheds, Lakes Rivers Panel

2:00-2:30pm EPA/NASA Summery Findings and Recommendations-Oceans, and Estuaries Panel

2:30-3:00pm EPA/NASA Summary Findings and Recommendations-Groundwater Panel

3:00-3:30pm Concluding Statements (Alex Tuyahov, NASA and Steve Lingle, EPA)

December 13, 1996

8:00-12:00am Breakout Panel EPA / NASA Co-Moderators prepare Draft Workshop Report

APPENDIX B

REMOTE SENSING DATA SOURCES AND INFORMATION

EARTH OBSERVATION SATELLITES: PAST

The following table includes those satellites that are no longer operational. It is limited to sensors that were intended for remote sensing of the Earth surface.

Table Appendix B.1. Listing of Past Earth Resource Satellites

Satellite Name	Source	Dates of Service	Sensors	Types	No. of Channels	Resolution (meters)
Landsat-1 (ERTS-1)	US	1972-1978	MSS	Multispectral	4	79
			RBV	Video	3	80
Landsat-2	US	1975-1982	MSS	Multispectral	4	79
			RBV	Video	3	80
SEASAT	US	1978-1978	SAR	Radar	1	25
Landsat-3	US	1978-1983	MSS	Multispectral	4	79
					1	240
			RBV	Video	1	30
Nimbus-7	US	1978-1986	CZCS	Multispectral	6	825-1000

Table Appendix B.1. Continued. Listing of Past Earth Resource Satellites

Satellite Name	Source	Dates of Service	Sensors	Types	No. of Channels	Resolution (meters)
NOAA-6	US	1979-1987	AVHRR	Multispectral	4	1100
NOAA-7	US	1981-1986	AVHRR	Multispectral	5	1100
NOAA-8	US	1983-1985	AVHRR	Multispectral	4	1100
SPOT-1	France	1986-1990	HRV	Multispectral	3	20
				Panchromatic	1	10
MOS-1	Japan	1987-1995	MESSR	Multispectral	4	50
			VTIR	Multispectral	1	900
					3	2700
NOAA-11	US	1988-1994	AVHRR	Multispectral	5	1100
MOS-1b	Japan	1990-1996	MESSR	Multispectral	4	50
			VTIR	Multispectral	1	900
					3	2700
ALMAZ-1	Russia	1991-1992	SAR	Radar	1	11-18

EARTH OBSERVATION SATELLITES: CURRENT

The following table includes those satellites that are operational. It is limited to sensors that are intended for remote sensing of the Earth surface.

Table Appendix B.2. Listing of Current Earth Resources Satellites

Satellite Name	Source	Dates of Launch	Sensors	Types	No. of Channels	Resolution (meters)
Landsat-4	US	1982	MSS	Multispectral	4	82
			TM	Multispectral	6	30
					1	120
Landsat-5	US	1984	MSS	Multispectral	4	82
			TM	Multispectral	6	30
					1	120
NOAA-9	US	1985	AVHRR	Multispectral	5	1100
NOAA-10	US	1986	AVHRR	Multispectral	4	1100
IRS-1A	India	1988	LISS-I	Multispectral	4	72.5
			LISS-II	Multispectral	4	36.25

Table Appendix B.2. Continued. Listing of Current Earth Resources Satellites

Satellite Name	Source	Dates of Launch	Sensors	Types	No. of Channels	Resolution (meters)
SPOT-2	France	1990	HRV	Multispectral	3	20
				Panchromatic	1	10
IRS-1B	India	1991	LISS-I	Multispectral	4	72.5
			LISS-II	Multispectral	4	36.25
NOAA12	US	1991	AVHRR	Multispectral	5	1100
ERS-1	ESA	1991	AMI	Radar	1	26
			ATSR	Multispectral	4	1000
JERS-1	Japan	1992	SAR	Radar	1	18
			OPS	Multispectral	7	18 x 24
SPOT-3	France	1993	HRV VTIR	Multispectral	3	20
				Panchromatic	1	10

Table Appendix B.2. Continued. Listing of Current Earth Resources Satellites

Satellite Name	Source	Dates of Launch	Sensors	Types	No. of Channels	Resolution (meters)
RESURS-01-3	Russia	1994	MSU-SK	Multispectral	4	170
					1	600
NOAA-14	US	1994	AVHRR	Multispectral	5	1100
IRS-1C (link2)	India	1995	LISS-II	Multispectral		
					1	70
			Pan	Panchromatic	1	5.8
ERS-2	ESA	1995	AMI	Radar	1	26
			ATSR	Multispectral	4	1000
RADARSAT	Canada	1995	SAR	Radar	1	9-100
ADEOS	Japan	1996	OCTS	Multispectral	4	16
			AVNIR	Multispectral	4	16
				Panchromatic	1	8

EARTH OBSERVATION SATELLITES: FUTURE

The following table includes those satellites that were planned for future operation at the time of the Workshop. It is limited to sensors that are intended for remote sensing of the Earth surface. Updates on the status of various sensors are provided where possible. Keeping the perspective of this list from the vantage point of 1996 helps the reader understand what the Workshop participants considered future technologies.

Table Appendix B.3. Listing of Future Earth Resource Satellites

Satellite Name	Source	Launch	Sensors	Types	No. of Channels	Resolution (meters)
Early Bird	EarthWatch	1997 in-orbit		Multispectral	3	15
				Panchromatic	1	3
Lewis	US (TRW) re-entered	1997	HSI	Multispectral	384	30
				Panchromatic	1	15
Clark	US (CTA)	1997	Clark	Multispectral	3	15
				Panchromatic	1	3
NOAA-K (#15)	US in-orbit	1997	AVHRR	Multispectral	5	1100
SeaStar	US / Orbimage	1997 in-orbit	SeaWIFS	Multispectral	8	1130

IKONOS	Space Imaging / EOSAT	1998 failed	Space Imaging	Multispectral	4	4
				Panchromatic	1	1

Table Appendix B.3. Continued. Listing of Future Earth Resource Satellites

Satellite Name	Source	Launch	Sensors	Types	No. of Channels	Resolution (meters)
OrbView-3	Orbimage	2000	OrbView	Multispectral	4	4
				Panchromatic	2	1-2
SPOT-4	France	1998 in-orbit	VI	Multispectral	4	1000
			HRV	Multispectral	4	20
				Panchromatic	1	10
RESURS-O2	Russia	2002	MSU-SK	Multispectral	4	170
					1	600
CBERS	China/Brazil	1999	CCD	Multispectral	5	20
			IRMSS	Multispectral	3	180

					1	160
Landsat-7	US	1999 in-orbit	ETM+	Multispectral	6	30
					1	60
				Panchromatic	1	15

Table Appendix B.3. Continued. Listing of Future Earth Resource Satellites

Satellite Name	Source	Expected Launch	Sensors	Types	No. of Channels	Resolution (meters)
EOS AM-1 now Terra	US	1999	ASTER	Multispectral	14	15-90
			MISR	Multispectral	4	275
			MODIS	Multispectral	36	250-1000
QuickBird		2000	Multispectral	Multispectral	4	3.2
			Panchromatic	Panchromatic	1	0.82
ALMAZ-2	Russia	1999	OES	Multispectral	3	4
				Panchromatic	1	2.5

			MSU-E	Multispectral	3	10
			MSU-SK	Multispectral	4	80
					1	300
			SROSM	Multispectral	11	600
			SAR	Radar	9	15-30

Table Appendix B.3. Continued. Listing of Future Earth Resource Satellites

Satellite Name	Source	Expected Launch	Sensors	Types	No. of Channels	Resolution (meters)
IKONOS 2	Space Imaging	1999 in-orbit	Space Imaging	Multispectral	4	4
				Panchromatic	1	1
Resource 21	Resource21	1999	Multispectral	Multispectral	5	10-20
			Cirrus	Multispectral	1	100+
NOAA-L	US	2000	AVHRR	Multispectral	5	1100
LightSAR	US	2002	SAR	Radar	4	3-100
ADEOS-II	Japan	1999	GLI	Multispectral	34	250-1000

ENVISAT						
	ESA	1999	ASAR	Radar		
			MERIS	Multispectral		
EOS PM-1	US	2000	MODIS	Multispectral	36	250-1000

Table Appendix B.3. Continued. Listing of Future Earth Resource Satellites

Satellite Name	Source	Expected Launch	Sensors	Types	No. of Channels	Resolution (meters)
ALOS	Japan	2002	VSAR	Radar	1	10
			AVNIR-2	Multispectral	4	10
				Panchromatic	1	2.5
NOAA-M	US	2003	AVHRR	Multispectral	5	1100
SPOT-5	France	2002	HRV	Multispectral	3	10
					1	20
				Panchromatic	1	5
EOS AM-2	US	2004	LATI	Multispectral	[redacted]	
			AMISR	Multispectral		
			AMODIS	Multispectral		

APPENDIX C

EPA/NASA WORKSHOP ON WATER MONITORING, REMOTE SENSING, AND ADVANCED TECHNOLOGIES ATTENDANCE LIST

Joe Alexander USEPA 401 M Street SW Washington, DC 20460 Phone: Fax: E-mail:	John Anderson Virginia Institute of Marine Sciences Gloucester Point, Virginia 23062 Phone: 1-804-642-7182 Fax: 1-804-642-7335 E-mail: johna@vims.edu
Jim Arnold Virginia Institute of Marine Sciences Gloucester Point, Virginia 23062 Phone: 1-202-358-0540 Fax: 1-202-358-2770 E-mail: jim.arnold@hq.nasa.gov	Roger C. Bales Department of Hydrology & Water Resources University of Arizona P.O. Box 21001 Tucson, Arizona 85721 Phone: 1-520-621-7113 Fax: 1-520-621-1422 E-mail: roger@hwr.arizona.edu
Jim Brass NASA Ames Research Center MS 242-4 Moffett Field, California 94035 Phone: Fax: E-mail: jbrass@mail.arc.nasa.gov	Don Brown USEPA - ORD 26 W. M. L. King Drive Cincinnati, Ohio 45268 Phone: -513-569-7630 Fax: 1-513-569-7185 E-mail: brown.donald@epamail.epa.gov
David Burden USEPA - NRMRL P.O. Box 1198 Ada, Oklahoma 74820 Phone: 1-405-436-8606 Fax: 1-405-436-8597/8614 E-mail: burden@ad3100.ada.epa.gov	Barry Burgan USEPA 401 M Street SW Washington, DC 20460 Phone: 1-202-260-7060 Fax: 1-202-260-1977 E-mail: burgan.barry@epamail.epa.gov

Virginia Burkett U.S. Geological Survey National Wetlands Research Center 700 Cajundome Boulevard Lafayette, Louisiana, 70506 Phone: 1-318-266-8636 Fax: 1-318-266-8592 E-mail: burkettv@nwrc.gov	Janet W. Campbell University of New Hampshire Ocean Process Analysis Laboratory Morse Hall Durham, New Hampshire 03824 Phone: 1-603-862-1070 Fax: 1-603-862-0243 E-mail: Campbell@kelvin.sr.unh.edu
Jeff Chanton Florida State University Dept of Oceanography Tallahassee, Florida 32306-3048 Phone: 1-904-644-7493 Fax: 1-904-644-2581 E-mail: jchanton@mailer.fsu.edu	Paula G. Coble University of South Florida Department of Marine Science 140 Seventh Ave S St Petersburg, Florida 33701 Phone: 1-813-893-9631 Fax: E-mail: pcoble@seas.marine.usf.edu
Tim Collette USEPA - ORD Ecosystems Research Division 960 College Station Road Athens, Georgia 30605 Phone: 1-706-355-8211 Fax: 1-706-355-8202 E-mail: collette.tim@epamail.epa.gov	Tod Dabolt USEPA Mail Code 4503F OWOW 401 M Street SW Washington DC 20460 Phone: 1-202-260-3697 Fax: E-mail: dabolt.thomas@epamail.epa.gov
Thomas J. Danielson USEPA Mail Code 4502F Wetlands Division 401 M Street SW Washington, DC 20460 Phone: 1-202-260-5299 Fax: 1-202-260-8000 E-mail: danielson.tom@epamail.epa.gov	Joseph J. DLugosz Research Hydrologist National Health and Environmental Effects Research Laboratory Mid-Continent Ecology Division 6201 Congdon Boulevard Duluth, MN, 55804-2595 Phone: 1-218-720-5550 Fax: 1-218-720-5539 E-mail: jdlugosz@michigan.dul.epa.gov
Marla Downing USEPA 726 Minnesota Kansas City, Kansas 66215 Phone: -913-551-7362 Fax: E-mail: downing.marla@epamail.epa.gov	Peter R. Jutro USEPA Mail Code 8106 401 M Street SW Washington, DC 20460 Phone: 1-202-260-5937 Fax: E-mail: dutro.peter@epamail.epa.gov

Dr Edwin T Engman Code 974 NASA, Goddard Space Flight Center Greenbelt, MD 20771 USA Phone: 301-286-5355 Fax: 301-286-1758 tengman@neptune.gsfc,nasa.gov	Elizabeth Fellows USEPA 401 M Street SW Washington, DC 20460 Phone: Fax: E-mail: fellows.elizabeth@epamail.epa.gov
Murray Felsher Associated Technical Consultants P.O. Box 20 Germantown, Maryland 20875-0020 Phone: 1-301-428-0557 Fax: 1-301-428-0557 E-mail: mfelsher@hq.nasa.gov	Tim Foresman University of Maryland Baltimore County Department of Geography 1000 Hilltop Circle Baltimore, Maryland 21250 Phone: 1-410-455-3149 Fax: 1-410-455-1056 E-mail: foresman@umbc.edu
David Friedman USEPA Mail Code 8104 401 M Street SW Washington, DC 20460 Phone: 1-202-260-3535 Fax: E-mail: friedman.david@epamail.epa.gov	Valerie Garcia USEPA Mail Code 8102 401 M Street SW Washington, DC 20460 Phone: 1-202-260-7492 E-mail: garcia.val@epamail.epa.gov
Donald Garofalo USEPA - ORD 12201 Sunrise Valley Drive 555 National Center Reston, Virginia 20192 Phone: 1-703-648-4285 Fax: 1-703-648-4290 E-mail: garofalo.donald@epamail.epa.gov	Marilyn Ginsberg USEPA Mail Code 4606 401 M Street SW Washington, DC 20460 Phone: 1-202-260-8804 Fax: 1-202-260-0732 E-mail ginsberg.marilyn@epamail.epa.gov
Charles Groat University of Texas at El Paso Center for Environmental Resource Management P.O. Box 645 El Paso, Texas 78812 Phone: 1-915-747-5954 Fax: 1-915-747-5145 cgroat@utep.edu	Diane Alford Guthrie USEPA - Region 4 Science and Ecosystem Support Division 980 College Station Road Athens, Georgia 30605 Phone: 1-706-355-8672 Fax: E-mail: dgutherie@epamail.epa.gov

Joe Hall Mail Code 4504F - OCPD 401 M Street SW Washington, DC 20460 Phone: 1-202-260-9082 Fax: 1-202-260-9960 E-Mail: hall.joe@epamail.epa.gov	Jack Hess Desert Research Institute Water Resources Center P.O. Box 19040 Las Vegas, Nevada 89132-0040 Phone: 1-702-895-0451 Fax: 1-702-895-0496 E-mail: jack@snsc.dri.edu
Oscar K. Huh Louisiana State University Costal Studies Institute Baton Rouge, Louisiana 70803 Phone: 1-504-388-2952 Fax: 1-504-388-2520 E-mail: oscar@antares.esl.lsu.edu	Mike Kearney University of Maryland Department of Geography College Park, Maryland 20742 Phone: 1-301-314-9299 Fax: 1-301-405-4057 E-mail: mk11@umail.umd.edu
Darryl Keith USEPA Atlantic Ecology Division 27 Tarzwell Drive Narrangansett, Rhode Island 02882 Phone: 1-401-782-3135 Fax: 1-401-782-3030 E-mail: keith.darryl@epamail.epa.gov	Stuart Kerzner USEPA Water Protection Division 841 Chestnut Building (3WP40) Philadelphia, Pennsylvania 19107 Phone: 1-215-566-5709 E-mail: kerzner.stu@epamail.epa.gov
Vic Klemas University of Delaware College of Marine Studies Newark , Delaware 19716 Phone: 1-302-831-8256 Fax: 1-302-831-6838 E-mail: victor.klemas@mvs.udel.edu	Art Koines USEPA - OPPE 401 M Street SW Washington, DC 20460 Phone: 1-202-260-4030 Fax: 1-202-260-0275 E-mail: koines.arthur@epamail.epa.gov
Tim Kratz University of Wisconsin Trout Lake Station 10810 County N Boulder Junction, Wisconsin 54512 Phone: 1-715-356-9494 Fax: 1-715-356-6866 E-mail: kkratz@facstaff.wisc.edu	Harold R. Lang Jet Propulsion Laboratory M183-501 4800 Oak Grove Drive Pasadena, California 91009 Phone: 1-818-354-3440 Fax: 1-818-354-0966 E-mail: harold@lithos.jpl.nasa.gov

Steve Lingle USEPA Mail Code 8722 ORD 401 M Street SW Washington, DC 20460 Phone: 1-202-260-2619 Fax: 1-202-260-4524 E-mail: lingle.stephen@epamail.epa.gov	George Loeb USEPA Mail Code 4504F - OWOW 401 M Street SW Washington, DC 20460 Phone: 1-202-260-0670 Fax: 1-2020-260-9960 E-mail: loeb.george@epamail.epa.gov
W. Berry Lyons University of Alabama Department of Geology Box 870338 Tuscaloosa, Alabama 35487-0338 Phone: 1-205-348-0583 Fax: 1-205-348-0818 E-mail: blyons@wgs.geo.ua.edu	Thomas H. Mace USEPA Mail Code MD-34 OIRM Research Triangle Park, NC 27713 Phone: 1-919-541-2710 Fax: 1-919-541-7670 E-mail: mace.tom@epamail.epa.gov
Tom Maddock University of Arizona Department of Hydrology Harshberger Bldg Tucson, Arizona 85271 Phone: 1-520-621-7115 Fax: 1-520-621-1422 E-mail: maddock@hwr.arizona.edu	Nancy Maynard Science Division - Code YS 300 E Street SW Washington, DC 20546 Phone: 1-202-358-2559 Fax: 1-202-358-2770 E-mail: nancy.maynard@hq.nasa.gov
John Melack University of California Santa Barbara Environmental Science and Management Santa Barbara, California 93106 Phone: 1-805-893-3879 Fax: 1-805-893-4724 E-mail: melack@lifesci.ucsb.edu	Rick Miller NASA Earth System Science Office 5A00 Stennis Space Center, Mississippi 39529 Phone: 1-601-688-1904 Fax: 1-601-688-1777 E-mail: richard.miller@ssc.nasa.gov
Leslie Morrissey University of Vermont School Natural Resources Burlington, Vermont 05405 Phone: 1-802-656-2695 Fax: 1-802-656-8683 E-mail: lmorriss@nature.snr.urm.edu	Peter H. Murtaugh USEPA - Region 8 GIS RF3 999 18th Street, Suite 500 (8TMS-D) Denver, Colorado 80202-2466 Phone: Fax: E-mail:

John Mustard Brown University Department Geological Science Box 1846 Providence, Rhode Island 02912 Phone: 1-401-863-1264 Fax: 401-863-3978 E-mail: john.mustard@brown.edu	Doug Norton USEPA Mail Code 4503F 401 M Street SW Washington, DC 20460 Phone: 1-202-260-7017 Fax: 1-202-7024 norton.douglas@epamail.epa.gov
Jeff G. Paine University of Texas at Austin Bureau of Economic Geology University Station Box X Austin, Texas 78713 Phone: 1-512-471-1260 Fax: 1-512-471-0140 E-mail: paine@begu.beg.utexas.edu	Earnest D. Paylor II NASA Code YS 300 E Street SW Washington, DC 20460 Phone: 1-202-358-0756 / 0273 Fax: 1-202-358-2770 E-mail: epaylor@hq.nasa.gov
Jim Perry Virginia Institute of Marine Sciences Gloucester Point, Virginia 23062 Phone: 1-804-642-7182 Fax: 1-804-642-7388 E-mail: jperry@vims.edu	Liz Porter USEPA Mail Code 2162 OPPE 401 M Street SW Washington, DC 20460 Phone: 1-202-260-6129 Fax: 1-202-260-4903 E-mail: porter.elizabeth@epamail.epa.gov
Dale Quattrochi NASA Marshall Space Flight Center Global Hydrology and Climate Center 977 Explorer Blvd Hunstville, Alabama 35806 Phone: 1-205-922-5887 Fax: 1-205-922-5723 Fax: dale.quattrochi@msfc.nasa.gov	Jon Ranson NASA Goddard Space Flight Center Code 923 Greenbelt, Maryland 20771 Phone: 1-301-286-4041 Fax: 1-301-286-1757 E-mail: jon@taiga.gsfc.nasa.gov
Jerry C. Ritchie U.S. Department of Agriculture Agricultural Research Service Hydrology Lab BARC-West Building 007 Beltsville, Maryland 20705 Phone: 1-301-504-8717 Fax: 1-301-504-8931 E-mail: jritchie@hydrolab.arsusda.gov	Doreen Robb USEPA Mail Code 4502F 401 M Street SW Washington, DC 20460 Phone: 1-202-260-1906 Fax: 1-202-260-8000 E-mail: robb.doreen@epamail.epa.gov

Alan C. Rush USEPA Mail Code 6301 Office of Air Quality Planning & Standards 401 M Street SW Washington, DC 20460 Phone: 1-202-260-5575 Fax: 1-202-260-0451 E-mail: rush.alan@epamail.epa.gov	Jill Scharold USEPA Med 6201 Congdon Blvd Duluth, Minnesota 55804 Phone: 1-218-720-5783 Fax: E-mail: epajvs@du4500.dul.epa.gov
Sue Schock USEPA NCEA-Cincinnati, Ohio Phone: 1-513-569-7551 Fax: E-mail: schock@epamail.epa.gov	Gary Shelton NASA Code YS 300 E Street SW Washington, DC 20546 Phone: 1-202-358-0752 Fax: 202-358-2770 E-mail: gary.shelton@hq.nasa.gov
Bob Stewart U.S. Geological Survey National Wetlands Research Center 700 Cajundome Boulevard Lafayette, Louisiana 70506 Phone: 1-318-266-8501 Fax: 1-318-866-8610 E-mail: stewartb@mwrc.gov	Peter Stokely EPA/EPIC 12201 Sunrise Valley Drive 555 National Center Reston, Virginia 20192 Phone: 1-703-648-4292 Fax: 1-703-648-4290 E-mail: stokely.peter@epamail.epa.gov
David Stoltenberg USEPA Region 5 Water standards & Applied Sciences Branch 77 W Jackson Chicago, Illinois 60604 Phone: 1-312-353-5784 Fax: 1-312-886-7804 E-mail: stoltenberg.david@epamail.epa.gov	Ray Thompson USEPA Region 1 Office of Environmental Measurement & Evaluation 60 Westview Street Lexington, Massachusetts 02173 Phone: 1-617-860-4372 Fax: 1-617-860-4397 E-mail: thompson.ray@epamail.epa.gov
David Toth USEPA Region 3 841 Chestnut Bldg Philadelphia, Pennsylvania 19107 Phone: 1-215-566-2720 Fax: 1-215-566-2782 E-mail: toth.david@epamail.epa.gov	Ramona Pelletier Travis NASA Building 1100 Code 5A00 Stennis Space Center, MS 39529 Phone: 1-601-688-1910 Fax: 1-601-688-1777 R-mail: ramona.travis@ssc.nasa.gov

Alexander J. Tuyahov NASA Code YS 300 E Street SW Washington, DC 20546 Phone: 1-202-358-0250 Fax: 1-202-358-3098 E-mail: atuyahov@hq.nasa.gov	Susan Ustin University of California, Davis Depart. of Land, Air, and Water Resources 113 Veihmeyer Hall Davis, California 95616 Phone: 1-916-752-0621 / 5092 Fax: 1-916-752-5262 E-mail: slustin@ucdavis.edu
Ming-Ying Wei NASA Code YS 300 E Street SW Washington, DC 20546 Phone: 1-202-358-0771 Fax: 1-202-358-2771 E-mail: ming-ying.wei@hq.nasa.gov	Bill Wilen U.S. Fish and Wildlife Service 4401 North Fairfax Drive 400 ARLSQ Arlington, Virginia 22203 Phone: 1-703-358-2161 Fax: 1-703-358-2232 E-mail: bill_wilen@mail.fws.gov
Janice Wiles University of Maryland 1420 Webster Street NW Washington, DC 20011 Phone: 1-202-829-0346 Fax: E-mail: wiles@cbl.cees.edu	Randolph H. Wynne VPI and State University Department of Forestry Blacksburg, Virginia 24061-4024 Phone: 540-231-7811 Fax: 540-231-3698 E-mail: wynne@vt.edu
James A. Yoder NASA Code YS 300 E Street SW Washington, DC 20546 Phone: 1-202-358-0310 Fax: E-mail: jyoder@hq.nasa.gov	

APPENDIX D

COMMENTS ON MONITORING NEEDS FROM EPA's REGIONAL OFFICES

Comments were sorted into four categories that correspond with the four questions asked in the EPA survey. These comments are identified with specific EPA Regions when the respondent chose to include that information. In cases where the respondent did not identify the EPA Region, that information was left blank. There have been very few edits to the solicited responses in order to prevent any misinterpretation of the respondents' message.

Answers to the four main questions:

1. What are the most prominent water quality problems in your area and in what kind of water bodies are they occurring?

In **Region 9**, there are three kinds of important water quality issues: First, the deterioration of fish stocks and biological quality of streams because of engineered alterations of water flows, including dams and water diversions. Second, the eutrophication of water bodies because of sediment and nitrogen inputs from a number of non-permitted sources, including forestry activities, agricultural practices, and urban activities. Third, input of toxic materials and pesticides to water bodies from a variety of sources, the largest contributors being large scale agriculture and oil related industries. Water bodies affected are rivers and streams, and coastal marine resources.

Almost all of the water quality problems within **Region 7** are the result of agricultural stresses. Top areas include Non-point sources--agricultural runoff; confined animal feeding operations; agricultural--irrigation diversions (flow reduction); agricultural--irrigation returns; point sources--TMDL's; and "Manipulated " water systems--altered flows; reservoirs; impoundments.

Non-point source inputs from agriculture are most prominent; most importantly the destruction of habitat and sediment loading in streams. Pesticides and herbicides in the water column may be more of a perception than a problem. Is about to look at some data collected as part of a REMAP project. Alteration of habitat including siltation and channel straightening is a problem. Draining of wetlands has also been a contributor.

The most prominent water quality problems in the **north central states** are:

- In stream aquatic life habitat degradation in rivers, streams, and linear wetlands; caused by a variety of factors, including channelization, storm water runoff, non-point source runoff, draining of wetlands, acid mine drainage, and impoundments.

- Eutrophication and sedimentation of lakes; caused by nutrients and sediments from both point sources and non-point sources of discharge.

- Specific toxics problems in specific areas, some of which result in fish advisories.

- Great Lakes water quality issues, which involve toxic substances and air deposition.

For the **south-central US**, land use information that gives greater insight into nonpoint source pollution is the greatest general need. Precipitation and flow data would be useful. Water temperature problems abound. Habitat structure is a widespread problem, as is sediment. Best management practices related to various nonpoint problems would be welcome, as would real-time data, and such advancements as telemetry for real-time feedback on issues such as flow.

There are several areas of concern in **Missouri**. It depends on from what point of view one looks for problems. In the area of domestic (private) wells. The primary problem is bacteria. This is for the most part fecal coliform. The most direct and perhaps least sensitive is to say that a lot of people are probably drinking out of their septic tanks. The close second problem is nitrates. The sources are varied, running the gamut from nitrogen fertilizer, CAFO runoff, lightning, etc, etc. The third area of concern in private wells is fairly distant from the other two - pesticides. While there are pesticide detections, they are few and low in concentration. Many of the positive wells are poorly constructed creating a strong case for localized point source contamination.

There are very few problems in public drinking wells. There have been a few, low concentration pesticide detections picked up by the Safe Drinking Water Act monitoring. Perhaps our most widely publicized problem is in small surface water reservoirs used as public drinking water supplies. Some of these are so small that you can stand on the dam and see the entire watershed. In 1994 10 of these small watersheds were given notices of violation for exceeding the atrazine MCL. Other watersheds were very close. There were numerous other watersheds that had detections of other pesticides. Again these were monitored through the SDWA.

New England's most common problems include: Non-point source identification and its contributors: eutrophication problems, e.g., algae blooms, Eurasian milfoil, expansion of eel grass beds in estuaries. Metal and toxics in fish tissues. Acid sensitive lakes and forests - states monitor, but do not provide the resulting information. Ability to assess overall condition of forests, habitats and surrounding water bodies. Can now break out upland versus coastal water quality; but within the lowlands there is a need to differentiate at the sub-eco levels. Need to separate out the impacts of high density urbanization on water quality versus the impacts of suburban or rural areas on water quality. Need to address issues of scale. Wetlands - need information on wetlands losses and gains by wetland type; need to know where the losses are occurring; this information should be made available through the permits program nationally.

Although the most obvious issues relate to surface water contamination, a major problem is that there isn't good monitoring data to use in determining the real type and magnitude of contamination in either surface or groundwater. All types of water bodies have been impacted, including such rare forms as vernal pools. One of the most widespread problems in surface water is pesticides and nitrates. Groundwater also has nitrate problems as well as contamination by various types of chemicals, including pesticides. Pesticides occur within both urban and rural groundwater. Groundwater has an additional monitoring problem in that part of the cause of a lack of quality monitoring data is due to Safe Drinking Water Act sampling which samples mainly water supply wells and these often do not represent the actual groundwater quality. The following list is not prioritized. Prioritization is difficult for an entire region since different parts of the state/region will have different "big" problems in their area:

- pesticides and nitrates in surface and groundwater (often considered nonpoint source)
- acid mine drainage and/or metals into streams and/or rivers - can be somewhat "localized" in that the concentrations are significantly diluted within a few miles
- pesticides and nitrates, sediment, and NPDES chemicals brought into estuaries by rivers as well as discharged directly into the estuaries
- insufficient flows and inappropriate water temperatures for maintaining healthy aquatic ecosystems
- siltation due to farming sediment, construction sediment, timber harvesting, etc.
- contamination of shallow groundwater by industrial chemicals emplaced by various means
- landfill leakage into groundwater and/or surface water
- nonpoint source pollution of surface waters and bays in the urban areas, usually via storm drains

- contaminated sediments due to industrial and military activity found in rivers, bays, and along the coast

2. ***Which of these are not well monitored and why?***

None of the problems are monitored well enough so that the information could be used for management and regulatory decisions that would have an influence on water quality.

None of the above are well monitored and many are not monitored at all. The lack of quality monitoring data on all aspects of water quality cannot be overemphasized. The reason is simply that the funds necessary to build the sampling infrastructure and maintain data collection over time has never been appropriated at any governmental level, particularly on the necessary scale. The sampling frequency is usually insufficient. Sampling locations are too few and often based on convenience rather than optimal sites. Sampling procedures are not uniform and the reporting of results is not standardized. Most of the older data is not readily accessible because it is on paper or in obsolete databases and there are no plans to translate it to electronic format or into fully relational databases. Good spatial location information (<1 m accuracy) is rarely available so the information cannot be readily input to a GIS.

The State is doing the monitoring (except for REMAP). There is a lack of on-the-ground empirical data on water quality and biology (305b assessments are not very good). Remote sensing is a good thing which might have some utility, but it is hard to see it benefitting without available empirical data. The CWA is not very prescriptive regarding how to monitor or the amount of monitoring which should be conducted. More often, monitoring is not very good and some states are not politically motivated to do this. If they do find problems, they then have to figure out how to fix them. Remote sensing is just one of the tools to be used for monitoring.

Eutrophication is well monitored. Non-point sources and supporting land use/land cover is not well monitored. Physical habitat is not monitored at all, except for the collection of some biological integrity information.

Region uses databases developed and maintained by the States and USGS. Much of the data are collected using different methods and technologies, so often the data cannot be aggregated. They have resorted to overlaying the different data sets within a GIS framework to define trends from the data. The Region only collects its own data for enforcement activities. They have an interest in metals, microbiology, pesticides, temperature, and biology.

Outside of the SDWA monitoring there is little regular monitoring of water quality. Therefore, the worst monitoring would be in private well sector. The reason? Funding, or the lack thereof. There is some difficulty in the public drinking reservoirs. While we know that there is atrazine et al applied in the watershed, and we know there is atrazine et al in the reservoir, we don't know from which acres the contamination really comes. We feel that if we could apply the 80/20 rule we could solve our problem. That is, if we could work with the 20% of the acres causing 80% of the contamination, we could limit contamination with minimal impact on the grower. There are two difficulties, lack of funding and the lack of an inexpensive easy-to-use method to monitor the watershed to learn from where the contamination is coming.

All of the water bodies are not well monitored. The states do very little "random" monitoring, but rather focus almost entirely on problems. As to what data are available for their use, RF3 data are incomplete and cannot be used; use/attainability data are not random enough for broad projections; in short, there are few data available for any unbiased scientific analyses. A REMAP project did involve random sampling--quantitative analysis--only at a very large scale (ecoregion). It was difficult to draw "regional" conclusions, as one state did not participate in the study. There are some follow-on land cover activities planned, however data are inconclusive to project to future "condition" scenarios.

In stream habitat conditions are not effectively monitored, due to the requirement for voluntary efforts and other resources, and the need to contact landowners for access. This might be a candidate for remote sensing, as represented by turbidity, light transmissivity, or some suitable measure.

A universal problem is the lack of the ability to monitor 100% of the major surface waters in any given State in any given 2-year 305(b) cycle. The main reason for this is a lack of resources. If there were a way to remotely monitor waters over a large area, with some degree of specificity, this would be of immense help to both Federal and State agencies.

A problem has developed in the **Gulf of Mexico**, west of the mouth of the Mississippi River. A large area of oxygen-deficient water has formed and has been in place for several years. The cause of this "Gulf Hypoxia" zone has not been fully determined, but is thought in part to be due to nitrogen loads coming down the Mississippi River. The implication, then, is that part of the problem originates in **Region 5**, but this has not been proven. A remote sensing technology would be of benefit in determining both the extent and cause(s) of this problem.

Changes in watersheds, such as land cover, wetland loss, and soil loss are not being effectively monitored; due to the large areas involved coupled with lack of resources. Remote sensing could be of great benefit here.

3. If you could reinvent water monitoring, what would you ideally like to be able to measure?

I would match the scale of monitoring activities to the scale of the regulatory and management decisions that affect water quality. I would put a lot of time into developing a "distributed" monitoring and information system that combined resources of different agencies and monitoring activities into a coordinated network over the landscape.

In addition to an inexpensive way to know the true condition of the water quality, it is critical to know from where the contamination is coming. With this knowledge, resources could be narrowly focused to the problem. This would eliminate "preaching to the choir" and over regulating those that are not causing the problem.

Extremely accurate spatial location information for each sampling point, such that the location would be accurate enough for use in geophysical surveys as well as GIS and other modeling programs (<0.5 m accuracy). The ability to detect and quantify trace concentrations of specific chemicals in all types of water bodies. The ability to accurately measure subsurface water quality with techniques that are easier, faster, and cheaper than monitoring wells. Perhaps too futuristic is the development of probes that could be placed in the ground to whatever depth needed that could take readings of water, soil/rocks, and air (vapor) compositions, temperature, pressure, etc. and have it sent via modem, phone or whatever directly to offices and into fully relational databases. The toxicity of the water body to all types of life and the ability to easily trace the key toxic component.

The simple collection of quality data isn't enough. The data should be collected in a format that is easily loaded into a fully relational database and GIS coverages routinely made. The data should be easily accessible so that GIS coverages, comparisons and interpretations can be made via computer graphics and programs at the staff level. The creation of GIS coverages should be automated.

Reinvention should follow a REMAP sampling regime, but with more funding to support more intensive sampling. Bring to bear available remote sensing tools and products to determine which sensors are reliable (confidence/statistical) for which levels of detail. Charcoal kilns in southwest **Missouri** and particulate matter emissions (P10) are a current problem. Current "manual" monitors overload almost immediately, and a sensor could provide good data (if available) for these high levels. Of course no legislation exists to deal with the issue.

A national monitoring program; a framework to consistently assess water quality in terms of chemical and biological integrity. Need more work on condition measurements.

Would like EPA first to be more prescriptive regarding a minimum level of monitoring; requirements for monitoring should be made stringent; for example, a certain percentage of a state must be monitored; certain kinds of data should be collected with specific quality assurance requirements. Need more dedicated resources to do monitoring. Monitoring is not well coordinated; must examine how data are/should be collected, and EPA should be the catalyst to make the coordinated monitoring happen. Note: a comment related to this - a fear that people using, for example, GIS, will go out and gather data collected from various sources using various methods, and will not understand or be able to properly assess the quality of the data they are using.

Biological assessments should be expanded and refined, and moved to the realm of remote sensing if possible.

Chemical and physical monitoring should be moved into the realm of remote sensing, if possible (as opposed to field sampling and lab analyses). This would increase the feasible area of assessment, and also decrease manpower requirements for monitoring.

Field and lab methods should be improved and made more cost-effective, especially for organics and metals.

Remote sensing would be a good way to track wetlands loss (or gain), one of the proposed environmental assessment indicators.

If possible, remote sensing should be used to track **Great Lakes** water quality issues.

If possible, remote sensing should be used to assist in watershed management, to address issues such as land cover, rain event impacts, and soil loss sediment loads in streams.

4. What are your ideas of "condition" in watersheds and water bodies, and how would you measure this?

I would adopt a multi-metric indexing system, based on econometric statistics. This is the method that was adopted by the EPA Rapid Bioassessment Program, and it could be developed and improved in significant ways.

There are insufficient data of adequate quantity and quality to really evaluate the health of most systems.

Region 7 does nothing like that now. They are working with their states through GAP to develop broad-scale vegetation classification maps (greenness ratios) to assess areas of high water quality. And they are utilizing more land cover data to approach assessments of condition, but are a far ways off. They have recently been asked by their RA to provide a briefing of their regional remote sensing capabilities...not EPA, but rather "local" centers of expertise within the region.

Databases dealing with chemistry and microbiology are not enough to address the problems...a strong biological component is also needed...perhaps something like an index of biological integrity. He gives strong support to holistic ecosystem approaches to addressing the problems in water, as they need quicker ways to develop and project status and trend for water bodies. Relative to NASA technologies, he very much supports continuation of remote sensing methods for land use/land cover changes over time, especially if the technologies could include a measure of animal counts (density).

The condition of **Region 5** water bodies can best be described in terms of the latest 305(b) water quality assessment reports, which show that, on the average, for rivers and streams, 66% of waters assessed were "good" (fully supporting or threatened for aquatic life use); and 34% were "fair to poor" (partially or non-supporting for aquatic life use). These figures are averages for the six States for 1994. The 1996 figures are not yet available. It should be noted that the 1994 assessments were based on only 23% of the total miles of rivers and streams in Region 5 (75,350 out of a total 324,000 mi.). Hopefully, by using advanced remote sensing techniques, the percentage of waters assessed could be significantly increased.

Ecological condition; the assemblages that we can identify and indicators to let us know when change is occurring and the causes of these changes; also linking rates of change and causes; e.g., fish assemblages and macroinvertebrates may not be the best indicators; a good indicator might be algae blooms; what are the indicators? Toxics - not only fish contamination but how the toxic pollutant is being transferred throughout the ecosystem; e.g., mercury - where is it coming from and how is it transferred; are there certain environmental conditions which cause higher levels of mercury in fish? Need to distinguish between natural causes and man-made causes, and be able to modify our behavior/actions to reduce/eliminate the impact of man-made causes. Need an easy method to measure pesticides residues in aquatic environments; now they cannot measure residues because they are short-lived; and the causes are not known.

Other general answers and recommendations:

The most prominent water quality problems are non-point source related... temperature, sedimentation in streams and rivers. In agricultural areas, nutrients are another issue. These parameters are currently not well monitored, due to insufficient funds. Data are usually obtained from states or other federal agencies. The only database used routinely is STORET, however data are not current. A USGS Home page has much more current data, but there are concerns about the quality/reliability of that data. The issue may not be one of requiring new technologies for monitoring, but rather using technologies that currently exist. If new technologies are cheaper, faster, more fieldable...and result in better, current data bases, then people will support their development/applications. Needs include having access to data for, temperature, sedimentation, nutrients, etc. Condition assessment would include holistic integration of biological, chemical, and physical parameters. Some parts of the region are attempting watershed analyses using this approach (TFW monitoring), however they still focus inordinately on habitat issues (no chemical). They currently use remote sensing imagery in GIS maps to identify forested land, soil types, and vegetation types.

The 1994 National Report identifies the number one cause of impairment in streams as bacteria. Yet, I still feel that the impairments due to bacteria are under-reported. There many reasons why this pollutant is under-reported including a 6 hour holding time on the sample preservation, representativeness of a bacteria sample, and a 48 hour processing time from sample collection to quantification. I find it amazing that we take a sample a water body, let people swim in it for 48 hours, and then decided to close a beach due to potential human health threats from bacteria identified in a sample that was collected 48 hours earlier. We need a better method. The FDA has been working on a instantaneous bacteria sample for E. coli in meat products. Perhaps we could build on that and come up with an instantaneous process for our beaches. The second biggest problem, again according to the 305b Report, is siltation. This is a problem that NASA may be able to assist in monitoring and identifying sources using remote sensing. This could be done by identifying areas where heavy erosion is occurring. We could also expand this parameter to examine areas of habitat modification using parameters such as erosion, temperature, channelization, and others. The NASA information could help identify areas were BMPs are most needed. Lastly, and more of Regional concern, is abandon mine drainage and acid deposition. Abandon mine drainage is the single largest source of impairment of aquatic life use in **Region III**. Approximately, 5,000 miles are impaired in R3 due to this pollutant. We feel that this is under-reported. Could NASA help identify other streams impaired across the Region? Can pH be monitored remotely? Is there another indicator that can be used? What about acid deposition from air pollution? Many of our states do not recognize acid deposition as a major problem. Some of our Regional Data have indicated that there is significant impacts on first order streams that are not routinely monitored by the states. Could NASA help identify impacted streams?

It appears to me, though a novice in this area still, that in a State like **New York** there are just too many water bodies to assess and that may be their biggest problem RE monitoring. NY indicates to me that because they can't assess more of the water bodies, they can't depict the percentage that support designated use or impacted by agriculture (for instance) accurately. Therefore, what tech. or application thereof could assess MORE water bodies w/ the same amount of State resources? I also get the impression that NPS pollution is not measured adequately enough and possibly not in enough areas.

There are several important indicators to an effective water quality/ecological assessment for both terrestrial aquatic and marine environments. Marine/estuarine/lacustrine environments are classified as terminal systems, where water/sediment/pollutants (stressors) are transported into and stored. In the larger systems mixing occurs allowing for longer time periods before a problem is identified. Certain habitats and biota are indicators of these stressors. Therefore, it is important to identify the ecological habitats within a particular watershed/lake/estuary/coastal system. To do this identification remote sensing is the ideal methodology for the classification of habitats. With recent advancements in marine acoustics high-resolution swath mapping provides an ideal mechanism for determining ecological habitats within marine/estuarine/lacustrine environments.

Data collected in a high-resolution swath mapping survey are backscatter and bathymetry at sub-meter scale. With the collection of the high-resolution bathymetry (DEM) the backscatter data can be scientifically visualized in three-dimensions for better identification of habitats. At present there does not exist a classification scheme for identifying habitats using acoustic backscatter data. I am in the middle of writing a proposal to the USGS and the University of New Brunswick, Canada, to develop a classification scheme for the identification of sea floor/lake bottom sediment types and environmental habitats. If I were to reinvent monitoring, I would like to improve the use of satellite and acoustic remotely sensed data for fluvial/marine/estuarine/lacustrine systems. Especially were stream/lake and stream/estuarine/marine systems come together. Is there a means in which we can join forces to identify resources to further the advancement and use of remotely sensed data? My philosophy is the collection of sediment, water, physical habitat and biotics is to ground truth the remotely sensed data, which in turn greatly enhances the analyses and interpretation of the sampling data.

Bacteria/pathogen indicators. We need better bacteria and pathogen indicators that are good indicators of human health threat, and also allows us to distinguish sources (e.g., wastewater vs. natural vs. animal waste, etc.). Some of our States are continuing to look for better pathogenic and bacteriological indicators. Often, the indicators (e.g., Enterococcus) do not correlate well with disease susceptibility and human health threat. Also, sometimes the indicators do not necessarily reflect anthropogenic sources. Source identification is important so that the right control measures can be placed. (See also #2 below) 2. Molecular markers for source identification. As we move away from emphasis on point source controls and more toward nonpoint sources, it becomes more important to distinguish other sources of pollution (storm water runoff, other nonpoint sources). Some work has been done on markers such as linear alkylbenzenes (LABs), but other markers that help us distinguish between the various anthropogenic sources would be extremely helpful. This information would assist us in identifying the nonpoint source so that appropriate control strategies can be implemented. 3. Rapid and/or easy coral reef assessment. Many of our **tropical States** need a quick and easy way to establish baseline and assess long-term health of their coral reef ecosystem. It is difficult for our outer **Pacific Islands** to collect intensive monitoring information for coral reefs. However, certain physical parameters like nutrients, sea surface temperature, etc. may be collected long-term that provides long-term historical trends of important or limiting coral reef health parameters.

My responsibilities include providing direction on emerging monitoring and information management technologies for an Interagency Program monitoring the ecological health of the **San Francisco Bay** estuary. I would like to briefly point out some of my experience from the over 40 monitoring elements of IEP. 1.) "Real time" bio monitoring needs. If you would like a real life demo I'd be happy to show you what we have on-line with IEP on one of our home pages. This is real time bio-monitoring, uploaded daily from boat to data scrub to edit checks to data base to WWW home page to GIS maps. 2.) Geo-positioning data needs. GPS, Loran-C, interactive data entry via GIS software such as ArcView E.g., some city storm water programs have voice activated systems installed in mobile units. 3.) New instrumentation for chemical and physical parameters. Real time monitoring needs require new instrumentation for chemical and physical parameters. My division at USBR has several data loggers with GPS time stamp, Loran C connected on a boat. We use wonderware as the software (I believe) which combines the data stream each second from all sensors and puts it into storage.

Need to analyze the annual variation in Normalized Vegetation Difference Index (NDVI) values along the south **Texas** coast, relate those changes to climatic events (I.e. periods of drought) and examine associations with changes in coastal condition (e.g. salinity variations). The second project involves 3 phases: a) the development of physiological indices of health for wetland plants, b) the association of these indices with the aircraft collected spectral signatures of wetlands, and c) the large scale mapping of wetland health based on their reflectance/irradiance character. AED is also a participant in a study, with remote sensing scientists at Brown Univ. and the Graduate of School of Oceanography at the Univ. of Rhode Island, to apply aircraft and satellite technology to monitor selected parameters in the waters of **Narragansett Bay**.

Regardless of the type of monitoring, it is critical to have highly accurate (<0.5 m) vertical and lateral elevation/location information for each sample location to ensure that the collected data can be used by many different techniques and purposes.

APPENDIX E

ACRONYMS

ADEOS - Advanced Earth Observing Satellite

ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer

AVHRR - Advanced High Resolution Radiometer

AVIRIS - Airborne Visible InfraRed Imaging Spectrometer

CWA - Clean Water Act

DEM - Digital Elevation Model

DOC - Dissolved Organic Carbon

EOS - Earth Observing System

EPA - Environmental Protection Agency

ERS - European Remote Sensing Satellite

EROS - Earth Resources Observing System

ESE - Earth Science Enterprise

ETM - Enhanced Thematic Mapper (see TM) (aboard Landsat 7)

GIS - Geographic Information System

GPS - Global Positioning System

GOES - Geostationary Operational Environmental Satellites

HUC - Hydrologic Unit Code

IWI - Index of Watershed Indicators

LAI - Leaf Area Index

LIDAR - LIght Detecting And Ranging

MASTER - MODIS - ASTER Simulator

MODIS - Moderate Resolution Imaging Spectrometer

MSS - Multi Spectral Scanner, has a visible/near infrared/thermal radiometer

MTPE - Mission to Planet Earth

NASA - National Aeronautics and Space Administration

NEXRAD - Next Generation Radar

NDVI - Normalized Difference Vegetation Index

NOAA - National Oceanic and Atmospheric Administration

NPS - Non Point Source - pollution

NSCAT - NASA Scatterometer

NWI - National Wetlands Inventory

OCTS - Ocean Color and Temperature Scanner

OGWD - Office of Ground Water and Drinking Water

ORD - Office of Research and Development

OWOW - Office of Wetlands, Oceans and Watersheds

PPM - Parts per Million

SAR - Synthetic Aperture Radar

SeaWiFS - Sea-viewing Wide Field of view Sensor

SIR - Shuttle Imaging Radar

SPOT - (Systeme Probatoire d'Observation de la Terre) European satellite

SRTM - Shuttle Radar Topography Mission

SS/MI - Special Sensor Microwave Imager

TIMS - Thermal Infrared Multispectral Scanner

TM - Thematic Mapper visible/near infrared/thermal radiometer (aboard Landsat 4 and 5)

TMDL - Total Maximum Daily Loads

TMI - TRMM Microwave Imager

TRMM - Tropical Rainfall Measuring Mission

TSS - Total Suspended Solids

USGS - United States Geological Survey

WSR-88D - Weather Surveillance Radar – Doppler