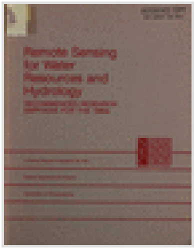

Remote Sensing for Water Resources and Hydrology: Recommended Research Emphasis for the 1980s (1980)

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REMOTE SENSING FOR WATER RESOURCES AND HYDROLOGY

Recommended Research Emphasis for the 1980s

A Report of a
PANEL ON WATER RESOURCES
to the
SPACE APPLICATIONS BOARD
of the
ASSEMBLY OF ENGINEERING
NATIONAL RESEARCH COUNCIL

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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SUMMARY

In 1978, the Space Applications Board recalled its 1974 summer study Panel on Water Resources to assess progress on the Panel's 1974 recommendations and to decide what changes in those recommendations or what new recommendations were appropriate. Discussions of a comprehensive draft report prepared by the Panel late in 1978 led the Board to ask that the Panel help identify where agencies of the federal government should focus their efforts in remote sensing for water resources, so as to meet the more urgent problems and to provide the largest return in practical benefits. Accordingly, the Panel continued its work, leading to this report. Having reviewed progress since 1974 in the use and capabilities of remote sensing to meet the needs of the community of users of water resources data, the Panel concludes that some progress has been made in the applications of Landsat data and in development of new space systems -- such as Seasat, the Heat Capacity Mapper and the future Landsat-D. *In the main, however, the Panel concludes that the recommendations in its 1974 report remain valid but mostly unmet.*

This report sets forth the problems and the areas of activity that the Panel believes should be emphasized in work on remote sensing for water resources and hydrology in the 1980s.

The report deals only with those activities and problems in water resources and hydrology that the Panel considers important, and where, in the Panel's opinion, application of current remote sensing capability or advancements in remote sensing capability can help meet urgent problems and provide large returns in practical benefits.

Because most water management problems involve complex interactions among many variables, hydrologic models have become an important tool in water management. Most models in current use need improvement if the information they produce is to be dependable and accurate. In addition, the new information that remote sensing can provide should lead to models based on new concepts. Up to this time, requirements for data to be used with models have been based almost entirely on judgment. The Panel recommends that in its research program and in its joint activities with other agencies, NASA emphasize work toward the improvement of current hydrologic models and toward the development of new models designed to take advantage of remotely sensed data. In addition, the Panel recommends that NASA initiate a set of sensitivity studies designed to provide a more solid base for data and information requirements.

The Panel reaffirms its conclusion of 1974 that an operational remote sensing program is imperative to provide the incentive for the private sector to invest in existing and new applications. The assignment to NOAA of responsibility for operational remote sensing is an encouraging development.

The applications of remote sensing that the Panel concludes should be emphasized have been grouped into three categories. The first category contains applications routinely used by some or many water resource managers and hydrologists ("operational uses") and about which potential users are generally knowledgeable as a result of demonstrations and trial uses. The Panel believes that these applications would be more widely used if potential users were not inhibited because current remote sensing spacecraft, being experimental, do not assure continuity of data. In the Panel's opinion, the important uses for an operational system would be:

- forecasting runoff from mountain snow packs
- survey of aquatic vegetation
- mapping of land use
- surveillance of ice conditions

The Panel's conclusion that these uses are currently ready for operational or quasi-operational application should not be interpreted to mean that research and development related to these uses should be reduced or terminated. On the contrary, because these applications are important and beneficial, advances in related technology are needed to bring additional and significant benefits.

The second category contains important potential applications that, in the Panel's opinion, are sufficiently developed to be used operationally but are not because additional work in the form of demonstration and trial use is needed. These applications are:

- relating urban development to changes in runoff
- assessment of shoreline processes and river channel migration

Again, the Panel emphasizes the fact that these applications are considered ready for demonstration and trial use does not mean that related research and development should be reduced or terminated.

The third category includes important applications judged by the Panel to need additional research and development:

- assessment of soil moisture

- mapping indirect indicators of the areal extent and depth of groundwater
- prediction of flood conditions
- real-time measurement of rainfall
- measurement of the effects and sources of acid rain
- detection and measurement of suspended solids and salinity
- assessment of lake eutrophication
- assessment of tidal regimes in estuaries

The Panel recommends that during the 1980s work on these applications be emphasized in research and development on remote sensing. Research and development on applications in the operational and technology transfer stages should not be neglected because improvements in capability can be expected to bring significant and relatively near-term benefits.

BACKGROUND

In 1974, as part of a summer study of the Practical Applications of Space Systems, the Space Applications Board (SAB) convened a Panel on Inland Water Resources. The Panel was charged with determining how and to what extent space systems of the 1980s might be used in the future development and improved management of the nation's water resources. The Panel's conclusions were presented in a report* supporting the summary report of the SAB on the results of the summer study**.

In October 1978, the SAB recalled the Panel for a two-day meeting to assess progress to date on the Panel's recommendations and to decide what changes in its earlier recommendations or what new recommendations might now be appropriate. In the October 1978 meeting, the Panel concluded that NASA and other federal agencies were making some progress toward meeting the needs of the community of water resources users. The Panel noted in particular the usefulness of Landsats-1 and -2, Seasat and the Heat Capacity Mapper, as well as planning for a future Landsat-D with improved spatial and spectral resolution. In the main, however, the Panel concluded that its 1974 recommendations remained valid but mostly unmet.

The Panel's findings were reported to the SAB at a meeting immediately following the Panel meeting. NASA's Associate Administrator for Space and Terrestrial Applications participated in the discussions. Noting that the Panel's summer study report and the Panel's current findings were based on a comprehensive assessment of water resource management needs, the Associate Administrator asked the Panel to help identify where federal agencies should focus their efforts to meet the most urgent problems and to provide the largest return in practical benefits.

Accordingly, the Panel met again on September 18 and 19, 1979, for further deliberations. Representatives from the Corps of Engineers and NASA provided advice and consultation to the Panel during this meeting.

This report presents the results of the Panel's work over the 1978-1979 period.

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* National Research Council. Practical Applications of Space Systems, Supporting Paper No. 5, Report of the Panel on Inland Water Resources. National Academy of Sciences, Washington, D.C. 1975

** National Research Council. Practical Applications of Space Systems. National Academy of Sciences, Washington, D.C. 1975.

THE NEED FOR EMPHASIS ON HYDROLOGICAL MODELING

At its initial meeting in 1974 and at subsequent meetings, the Panel observed that much of the work in the field of water resources has been descriptive in nature, and remote sensing from space is viewed by many as an extension of the descriptive (monitoring and measuring) process. However, a mature program using remote sensing must be useful for prediction as well as for description. To be useful for prediction remotely sensed data must be compatible with mathematical modeling of hydrologic systems.

Remotely sensed data can be used in several ways in models. Data from synoptic coverage of large geographic areas at frequent intervals can be used in current models. To be widely accepted and used by professionals in the field of water resources, however, current models need to be improved to be more dependable and more accurate. There is considerable interest in using real-time modeling for water management, and remotely sensed data promptly delivered to the user can help make real-time modeling possible.

Up to the present time, expressions of data and information needed to be used directly or in models (including statements of requirements for such parameters as resolution, accuracy and frequency of measurement) have been based almost entirely on the judgment and experience of experts. To rely on judgment has been appropriate and useful in the early stages of applying remote sensing to water resources management, but the Panel believes that it is essential now to provide a more solid foundation for data and information requirements. As the first step toward accomplishing this, the Panel recommends that NASA initiate a set of in-depth quantitative sensitivity studies designed to show what data and what information are likely to provide the greatest returns. These sensitivity studies should be very pragmatic, addressing directly questions such as whether any significant improvement in flood prediction or other practical water management problems should be expected to result from such factors as better or more accurate data, more timely delivery of data, or improvements in existing hydrologic models.

As a complementary project, the Panel recommends that NASA in consultation with the Corps of Engineers select one water resources problem and undertake systematic sensitivity studies of pertinent water resource and hydrology parameters to determine what requirements might be fulfilled by remote sensing systems.

Almost without exception, models to date have been designed to use data that can be collected by conventional ground-based means. Remote sensing can provide information not previously available -- for example, data on spectral reflectance or a synoptic view. Microwave sensors can penetrate vegetation and may provide data on soil moisture. New elements of information such as these can and should lead to water resource models based on completely new concepts.

As additional research confirms the relationship of remotely sensed data to the behavior of water resource systems, reliance on new elements of information will grow.

The Panel believes that it would be useful to explore the possibility of new concepts that take advantage of the possibilities of remotely sensed data for models including but not limited to the following areas:

- general hydrology and water balance
- soil moisture and groundwater
- streamflow, including flooding
- snow depletion and snowmelt
- urban hydrology
- lake and reservoir quality
- flow and water quality in estuaries and tidal rivers

In addition, the Panel recommends that either NASA or the Corps of Engineers begin conceptual development of a water resources/hydrology model, designed to take advantage of remotely sensed data, for a high priority water-related activity such as determining potential urban runoff for design purposes. It must be recognized that at the outset such a model is not likely to match the accuracy of existing models, but the goal should be eventually to develop accuracy exceeding that of models using conventional data (current accuracy ranges from ±10% to ±20%).

THE NEED FOR AN OPERATIONAL REMOTE SENSING SYSTEM

Progress in application of remote sensing to water resources has been disappointingly slow. The technology has far outstripped the institutional resources to exploit that technology. A major factor is the lack of assurance that current services for acquiring remote sensing data will continue to be available. In addition, data acquisition systems to date have been constrained to the research and development phase. Individuals, firms, and agencies remain reluctant to invest in equipment and education and training of personnel for using a specialized set of scientific data until they are convinced of its operational utility and until continuity and consistency of the data is assured. Reliability and assured service -- lacking as long as the systems remain in the research and development mode -- are essential to broader application and greater benefits. It follows that the full range of benefits and the economic value of remotely sensed data cannot be appraised adequately from the applications made to date. An operational system will permit aggregation of potential users and bring about increased use.

It is not realistic to expect that a totally credible benefit-to-cost ratio for using remote sensing to improve the management of water resources can be compiled at this stage. The problem is not limited to water resources. There are many important, often intangible, national and worldwide objectives that cannot be priced but that are more likely to be achieved with greater knowledge about our universe and enhanced ability to interact favorably with it.

The Panel recognizes that another reason for the slow adoption of remote sensing techniques stems from the fact that in many urban areas a large number of state and local agencies and regional authorities have some role in water management. At the local level, and often at the state level, funds and personnel for equipment and training required to begin using remote sensing are not available. The advantages, for other reasons, of aggregating water management activities in councils of government or other metropolitan or regional authorities are increasingly being recognized. An advantage of such aggregation may be to facilitate the use of new technology -- such as remote sensing -- which would be beyond the resources of single communities.

The Panel believes that far more attention needs to be given to exploring various approaches to creating operational systems that would be available to potential users and beneficiaries of remote sensing. The communities that could make use of this technology, together with the consulting engineers who serve them, need to be made aware of the benefits and an operational system must be available which they can tap.

The Panel reaffirms its conclusion of 1974 that an operational remote sensing program is imperative if we are to provide the incentive for the private sector to invest in existing and new applications. The Panel views as constructive the recent Presidential decision to assign responsibility for operational land remote sensing from space to NOAA*.

* The White House announced on November 20, 1979, that the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, would manage all operational civilian remote sensing activities from space.

SOME IMPORTANT USES FOR AN OPERATIONAL SYSTEM

Some important applications that in the Panel's judgment have reached the operational stage are discussed below. It must be emphasized that the fact that operational use of these applications is now feasible does not mean that research and/or development to advance the associated science or technology should cease, and in some cases the Panel has pointed out where advances are needed.

Forecasting Runoff from Mountain Snow Packs

Operation of reservoirs for hydroelectric power production, irrigation, flood control, and water supply can be significantly improved with more accurate knowledge about the total amount of water available from basins and its probable rate of runoff on a near-real-time basis. The knowledge could be based on data acquired from space or collected by spacecraft from ground sensors. Data provided by present space systems such as Landsat should be fully used, and new sensor systems should be developed to provide extensive, repetitive, all-weather observations and measurements of areal extent, water equivalent and liquid water content of snow and ice, and thus improve monitoring of snowpack accumulation and melt rates. Types and characteristics of measurements required to make these forecasts are: snow area with a resolution of 1 km^2, water equivalence in the range of 1 cm to 100 cm per resolution unit and liquid water content within $\pm 3\%$ to $\pm 5\%$ by weight.

From experience in a four-year quasi-operational test program in four major western U.S. snow zones, it has been concluded that to make decisions about diverting scarce water or releasing excess impoundments before dams are endangered, snowpacks should be monitored weekly and remotely sensed data should be delivered to users within three days of its collection. The test program included independent projects by the California Department of Water Resources in the Kings, Kern, Kaweah, and Feather River basins and the Colorado Division of Water Resources in the Rio Grande, Arkansas and San Juan River basins*.

* Rango, Albert. "Pilot Tests of Satellite Snowcover/Runoff Forecasting Systems," Proceedings of the 46th Annual Western Snow Conference, Otter Rock, Oregon, 1978.

It has been estimated* that an annual savings of approximately $36 million could be readily achieved with current remote sensing systems, using only the areal extent of snow cover. The benefits are based on extensive studies of the Colorado River basin extrapolated to those portions of the Western U.S. where runoff from melting snow is a significant natural resource. The benefits accrue from reduced costs of water for irrigation and hydroelectric power because of the improvement of accuracy in predictions of runoff when NOAA and NASA satellite imagery are used. Further improvement will be possible with the development of capability to sense snow water equivalent and liquid water content, and when modeling techniques have been developed that are more closely attuned to remote sensing information. Such modeling techniques remain a high priority research area, where results of progress can easily be incorporated into the operational framework developed for using areal snow-cover data.

Survey of Aquatic Vegetation

The abundance and distribution of rooted and attached aquatic plants are important to inland water management and the related fields of fisheries and wildlife management. When such plants are in excessive abundance, they can interfere with navigation, impede water flow, trap sediment, accelerate shoaling, and clog water intakes. Water management agencies use observations from space, aircraft and earth to monitor distribution and species of aquatic plants. Turbidity limits the effectiveness of remote sensing of aquatic vegetation from space and from aircraft, but in many areas turbidity is not a problem. The U.S. Army Corps of Engineers has found remote sensing from Landsat and aircraft to be a rapid and inexpensive method for detecting and monitoring infestations of aquatic plants.**

The Panel believes that remote sensing could be employed more extensively than it now is in surveying aquatic vegetation, with substantially increased benefits. Logical sites for demonstration projects are in the southeastern United States or in states that have important waterfowl wintering grounds.

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* Castruccio, Loats, and Newman, "Cost Benefit Analysis for the Applications System Verification and Transfer (ASVT) on Operational Applications of Satellite Snow Cover Observations." Report of NASA Contract NAS 5-237229, ECO Systems International Inc., Gambrills, Maryland, 1979.

** U.S. Army Corps of Engineers Information Exchange Bulletin, Vol. A-78-2, March, 1978, U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Mapping of Land Use

Accurate data on general and specific land uses and characteristics are vital ingredients in planning and, to a lesser degree, in operations related to water resources. Such data are also necessary in waterfowl and other wildlife management programs, in wetlands and other environmental preservation and management programs, and in numerous related activities. In general, the data required include location, extent and classification by character of use. The level of detail needed varies according to the user and the intended use.

The data needed can be acquired by a remote sensing system designed to serve a variety of users, all part of a community concerned with land use. It is recommended that priority be given to development of a system capable of supplying land use data at federal, state, and local levels. Ground resolution of 15 to 30 meters is desirable.

A land use mapping program will significantly assist water resource programs. Historically, data on water resources are collected by expensive, time-consuming techniques, including field surveys, aerial photographic interpretation, and questionnaires. Timely information often cannot be collected in the detail needed because the cost of using current methods is too high. The use of remotely sensed data in some cases can be cost effective. For example, using Landsat data, the Great Lakes Basin Commission mapped the entire basin in nine land use categories at a cost of $55,000, a task that would have cost several times this amount using conventional means. Nationwide, land use mapping derived from remotely sensed information could help the EPA enforce non-point-source water quality laws* at a substantial saving over currently employed methods. Further, modern information processing systems are beginning to make possible the merging of data collected from many sources, thus making frequent updating (change detection) economically feasible.

Surveillance of Ice Conditions

Navigation and the operation of hydroelectric power systems in the northern United States during winter are drastically affected by formation, type, thickness, and areal extent of ice. The navigable portions of the Great Lakes, the Illinois River, the St. Lawrence, and the upper Mississippi and Missouri Rivers are particularly affected. Based on the experience of the Panel members, information for management uses requires spatial resolution of about 20 meters and an absolute positional accuracy of ±15 meters. Vertical accuracy should be within

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* Federal Water Pollution Control Act amendments of 1972, PL 92-500, Sec. 208.

10 centimeters. Data must be delivered within one day and preferably within one or two hours following observation. The region of interest may extend over 500 kilometers. Information on types of ice and its thickness, movement, and location is needed to help predict the onset of ice formation and breakup and to permit correlation of this information with navigation and power system operations.

THE NEED FOR MORE EMPHASIS ON TECHNOLOGY TRANSFER

NASA has made an important start in technology transfer through establishment of regional applications centers at the Ames Research Center, the National Space Technology Laboratory and the Goddard Space Flight Center. The work of these Centers -- for example, the work of the Regional Center at NASA's Ames Research Center with the Pacific Northwest Regional Commission and other western states -- has been particularly successful in transferring technology to states, using a mechanism referred to as "Applications Systems Verification and Transfer" projects*.

Federal agencies should, where appropriate, incorporate remote sensing technology into their own operating procedures for fulfilling their missions and assure that their procedures do not inhibit states and local agencies from using remote sensing where it can satisfy federal requirements. Strong, deliberate efforts should be undertaken to transfer the capability to use remotely sensed data from federal research agencies to a wider community, and particularly to state and local agencies, universities, industries, and private consultants.

Federal agencies should maintain a partnership with non-federal users to accelerate the technology transfer process. Appropriate uses of remotely sensed data should be encouraged in federally-funded water resources programs. Programs should be sponsored to inform and train potential users of remotely sensed data. Education on remote sensing is becoming more widely available at the university level, and the federal government should encourage this trend and provide assistance.

The results of research on applications of space technology to water resources problems should be published in mainstream water resources journals, rather than in aerospace journals. Joint sponsorship by water resources technical societies of conferences should be sought by NASA and the Corps of Engineers. Emphasis should be to move actively into communication with the community of water resource practitioners, while showing a strong commitment to providing ongoing technical support.

Creation of an organizational framework to provide services to users, parallel to that used by NOAA to provide satellite meteorological data, is urgently needed in managing all aspects of data use.

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* Trials of applications of remotely sensed data (judged by NASA to have reached the stage where they are technically sound), undertaken cooperatively by NASA and user organizations -- leaders in their communities -- that have technical capability and sufficient interest to participate and are willing to provide matching funds or in-kind support.

USES JUDGED READY FOR TECHNOLOGY TRANSFER

Remotely sensed data are already being applied to some water resource problems -- for example:

- o inventorying, and assisting in location and monitoring of dams (by the Corps of Engineers)
- o improving forecasts of snowpack runoff (by the Department of the Interior and the States of California and Colorado)
- o surveillance of river channel and beach migration (by the Corps of Engineers)
- o monitoring of silting in lakes and reservoirs (by the Corps of Engineers and the State of Virginia)
- o measuring the relative imperviousness of watersheds (by the Bendix Corporation for the Metropolitan Washington Council of Governments)

The Corps of Engineers now accepts the use of Landsat data for defining land-cover-based parameters in hydrologic models for watershed planning studies of basins larger than ten square miles.

Research has shown other uses to be feasible, but some of these uses have not had sufficient user trials for their practicality to be apparent. The Panel recommends that the projects described below be undertaken as part of a technology transfer activity to demonstrate the practicality of certain applications. The Panel believes that the demonstrations should be sponsored primarily by the federal government (not just by NASA), with the state or local governments involved sharing some of the cost. (In past demonstrations, contributions by state governments have been mostly in the form of participation by state agency personnel). Where feasible, participation by universities and the private sector should be sought.

Relating Urban Development to Changes in Runoff

The existing data base on quantity and quality of urban runoff is small, and few comprehensive attempts have been made to relate urban growth and changes in watershed characteristics to changes in runoff. Much damage to water resources has been caused by urban development, and remedial measures are now being widely instituted without sufficient understanding of the effectiveness of these measures. Harmful effects of storms in urban areas occur, often during and following thunderstorms, when short periods of intense rainfall produce high flow rates. Severe local flooding, high concentrations of pollutants, and silting of streams, lakes and rivers often result. Conventional data-gathering techniques can contribute much of the information needed in studies of urban runoff, but remote sensing may be a more effective way to collect important data on land use patterns, stream configurations, and permeability of surfaces.

The use of remotely sensed data from spacecraft or from high altitude aircraft seems, intuitively, to have potential value for assessing short-term or long-term damage and for understanding the effectiveness of remedial measures. To date, however, such applications have been few and have been so tailored to the solution of immediate emergencies that little has been learned about the general utility of remotely sensed data for relating urban development to changes in runoff.

The Panel recommends initiation of a project designed to develop understanding of the role of remotely sensed data (from aircraft, as well as from satellites that observe directly or interrogate ground sensors) that could trace basic changes and permit relating them to changes in flow and quality transmitted from conventional data relay systems. Such an experimental project should be designed through careful study. The Panel suggests that one or more rapidly developing areas be selected and monitored over a period of 5 to 10 years. Examples of areas that could have been studied to advantage are the Santa Ana Valley in California and Fairfax County in Northern Virginia as they existed 10 or more years ago. Complete records of land use should be compiled annually during the study period. In addition to traditional measures of land use, such items as permeability, ground cover, channel modification, installation of sewers, and changes in topography should be noted. Rainfall, runoff and runoff quality should be monitored from space when possible and from a network of closely spaced ground locations. The water quality parameters to be measured routinely should include biochemical oxygen demand, suspended and total solids, nutrients, and temperature. At least three major storms -- more if possible--should be sampled annually.

Data sensed from space for use in the study would require a resolution of approximately one-half hectare (one acre) for land use characteristics and about 25 meters for variables related to streams. Flow and quality should be established to an accuracy of ± 10 percent or better.

Several good mathematical models of urban systems exist, but their use is severely hampered by lack of data on stream flow, water quality and rainfall. Land use information is generally known to the accuracy needed but updating the information to monitor changes is expensive and time-consuming. It is recommended that this study use existing models. As the study proceeds it may point the way toward new and improved models. The resulting tools will be valuable to urban planners and engineers. Not only will the tools directly benefit planning for flood control and pollution abatement, they will also make possible more deliberate and rational planning for urban development and resource conservation.

Assessment of Shoreline Processes and River Channel Migration

The interface of land and water along shorelines and rivers is constantly changing due to displacement, transport, and deposition of soil particles by moving water. Stream banks erode, river channels shift, shoals build up, beaches wash away and build up. Such natural processes often have serious economic consequences. Property of high value is lost, water uses are impaired, and navigation is hindered. Remote sensing, by providing a synoptic view, offers the potential of advancing our understanding of the processes involved. It also offers possibilities for assessing conditions over time and for evaluating the effectiveness of remedial measures.

Currently, shoreline and channel data are gathered by conventional aerial photography and actual field measurement, but the extent and frequency of data collection, limited by high costs, are not adequate. Remote sensing offers the possibility of increasing the extent and frequency without proportional increase in cost. This possibility should be tested in realistic situations. The Panel therefore recommends that a demonstration project be undertaken to develop remote sensing capabilities for monitoring shoreline and river channel processes. Monitoring should focus on shoreline changes and quantities of materials removed or deposited, location and nature of sedimentation in river channels, and mechanisms of sediment transport. Resolution compatible with the detail on maps currently in wide use (at a scale of 1:24,000) is needed to permit easy overlaying.

IMPORTANT USES NEEDING MORE RESEARCH AND DEVELOPMENT

In addition to activities discussed in the previous sections, other important water management needs may be satisfied by information derived from remote sensing. For a number of such needs, however, progress in using remote sensing is limited or non-existent. Substantial research and development efforts will be required to explore fully the benefits possible from remote sensing. NASA and the federal water agencies should continue to support such research efforts.

The Panel recommends that NASA continue to perform research directed toward expanded use of remote sensing for water management and that priority be given to:

- research on soil moisture
- groundwater mapping
- prediction of flood conditions
- real-time measurement of rainfall
- measurements of the effects and sources of acid rain
- monitoring of suspended solids and salinity
- assessment of lake eutrophication
- assessment of tidal regimes in estuaries

Assessment of Soil Moisture

Research on the measurement of soil moisture, one of the important elements in the hydrologic cycle, deserves the significant emphasis it currently receives in NASA's R&D program. The goal is to map, on a quasi-operational basis, watersheds greater than 1000 km^2 and, with selected coverage, areas smaller than 1000 m^2. The mapping should include the entire watershed, including rangeland, pastureland, wildland, irrigated and dryland farming, and other uses of watershed areas. Soil moisture estimates from all these areas are required in various watershed modeling techniques. On a global basis, soil moisture is important in establishing boundary conditions for climate models.

Vegetation can be penetrated by microwave radiation. The current ground-based and aircraft passive microwave program should be extended to include additional wavelengths and to study different soil types. Algorithms for extracting soil moisture information should be extended over additional soil types. Models should be developed for extrapolating data obtained by microwave techniques on soil moisture in the near surface layer to greater soil depths (preferably through the root zone) and over time. Subsequently, these techniques and the soil moisture data should be tested for their usefulness in water balance models, preferably in experimental watersheds where comparable conventional soil moisture data are available.

Mapping Indirect Indicators of the Areal Extent and Depth of Groundwater

Subsurface water is difficult to detect. Just as in exploration for minerals and petroleum, exploration for water makes use of a number of indicators, some direct, and some -- such as ground cover and geology -- indirect. The new understanding that space imagery has brought to geomorphology -- for example, detection of previously unrecognized lineaments -- has already given important hints as to the location of deep water sources.

Much of the nation's water supply is produced from groundwater aquifers at depths of the order of 100 meters. The areal extent of aquifers, along with their depths and characteristics, are important factors in their use. The understanding of groundwater basins is complicated by certain phenomena, including the frequent occurrence of several aquifers at varying depths, separated by aquicludes or other geologic formations of low permeability. In such cases slow and costly subsurface drilling, logging and testing are among the procedures normally used to locate and measure the aquifers.

A definite need exists for the development of sensors capable of measuring indirect indicators of the depth of groundwater below the earth's surface. The Panel recognizes that development of the required sensors may be difficult, but the importance of finding and managing groundwater justifies exploring the possibility.

Nationwide, significant levels of contamination in groundwater are being found. Hundreds, perhaps thousands, of cases have been discovered where hazardous materials have mixed with groundwater supplies. Knowledge of groundwater and its movement, particularly in relation to toxic disposal sites, would be valuable for planners.

Irrigation of agricultural lands alters groundwater regimes and usually causes a rising water table. If groundwater invades the root zone, crop growth is adversely affected by the excessive moisture. With irrigation, soluble salts, detrimental to crop growth, tend to concentrate at the soil surface and in the root zone. The resulting waterlogged, salinized soil poses serious threats to continuance of productive agriculture within the affected areas.

Drainage studies have been and are being conducted in areas affected by rising water tables but these studies are costly and entail considerable expenditure of time. The potential savings in time and money that would result from the successful use of remote sensing techniques to detect the location, nature, and extent of drainage problem areas have led the Department of the Interior's Water and Power Resources Service (formerly the Bureau of Reclamation) to initiate studies using data acquired from Landsat and aircraft. The studies* show that multifeature analysis of thermal imagery has the potential for enabling detection of near-surface groundwater.

Sensor development should emphasize a spatial resolution of approximately $4000M^2$ and a vertical resolution equal to approximately 15 percent of the total ground penetration. The performance of the sensors should be independent of surface conditions.

It has been estimated** that if techniques were developed for detecting local water tables at depths of 1.2 meters (4 feet), savings of 40 percent could be realized in field studies of irrigation drainage alone. The average savings per square kilometer would be more than $2,000 -- based on an average cost, in 1973, of $5,000 to $6,000 per square kilometer investigated.

Prediction of Flood Conditions

Regional flood damage estimation models are needed for water management and control, alternative flood control project planning, and regional flood damage estimation. There is a need both to expand the capabilities of these models and to develop more economical procedures for updating the land use patterns used in regional damage estimates. This updating of land use information can best be accomplished through interpretation of satellite acquired data, particularly because of the large geographic region to be considered. Satellite classifications should be developed which permit the acquisition of information on past floods as well as the ability to update the land use information used in the damage estimation model.

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* Lidster and Schmer, "Remote Sensing Techniques for Determining Water Table Depth in Irrigated Agriculture," Proceedings of XX Congress of the International Commission on Irrigation & Drainage, Question 34.1, May 1977.

** See footnote above.

Estimates of costs and benefits are difficult to obtain. As one measure, the U.S. Corps of Engineers expended over $91 million for operations during flood and coastal emergencies during fiscal year 1979 (the amount includes costs of remedial measures taken during emergencies -- for example, levee repairs). It is difficult to estimate what part of the amount expended would be saved by using remote sensing to improve damage assessment models but it seems clear that some improvement in operations could be achieved and that the expenses of assessing potential flood damage by conventional means are large.

Real-Time Measurement of Rainfall

Real-time estimation of rainfall using satellite imagery has been recognized as an important benefit for many water resources management problems. Promising developments have occurred with the launching of the Synchronous Meteorological Satellite and the Geostationary Operational Environmental Satellite (GOES) in 1974 with their better resolution and infrared scanning capabilities. A 1976 study* concluded that "we are now at the point where given the high quality digitized satellite pictures, the processing equipment and time, reasonable accurate estimates of precipitation can be made..." The technique used in this study is empirical. It can provide half-hourly or hourly rainfall estimates in real time for convective-type precipitation. Enhanced infrared imagery from GOES is examined to identify characteristics of convective clouds such as the active portion, temperature gradients in the anvil area, overshooting cloud tops, and merging thunderstorms. Using decision tree techniques, these subjectively determined cloud characteristics are translated to half-hourly or hourly rainfall amounts.

The technique was originally developed to predict rainfall from short-lived, isolated thunderstorms that produce heavy rain due to large updrafts. Continued field testing of the technique appears to indicate that space imagery can also be used to predict rainfall from long-living, slow-moving, large-area thunderstorms including remnants of tropical storms**.

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* Oliver and Scofield, "Estimation of Rainfall from Satellite Imagery." Preprint Vol. 6th Conference on Weather Forecasting and Analysis; May 10-14, 1976; Albany, N.Y., American Meteorological Society, Boston, Massachusetts. (Page 242).

** Scofield and Oliver, "A Scheme for Estimating Convective Rainfall from Satellite Imagery, "NOAA Technical Memorandum NESS 86, Applications Group, Washington, D.C., April 1977. Also new appendix dated October 12, 1978.

For a variety of operational problems -- such as flash flood warnings, reservoir management, and agricultural operations -- a technique with a sound scientific basis is needed to provide estimates (or predictions) of rainfall in near real time. The Panel recommends that emphasis be placed on efforts to develop such a technique.

Measurement of the Effects and Sources of Acid Rain

Acid rain is produced when rain combines with sulphur dioxide and nitrogen oxides from the air to form sulphuric and nitric acids. Oxides of sulphur and nitrogen are emitted in all forms of fossil fuel combustion. Power plants, smelters, steel mills, home furnaces, and automobiles may all contribute to acid rain. Adverse effects on crops and forests are suspected. Many lakes are losing their fish life and other biotic components because of excessive acidification, perhaps caused by acid rain*.

Because of the large areas involved, the transient nature of plumes, and the complex effects, remote sensing can be valuable in monitoring the transport and the constituents in the lower atmosphere and in determining, over time, whether damage to vegetation is occurring in areas potentially subject to acid rain, and thus aid in finding sources, determining the extent of the effects, and in assessing the effectiveness of remedial measures.

Detection and Measurement of Suspended Solids and Salinity

The Panel believes that remote sensing of suspended solids and/or salinity will be of major assistance in the management of inland water resources. While the occurrence and extent of suspended solids and salinity vary widely through the United States, they affect many aspects of the beneficial use of water. With the shift in this country toward wider use of coal and toward oil shale processing, more streams will be threatened by suspended solids, acids, or salinity. Some of these effects will be easy to locate and monitor by conventional means but some are also likely to be difficult to locate and may be in remote areas. The State of Kentucky has recently settled on remote sensing as an essential tool in monitoring strip mining and land restoration after mining, and the State of Ohio has been using the technique for some time.

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* In a memorandum of August 2, 1979, directing the establishment of a federal Acid Rain Coordinating Committee, the President stated that "it is important that we undertake efforts to describe the magnitude of acid rain effects, to develop a more thorough understanding of its causes, and to identify measures which can mitigate acid rain impacts."

The movement of suspended solids into waterways has many undesirable effects. Reservoirs -- particularly in the arid western states -- lose storage space when suspended solids are deposited. Deposits of solids in waterways and bays become an impediment to navigation and make frequent dredging necessary. Suspended solids often adsorb and transport undesirable pollutants such as pesticides, heavy metals, and excess nutrients. Fish spawning areas and coastal processes can be affected by the deposition or entrapment of suspended materials.

The measurement of salinity in waters and soil is important in many aspects of water resources planning. Salt water intrusion in estuaries affects water use for irrigation, municipal, and industrial purposes. Salinity of soils affects pipeline location and corrosion, and has an important effect on agricultural uses of soil. Salinity of surface streams is affected by both point and non-point source degradation. The usefulness of these streams for agriculture is dependent upon the amount of salt in the irrigation water.

Currently, suspended solids and salinity in surface waters are measured by field sampling. Often a "grab sample" is taken monthly and analyzed in a laboratory. This process is expensive, especially in remote locations and, because it is not sufficiently timely, often inaccurate. The movement of suspended solids, in particular, is related to storms, so that monthly sampling programs often miss significant movements. An alternative to infrequent sampling is the daily sampling station, but because of its high cost -- especially in isolated areas -- its use is limited. Frequent sampling is needed to determine the quantities of various types of sediment so as to estimate attached phosphorus and pesticides and thus to measure loading of streams and lakes.

An experiment is recommended to determine whether satellite remote sensing can be used for the detection and measurement of suspended solids and salinity. The sensors should be capable of measuring suspended solids along a stream, at concentrations up to 5,000 parts per million, with an accuracy of ±10 percent. For salinity, the measurements should cover concentrations from 100 to 15,000 parts per million with an accuracy of ±5 percent. The experiments will require some gathering of "ground truth", and would be enhanced through modeling the dynamics of water movement through various types of soils.

Assessment of Lake Eutrophication

Many state and local agencies are involved in evaluation, management, and improvement programs for lakes. Eutrophication of natural and man-made lakes is a problem of nationwide concern. Monitoring of the trophic status of lakes using conventional techniques for data collection is costly, labor intensive, and requires considerable logistic and laboratory support. Adequate evaluation often requires repetitive sampling at different seasons of the year. Many thousands of lakes are involved.

Remote sensing has the potential for providing a broader assessment of lakewide conditions by eliminating or reducing the frequency and extent of conventional water sampling and by augmenting conventional data, which are generally a limited number of point samples.

It is recommended that NASA and EPA develop joint research programs to implement a space-borne sensing system for assessing the trophic status of inland lakes. Efforts should also be directed toward designing models that can relate spectral values to trophic indicators, like chlorophyll and Secchi disk transparency.

Assessment of Tidal Regimes in Estuaries

Estuaries -- the zones where fresh and salt waters mix -- are usually shallow and relatively well sheltered. Here copious quantities of nutrients contributed by the rivers and mineral salts supplied by the sea are synthesized by sunlight into a basic substance of life: the protoplasms of the phytoplankton. Estuaries, providing abundant phytoplankton, support vast populations of mollusks, crustaceans, and other invertebrates which feed directly on unicellular plants and in turn become a source of energy for higher forms of life.

Estuaries have also become other things: avenues of commerce, sites of intensive commercial and sports fisheries, loci of residential and industrial development, convenient receptacles for enormous quantities of industrial and domestic wastes, and, in recent years, heat sinks for producers of electrical energy. Despite enormous capacities of estuaries for assimilation of pollutants, agencies with environmental responsibilities are confronted with the difficult problem of preventing further degradation while accommodating continued residential and industrial growth. Increased knowledge of the dynamics of estuaries, and particularly of tidal regimes, is central to resolution of the problem.

With data from satellite-borne sensors, there is promise of acquiring definitive knowledge of the tidal regimes of estuaries -- knowledge that is too expensive to acquire by conventional means. Accurate measurements of surface temperature, salinity, current velocity and direction, and surface elevation should be obtained synoptically on a precise schedule. Resolution of 100 meters in open waters and 20 meters in more confined waters is needed. Required accuracies are: temperature, 0.1° C; salinity, 100 parts per million; current velocity, 15 cm/sec; current direction, 1 degree; and surface elevation, 5 cm. Necessary modifications of contemporary space-based remote sensors appear technically and economically feasible.

If the required data cannot be obtained at hourly intervals by remote sensing, the employment of *in-situ* sensors reporting through a geosynchronous satellite may be a viable alternative.

The Chesapeake Bay appears to offer significant advantages as a site for a demonstration project. The Chesapeake is large, complex, highly productive, reasonably well researched, and in trouble. It needs early attention. Models of the Chesapeake are under development, and data for validating the models are in critically short supply.

The Panel is not able to quantify the benefits and costs of the proposed demonstration project. It is believed, however, that if the required data are obtainable by remote sensing, the ratio will be favorable. The ratio for *in-situ* sensing with satellite interrogation will be somewhat less favorable but still positive. In both cases, the advantage stems from the probability of a reduction in the time required to achieve the objective and the fact that only remote sensing can provide truly synoptic data.

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