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ADVANCES IN WATER RESOURCES MONITORING FROM SPACE

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ABSTRACT

Very substantial advances have been made since the launch of TIROS 1 in 1960 in monitoring by remote sensing from spacecraft the presence and quantity of water in the atmosphere and on the surface of the earth. Recent Nimbus-5 observations indicate that over the oceans the total precipitable water in a column of atmosphere can be estimated to within ±10%, the liquid water content of clouds can be estimated to within ±25%, areas of precipitation can be delineated, and broad estimates of the precipitation rate obtained. ERTS-1 observations permit the measurement of snow-covered area to within a few percent of drainage basin area and snowline altitudes can be estimated to within 60 meters. Surface water areas as small as 1 hectare can be inventoried over large regions such as playa lakes region of West Texas and Eastern New Mexico. In addition, changes in land use on watersheds occurring as a result of forest fires, urban development, clear-cutting, or strip mining can be rapidly obtained. Given the recent and rapid progress that has been made in developing spacecraft observations for the monitoring of hydrologic parameters and the plans for the future, it appears quite probable that these observational tools will be providing increasingly valuable information for the management of the water resources of the world.

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ADVANCES IN WATER RESOURCES MONITORING FROM SPACE

INTRODUCTION

Some very significant advances have been made in recent years in terms of being able to study and monitor from space various parameters and phenomena that are commonly associated with the hydrological or water resources disciplines. Since 1960 meteorological satellites have provided a means for better observing and understanding the global and synoptic scales of atmospheric dynamics that strongly govern the atmospheric portion of the hydrologic cycle. Photographs taken from manned space flights such as those obtained from the Mercury, Gemini, and Apollo flight series revealed that hydrologically relevant features such as surface water could be meaningfully observed. The recent launch of the first Earth Resources Technology Satellite (ERTS-1) has shown that these same features can be repetitively observed in several spectral regions and the dynamics associated with these features followed from month to month and season to season.

The purpose of this paper is to review some of the major specifics associated with the advances mentioned above and provide a glimpse of what steps may be taken in the next 5-10 years in terms of the capabilities of spaceborne systems and ancillary data processing facilities. In reviewing accomplishments, both advances in sensor capability and accuracy will be mentioned wherever possible along with descriptions of instances where these sensor capabilities have been applied to better management or specification of water resources systems.

SPECIFIC ADVANCES IN THE MONITORING OF WATER RESOURCES PARAMETERS

ATMOSPHERIC PARAMETERS

Liquid water appearing in the form of clouds was one of the very first parameters observed by meteorological satellites. Certainly this information was and is still relevant to hydrology, particularly global and regional hydrology. These observations have been improved considerably as higher spatial resolution and more frequent observations have been provided. As an example, the National Oceanic and Atmospheric Administration NOAA 2 Very High Resolution Radiometer (VHRR) now provides 1 km resolution in the atmospheric window (10-11 μm) and visible (0.4-0.7 μm) portions of the electromagnetic spectrum. Significant cloud top temperature features that are useful in the study of severe storms can now be seen every 12 hours. In the case of reflectance variations in the visible region, the frequent (several in one hour) observations from geosynchronous satellites such the Applications Technology Satellites, ATS 1 and 3, permit the growth and decay of very dynamic features to be monitored. Convective clouds associated with severe thunderstorms and tornadoes can be meaningfully studied and better understood. These severe storms, of course, usually provide heavy precipitation that is the basic input to watershed systems resulting in runoff and occasionally hazardous or damaging floods. Therefore, these satellite observations are of direct relevance to hydrology and need to be exploited more by that discipline. A review of satellite rainfall estimation methods is given by Martin and Scherer (1973).

Observations of the spatial distribution of water vapor in cloud free regions have been provided for several years by spaceborne radiometric observations in the 6.7 and 20-23 μm spectral regions. These observations have been used to map relative humidity and to infer the location and extent of dynamic features in the upper tropospere (Nordberg et al., 1966; Raschke and Bandeen, 1967; Beran et al., 1968; Martin and Salomonson, 1970). The applications of Nimbus-4 6.7 μm observations to global and regional moisture analyses were recently described by Steranka et al. (1973), and Rogers et. al. (1972) have explored the relationship of 6.7 μm observations to the atmospheric water balance in the upper troposphere.

In a more quantitative sense some quite important recent advances have been made by utilizing spectrometric measurements in the far infrared. Smith and Howell (1971) have found using Nimbus-4 Satellite Infra-Red Spectrometer (SIRS-B) observations in the water vapor rotation bands (18-36 μm) that the errors in the derived relative humidity estimates for the middle troposphere (400-600 mb) are less than 20%. Relative humidity errors in the lower troposphere are larger but still less than 30%. In spectrometric estimates of total precipitable water using data from SIRS-B Shen and Smith (1973) report that the relative error in precipitable water above the 1000 mb level was approximately 20 percent.

The far-infrared measurements just described are optimally obtained in a cloud-free atmosphere. In order to make estimates of water vapor content, the liquid water content of clouds, and precipitation, observations in the microwave are needed. The launch of Nimbus-5 provided spectrometric and radiometric microwave measurements that appear to provide very useful observations over the oceans of the parameters just mentioned (ERTS/Nimbus Project, 1972). The spectrometric measurements are made at five wavelengths near the 5 millimeter oxygen resonances and the 1.35 cm water vapor resonance by the Nimbus E Microwave Spectrometer (NEMS). The radiometric measurements are provided by the Electrically Scanning Microwave Radiometer (ESMR) having a receiver centered at 19.35 GHz (1.55 cm). The early results from the NEMS indicate that the total precipitable water vapor in the atmosphere can be estimated to within 10% and the liquid water content of clouds to within 25%*. The ESMR very clearly delineates precipitating areas over the oceans, (see Figure 1) and also gives an indication of the precipitation rate that appears to be accurate to within a factor of 2*.

SURFACE WATER PARAMETERS

Aircraft data and photographs taken from manned spaceflight have shown for some time that it is feasible to remotely observe features from high altitudes that are associated with surface water hydrology. Meteorological satellites were able to repetitively monitor snow cover and surface water over large regions and provide hydrologically useful information (Barnes and Bowley, 1970: Salomonson and MacLeod, 1972) but very little information was available for more localized water resources problems. The recent launch (July 1972) of the ERTS-1 has shown some very dramatic results that represent a very large step forward in the monitoring of surface water resources from space.

The ERTS-1 Multispectral Scanner Subsystem (MSS) is capable of providing observations in the 0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1 μm spectral regions over any point on earth every 18 days. Using the near infrared observations and the fact that in this spectral region water contrasts markedly with surrounding dry soil and vegetation, ERTS-1 has provided extensive and useful observations of the extent of surface water over large areas and the change with time in this extent. The results indicate that bodies of water as small as 1 hectare (10,000 m^2) can be recognized and mapped (for example, see Figure 2). In the southern high plains of Texas and New Mexico, ERTS-1 has provided a means of repetitively monitoring the number and area covered by the thousands of playa lakes in this region. This was a task that was completely impractical to undertake before the launch of ERTS-1. The Texas Water Development is now reportedly developing procedures to make a wet lake census of the Texas portion of the Southern high plains. The U.S. Army Corps of Engineers has found ERTS-1 data useful for locating and counting bodies of water larger than 6 acres, identifying their size and shape, and locating dam sites on major rivers (McKim, et al. 1972).

Wetlands can also be accurately monitored and mapped on map scales of 1:250,000 or smaller. The land-water interface, upper wetland boundaries in coastal regions, and gross vegetative communities can be defined. Additional information concerning drainage patterns, ditching activities, and lagooning for waterside homes can be observed with detail that is commensurate with map scales larger than 1:250,000 (Anderson, 1973). The combination of ERTS imagery and data relay capability now permits volumetric estimates of the water in wildlife refuges to be made more accurately and repetitively than in the past.

* Personal Communication, Dr. T. Wilheit, Goddard Space Flight Center, Greenbelt, Md.

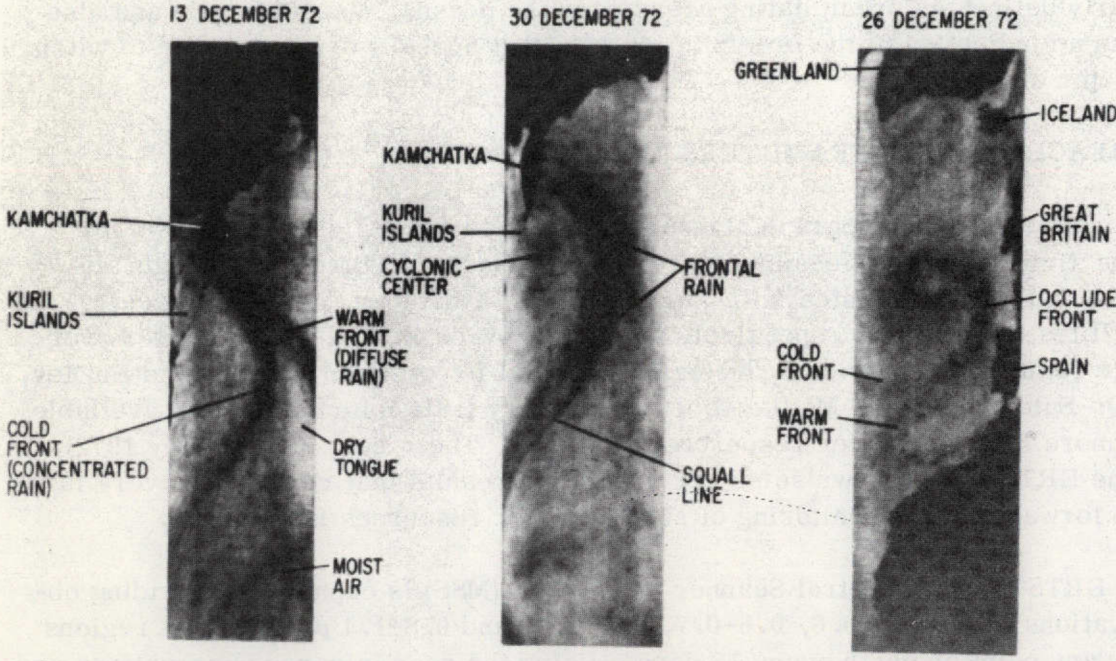


Figure 1. Passive Microwave (1.55 cm) Observations from the Electrically Scanning Microwave (ESMR) on Nimbus 5 (Courtesy of T. Wilhite, NASA, Goddard Space Flight Center)

Several instances have been reported wherein the extent of flooding has been surveyed from ERTS-1 (Freden et al. Vol. 1, 1973; Deutsch, 1973). Floods with recurrence intervals of one in 20 years can be observed along rivers the size of the James, Nottoway and Appamattox Rivers in Virginia. (Rango and Salomonson, 1973). Most recently Rango and Anderson (1973) and Deutsch et al. (1973) have reported that flooding along the Mississippi was rapidly mapped after the floods that occurred during the Spring of 1973 with accuracies that exceed 5% of the flood inundated area. (See Figure 3). In addition, they note that flood prone areas and other features such as natural and artificial levees can be recognized and mapped before a flood actually occurs.

Next to surface water, the easiest parameters to observe in the ERTS-1 data have been snow and ice. The 0.5-0.6 and 0.6-0.7 μm observations are the most appropriate for this purpose. The change with time in the amount of snow-covered area and the elevation and location of snow lines as seen from ERTS-1 imagery offers useful information for seasonal snow runoff predictions and management. Meier (Freden, et al., Vol. I, 1973) has reported that the snow covered area and the snowline altitude can be estimated to within 60 meters under good conditions. Figure 4 shows an example of snow cover variations with time in the

Figure 2. Mosaic of ERTS-1 Observations covering the State of Florida (Courtesy of A. Higer, USGS/Miami)

Wind River Mountains of Wyoming. Barnes (Freden, et al., Vol. I, 1973) has reported results from the central Arizona Mountains and the southern Sierra Nevadas in California which indicate that the extent of snow can be mapped in more useful detail than is normally depicted on aerial snow survey charts. The agreement between percentage snow cover as determined from ERTS-1 data and from aerial snow survey charts is near 5 percent for most cases.

The ERTS-1 data has provided some observations that appear to be particularly useful to glaciologists. The resolution and spectral observation capability of the ERTS-1 MSS is adequate to recognize and study glaciers that cover only a few square kilometers in surface area. The medial moraines can be distinquished in most cases as well as the movement of snow lines on the glacier itself in response to climate. In the latter instance this capability provides a means of inferring the mass balance of the glaciers occurring in very remote regions. In

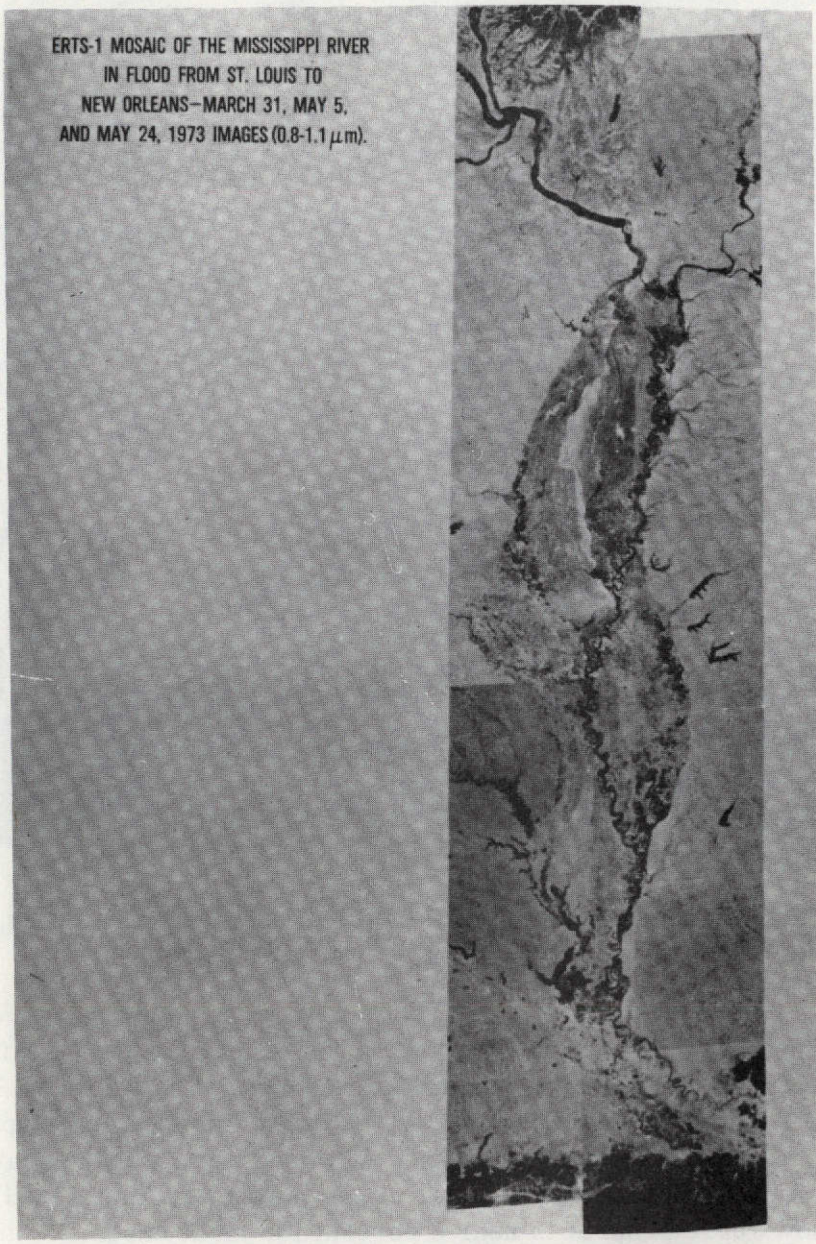


Figure 3. ERTS-1 Mosaic covering a portion of the Mississippi River between St. Louis, Mo. and New Orleans, La. The darker tones along the river generally depict the area flooded during the spring of 1973.

the first instance being able to distinquish the medial moraines offers a means of distinguishing surging glaciers (see Figure 5) from non-surging glaciers. The surging glaciers have undulating or "wiggly" moraines that distinguish them from their non-surging counterparts. The 1800 meter surge of the Yentna that occurred in 1972 near Mt. McKinley in Alaska was observed from ERTS-1 and reported by Meier (Freden et al., Vol. I, 1973). Meier has also reported* that ERTS-1 has seen the evidence of the recent surge of the Medvezhii (Bear) glacier in the Pamir Mountains in Tadzhikistan, Soviet Asia. This glacier surged in early 1973 and dammed off the Abdukagor River forming a lake impounding as much as 20 million m^3 of water before it broke through its ice dam in June of 1973. Using the ERTS-1 imagery over this extremely remote region six other surging type glaciers have been identified. Several other surging glaciers in Canada and the U.S. are now being monitored and studied.

ERTS-1 has also provided many very intriguing observations over water bodies in which remarkably detailed variations in turbidity can be seen, particularly in the 0.6-0.7 μm observations. These turbidity variations are caused by suspended sediments, organic pollutants, or algae material that cause relative variations in the color or reflectance of the water body. Figure 6 shows a typically intriguing scene over Lake Huron and Lake St. Clair on the Michigan-Canadian Border. Yarger (Freden et al., Vol. I, 1973) has reported that ERTS-1 MSS data is well correlated (±10 ppm) to suspended sediment load up to concentrations of 100 ppm in certain reservoirs of Kansas and to a lesser degree (±30 ppm) correlated for concentrations up to 1000 ppm. Strong (Freden et al., Vol. I, 1973) has reported some dramatic instances where algal material has been observed in water bodies, particularly on Utah Lake near Provo, Utah.

The other significant, but less well-known, instruments that have provided or show the capability of providing highly useful water resources information from space are the NOAA-2 VHRR (Wiesnet and McGinnis, 1973) and the Nimbus 5 Surface Composition Mapping Radiometer (SCMR) (ERTS/Nimbus Project, 1973). The principal and important aspects of these instruments are that they have provided a combination of daily 1 km - 0.6 km resolution coverage in the visible region of the electromagnetic spectrum and twice daily coverage at the same spatial resolutions in the 10-11 μm region. The NOAA-2 instrument has observed day to day variations in melting snow patterns and in ice coverage such as occurs during the Winter and Spring months. Examples of the NOAA-2 VHRR observations are shown in Figure 7. Having the day to day coverage is very useful in water resources management applications for getting cloud free observations and for observing phenomenon that change considerably over periods of days or a week such as snow cover.

* Personal Communication, Dr. Mark Meier, U.S. Geol. Survey, Tacoma, Wash.

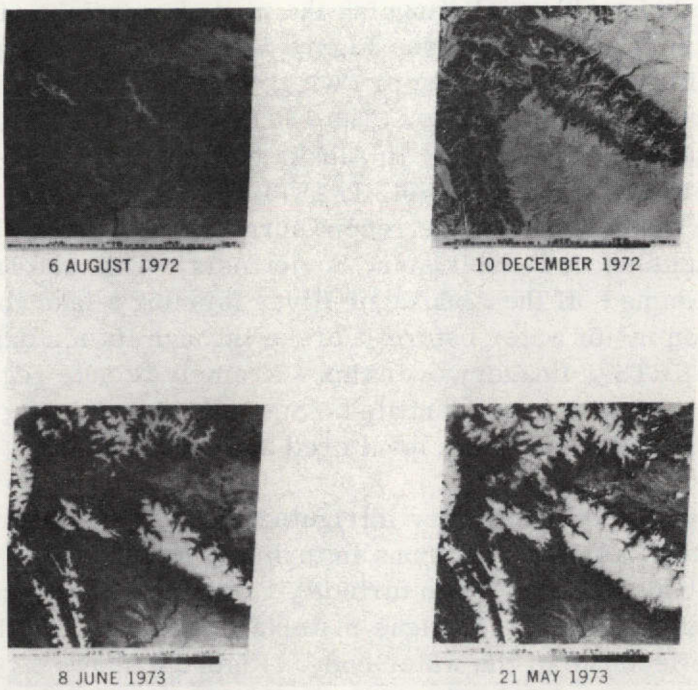


Figure 4. Four scenes (0.6-0.7 μm) from ERTS-1 showing changes in snow-cover on the Wind River Mountains in Northwestern Wyoming.

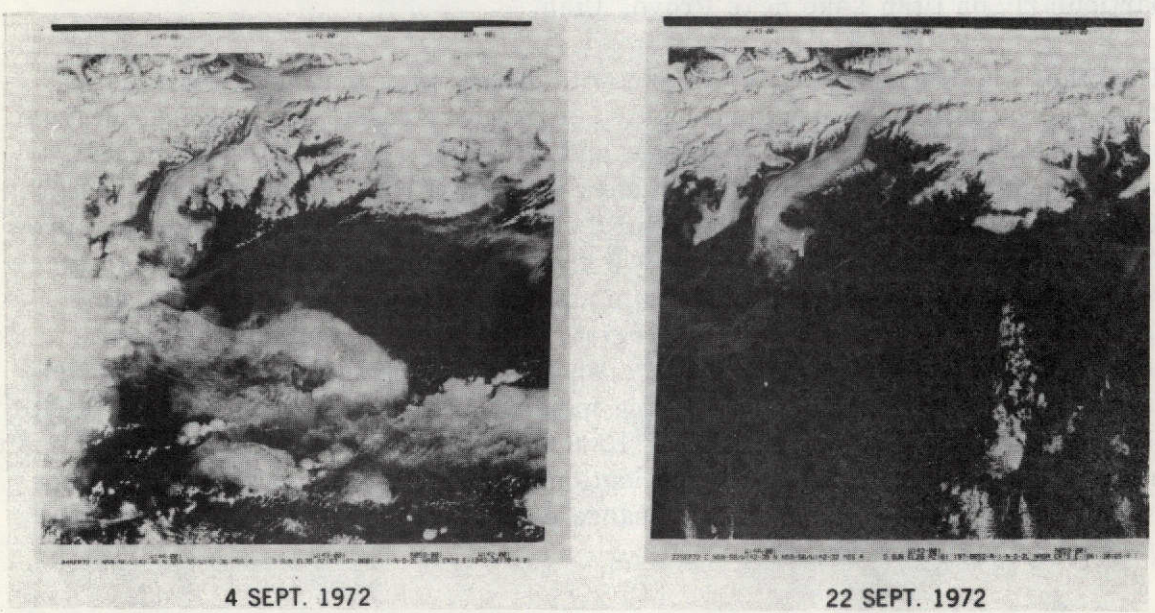


Figure 5. Sequential 0.5-0.6 μm views of the Bering Glacier in South-Central Alaska from ERTS-1

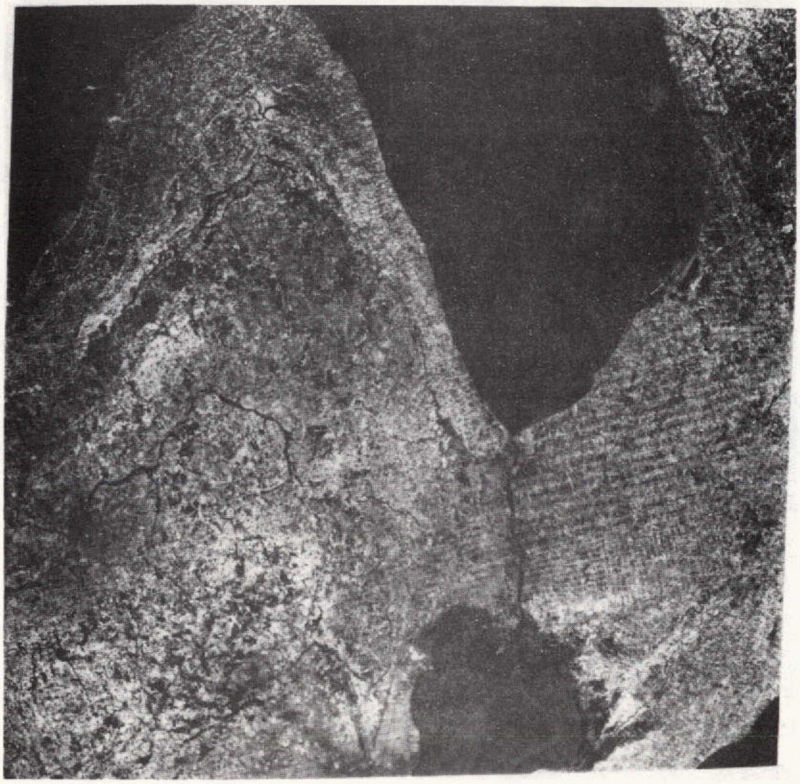
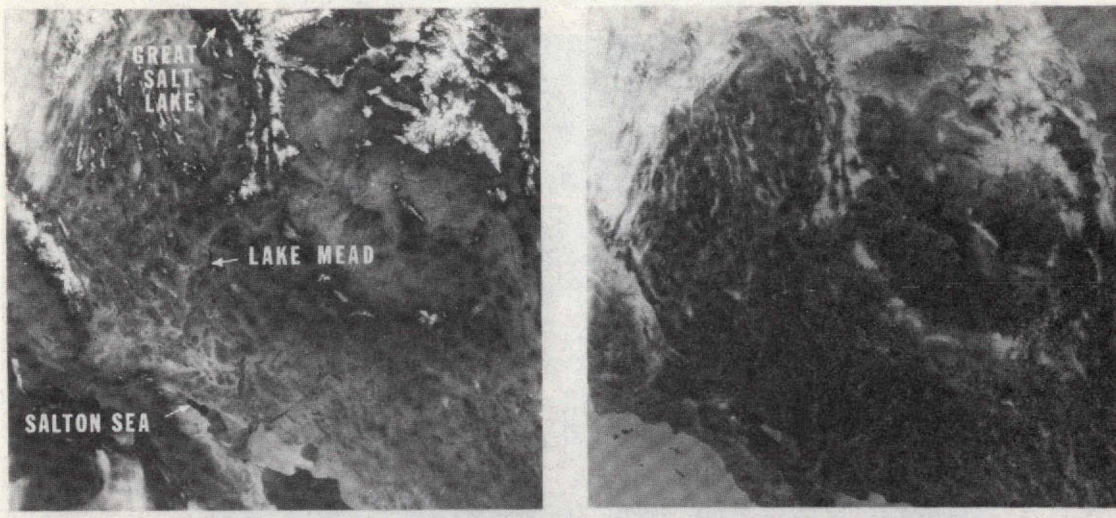


Figure 6. 0.6–0.7 μm observation from ERTS-1 on 27 March 1973 showing turbidity variations in Lake Huron and Lake St. Clair.

It should be noted that ERTS-1 has also provided observations that are quite meaningful for defining watershed systems in terms of the projected area, physiographic features, and land use. Such pertinent land use features as vegetation cover including major types of vegetation, standing water area, bare soil area, and impervious area on watersheds can be delineated usefully and repetitively for 1:250,000 map scales or smaller. The particularly important contribution of ERTS-1 is that it allows more timely and accurate detection of changes in these features and others such as areas recently affected by strip mining, clearcutting, or forest fires.



VISIBLE (0.6-0.7 μm) INFRARED (10.5-12.5 μm)

Figure 7. NOAA-2 VHRR Observations over the Southwestern United States Taken on 5 May 1973

SUB-SURFACE WATER PARAMETERS

When attempting to observe soil moisture one has wavelengths extending from the gamma ray wavelengths into the microwave from which to choose. Some very successful remotely sensed measurements of soil moisture have been made by monitoring emitted gamma radiation using low-flying aircraft (Peck, et al., 1971). However, from high flying aircraft and spacecraft one cannot use the gamma radiation approach because of the obscuring effect of the intervening atmosphere. When a surface becomes moist the reflectance drops considerably in the near infrared and contrasts markedly with neighboring dry or vegetated surfaces. If surface moisture extends some distance below the surface in a known way, then the near infrared wavelength can be used to infer or delineate regions of high soil moisture. Relative variations in soil moisture occurring in irrigated fields and in regions recently covered by precipitation have been observed from aircraft, manned, and unmanned spacecraft. From a fundamental point of view, however, the near infrared wavelengths reflected by the surface have not penetrated the surface more than a few micrometers at most and are not directly, therefore, sampling the soil moisture content except at the very "skin" of the soil. As a result it is quite difficult to obtain quantitative measurements of soil moisture using near infrared reflectance. A similar problem exists when applying far infrared (10-11 μm) observations. However, monitoring the daily variation in surface temperature may be a possibility that needs to be explored further in that the soil moisture will vary inversely with the range in surface temperature assuming compatible solar illumination conditions.

A more promising wavelength region for measuring soil moisture is in the microwave. In the case of emitted or passive microwave, the radiation is arising from depths that are roughly proportional to the wavelength being observed. Schmugge et al. (1973) have shown evidence from aircraft data that soil moisture between 0 and 35% can be estimating with an accuracy of ±5% when observing emitted 21 cm. radiation. In Kansas using active radar in the 4-8 GHz region it has been reported (Ulaby, 1973) that similar results can be obtained. No conclusive results from spacecraft have been reported as yet. However, the results from the Nimbus 5 ESMR are encouraging and the results expected from the Skylab flights may be expected to yield some useful results.

If one wishes to sample regions several meters below the surface it appears that radio waves must be employed in order to yield data that results from the direct interaction of the electromagnetic radiation with water. Results indicating that this is a viable approach to utilize from spacecraft/or high flying aircraft very scarce at this time. It is possible to infer the presence of ground water supplies beneath the surface from surficially observed geologic features. Faults or linear features may be reflecting subsurface structure, such as limestone deposits, in which reservoirs of ground water may exist. The use of ERTS-1 data from this purpose has been reported in some instances by Gold et al. and Morrison et al. (Freden et al., Vol I, 1973). Therefore, remotely sensed data does play a significant role in ground water hydrology and hydrogeology.

OTHER WATER RESOURCES PARAMETERS AND SPACECRAFT DATA RELAY

There are some parameters which are difficult to observe via remote sensing techniques. These include many water quality parameters, ground water information, and river stage or discharge measurements. These parameters can be obtained from in-situ platforms but then there is the difficulty of collecting the data rapidly and over large and remote regions. Collecting the data from these platforms and relaying the data via satellite to ground-based collection stations can solve many of these problems. The most recent demonstration of spacecraft data relay capability has occurred using the Data Collection System (DCS) on the ERTS-1 satellite and Data Collection Platforms (DCP) that broadcast the data to the satellite as it passes overhead. Over one hundred of the ERTS-1 DCP's are now operating very successfully in areas stretching from Iceland to Hawaii and Northern Canada to Central America. Particularly noteworthy applications of this capability are occurring in the Delaware River Basin, on the Merrimack and St. Johns Rivers in New England, in Florida, and in

Arizona. In many cases data are being relayed to water resources management agencies in time periods of less than one hour. This kind of capability will be continued on polar orbiting spacecraft such as ERTS and Nimbus and, in particular, will be included on the operational geostationary satellite series, GOES (Geostationary Operational Environmental Satellite), operated by NOAA.

FUTURE SYSTEMS

There are still a great number of areas where there is considerable room for improvement if highly useful spacecraft measurements and results are to be provided the water resources and hydrology communities. These are two general categories in which improvement is needed and can be expected in the next few years in the applications of space technology to water resources monitoring. One category includes sensor and spacecraft improvement and the other is in data processing and analysis.

SENSOR AND SPACECRAFT IMPROVEMENT

As one considers the various phenomena that can be observed in water resources, they may note that these phenomena occur on different time and distance scales. A representation of the various times and distance scales and the phenomenon involved is depicted in Figure 8. Also depicted by the shading are the time and distance scales sampled by various existing or planned spacecraft systems. Note that ERTS, for instance, samples phenomena no more often than once every 18 days and identifies objects as small as 80 meters in dimension. The possible launching of the EOS (Earth Observatory Satellite, EOS) satellite series presently being considered for the late 1970's would provide sensors that could have up to 10 meter spatial resolution capability but much the same temporal sampling frequency. Note that the Nimbus/EOS/NOAA satellites series have or are sampling as often as once every 12 hours with spatial resolutions as good as 0.6 km (Nimbus 5 SCMR). The Skylab Earth Resources Experiment Package (EREP) includes sensors with approximately 10 meter resolution (Earth Terrain Camera, Experiment (S190B) and is covering some areas at irregular time intervals for a total duration amounting to more than 1/2 year. Beyond the EOS series a Synchronous Earth Observation Satellite (SEOS) Series is currently being considered which may provide the capability of sampling specific areas every few minutes with spatial resolutions in the 100 meter range. Certainly this satellite series will make a unique contribution toward the monitoring of rapidly varying, dynamic water resources phenomena.

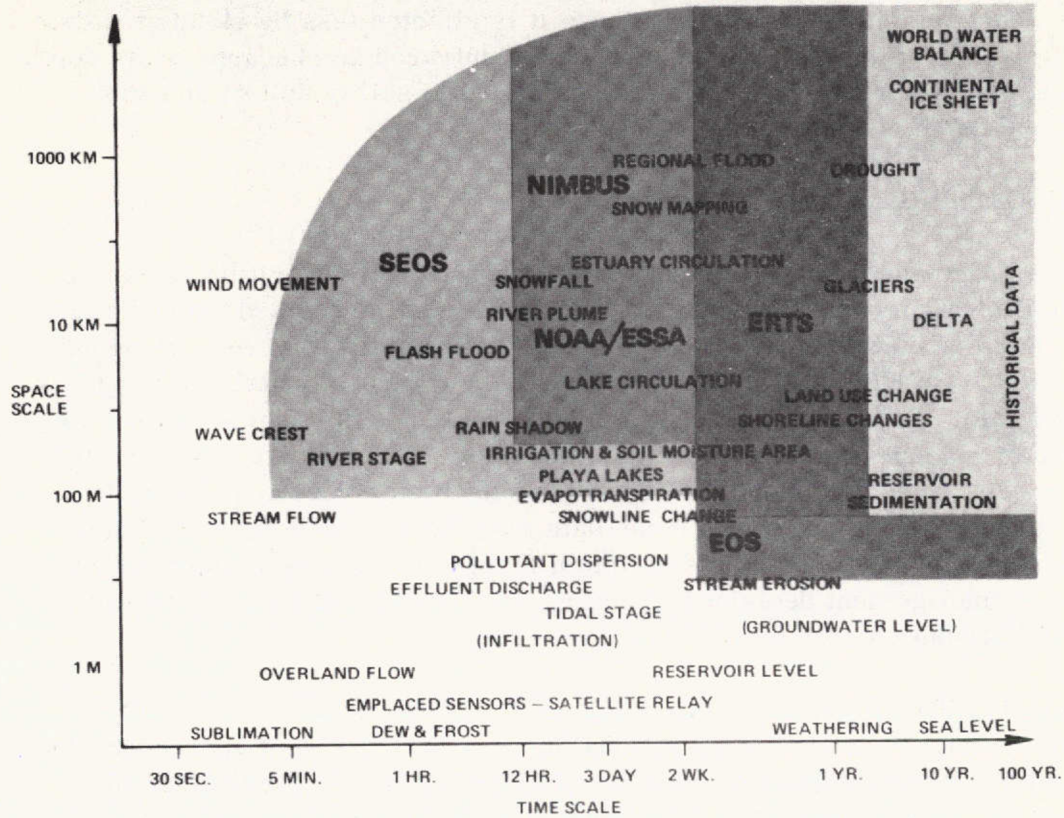


Figure 8. A time versus distance diagram indicating the observing capabilities of existing and planned spacecraft systems. Those phenomena in parentheses are most readily observed by ground-based sensors.

Better sampling rates involving more frequent coverage, better spatial resolution, and longer spacecraft lifetime still leave one more dimension that must be considered in order to provide more useful remote sensing observations. This dimension is the spectral or wavelength domain defining in what portion of the electromagnetic spectrum observations should be taken. Certainly the Skylab EREP program is directed toward this problem and is providing new information about the advantage of taking observations in various regions of the spectrum with different and more narrow bandwidths. As research from aircraft and ground based efforts indicate feasibility new instruments will be flown on the research satellites such as Nimbus, EOS and SEOS. As these concepts prove successful operational satellites dedicated to Earth resources will evolve. From the progress that has been made to date, certainly a promising portion of the electromagnetic spectrum is in the microwave utilizing both passive and active systems. This region is attractive because it is affected less by cloudy weather than systems employing the visible, near or far infrared and because of its depth penetrating capability that appears to be applicable to soil moisture and snow moisture and depth measurements.

DATA PROCESSING AND ANALYSIS

As sensors and spacecraft are devised with higher spatial resolution and more frequent observation capability the data rates that must be handled expand rather rapidly. For instance the data rates on the Nimbus satellites were approximately 4 kilobits/sec. On ERTS-1 the MSS produces data at approximately 15 megabits per second rate. Data rates on the EOS series could possibly be as high as 200 megabits per second. To handle these data and apply them require systems that will preprocess some of the data on board the satellite or very rapidly on the ground. A very sizable portion of these data must be analyzed and techniques or methods used to reprocess the data into a form where it can be interpreted and used for management decisions affecting, in this case, the improved monitoring and distribution of our world's water resources.

A particularly difficult aspect of this total task is devising means of rapidly delivering the data to users for operational application. Present approaches to these problems seem to generally consist of sampling (e.g., every other observation) the sensor-generated data stream over large areas with preprogrammed sampling at full resolution over selected, relatively small regions. Rapid ground processing and product delivery will possibly be accomplished through preplanning and programming for selected regions and investigators.

It seems clear that satellite platforms offer the means whereby one can monitor large regions, including the entire globe. Furthermore these satellite sensors provide data that enable quantitative determinations to be made as to the status and trends in its available resources, and, thereby, offer input for well-founded allocation decisions to be made. Certainly a large part, if not the major part, of the challenge that must be addressed by the aerospace/applications satellite and aircraft community is in the area of data processing and analysis. In view of the expanding pressures on the world's resources, including water resources, it would seem very important that every effort be made to make sure that this challenge is met satisfactorily.

SUMMARY AND CONCLUSION

Considerable advances have been made since the launch of TIROS 1 in 1960 in monitoring or inferring by remote sensing from spacecraft the presence and quantity of water in the atmosphere, and on or beneath the surface of the earth. Recently on Nimbus 5 spectrometric measurements involving in particular microwave measurements permit the measurement of total precipitable water to within about 10% and the liquid water content of cloud to ±25%. Using microwave radiometry the location of precipitating areas over the ocean and broad estimates of precipitation rates over the ocean can be obtained. The launch of ERTS-1 and the NOAA-2 VHRR has greatly contributed to the repetitive observation of parameters important in surface hydrology. Snow covered areas can be measured to within a few percent of drainage basin area. Snowlines altitudes can be estimated to ±60 meters and the location of snowlines can be extracted from ERTS-1 imagery in more detail than is normally obtained from operational aircraft surveys. Surface water area can be estimated to within a few percent accuracy over large regions such in the playa lakes regions of the southern high plains of Texas and New Mexico. Lakes are small as 1 hectare can be recognized and mapped accurately on scales of 1:250,000. Other landuse features such as impervious area, vegetation and bare soil can be mapped. In addition, changes in land use on watersheds resulting from forest fires, clear cutting, or strip mining can be rapidly noted and this information incorporated into watershed management operations. Relative soil moisture variations can be observed from ERTS-1 such as occurs after rainstorms or in irrigated areas. Based on airborne measurements of emitted microwave radiation quantitative estimates of soil moisture using wavelengths between 6 and 21 cm appear to hold promise. The observations of lineaments and fractures plus other geological features are offering new information that contributes to more effective ground water exploration.

New spacecraft systems such as the EOS and SEOS series which would improve the observational frequencies and lifetime of space observations are being studied. Included on these spacecraft will be improved sensors providing higher spatial resolution and higher spectral resolution in several spectral bands including the microwave. With high data rates, possibly as high as 200 megabits/second, coming from these spacecraft sensors means of processing and analyzing these data are also being studied that will rapidly speed the data to water resources management agencies in a form that will be more timely and utilizable. Given the recent and rapid progress that has been made in developing and applying spacecraft observations to the monitoring of hydrologic parameters and the plans for the future, the general appropriateness of increased efforts to further develop this tools for the study and management of water resources systems seems quite apparent.

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