Review of Remote-Sensing and GIS Technologies and Approaches That May Provide Alternative Ecological Monitoring Tools for the Grand Canyon Monitoring and Research Center

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EXECUTIVE SUMMARY

This report reviews the parameters being monitored by the three resource programs with the Grand Canyon Monitoring and Research Center (GCMRC) in terms of the current methods employed and their stated or inferred spatial resolutions and accuracies. The current methods used by the various service groups within the Information Technology Program are also reviewed. Within the discussion for each program alternative remote-sensing approaches are presented from recently published literature and specific recommendations are made for exploring selected alternative approaches. Many of the parameters that are monitored by the GCMRC resource programs are interrelated to various degrees and, as such, possible alternative remote-sensing approaches for some parameters are very similar and these parameters may in fact be monitored by a single remote-sensing approach. As a result, various program-specific recommendations are summarized in a final section, where interrelated program elements are addressed as a whole with respect to a remote-sensing approach that appears to be most appropriate for that group of elements or parameters. The primary objective of this assessment was to determine if the GCMRC monitoring program could benefit from a broader and more rigorous remote-sensing approach. The recommendations presented in this report suggest that the GCMRC program can benefit from an expanded remote-sensing program in terms of wider areal analyses, more rapid data acquisition, more computer-driven analysis, and more cost-effective monitoring. The transition towards a more capable and comprehensive remote-sensing approach will require some research on specific issues in order to determine the best approaches and the limitations of each approach for the resource programs.

The alternative remote-sensing approaches that are recommendations for the three GCMRC resource programs fall into two general categories: those approaches that may augment or extend current field measurements and those that may largely replace current field measurements. The resource elements that may be augmented or extended by alternative remote-sensing technologies include water and aquatic foodbase studies, aquatic and terrestrial faunal habitat studies, historic and prehistoric resource monitoring for mitigation, and small-scale, non-vegetation cultural resource monitoring. The resource elements that may be largely replaced by alternative remote-sensing technologies include channel bathymetric and terrestrial topographic mapping, channel geomorphological mapping, terrestrial vegetation and cultural ethnobotanical surveys, terrestrial geomorphologic mapping and marsh and backwater surveys, and camping beaches and camp site monitoring. This assessment report also presents specific recommendations for improving the contracting process for acquiring remotely sensed data, the archival of GCMRC historical and future data, the database management system, the library search system, and the control network and storage of survey data. General remote-sensing issues are discussed with respect to specifications for spatial resolution, for positional and vertical accuracy, for the timing and frequency of data acquisition, and for the types of data that need to be acquired. The latter issue needs further investigation in order to determine the optimal sensor configuration for the resource programs. In addition, there are other unresolved issues with respect to capabilities and limitations of LIDAR data (spot spacing, water penetration, vegetation penetration) and with respect to the digital processing required to produce consistent system-wide orthophoto mosaics. These issues need to be addressed by experimentation and demonstration.

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INTRODUCTION

Since 1982, the Grand Canyon Monitoring and Research Center (GCMRC, which was known as the Glen Canyon Environmental Studies Program between 1982 and 1995) has been monitoring the ecological effects of reduced flow levels of the Colorado River within the Grand Canyon as a result of the construction of Glen Canyon dam. The study area extends over about 300 river miles of remote terrain produced by the extremely steep and high sidewalls of the Canyon. The GCMRC consists of four program elements: Physical Resources, Biologic Resources, Cultural Resources, and Information Technology. The first three programs collect and analyze data for their specific resources, while the Information Technology element obtains remotely sensed data for the other programs, provides surveying support to the other programs, and stores all data collected for and by the other programs in a GIS environment. In order to obtain a detailed understanding of the processes affecting the ecology in this remote region, data collection and analysis have been performed during this time period using mostly conventional methods. These methods are expensive, time consuming, ecologically invasive, and because of the time and expense can only address parts of the 250 km^2 ecological system. Although remotely sensed data have been acquired annually over this time period, the data have mainly consisted of conventional, high-resolution, black-and-white (and some natural-color) aerial photography.

In an effort to determine alternative methods for data collection and analysis that are more cost-effective, efficient, and regional, but less invasive, and that provide similar or additional data to that already being collected *in situ*, the Information Technology program within GCMRC commissioned an assessment during calendar year 2000 of more advanced remote-sensing systems and methods that can provide data that approach or meet these desired characteristics. As similar assessment was performed by a scientific panel during 1998 (Berlin et al., 1998). Time and budget limitations did not allow that panel to fully evaluate each the four GCMRC programs, hence their recommendations often have caveats. This prompted the current examination in which program objectives, data requirements, and current methods of data collection and analysis were assessed, along with alternative remote-sensing technologies and methods for data collection and analysis. The results of that assessment are presented in this report. This evaluation is the first step in a process to establish a set of comprehensive, state-of-the-art, remote-sensing protocols that can augment current monitoring protocols of the GCMRC programs. The recommendations presented in this report, which are supported by previously published results, need to be tested and validated using actual remotely sensed data for the Grand Canyon to ensure that the recommended approaches satisfy program protocols. The following sections briefly review, for each of the four programs, their objectives, the parameters being measured, and the methods currently being employed to collect, store, and in some cases analyze the data. Each of these four review sections are followed by a recommendations section that addresses alternatives for data collection and/or analysis using remotely sensing data. All of the individual recommendations are summarized at the end of this report.

REVIEW OF GCMRC PROGRAM REQUIREMENTS

Physical Resources

<u>Objectives</u>:

The Physical Resources Program provides information and assessments of the dynamic hydrologic and geomorphic processes that directly and indirectly effect the ecosystems from Lake Powell to Lake Mead resulting from Glen Canyon Dam operations. The overall objective of the program is ecosystem sustainability in terms of restoration, or at least maintenance, of hydrologic and geomorphic processes and interactions and long-term conservation of sediment in mainstem and riparian environments. The habitats of concern include channel environments (cobble and gravel bars, debris fans, and talus shorelines) where benthic organisms occur and which are used by spawning fish, aquatic near-shore habitats (sandy shorelines and backwaters) that are used by juvenile native fish and that provide substrates for plants, terrestrial habitats that support riparian flora and fauna, terrestrial substrates used by recreational visitors, and terrestrial substrates that support and preserve cultural resources up to the stage associated with pre-dam river terraces. This overall objective is being approached through a set of primary and secondary objectives that include:

1. Long-term monitoring of fine-grained sediments to document system-wide changes in these deposits relative to dam operations and natural tributary inputs, with emphasis on key storage settings. The monitoring includes morphology, volume, area distribution, and grain-size characteristics of fine-grained characteristics in both aquatic and terrestrial settings. A secondary goal is to relate dam operations and fine-grained sediment storage to short- and long-term trends in distribution and condition of physical aquatic and terrestrial habitats related to biological and socio-cultural resources. This secondary goal includes (1) determination of erosion or stability of pre-dam river terraces associated with cultural resources; (2) determination of near-shore aquatic and terrestrial substrates related biological and cultural resources; (3) determination of texture and volume of sediments available to restore and preserve sediment-dependent resources above the 708 m^3/s flow level; (4) monitor quantity and quality of recreational campsites; and (5) monitor system-wide distribution of fine- and coarse-grained channel beds.

2. Long-term monitoring and evaluation of coarse-grained sediment inputs (with respect to volume, grain-size, and topographic changes within debris fans, eddies, cobble bars, and the channel substrate) from tributary debris flows and Glen Canyon dam operations relative to system-wide coarse-sediment mass balance and distributions of aquatic and terrestrial habitats. Secondary issues are (1) the effect of annual dam flow rates on the distribution and abundance of coarse-grained substrates associated with biological habitats; (2) the effect of annual tributary events on the quality of campsites, cultural sites, and navigation; and (3) the effect of main-channel coarse sediment o fine-sediment storage in pools and eddies.

3. Developing or refining existing streamflow and suspended-sediment transport models, considering a subset of river reaches grouped by their common characteristics and behavior, to better predict (1) average sand bar deposition and erosion responses to varied discharge rates, fine-sediment supply, and thermal conditions, and (2) a better understanding of coupled suspended-sediment and streamflow processed along the main channel. Secondary issues are (1) determining whether any geomorphic reach displays unique response characteristics; (2) determining potential responses of pre-dam terraces to a range of bar-building flow releases; (3) evaluating the evolution of reattachment bars, which form backwaters, and other near-shore physical habitats under different hydraulic conditions; and (4) evaluating the effectiveness of current record-of-decision and alternative dam operations on the sustainability of sand bars and system-wide sand conservation.

Within any given year there may be two types of conditions studied: low-frequency, high-flow (125,000>cfs>25,000) conditions and the higher frequency, low-flow (≤25,000 cfs) conditions. The latter condition has been the norm since the dam became operational. As evidenced by the above program objectives, grain size is a very important parameter, especially with respect to the 10 lowest size classes within the sand, silt, and clay categories. Currently, data suggest the most effective rating curve for estimating system-wide export of fine sediment is the Phantom Ranch station. Most studies in this program concentrate on particular river reaches within the first 100 river miles, because reaches in this area are more likely to reflect changes from dam operations, although more system-wide studies are now being advocated and encouraged.

Parameters Measured and Methods Employed:

The types of parameters currently being measured by investigators within the Physical Resources Program, separated by environment, are as follows:

1. Water parameters - mainstem and tributary flow rate, sediment load, turbidity, temperature, and grain-size distribution of suspended sediment. The first four of these parameters are measured with stream gages, which is transmitted by telemetry to the Flagstaff Field Center. The gaging stations are: near Lee's Ferry are at RM 0, -3, -6, -9, -11, and -16; downstream within the Paria River, Shinumo Creek, Tapeats Creek, Spenser Creek, Havasu Creek, Kanab Creek, Bright Angel Creek,

Little Colorado River, and Diamond Creek); and within the main channel above the Little Colorado River confluence, near the Grand Canyon, above National Canyon, and above Diamond Creek. Spatial water temperature is measured with strings of thermistors which are deployed by boat crews. Grain-size distribution is performed manually from collected water samples. One investigator is attempting to develop a remote sensing technique to determine/monitor suspended load and turbidity using visible and near-infrared wavelength detectors stationed at two locations, one being at the Grand Canyon stream gaging station.

2. Channel substrate - mainstem and tributary bathymetry, median grain-size distribution in vertical profiles of river beds, thickness of beds, and fine- versus coarse-grain-size distribution on beds. Bathymetry is currently being obtained using a multi-beam, hydro-acoustic instrument for various small, selected reaches because data acquisition is time consuming. For shallow near-shore environments, which cannot be approached by the hydro-acoustic instrument, bathymetry is being measured by ground survey crews using GPS stations. The remaining parameters for the substrate are being obtained by analysis of hand and core samples and by analysis of side-scan sonar. A new acoustic technique (QTC) is being explored for mapping bed composition along cross-sectional profiles. Both the side-scan sonar and hydro-acoustic surveys are performed annually.

3. Terrestrial fluvial geomorphology and topography - change in area and volume of fine-grained sediment deposits, e.g., active sand bars in New High Water Zone, return-current channels within fan/eddy complexes (backwaters), and pre-dam river terraces with cultural resources both on a historical basis and on a short-term, event basis. Topographic data are being currently acquired by photogrammetric analysis of aerial and land-based photography and by manual field survey measurements. Photogrammetric analyses and geomorphic mapping are being applied to historical photographic data to determine the changes in area and volume of geomorphic units under different flow regimes. The photogrammetric data being derived partly overlaps the time periods for the land-based topographic surveys, and as such, the land-based surveys provide ground truth data for photogrammetry. Geomorphology is being interpreted and mapped at various reaches between Lee's Ferry and Middle Granite Gorge by a series of mapping steps that start with stereo-pair photographs and end with polygonal units within an ArcInfo coverage. The land-based topographic surveys are conducted annually at 35 sites between river mile -6 and 225; the land-based surveys have decreased in frequency to now be performed once a year.

4. Terrestrial surficial geology of more stable terrain - mapping of reaches and debris flows, distinguishing units based on elevation (terrace level), hill slope, grain size, relative age, and composition. This information is currently acquired by photointerpretation of aerial photographs supported by field investigations and follow the series of manual mapping techniques that are being used for the more transient, younger, fine-grained sediment terrain. Some analysis of multispectral data are being attempted to map the mineral compositions of the debris flows to determine if their movement can be predicted from such information. The reach-scale geomorphology is being mapped within the same regions that the young, transient sediment deposits are being mapped. The debris flows are mapping and monitored on a system-wide scale.

<u>Physical-Resource Models</u>:

Wiele et al. (1996) have developed 1D and 2D sediment models that predict the location and volume (thickness) of sediment deposition within the Colorado River based on water velocities, bathymetry, and average grain size, location and influx of sand. In terms of the bathymetry, the model has used data with contour intervals coarser than 0.5 m and has still yielded good correspondence between modeled and observed storage volumes and locations. Webb is working on a model to predict the sediment yield from tributary debris flows and Korman and Walters are developing an ecological model that considers both physical and biological factors for prediction of the integrated effects of dam flow rates.

Remote Sensing Recommendations:

Progress has been made within the past few years toward increased and better use of remote sensing techniques to obtain information necessary to address protocols of the Physical Resources Program. However, there is considerable room for improvement in both the data acquired and the methods employed in the analysis of these data. In addition, there appears to be a concerted effort in this program to perform more integrated studies (where parameters overlap) and more regional studies, both of which were recommended by the program's last protocol evaluation panel (Wohl et al., 1999). The following are specific comments and recommendations on specific aspects of the Physical Resources Program. The comments include responses to pertinent recommendations offered by the protocol evaluation panels (PEP) for both Physical Resources (Wohl et al., 1999) and Remote Sensing (Berlin et al., 1998).

Water parameters

The most dependable method to obtain the characteristics of the water (mainstem and tributary flow rate, sediment load, turbidity, temperature, and grain-size distribution of suspended sediment) is by in-situ instrumentation whose data are transmitted by telemetry. The PEP for remote sensing suggested that turbidity using in-stream optical devices be explored (Berlin et al., 1998), but turbidity is already measured and transmitted from the gaging stations. However, grain-size distribution within the suspended sediment is currently not obtained by the water gaging stations. There are commercially available grain-size detectors, whose output could be combined with current telemetry transmissions from the water gages. This should be implemented an instrument proves reliable for this river environment.

Although stream gages are the most accurate method for obtaining sediment load, turbidity, and temperature, the gages provide only point-specific data. Multispectral, visible-wavelength image data have been used to estimate turbidity and total suspended sediment load, but all techniques to date require ground-truth calibration data (i.e., in water measurements) to relate spectral response to absolute water values (e.g., Whitlock et al., 1978; Goodin et al., 1993; Jerome et al., 1996; Sathyendranath et al., 1997; Fraser, 1998a, 1998b; Pozdoyakov et al., 1998; Tassan, 1998). This is by no means a serious limitation because the water gages can provide such ground-truth data and because remotely sensed image data has the potential for extrapolating point-specific data to map the distribution of a water parameter over entire river reaches. Such areal distribution data would improve knowledge of the relations between sediment transport and deposition within the main-channel and near-shore environment. The relation between spectral response and a water parameter is not apparently effected by differences in solar zenith or elevation angle (Whitlock et al., 1978; Jerome et al., 1996), but sun glint is an issue that can be overcome either by careful planning for data acquisition or by stereo image acquisition. Some of the better correlations between turbidity or total suspended sediment and spectral response were obtained within the 0.695-0.720 micrometer wavelength region (Goodin et al., 1993; Tassan, 1998; Fraser, 1998a), but this is not the wavelength region that provides the greatest penetration into water. Although some studies have found good correlations between suspended sediment load or turbidity and the spectral radiance or reflectance within a single wavelength band, it appears that more reliable results are obtained using wither band ratio values or the first derivative (difference) of two adjacent wavelength bands. Relations between total suspended load or turbidity and spectral response is not simple; spectral response is influenced by the mineral composition and quantity in suspension, dissolved organic matter, etc., all of which affect the backscatter and absorption coefficients of water. Thus, the relations need to be established (understood) for a particular aquatic environment. A current GCMRC-funded investigation by Pat Chavez is trying to develop these relations at two water gaging stations (Chavez et al., 1999), but the gaging stations are upstream of tributary confluences and the relations that are developed at these two sites may not extrapolate well to regions downstream of the tributaries because the suspended mineral composition from each tributary can vary with the source region for the tributary.

Future remote-sensing image data will probably be acquired using multispectral sensors that are calibrated, which is a requirement for their use in deriving water properties. However, such image data are expensive and may be acquired routinely only one a year. If shorter time frames are necessary for these data to be useful, then less expensive data acquisitions need to be explored. An alternative may include procurement of a simple four-band, CCD sensor (costs about $10,000) that can be mounted on existing aircraft at the Grand Canyon and flown when needed; a method to record GPS data for these image data will have to be developed. Another alternative is the use of "high-resolution" (4-m), four-band IKONOS data that can provide images every 16 days (costs about $26/km^2 orthorectified; $12/km^2 unrectified) . However, IKONOS is a sun-synchronous satellite and acquires data at about 9:30 AM, which will result in shadows during the winter months for most reaches and shadows year around for some reaches. Almost all satellite data present the acquisition limitations mentioned for IKONOS, but have even lower spatial resolution. The satellite option does not appear to be a viable alternative because of shadows and because the gain on most satellite systems cannot be changed, which would be desirable for water investigations.

Water surface (radiant) temperature can be obtained using airborne thermal-infrared (TIR) sensors. Such data can provide areal context that is not provided by stream gages or thermistor string surveys. The airborne TIR data are recorded as absolute (radiant) temperature values, thus there is no need for ground calibration. However, there are some disadvantages to airborne data acquisition: (1) The temperature data represent the water's surface, whereas ground surveys are more interested in water temperature at some depth. (2) The TIR sensor needs to be cryogenically cooled close to absolute zero degrees (black body) in order to obtain temperature differences of 0.1 degrees. A recent data acquisition of TIR data using a Daedalus 12-band 1268 (ATM) sensor during July, 2000 showed that cooling the sensor under very high ambient air temperatures (>100 °F) at a flight height near 1,200 feet above ground (to obtain 1 m spatial resolution) was extremely difficult. The cooling problem could be overcome by Fall or Winter flights, but data need to also be acquired during the Summer. Airborne TIR data are most applicable to relatively quiescent waters; most of the churning water reaches would provide no subsurface temperature information due to rapid advective mixing of the water column. The cost for such data is about $500/river mile, but this cost could be reduced if a more simple sensor was flown that had fewer wavelength bands, or only a single TIR band. The utility of such airborne data is currently being evaluated and a more firm recommendation will follow that analysis.

Channel substrate

Bathymetry is being collected using a multi-beam, hydro-acoustic instrument in accordance with the recommendations of the last PEP for physical resources (Wohl et al., 1999). However, the method is relatively slow in data acquisition and thus data have been acquired only for selected river reaches. In addition, the hydro-acoustic instrument cannot obtain data for the shallow near-shore environment, which is currently obtained using manual survey methods. Alternative airborne remote-sensing techniques include the SHOALS LIDAR and optical image data. The physical resource PEP (Wohl et al., 1999) recommended that SHOALS be considered for bathymetric surveys. The SHOALS LIDAR system is a dual-beam laser system that obtains water depth differencing the distances recorded from the green wavelength laser (substrate) and from the near-infrared laser (water surface). The gain on the near-infrared laser is set to reflect off of the surface of water, and as such, the near-infrared laser cannot record distances to hard objects because the return signal is saturated. The green laser is not used for land because the reflected signal is affected by materials that preferentially absorb or reflect light within the green wavelength region. This system could be employed within the Grand Canyon to derive bathymetry. The maximum depth that can be detected by the green SHOALS laser in clear water is about 40 meters with an accuracy of 15 cm (Riley, 1995). Because its penetration is constrained by turbidity, SHOALS is generally not recommended by the Army Corps of Engineers (the developers of SHOALS) for use in turbid river waters. In addition, its spot spacing is only 4 meters at normal flying altitudes of 400 m above ground level (AGL). A 4-m spot spacing can generate a 1-m contour interval, which may be acceptable for sediment budget models (Wiele et al., 1996) that currently produce good results using bathymetric data at contour intervals equal to or coarser than 0.5 meters, but a better approach would be to lower the flight AGL below 400 m in order to decrease the spot spacing. The Summer, 2000 helicopter survey by Bechtel at 400 m AGL showed that slow-moving aircraft can maintain lock on GPS satellites at that altitude; it is uncertain if that can be attained at much lower AGL.

Two alternative approaches to map bathymetry that involve optical image data are (1) deriving relative water depth from images acquired in two wavelengths, and (2) deriving water depth from stereo-image pairs acquired at a single wavelength. Application of the first of these two techniques has been performed in a variety of water bodies (Lyzenga, 1978, 1981; Bagheri et al., 1998; Bryant and Gilvear, 1999; Roberts and Anderson, 1999;

Woodruff et al., 1999; Durand et a., 2000). This technique requires two wavelength bands because reflectance from the substrate can change with the composition of the substrate. However, the technique, which was proposed and first applied by Lyzenga (1978, 1981), can map both water depth and bottom composition, as long as both wavelength signals are reflected off of the substrate. The relation between reflectance and water depth for any given substrate is linear and quite accurate in a relative sense; a ground control elevation value is required to convert the relative values to absolute elevation. For this application, Bagheri et al. (1998) found that the 0.57 micrometer and 0.65 micrometer wavelength regions provide the clearest bottom detection versus water penetration, however, Lyzenga (1981) preferred to use bands centered at 0.54 μm and 0.61 μm in balancing sensitivity versus penetration depth. An indication of the water depths that can be measured by this technique is the study by Bagheri et al. (1998) who obtained reliable water depths down to 20 meters. However, the maximum water depth that can be determined using this method is limited by the maximum depth of penetration of light within the longest of the two wavelength images, as well as by the optical properties of the water. In addition, mapping bottom composition and subsequently deriving water depth has higher uncertainties in deeper water areas because light is attenuated more with increasing water depth, thus the signal-to-noise ratio is lower in the deeper water areas (Lyzenga, 1978). Application of the techniques is relatively straightforward and should be explored for use within the Grand Canyon. The second alternate approach, using single-band optical image data, is the use of a photogrammetric approach on a set of stereo-pair images. Although trial of this approach was suggested by the remote-sensing PEP (Berlin et al., 1998), this approach has not been documented in published literature. It may be that exponential behavior of light transmission in water may make this approach untenable. A lesser concern, but one that merits examination, is how much the angular separation provided by an aerial stereo-pair of images decreases within the water and will that amount of decreased separation preclude accurate measurement of height (depth). This approach should be considered, at least on a theoretical basis. There are stereo-pair imagery over reaches that were mapped by the hydro-acoustic instrument; these data can provide the test data to determine the relative difficulty of this approach. It would be better if the approach was partly automated to reduce cost of analysis. The SHOALS approach and the two optical-image approaches just discussed will provide bathymetry data for large areas faster than that obtained by the acoustic system, but these optical techniques may be more limited in terms of the levels of turbidity in which the methods will provide reliable data. The advantages of using SHOALS over other techniques are that (1) the instrument can now obtain both bathymetry and terrestrial topography within the same flight line acquisition using the green laser signal (Guenther et al., 2000), (2) the technique is much more straightforward, and (3) the technique provides high accuracy (15 cm). The spot spacing would have to be denser than 4 m (<<400 m AGL) for SHOALS to be used for GCMRC topographic/bathymetric protocols.

In terms of mapping the composition of the channel substrate, side-scan sonar is currently being used to map the distribution of sediment deposits, as well as to infer average grain size of the deposits. However, the processing of the data takes many months and the positional accuracy of the resulting image data is only 2-3 meters. If the side-scan sonar image data prove more useful than other types of data that map sediment distribution in the channel, then the image data need to be registered to a good orthophotographic image base with positional accuracy near 0.6 meters. Registration of an image to another image base always produces lower positional accuracy than that of the image base, thus the need for such an accurate base map. Many different applications in all of the GCMRC programs require such an accurate base map for registration in order to rectify image data or to locate collected point data to an accuracy that permits more automated, cost-effective, and system-wide analyses of these data, whether the analysis is for a particular attribute or especially for an integrated analysis of many different parameters to address a complex issue.

There are two alternative approaches for mapping the distribution of physical resources that occur on the channel substrate. Both approaches offer cost-effective, wide-area coverage, rapid data acquisition and analysis, and positional accuracies within 1 meter. These two alternative approaches are either single-band or dual-band CCD image data acquisition from airborne imaging systems that allow variable detector gain settings to optimize water penetration. The dual-band mapping technique, which was discussed in a preceding paragraph, provides more capability for discriminating and mapping channel substrate than the single-band technique, but the dual-band technique may not map substrate at the depths of the single-band technique, but this will depend on the two wavelengths selected for dual-band analysis. The single-band approach will yield more ambiguous results than the dual-band approach in the same way that panchromatic image interpretation has more ambiguity than a multispectral approach. Both approaches need to be explored to determine their full potentials and their relative merits, limitations, and cost-benefit with respect to each other and to the sonar approach. Recent studies have shown that the combination of SHOALS bathymetry and color aerial photography can greatly assist in the mapping of coastal substrate and coral reefs (Chavez and Field, 2000a, 2000b; Chavez et al., 2000a, 2000b).

The remote-sensing PEP (Berlin et al., 1998) suggested two additional approaches for trial: underwater videography and ground penetrating radar (GPR). Videography is being used less each year because it presents the same visibility limitations as the airborne CCD image data, the cost for airborne CCD image acquisitions are deceasing, and videography presents orders of magnitude more problems with respect to producing an undistorted map of the substrate due to continuously changing viewing angle that range from nadir to oblique. Near the end of the remote-sensing PEP report, the panel recommended that airborne videography be replaced with alternative sensors. This should also dismiss any further consideration for underwater videography. The GPR approach suggested by the PEP is an intriguing idea; it may be able to see the consolidated substrate beneath sediment deposits. On terrestrial sand dunes, GPR can actually show all the fine-scale cross bedding within a sand dune. The same level of internal detail could be achieved for submerged sand deposits. Generally, GPR will also show the presence of graded bedding when it is present, but it is relatively insensitive to mineral composition. The disadvantages of using a GPR system on the river are the same as those listed for the side-scan sonar approach - increased time and cost in data acquisition and analysis and its invasiveness.

Terrestrial morphometry

There are two issues related to the measurement of terrestrial morphometry (two- and three-dimensional characteristics of shape and volume). The issues involve determining (1) the most cost-effective method to be applied and (2) the areal resolutions required to obtain acceptable accuracy for area and volume. In terms of methodology, there are currently six methods to derive terrestrial topography: land-based survey, aerial stereo-pair photogrammetry, land-based oblique photogrammetry, radargrammetry, and LIDAR. Land-based surveying produces the most accurate data because (1) ground personnel can adjust their spatial sampling based on observed local deviations from regional slope, (2) the survey crew can map under the vegetation canopy, and (3) the survey crew easily recognize the water-land boundary. However, this is also one of the most expensive methods (about $3,000 per river mile to map at a 0.25-m contour interval) and the most invasive of the five techniques. In addition, because of the time required to perform these detailed surveys, only a very small fraction of the river can be mapped by ground survey.

Aerial stereo-pair image data can be acquired for the entire river system in a few days at relatively low cost, but the photogrammetric data analysis to produce the topography is time consuming and very expensive ($6,400 per river mile to map at a 0.25-m contour interval; the cost decreases almost linearly with decreasing contour scale). In addition, there are two limitations inherent in aerial photogrammetry: (1) A stereoplotter operator cannot accurately map the topography beneath vegetation canopies unless there are scattered bare patches to extrapolate ground topography between the bare patches. Also, operators will not make judgements as to whether a particular shaded area that occurs in heavily vegetated regions is ground or lower-structure vegetation. (2) There is uncertainty in anyone’s judgement as to the exact location of the water’s edge in visible images, due to the penetration of light into shallow water and reflection from the near-shore substrate. Variations in film developing, but more so with film printing, can greatly increase that uncertainty. One way to preclude these two limitations with aerial photography is to acquire digital (CCD) color-infrared imagery because the digital data will maintain information within near-shore and shaded vegetation zones better than photography that is acquired with a set exposure time. Also, the near-infrared band of the CIR image will not penetrate water nearly as much as visible bands and the near-infrared-to-red ratio values within the shaded vegetation may indicate whether the area is ground or vegetation. The remote-sensing PEP recommended that photogrammetry be explored for examining system-wide and reach-specific topographic changes (Berlin et al., 1998), but they did not confine this recommendation to the historical data archives. Despite the expense of aerial photogrammetry, this is the only method that can produce historical (before the use of ground survey crews) topography for the Grand Canyon using the historical airborne photography, but due to the large expense in photogrammetric analyses its application should be confined to historical data. McCarthy et al. (1999) and Blank (2000) have shown that reliable topography can be obtained from the historical image data. The vertical and horizontal accuracies obtained in these studies were similar to those that can be achieved from LIDAR systems. In order to make this technique more operational, especially for larger river reaches, there first needs to be an established set of GPS control points on identifiable, temporally stable land features within or near the riparian zone for the entire river system. These control points can be natural features or man-made features that are made to look or conform to natural shapes so they are unobtrusive. Establishing such permanent control would also greatly benefit all aerial surveys that are performed in the future, at least until GCMRC is comfortable with the abilities of the majority of remote sensing companies to reliably locate data to within 0.5 meter (or less) on the ground using airborne GPS (Global Positional System) and IMU (Inertial Measurement Unit) instrumentation. The recommendation of the remote-sensing PEP (Berlin et al., 1998) pertaining to GPS and IMU needs to be extended and strengthened to state that all future data acquisitions need to have reliable, accurate GPS and IMU information for each data item. In order to make photogrammetric or any analysis of historical data more efficient, the photographic film library needs to be converted and archived using a uniform, accurate procedure, which will then eliminate all future time and expense in using these data that is currently borne by each of the three research programs. The remote-sensing PEP (Berlin et al., 1998) recommended that all existing contour map data be converted to DEM data. This recommendation should be expanded to state that contour maps should no longer be produced by such analyses, or by any analysis, and that only digital terrain models (DTMs) and/or digital elevation models (DEMs) should be produced that can be easily used in a GIS environment for integrated research and monitoring purposes.

Land-based oblique photogrammetry has been explored by a scientist at Northern Arizona University for determining small-scale changes in sand bar topography in the Grand Canyon. This technique uses land-based camera stations to periodically photograph a sand bar and uses photogrammetric techniques to derive topography for the sand bar for the photographic periods. The biggest advantage that this technique has over all other techniques is its small scale. However, the technique also has numerous disadvantages which include all those mentioned for aerial photogrammetry, plus the fact that the camera stations need to be serviced periodically, the stations and their servicing are invasive, and the corrections for their severe oblique viewing requires significant technique development. Although the remote-sensing PEP (Berlin et al., 1998) highly recommended continued pursuit of this technique, there are less intrusive and more efficient methods to obtain topography for more expansive river reaches.

Radargrammetry uses the principles of photogrammetry on stereo-pair radar images. This method has three advantages over the aerial and land-based photogrammetric methods. First, radargrammetry can use long-wavelength (L-band = 25 cm) image data whose radar signals can penetrate vegetation canopies. Even though L-band image data will not penetrate dense understory vegetation, the method does provide a more accurate topographic map than optical photogrammetric methods. Second, there will be no ambiguity in determining the water's edge because radar signals do not penetrate water. Third, radar signals are not affected by cloud cover and are independent of solar elevation because it is an active imaging system. However, radar stereo imaging does have the following limitations: (1) Data acquisition will have to be airborne because there are no radar satellites that provide stereo image pairs. Airborne radar systems are expensive to operate; data acquisition alone is normally over $1,000 per mile and some contractors will not mobilize for less than $100,000. (2) The highest spatial resolution provided by airborne radar systems is 5 meters, which may provide data that is too coarse for sand bar change detection. (3) Most airborne radar imaging systems are flown on large jet aircraft (Boeing 747) which would cause high levels of flight safety issues with the commercial traffic over the Grand Canyon.

An alternative radar method is for obtaining topography is Interferometric Synthetic Aperture Radar (IFSAR, INSAR). This method does not use stereo images, but detects changes in surface topography between two radar images acquired of an area at different times. This method can detect changes in topography at the mm scale, however, the two images that are used must be coherent or correlated, which means that there can be little change in surface material between the two image acquisitions (especially with respect to vegetation growth) to obtain reliable information (Gabriel et al., 1989; Gens and van Genderen, 1996; Zebker et al., 1997). On the other hand, IFSAR can be as accurate as land-based surveys for land areas with little to no vegetation (such as sand bars and debris flows) and only one new SAR image needs to be acquired for an area in order to examine its topographic change since the previous SAR acquisition. The fact that changes in surface composition can decorrelate interferometric SAR images has been shown useful in change-detection mapping, but it is difficult from the SAR data alone to determine the nature of the change (Wegmüller et al., 2000). SAR interferometry is also being explored for wide-area mapping of tree heights, but the technique is far from operational (Kobayashi et al., 2000). Unfortunately, IFSAR suffers from the limitations discussed above for airborne radar image acquisition, i.e., low spatial resolution (5 m at best) and very high data costs; satellite IFSAR is less expensive than aerial data, but its spatial resolution is lower (10 m).

The last method to be discussed is LIDAR (LIght Detecting and Ranging). A laser pulse is sent to the surface and the round-trip travel time and speed of light determines the one-way distance that it traveled. The speed of light is known for a vacuum, but it can vary with different atmospheric conditions. The level of vertical accuracy required for a topographic survey will determine how well (exact) the atmospheric parameters need to be known and modeled in the derivation of topography. Many LIDAR systems can record up to five returns from each laser pulse; the later returns are used to determine (infer) whether the pulse was returned from the bare ground or from the vegetation canopy. The degree to which this can be determined depends on well the system is calibrated to discriminate small differences in pulse returns. LIDAR is the most straightforward method for obtaining wide-area topography, is more cost-effective than any of the other methods if large areas are surveyed, and is independent of time-of-day or sun angle (but not rain or snow fall) because it is an active system. The mobilization costs for a LIDAR survey, and most other remote techniques, do not make LIDAR cost-effective for single, small-area surveys. If the costs associated with mobilization and contour-map production are ignored (contours should not be a deliverable with LIDAR), the cost for delivery of final, noise-reduced LIDAR point data for a segment of the Colorado River riparian zone that exceeds 100 miles is about $700 per river mile. If DEMs are requested to a deliverable, which will require the use of break lines, then the cost will increase. All LIDAR systems present the same limitation as far as vegetation penetration - they cannot penetrate vegetation with 100% crown closure. However, LIDAR may more accurately represent "bare-earth" topography than photogrammetry. The average laser shot spacing can be decreased to provide a denser array of return signals per square meter in an attempt to increase the probability that at least one signal with a square meter will hit the bare ground. However, increasing shot density will increase the cost. Because all LIDAR systems that are used for land mapping use a near-infrared light source, the LIDAR signal will not penetrate water which eliminates the ambiguity associated with determining the water's edge using visible-wavelength data. In order to develop a LIDAR approach that can approach land-based surveys and that stays within an acceptable remote-sensing budget, it is necessary to devise an approach that can distinguish a bare-ground return from a vegetation return using a moderate spot spacing. Originally, SHOALS was considered an answer to the vegetation problem because its green and near-infrared power return from bare ground would be very different from that from vegetation. However, the gain on the near-infrared SHOALS laser is set too high to record return power from a hard surface. The SHOALS system has now been revised to allow ground mapping using the green-wavelength laser (Guenther et al., 2000), but canopy penetration decreases with decreasing wavelength (Treitz and Howarth, 2000), which is the reason near-infrared wavelengths are preferred over visible wavelengths for mapping bare-ground topography. The remaining alternative approaches are (1) determine if the near-infrared power return from normal LIDAR systems, or the green power return from SHOALS, can distinguish a bare ground return from a vegetation return, or (2) use coincident color-infrared CCD imagery to make that judgement. These two approaches need to be explored in the order they are listed. The following two sections will now evaluate the accuracy in volume and area measurements that can be obtained (or need to be obtained) using different LIDAR spot spacings and different image pixel resolutions, respectively.

Accuracy of volume measurements versus elevation sample distance

In order to evaluate the accuracy that can be obtained at various LIDAR spot spacings for riparian areas devoid of vegetation a DEM image was generated from 0.25-m contour data for an area with relatively low relief (about 3.8 meters) and an area with relatively moderate to high relief (9.7 meters) by sampling the contour maps at 0.3 m intervals. This sampling interval shows topographic features as small as 30 cm in areal extent. The low relief area used in this analysis was the sand bar at the confluence of the Little Colorado River (Figures 1 and 2); the moderate relief area is the river-right bank of the main channel just west of that sand bar. The 0.25-m contour data were derived photogrammetrically from 1:4,000-scale aerial photography by a commercial firm. This scale is consistent with the contour data provided by by the land-based survey crews and the photogrammetric analyses of the historical aerial photogragraphy. LIDAR-derived topography was simulated by sampling the DEMs at the intersections of a rectangular grid that had a uniform cell size representing a LIDAR spot spacing. A total of 19 different grids were used whose cell dimensions ranged from 0.3 meters to 3.0 meters. Each grid was rotated and translated to provide ten different orientations for each grid in order to average out any bias in selected orientation to the land feature. Ten DTMs were compiled from each of the two DEMs using the ten grid orientations for the different cell dimensions. DEMs and their volumes were then computed from the DTMs; the average and standard deviation of each set of ten volumes are plotted on Figure 3 as a function of cell dimension. Figure 3 (bottom) shows that there is less than 0.5 percent error in volume estimation for relatively flat areas even at a 3.0 meter spot spacing, but the results for the moderate relief feature are very different. In order to maintain a 5 percent error in volume measurement, the LIDAR spot spacing can be no greater than 3 times the areal dimension of the smallest feature that needs to be detected and considered, which is 90 cm for our "ground-truth" sample size of 30 cm. The most recent LIDAR survey for sand bars used a spot spacing of 50 cm across track and 100 cm along track. For areas of moderate relief, these data probably provide an average error in volumetric estimation of 3-5 percent. This amount of error in volume measurement is very close to that currently achieved by the NAU ground-survey crews (2-3 percent; Matt Kaplinski, personal communication, 2000).

One of the primary objections of LIDAR surveys for the riparian zone is that such data may miss small topographic changes (positive or negative) that may reside under canopies and the data will therefore not provide useful volumetric data for sediment budget analysis. This argument can easily be countered by the fact that a LIDAR survey can cover 100 river miles in a few days at a 0.5-m spot spacing, whereas ground-based surveys could barely complete a 3 mile survey in that time period. If the average total width of the riparian zone is 50 meters along that 161 km corridor, and its average sediment thickness is 0.5 m, then the total sediment volume within that 161-km corridor would be just over 4 million cubic meters. If there was one topographic anomaly of the dimensions 4 m x 30 m x 0.5 m every river kilometer (or 0.6 river mile) that the LIDAR survey did not detect, then the error in measured volumes due to those oversights would amount to just 0.24% of the total volume. This magnitude of error is well within most levels of acceptable measurement error, as well as far below current levels of uncertainty in many of the model parameters being used in current sediment budget models. Regional LIDAR topographic surveys thus provide four advantages over the current land-based surveys: (1) they provide a much larger information base for testing and refining sediment budget models, (2) they provide a very low level of error in volume measurement because they consider orders of magnitude larger volumes of sediment, (3) they provide final topographic point data from acquisition to processing within a few weeks; and (4) they provide such data at a lower total cost and in a format that all investigators can immediately use for their own objectives. The remote-sensing PEP (Berlin et al., 1998) recommended that sand bar change program become more system wide. LIDAR may provide a cost-effective method to accomplish that.

Accuracy of area measurements versus image spatial resolution

There are two sources of error in the measurement of the area of a terrestrial sand bar: (1) delineation of the water's edge, and (2) the spatial resolution of the image data used in the measurement. Currently, area measurements for the terrestrial sand bars use digital scans of diapositive photographic film. Fortunately, the physical resource studies orthorectify these data before conducting their analyses. Some of the biological resource studies use photographic prints for area measurements of vegetation cover and their results will have additional errors because the prints are point perspective and do not accurately represent ground area. Monitoring changes in area of near-shore land regions using aerial photography presents a ambiguity in determining what actually is land versus water along the shoreline. This ambiguity is due to the penetration of visible light into the water and its reflectance from the water's near-shore substrate. This penetration and bottom reflectance in the red wavelength region can be as much as a few meters in clear water, with water penetration increasing with decreasing (toward the blue region) wavelength. A recent study of wetland boundary delineation (Barrette et al., 2000) found that wetland boundaries are more often stated on the wetland side than upland side, i.e., the wetland boundary is normally stated more downslope of the true boundary due to light penetration in water, using visible-wavelength image data. The following scenario examines the possible magnitude of error presented by this ambiguity.

Assume that a land feature is bounded on one of its elongated sides by water and that its river bank has an average slope of 30°. The horizontal distance between the true water's edge and the deepest bottom reflectance is 1.732 x D_p, where D_p is the depth of light penetration. The potential error in a land area measurement due to the ambiguity in defining the true water's edge is only a function of the depth of light penetration in the water and of the width of the land surface being measured. For example, for a river bank that slopes 30°, the error in a sand bar area measurement can be as much as the following relation: % error = 100 • (1.732 • D_p)/$W_{feature}$. If the river-bank slope is 15°, then the potential error doubles; if the river-bank slope is as low as 10°, then the potential error triples. If most of the sand bars being monitored for change in surface area are elongated, are on the order of a few thousand square meters in area (such as a 25 m x 200 m sand bar), and have an average bank slope of 30°, then measurement of their areas using visible image data can have associated errors of 7% to 20% just due to the ambiguity in delineating the true water's edge. Table 1 shows these potential errors as a function of sand bar dimension and light penetration depth in water. This error is very much more likely and on the high end of the range of possible error if photographic prints are used in the area measurements because the photographic printing process can arbitrarily expose any part of or the entire width of near-shore, water penetration zone. In addition, if the land feature being measured is bounded on more than one side by water, then the potential error in its surface area measurement will increase proportionally. This ambiguity and its associated measurement error would be precluded if (1) longer wavelength image data were used in the analysis (such as a near-infrared band) or, (2) predict the water's edge knowing the bathymetry and the water's flow rate. The later approach is much more error prone, even if bathymetry data did exist.

Table 1. Potential error in area measurements of terrestrial sand bars associated with ambiguity in delineating the water's edge, assuming water on only one of the sand bar's longest sides and the river bank slopes 30°.

Land Area Measured		Error in Area Measurement Assuming a 30° Slope		
Width (m)	Length (m)	1 m water penetration	2 m water penetration	3 m water penetration
15	20	12%	23%	35%
25	200	7%	14%	21%
75	200	2%	5%	7%

In order to assess the relation between accuracy in area measurements and spatial resolution of image data, an outline of a hypothetical sand bar and a series of rectangular grids (representing raster images with different spatial resolutions) were constructed in ArcView. The grids had square cells (pixels);the cell dimensions of the grids ranged from 0.08% of the area of the sand bar to 36.6% of the area of the sand bar. The sand bar polygon was 13.21 square meters, thus the grid cell dimensions ranged from 10 cm to 225 cm (as shown along the x axis in Figure 4). A set of 21 grids were derived from each raster grid of a particular cell dimension, which represented gird rotations of 30° to the right and left and grid translations of ½ and ¼ up and down the original and rotated grids' axes. For each set of 21 grids of a particular cell dimension, the area of sand bar polygon was estimated by counting the number of grid cells that contained at least 50% sand bar within a cell. The land area measured by each grid was then obtained by multiplying the number of sand bar cells by the area of the grid's cell. For each of the 21 different grid orientations with the same cell dimension, the absolute percent difference between measured and actual sand bar area was calculated and the average and standard deviation of these 21 values were then computed and are shown graphically in Figure 4 for each cell dimension.

Figure 4 shows that measurement error gradually increases with increasing cell dimension or decreasing spatial resolution, which is expected. This figure also shows that area can be measured with only a 2.5% error using image data with a spatial resolution that is only 1.9% of a feature's actual area. For a sand bar that is 100 m long and 10 m wide, this means that 97.5% of its true area could be retrieved on average by using a raster image that has a spatial resolution of only 4.4 meters. Small sand bars that are monitored in the physical and cultural resource programs have an average area of 300 m^2. If monitoring protocols can accept a 97.5% accuracy for area measurements, then the pixel resolution of image data necessary to monitor changes in area can be as low as 2.4 meters. Intuitively, this analysis may appear to be flawed or too hypothetical, but in reality this analysis represents the worst case scenario for area measurement. In a real area analysis, a human interpreter's trace of the sand bar's edge on an image would not treat pixels as only on or off of the sand bar, but would average pixel brightness and trace through pixels, which will result in a computed area that is closer to reality than the hypothetical on-off analysis. Currently, area is being determined from aerial photography that has 0.058-meter resolution. If only area was being derived from remote-sensing image data, the spatial-resolution protocol for remote-sensing data acquisition could be dramatically reduced from present standards. However, that is not the case; additional resource protocols need to considered so that required spatial resolution for remotely sensed data is decided by the average lowest common denominator.

Terrestrial geomorphology

Current mapping of the surficial geology uses a combination of photographic interpretation and field studies to determine the characteristics of surfaces and separate the surfaces into geomorphic units. Jack Schmidt at Utah State University is leading this effort for the sand bars. The remote-sensing PEP recommended that this type of mapping be extended as much as budgets will permit (Berlin et al., 1998). The PEP thought the 1-m contour interval adequate for this mapping. Schmidt prefers 0.25-m contour data for the sand bars, but he thought a 1-m contour interval is adequate for the debris fans. Robert Webb (Water Resources, U.S. Geological Survey) is investigating the use of hyperspectral data (mainly JPL AVIRIS data) for mapping debris flow characteristics (clay mineralogy) with a goal toward predicting movement, but his main trust as far as remote sensing is using annual aerial photography to map changes in and new occurrences of debris flows. However, mapping the abundance of clay minerals on any of the terrestrial surfaces within the Grand Canyon does not require the spectral resolution (10 nm) of hyperspectral data, unless the abundance of each clay mineral species was important. Although different clay minerals have slightly different expansion (absorption) characteristics with respect to water, careful wavelength band selection using more modest imaging systems could easily map the occurrence of those relevant clay minerals. The distinctive spectral bands for clay minerals occur at long wavelength between 1.4 µm and 2.5 µm. Acquiring image data in this spectral region requires a different detector than that used to acquire visible and near-infrared wavelength images, which also increases the cost of data acquisition. Merenyi et al. (2000) examined the use of AVIRIS hyperspectral data for classification at selected river reaches within the Grand Canyon. That analysis used all of the AVIRIS bands, but visual examination of their field spectra for various surface materials suggests that the same classification results could have been obtained using significantly fewer bands. Because the cost of remotely sensed image data increases at least linearly with the number of wavelength bands that are acquired, care should be exercised to minimize data collection to just those bands that can address the protocols of the different programs. The use of hyperspectral data present several problems: the ability to acquire high spatial resolution given the scan-rate limitations for 220 image bands, data storage, data rectification, and data analysis. All of these issues, especially the last two issues, equate directly to increased cost, but with little to no justification as yet.

Price (1997) performed a band-selection analysis of AVIRIS hyperspectral image data for representative areas within various climatic regions in the world to determine the subset of wavelength bands that provided the most information for land classification. He found that a subset of just 6 wavelength bands describes 99% of the spectral variance provided by all 220 AVIRIS bands for all of the regions that he examined. These 6 band wavelength bands include: 0.44-0.55 µm, 0.66-0.69 µm, 0.99-1.08 µm, 1.12-1.16 µm, 1.35-1.40 µm, and 2.08-2.20 µm. Increasing that size of the subset to 20 wavelength bands added 0.9 absolute percent of the AVIRIS variance. This is useful information, but should be used as a starting point for a similar analysis of hyperspectral data for the GCMRC program protocols, such as the HYDICE data (1.5-m spatial resolution) that was acquired in August, 1998.

The physical resource PEP (Wohl et al., 1999) recommended the use of CIR photography every year to map in-water features, land vegetation, debris flows, to use natural-color or B&W photography every third year for mapping other terrestrial protocols, and to use of the Normalized Difference Vegetation Index (NDVI) derived from 1-km resolution AVHRR satellite to monitor the dynamics of ungaged tributaries on a weekly basis. As far as the first of these recommendations, future remote sensing efforts should avoid photography due to fact that all future data should be in digital form and be delivered as orthorectified image mosaics so that they can be immediately used by all cooperators. The process of digital scanning photographic film is far too arbitrary for good image-to-image color calibration, which is essential for development of more automated methods of regional data analysis. The panel recommendation with respect to the type of data to be collected was probably based on an evaluation of the aerial image data that was acquired at that time, which was natural color and B&W. Color infrared data are much better than either of those data sets, but more advanced multispectral systems are becoming more commonplace and more cost effective. In addition, it is not clear as yet that just three wavelength bands will provide sufficient information for various program protocols. As far as the third recommendation regarding basin-wide changes, it is not clear from the results thus far obtained by sand bar monitoring that changes need to be monitored on a weekly basis. Changes within the ungaged tributaries can be monitored, if warranted by the physical resource program, on a periodic basis using 4-band, orthorectified IKONOS data that has 4-m resolution. These satellite data cost $26/km for orthorectified digital data. Thus, the entire Grand Canyon corridor could be imaged in four bands at 4-m resolution for about $6,000 (if Space Imaging Corporation would provide only a one-half kilometer corridor swath). The remote-sensing PEP (Berlin et al., 1998) suggested that existing land information databases be explored for establishing regional scale databases of the tributary watersheds in order to evaluate the effects of sediment source area on main channel. Most of these national and international databases have cell sizes that range from five minutes (about every 7.5 km) to one degree (about every 90 km).

The primary terrestrial mapping that occurs within the physical resource program pertains to geomorphic units. The criteria used to map the geomorphic units include: relative horizontal location, grain size, and terrace level. The later characteristic is related to river-stage elevation and somewhat, but not directly, related to relative age. Most of this mapping occurs within the riparian zone in close proximity to the river because the higher-elevation terraces that were produced by much higher flow levels are generally not affected by recent low flow levels. Most of these mapping characteristics can be seen on image data, even at spatial resolutions of 1 meter, but it would be extremely difficult to construct an algorithm to map the geomorphic features, but once the features were mapped, it might be possible to monitor their spatial and volumetric evolution in an autonomous manner within a GIS environment. As far as grain size, it is possible to detect and map the larger sized geomorphic units, such as cobble bars, debris fans, and rapids. Just as photointerpreters use visible textural differences to map these three units, a computer algorithm can easily be constructed to enhance, quantify, and map these textural units using optical data (Anys et al., 1994). Shih and Schowengerdt (1983) found that the use of both texture and spectral reflectance greatly increased the accuracy in mapping surface materials. Radar data are extremely sensitive to surface roughness or texture and are very much insensitive to compositional differences with respect to inorganic materials. The degree of sensitivity depends on the radar wavelength: C-band radar data (2.5 cm wavelength) is sensitive to ground features that are larger than 2.5 cm in cross section, whereas L-band radar (25 cm wavelength) is only sensitive to ground features larger than 25 cm cross section. Thus, texture maps derived from images of these two radar bands (Haralick et al., 1973; Ulaby et al., 1986: Dobson et al., 1997) could effectively map the occurrence of debris flows (boulders would be bright in both L- and C-band data), of cobble bars (cobbles would be bright in C-band data, but would be dark in L-band data), and of the finer sediment deposits (both L- and C-band images would be dark). The remote-sensing PEP recommended the use of SAR data and texture analysis for mapping rapids and debris-fan eddy complexes (Berlin et al., 1998). Unfortunately, satellite radar data are limited to C-band wavelengths and provide only 10 m resolution ($4500 for a 50 km x 50 km area that is orhtorectified); data acquisition by current airborne radar imaging systems is very expensive (minimum of $100,000 to initiate a flight from ERIM at the University of Michigan and $30-40,000 for a NASA AIRSAR flight for a 30 km long image; both employ DC 8 jet aircraft). However, optical data can do almost as well as radar data for textural differences given the appropriate textural filters.

Only thermal infrared sensors may be able to distinguish among the finer grained (<6 cm diameter) sediment deposits. Particle grain size does affect a surface's thermal inertia, but derivation of surface thermal inertia requires day and night thermal data for the same area. The relative age of a surface might be obtained from multispectral data where the rocks on the alluvial and fluvial surfaces are varnished, pitted, or more oxidized. Increasingly larger areal coverage of a rock by desert varnish or by erosional pits will both reduce the rock's reflectance. Low reflectance of a surface can also be produced by mafic igneous or metamorphic rock fragments, thus application of this spectral mapping technique would also have to determine the rock composition of the source rock. Surfaces with iron, which is quite ubiquitous in the southwestern United States, generally increase in redness with time, unless they are abraded; this relation is difficult to quantify for large areas due to a number of variables that affect the amount of ferric iron on geologic surfaces. Hereford et al. (1998) developed such field relations for specific river reaches, but even the field relations proved difficult to extrapolate to other reaches. Both the grain-size and age relations will be explored using existing multispectral (Bechtel ATM data) and hyperspectral data (HYDICE data) for particular river reaches to determine the extent to which surface units of interest can be identified or at least discriminated without the need for extensive ground truthing (after a period of ground calibration).

Image spatial resolution for terrestrial and aquatic physical resources

The main constituents that need to be discriminated and mapped on the channel substrate for the physical resource program are the various size fractions of the sediment deposits (clay, silt, and sand), the cobble bars, and mixed size fractions within debris flows. It is not possible to discriminate the fine size fractions within the sediment deposits even using the highest resolution (6 cm) aerial photographs that are currently collected. However, these data can identify areas containing boulders, cobbles, and the finer sized deposits, but is 6-cm resolution necessary for that discrimination? Cobbles can be detected if the spatial resolution of an image is similar to the diameter of a cobble. The cobble size range is 6.4 cm to 25.6 cm; the mean diameter is 12.8 cm. Webb currently uses aerial photographic images scanned to a 10-cm resolution. Schmidt believes that 2-m resolution may be adequate for sand bar mapping. For both applications, the answer is probably within this range, but not as large as 2 meters. The remote-sensing PEP (Berlin et al., 1998) estimated required spatial resolution to be 1-5 meters, but the panel said their estimate was difficult to make based on their limited understanding of the problems. In order to make an scientific judgement on this spatial resolution, it would be better to assess actual image data. Therefore, digital scans of 6-cm aerial photographs that were acquired in July, 2000, of 15-cm aerial photographs that were acquired in September, 2000, and 18-cm digital panchromatic images acquired with high gain in September, 2000 will be evaluated to determine a reasonable resolution limit for mapping cobble bars, sand bars, and channel substrate features. These data will be digitally filtered with image-processing software to incrementally degrade the resolution. These incremental products will be sent to selected physical resource cooperators for determination of an acceptable range for resolution. An issue related to spatial resolution of image data is the positional accuracy of the data. Positional and vertical accuracy of image data is controlled by the quality of navigation data, pixel resolution, (viewing) geometry, and CCD calibration (Mostafa and Schwarz, 2000). Assuming all other parameters being well controlled, positional accuracy is generally slightly better than three times the pixel resolution. For most applications, positional accuracy should not exceed 1 meter, thus pixel resolution should not exceed 0.33 meters. Increasing the pixel dimension to 1 meter, will probably produce a positional accuracy no better than 2.5 meters, which could add significant error in the area and volume measurements, especially in the measurements of small features. Mostafa and Schwarz (2000) also found that positional and vertical accuracies decreased with decreasing size of the CCD image array. For example, for 15-cm data acquired with a 1500 x 1000 CCD array camera, the positional accuracy was 90 cm and vertical accuracy was 1.8 m. Using a 4096 x 4096 CCD array camera to acquire 15-cm data, the positional accuracy was 40 cm and the vertical accuracy was 0.5 m.

Biological Resources

Objectives:

The primary objective of the Biological Resource Program is to understand the cause/effect relations between the operation of the Glen Canyon dam and the downstream aquatic and terrestrial ecosystem, and to develop a model that can predict ecological effects for different dam operations. This objective is approached in three ways: (1) inventory of biologic resources and, together with related physical resource data, development of a conceptual model that links biotic and abiotic components; (2) research on and development of cause/effect relations between dam operations and the ecology and testing the validity of the observed relations under various dam operations; and (3) monitoring both long- and short-term ecosystem behavior to determine if models are predictive for both natural (tributary) and dam perturbations.

Parameters Measured and Methods Employed:

The parameters that are measured are those deemed to be stressors, directly or indirectly, that have been previously established or suspected of having cause and effect relations, such as sediment load, temperature, flow discharge, inter-and intra-predation loads, non-native flora and fauna, recreational activities, and trout management effects. The parameters that are measured and the methods employed in their measurement are described below for both the aquatic and the terrestrial environment.

Aquatic Environment - Parameters monitored in the aquatic environment are those deemed important for the survival of aquatic species.

1. Water parameters - Water Resources Division of the U.S. Geological Survey collects data from water gaging stations and collects and analyzes water samples at various locations within Lake Powell, the main channel, and within major tributaries.

   a. Tailwaters to Lee's Ferry sites - Every hour remote monitoring stations measure and record flow rate, sediment load, turbidity, water temperature, specific conductance (total dissolved solids) in the main channel. These data are transmitted by telemetry to a permanent storage location every four hours. In addition, dissolved oxygen and pH are measured using hydrolab mini-sonde instruments every 5 minutes for a 48 hour period during various parts of the year. Theese remote measuring devices are located at river miles 0, -3, -6, -9, -11, and -16. Monthly water samples are also collected at these locations and are analyzed for nutrients [P, soluable reactive P, dissolved ammonia nitrogen, total Kjeldahl nitrogen, dissolved nitrate-nitrite nitrogen], major ions [Na, Ca, Mg, K, SO_4, Cl, CO_3, $(CO_3)_2$], chlorophyll, phytoplankton, and zooplankton.

   b. Main channel and tributary sites - Remote water monitoring stations measure the same water quality parameters at the same frequency as that described for the tailwaters within several tributaries (Paria River, Shinumo Creek, Tapeats Creek, Spenser Creek, Havasu Creek, Kanab Creek, Bright Angel Creek, Little Colorado River, and Diamond Creek) and within the main channel above the Glen Canyon dam, at Lee's Ferry, above the Little Colorado River confluence, near the Grand Canyon, above National Canyon, and above Diamond Creek.

   c. Lake Powell - Full lake-wide surveys are conducted quarterly (approximately March, June, September, and December) to obtain profiles of water temperature, specific conductance, dissolved oxygen, pH, turbidity, Secchi transparency, and weather conditions at approximately twenty stations north of Glen Canyon dam between mile 2 to mile 263. Water samples are also collected at some of these sites and are analyzed for nutrients [P, soluable reactive P, dissolved ammonia nitrogen, total Kjeldahl nitrogen, dissolved nitrate-nitrite nitrogen], major ions [Na, Ca, Mg, K, SO_4, Cl, CO_3, $(CO_3)_2$], chlorophyll, phytoplankton, and zooplankton. In addition, water quality profiles (water temperature, specific conductance, dissolved oxygen, pH, and turbidity) and biological samples (chlorophyll, phytoplankton, and zooplankton) are obtained on a monthly basis at the twenty monitoring stations.

2. Aquatic foodbase - At 10 day intervals for 90 days each year, foodbase is determined within pool, cobble-riffle, shoreline, and nearshore environments. The foodbase surveys are performed at river miles -15.5 (Glen Canyon gage), 0 (Lee's Ferry), 60 (60-Mile Rapid), 64 , 138 (138.5-Mile Rapid), and 205 (cobble bar). For the pools, foodbase is examined at five locations along each of three transects; each transect is about 30 m apart. The five sampling locations along the transects include the thalweg, $<28m^3/s$, baseflow, lower varial, and upper varial zones. Cobble riffle sample collections occur within the deepest accessible zone, as well as the lower and upper varial zones. Population data are collected for five biotic classes: (1) C. glomerata, (2) Oscillatoria spp., (3) detritus (both autochthonous [algal/bryophyte/macrophyte fragments] and allochthonous [tributary upland and riparian vegetation flotsum]), (4) misc. algae and macrophytes, and (5) macroinvertebrates (including Copepoda, Cladocera, Ostracoda, planaria, hydra, Gammarus lacustris, chrinomid larvae, simuliid larvae, lumbriculids, tubificids, physids, trichopterans, terrestrial insects, and unidentifiable animals). Associated data are also collected, such as water temperature, dissolved oxygen, pH, specific conductance, substratum type, microhabitat conditions, total P and N, Secchi depth, water velocity, depth, site, and time of day. Shoreline

habitats are sampled to determine (1) invertebrates in emergent vegetation, (2) fine sediment volume, and (3) tychoplankton. Nearshore habitats are surveyed to obtain (1) temperature profiles with reading every 5 cm within shoreline vegetation and 0.5 m from the shoreline and (2) surface (≤ 0.5 m depth) drift samples of coarse- (500 micron mesh) and fine-particulate (0.5 micron mesh) organic matter.

3. Marshes - The populations of cattail-reed-watersedge (Carex aquatilis)-rush "wet" marshes and horsetail "dry" marshes are measured at 11 sites, if they exist, during the Labor Day terrestrial flora survey. The sites are located at river mile 6, 43.5, 50.5, 55, 68.5, 71.5, 93, 123, 194, 209, and 243. Future monitoring will be system wide.

4. Fauna - Three times per year (near January, June, and September) the age class, recruitment, and population size of Humpback Chub, Razorback sucker (very rare), Flannelmouth sucker, Bluehead sucker, and Speckled dace are collected, along with food production and habitat quality (temperature, suspended sediment, nutrient supply). The surveys are performed at Fence Fault Springs (RM 30), Little Colorado Confluence (RM 67), Bright Angel Creek (RM 87.7), Shinumo Creek (RM 108.8), Middle Granite Gorge (RM 127), Havasu Creek (RM 156.9), and Pumpkin Springs (RM 212.9). In calendar year 2001, surveys will concentrate more on the Middle Granite Gorge, Havasu Creek, and Little Colorado Confluence to determine if mainstem Chub are relicts of a mainstem spawning population or originate from the Little Colorado Confluence population. The Rainbow Trout will be monitored between Glen Canyon dam to the Paria River confluence four times a year at 30 locations that sample different habitats. The exact locations are yet to be determined for calendar year 2001.

5. Backwater areas - The presence and number of backwaters within or near return-current channels, shoreline embayments, and tributary mouths are monitored during the above faunal surveys.

Terrestrial Environment - Parameters monitored in the terrestrial environment are those deemed important for bank stabilization, aquatic and terrestrial faunal habitats, tribal botanical resource, and recreation.

1. Avifauna - Populations of Bald Eagle, Peregrine Falcon, SW Willow Flycatcher, passerines, waterbirds, osprey, and belted kingfisher are measured in January, February, April, May, and June. There are a total of 110 patches throughout the entire system that are monitored, although the exact number of patches monitored during any given year is less than this and varies year to year. This effort will be expanded in calendar year 2001 to include insects, icthyofauna, and small mammals that may be related to avifaunal distribution and productivity.

2. Other fauna - Some effort is expended in monitoring the existence of the endangered Kanab Ambersnail and less so of the non-endangered, but rare Niobrara Ambersnail and Northern Leopard Frog. The Kanab Ambersnail prefers Monkey flower, Watercress, and poison ivy and therefore occurs mostly at Vaseys Paradise. The Niobara Ambersnail prefers Typha and other wetland vegetation and occurs near river lime -9 and at Indian Gardens; it is currently not being monitored. Flows greater than 20,000 cfs inundate their habitats; such flows occurred every year since 1998. The Northern Leopard Frog has been found at river mile -9 and in Spring Canyon at river mile 204.

3. Flora - Vegetation type, area, and height are mapped annually at 11 sites (river miles, 6, 43.5, 50.5, 55, 68.5, 71.5, 93, 123, 194, 209, and 243) using aerial photographs and field studies in September (Labor Day). This survey will be expanded in the future to include the entire river system and culturally significant plants (exotic/invasive species and ethnobotanical species); sampling will occur in April and May, in addition to the usual September survey. Vegetation of interest includes Acacia, Equisetum/sedge, Redbud (Cercis occidentalis), Tamarisk (Tamarix ramosissima), Arrowweed (Tessaria sericea), Bermuda and red brome monotypic grasses, Hackberry (Celtis reticulata), Cliffrose, Desert brome, Mesquite, Coyote willow (Salix exigua), Baccharis

seepwillow (Baccharis emoryi and salicifolia). Currently, downslope growth rates of Equisetum, Juncus, and Phragmites are being measured along selected transects on monthly basis for 4 months. The monthly field studies also monitor growth or removal of exotic plants, such as Tamarisk ramosissima and Alhagi camelorum (camelthorn), and sample low-elevation areas for changes in seed abundance and type.

Ecological Models:

Korman and Walters (1998) have developed an ecological model for the Grand Canyon river system that is designed for planning adaptive management experiments. The software system allows for the selection and variation of a wide range of environmental parameters associated with the river system; the algorithm operates under these conditions to produce (predict) changes in the environment. The model considers physical, aquatic, animal, and recreational/socio-economic factors using tabulated data and numerical codes to simulate the various processes.

Remote Sensing Recommendations:

Aquatic Environment:

1. *Water parameters* - It is not possible to obtain from currently available remote sensors even a qualitative estimate of individual elements or compounds that are measured by water sample analyses, which was also stated in a more limited sense by the remote-sensing PEP (Berlin et al., 1998). A remote sensing device was developed in the early 1980's (Fraunhofer Line Discriminator) that detected ppm levels of phosphorous, but that development was terminated by NASA and the instrument did not reach operational status. NASA recently convened a panel of remote-sensing experts to address this very issue and the panel produced a set of recommendations for future sensor development and deployment that was as extensive as the panel membership. It will be many years before any of these recommendations reach flight status. Water parameters that can currently be measured using remotely sensed image data include sediment load (as total suspended sediment), turbidity, chlorophyll a and b, total chlorophyll, and possibly total dissolved solids (specific conductance). There have been many studies conducted within the last decade to develop remote sensing algorithms to measure these parameters in water (e.g., Goodin et al., 1993; McFeeters, 1996; George, 1997; Sathyendranath et al., 1997; Fraser, 1998a, b; Tassan, 1998). Of the algorithms that could duplicate *in situ* measurements with high accuracy, some algorithms were linear, while others required exponential relations. Most of the studies determined that multiple wavelength bands are necessary to obtain accurate estimates; this is consistent with a theoretical study that found that accurate estimates of phytoplankton, suspended mineral, and dissolved organic carbon contents could not be obtained using just one or even two wavelength bands (Pozdnyakov et al., 1998). A review of all of these results does not indicate a consistent (dominant) set of wavelength bands that best duplicate in situ measurements, although the bands that proved most useful were between 0.420 µm and 0.710 µm. [The wavelengths that were found useful for estimating water parameters consist of the following: 0.429 µm; 0.440 µm; 0.485 µm; 0.486 µm/0.570 µm ratio; 0.570 µm; 0.600 µm-0.520 µm difference; (0.600 µm-0.520 µm)/(0.570 µm-0.450 µm) ratio; 0.660 µm; 0.695 µm; 7 bands between 0.420 µm and 0.710 µm; 0.840 µm; and 23 bands between 0.72 and 0.95.] It is apparent from the past studies that the algorithms to estimate water parameters need to be derived for a particular water body and probably require continuous calibration with in situ measurements. This last statement (limitation) might suggest to water resources personnel that remote sensing cannot benefit their monitoring protocols because it cannot replace their *in situ* measurements, but the real strength in using remotely-sensed image data is, in most cases, not the elimination of field verification, but it is the extrapolation of site-specific information to wide areas at a significant savings of time and expense. The current research by Pat Chavez is designed to develop such algorithms for a few water parameters by monitoring spectral radiance of the water at specific water gaging stations (Chavez et al, 1999). This effort should be expanded to include (1) additional *in situ* radiometer sites in order to consider different aqueous conditions, including Lake Powell, (2) the use of more sophisticated radiometers with more bands in order to determine the best set of bands that provide the most accurate algorithms, (3) the consideration of more water parameters than under investigation, which are

currently limited to the physical resource protocols, and (4) the use of airborne multispectral data to test the accuracy of the algorithms by extrapolation to nearby sites that are sampled by water resources personnel. A remote-sensing, image-analysis approach to monitoring particular water parameters is actually better suited to standing water bodies; George (1997) developed algorithms for lakes that can predict chlorophyll concentrations within 3 μg/l. Thus, this approach should seriously be considered for expanded areal mapping certain water parameters (chlorophyll, turbidity, suspended load) in Lake Powell, which was also suggested by the remote-sensing PEP (Berlin et al., 1998) and demonstrated by Chavez et al. (1997). However, it is not possible to derive the depth profiles of these parameters using remotely sensed image data. Even though the use of remotely sensed image data analyses for water parameters will probably increase somewhat the cost for such protocol monitoring, it will greatly increase the field area that is monitored, and may in the future reduce monitoring costs by targeting specific areas of change that should be sampled instead of continually monitoring the same sites each month or year.

It is also possible to map surface radiant temperature of water using airborne thermal-infrared sensors to a sensitivity of 0.1 degrees Celsius. This is most appropriate to non-turbid riverine and lacustrine environments, where it can provide near-surface water temperature maps that can either augment or possibly replace current lateral transects. However, thermal infrared sensors detect the near-surface temperature and thus will not provide thermal gradient information. Thermal-infrared data were collected in July, 2000 between river miles 30 and 74, coincident with a field survey in the area. These data will be examined during calendar year 2001 to determine the correspondence of the water temperatures measured by field profiles and by the airborne sensor. A recent study used *in situ* temperature and turbidity measurements in 3D hydrodynamic models to model effluent moving from Poplar Creek into the Clinch River in Tennessee (Garrett et al., 2000). The spatial distribution model results agreed qualitatively with temperature and turbidity maps obtained from an airborne multispectral scanner system; additional ground-truth data are being collected for a more quantitative assessment.

The water quality measurements are conducted at very short time intervals ranging from every few minutes to every 3 months. Augmenting these analyses at the minute interval is currently beyond spaceborne orbital capabilities (generally every 16 days) and would be extremely expensive using contractor airborne systems. However, bi-weekly or monthly data could be obtained from spaceborne multispectral sensors that have 4-m spatial resolution, which resolution would be more appropriate for Lake Powell. The usefulness of such data would depend on the wavelengths that were found to reliably estimate particular water parameters. Alternatively, GCMRC could purchase a multispectral sensor with wavelength capability between 0.4 and 0.9 and locally contract for periodic flights. This would provide flexibility in selection of wavelengths to be acquired and the spatial resolution and locations of the flights. In order to make such a sensor operational would require establishing a mount for the aircraft, a recording mechanism for the GPS and IMU, and a series of image-processing steps in transforming the point-perspective image data to a georectified or an orthorectified format.

2. *Aquatic foodbase* - Remotely sensed image data cannot however directly detect the small living organisms that are monitored in the foodbase surveys. In addition, the depth of penetration of remotely sensed data will depend on the clarity (turbidity) of the water and may not be able to reach the deepest parts of certain cobble riffles that are sampled by the foodbase surveys if the water is too turbid. However, some of the parameters that are measured related to aquatic foodbase can be approached using remotely sensed image data. These parameters include algae, vegetation flotsum, plankton, organic matter, surface drift, total dissolved solids (specific conductance), lateral water temperature profiles, depth, and substrate type. Published approaches to monitoring these parameters were discussed above for water quality and in the physical resource recommendations for the aquatic environment. In addition, Alberotanza et al. (1999) determined the best wavelength regions to detect specific characteristics of the aquatic environment. They found that the 0.430-0.510 μm wavelength region monitors absorptions due to organic matter, chlorophyll a, Beta carotene, and zeaxanthine; the 0.600 μm wavelength monitors the reflectance due to algal pigment; the 0.67-0.69 μm wavelength region monitors absorptions due to chlorophyll a; and the 0.700-0.710 μm wavelength region monitors reflectance due to absorptions on the sides of this region from algae, water, and

chlorophyll a fluorescence. The remote-sensing PEP (Berlin et al., 1998) recommended that underwater videography be explored mapping algal mat and suspended algae. They also suggested that airborne multispectral image data be explored for this purpose. The airborne imaging approach is a better recourse because visibility will limit underwater videography in the same way that it limits airborne image data and because the exact area covered by videography is uncertain, variable, and difficult to record. Even though the scientists currently involved with monitoring foodbase are skeptical about a remote sensing approach to part of their protocols, a remote sensing approach should be explored within the aquatic remote sensing research that is being conducted by Pat Chavez. As in the case of the water quality surveys, the foodbase surveys are conducted at numerous time intervals during the year, but the issue regarding frequency of measurement versus cost for remotely sensed data could be overcome by using a GCMRC sensor, if one is procured for water quality and other high-frequency monitoring needs within GCMRC.

3. *Marshes and Backwater Areas* - The presence of both “wet” and “dry” marshes, as well as backwater areas, can be approached using remotely sensed radar or multispectral optical image data. Microwave (radar) energy is very sensitive to the moisture content of a surface material with increasing moisture resulting in a decreasing radar return signal. Rio and Lozano-Garcia (2000) used very simple image=processing filtering techniques on single co-polarized (Chh) radar images to map marshes in Laguna Madre wetlands of Mexico at an accuracy of 95%. The least expensive, “high-resolution” (10 m) radar image data is derived from spaceborne instruments ($4000 per 50 km x 50 km area), which would require $40,000 to cover the entire ecosystem once. The fact that the marshes and backwater areas can be relatively small in areal extent and that the marshes can be totally covered with vegetation, suggests that a radar approach is not appropriate because of its rather low resolution (10 m) and because of the fact that the radar signal will not penetrate the dense stands of phragmites. A more reasonable approach that can detect either moisture or a collection of particular vegetation species is the use of multispectral optical image data. Optical data are sensitive to variations in soil moisture (especially standing water) and can distinguish certain vegetation species (or collections) by their characteristics reflectance spectra. The detection and discrimination of the marsh and backwater habitats would be straightforward if the spectral reflectance of their vegetation collections (or lack thereof) was appreciably different. Jensen et al. (1993) could accurately map the annual distributions of cattails and water lilies using three-band SPOT image data, but only using seasonal image data in which the water lilies were senescent during part of the year. Such a scheme may not be necessary for the two types of marshes (one marsh containing mostly cattails, reeds, and watersedge and the other containing mostly horsetails) if wavelength bands could be found that optimize their discrimination. Ground reflectance spectra of these vegetation types have been collected during calendar year 2000 and will be examined to determine if identification of these two marshes can be accomplished. There are indications in the published literature that remote-sensing data can map these two environments. Welch et al. (1988) used 1:10,000- and 1:24,000-scale CIR stereo imagery to map emergent, submergent, floating, and mixed aquatic vegetation. Although they could not identify submergent plant species, they were able to identify the other plant collections based on height, color, and texture. Thomson et al. (1998) could distinguish 10 riparian classes (wet sand, diatoms and sand, wet silt/mud, algae and silt/mud, and six types of salt-marsh vegetation) using six wavelength bands (0.535-0.545 μm, 0.647-0.657 μm, 0.665-0.675 μm, 0.680-0.685 μm, 0.705-0.715 μm, and 0.870-0.890 μm) with a single wavelength band (0.647-0.657 μm) accurately separating all vegetated areas from non-vegetated areas. Marsh surveys are to become system wide in the future; a remote-sensing approach could satisfy that requirement and at a very low cost; an algorithm to detect a set of textural and spectral characteristics should be easy to develop assuming the remote-sensing data are calibrated throughout the Grand Canyon. Timing may be an issue because the optimum period for airborne acquisition is around the Summer solstice, but the marsh surveys are generally performed around Labor Day when low solar elevations cause shadowing.

4. *Fauna* - The direct detection of any fauna, especially in water, is extremely difficult and rarely approached using remote-sensing data due to the fact that their detection is based solely on recognition of their shape and size. Roberts and Anderson (1999) were able to visually detect fish populations using high-resolution photography (used for resolution) and multispectral CCD image data (used for spectral content), but they were actually trying to detect the off-channel habitats of the fish. They concluded that, if aerial

photography is to be used for habitat mapping, the data need to be calibrated, which has been recommended previously in this report for any application. The habitats of sight feeders (trout) differs from that of the smell feeders (chub) in terms of turbidity levels, but other characteristics include the presence cobbles, vegetation, depth, and foodbase. Remotely sensed data can detect these characteristics, if the water is not too turbid; a set of these characteristics derived from remotely sensed data can be examined in a GIS environment to pinpoint a coincidence of a combination of selected characteristics or of all characteristics. Aquatic fauna target sites are examined 3-4 times per year. Small-area airborne data acquisitions are expensive because of mobilization costs. It would be better to use a GCMRC-owned multi-band sensor (as mentioned above) for such small-area temporal studies.

Terrestrial Environment:-

1. *Land-based fauna and avifauna* - Although remote-sensing data cannot directly detect fauna, especially at the size of birds, snails, frogs, and insects, it can be used to identify and map faunal habitats if the habitats have distinct characteristics. Sogge et al. (1998) showed that bird abundance in the Canyon is best predicted by total patch size (total land and vegetated areas) and by tree area, new-high-water-zone area, tamarisk area, tree volume, and shrub volume. He also found that bird richness and the Shannon diversity index was best predicted by tree area and volume, tamarisk area and volume, and new-high-water-zone area and that mesquite and tamarisk was most correlated with abundance, richness and diversity. He found tree volume to be the best predictor, but he felt that the extra field work necessary to obtain tree volume may not be worth the added expense because area predictors are almost as good as tree volume. Likewise, the Kanab Ambersnail prefers Monkey flower, Watercress, and poison ivy, whereas the Niobara Ambersnail prefers Typha and other wetland vegetation. It is likely that visible and near-infrared multispectral data can identify these vegetation collections and their physical attributes (such as height, volume, area), which would allow wide-area mapping of the habitats with only minimal human ground truthing. Such an approach was recently demonstrated for mapping the habitat of the Eurasian badger in the United Kingdom using a GIS model on data that reflect of the known characteristics of the badger habitat; the model produced an 80% accuracy in identifying badger habitats (Wright et al., 2000). A system-wide habitat mapping approach was also recommended by the remote-sensing PEP (Berlin et al., 1998).

Vegetation height or volume can also be approached without field measurement using optical or radar image data or LIDAR data. Using optical image data with known solar-elevation and solar-azimuth angles, a computer program can search for shadows cast by vegetation stands and automatically estimate their heights; the spectral signatures of the trees would allow automated mapping of tree area, thus providing tree volume. Such an analysis requires calibrated, orthorectifed image data; its operation beyond algorithm development would be essentially no cost. This approach differs from attempts to derive leaf area index (LAI, which is vegetation mass per unit area) using optical data; that approach has produced inconsistent results. Hurcom and Harrison (1998) found good correlation between NDVI and surface leaf area, but no correlation with LAI. Todd et al. (1998) found that the green vegetation index (where a green wavelength band replaces the red wavelength band in the NDVI), the NDVI, the wetness index (from a tasselled-cap analysis), and just a red wavelength band do not estimate biomass in grasslands very well. Blackburn (1999) found no mathematical relation between any spectral ratio index and LAI. Cusack et al. (1999) found an exponential relation between NDVI and biomass, but no relation to LAI. However, Blackburn and Steele (1999) found a good correlation between certain near-infrared spectral-reflectance ratios (0.836 µm/0.817 µm; 0.969 µm/0.931 µm; first derivative of 0.750 µm region; second derivative of 0.753 µm region) and unit leaf mass. More recently, Elmore et al. (2000) have determined that spectral mixing analysis using a pre-defined spectral library of all vegetation types can predict the percent area of live vegetation with an accuracy of 4 absolute percent, far superior to the results obtained using NDVI.

A more straightforward approach would be to acquire L-band radar imagery of particular areas of interest whose signal is scattered internally by tree trunks and branches, which causes the reflected signal to be depolarized relative to its incident polarization. This depolarization is called volume scattering and has been quantified by field analysis. The one pitfall of that approach is the level of interaction between the L-band signal and the vegetation decreases with decreasing branch/trunk density. Therefore, some vegetation might not be seen. If an autonomous approach is desired for habitat characterization, it would be better to use optical data, unless multiple wavelength (both C- and L-band) radar can be employed. Hill et al. (1999) found that L-band radar data are good for detecting short vegetation, but C-band radar data is better at detecting low herbaceous vegetation. Musick et al. (1998) found a linear relation between average stand density and Lhv backscatter coefficient. [Lhv is L-band data whose signal is sent with horizontal polarization and received at the antennae in only vertical polarization.] A third approach is to acquire LIDAR data with a large spot size (10 m for trees, so that it has a highly probability of hitting both vegetation and the ground surface) with an instrument (called the SLICER) that records the entire LIDAR return waveform from the surface. Means et al. (2000), using large LIDAR spot sizes, were able to accurately estimate tree height, basal area, and volume at one-half the cost of conventional methods. Also, very accurate estimates of vegetation volume, mean tree diameter at breast height, number of stems greater than 100 cm in diameter, basal area, biomass, and leaf area index have been obtained by LIDAR waveform analysis of large-diameter LIDAR signals (Lefsky et al., in press). The LIDAR surveys are less expensive and more accurate than the optical image surveys for measuring certain physical characteristics of vegetation stands, but a LIDAR approach should be fully evaluated for the vegetation stands with the Grand Canyon. With respect to the SLICER instrument, the broad spot size used in the LIDAR's waveform analysis is not appropriate for detailed topographic mapping of the ground. Thus, a more universal LIDAR system should be explored to monitor both terrestrial topography and vegetation characteristics. Whether an optical or a LIDAR approach proves to be most viable, the selected system will offer wide-area, semi-automated analyses that will be more rapid and less expensive than human field surveys per unit area.

2. *Flora* - More advanced remote-sensing methods should be explored to replace the current methods for mapping terrestrial vegetation. At this time aerial photographic prints (just recently CIR) are used to manually trace the distribution of vegetation species, based on a visual interpretation of what CIR color and texture versus known vegetation occurrences. All derived polygons are then field checked. More appropriate wavelength bands should be considered for this analysis so that identification can be automated as much as possible using vegetation spectral signature and texture, both of which are easily assessed in commercial image-processing systems. In order to perform such an automated, or at least a aemi-automated, analysis requires calibrated image data, preferably orthorectified so that absolute areas and volumes can be automatically computed. The accuracy of an autonomous approach will be greater, the greater the spectral distinction between different vegetation species. Figure 5 shows spectra of some vegetation common to the southwestern U.S. Similar high spectral resolution data have been acquired for the different vegetation species that occur specifically within the Grand Canyon during calendar year 2000. These spectral data will soon be evaluated to determine the degree (accuracy) to which spectral mapping for vegetation can be autonomous just using spectral data. Of course, texture also needs to be considered in that analysis.

The presence and concentrations of several constituents control the spectral reflectance signature of vegetation: water, chlorophyll a (green; absorbs at 0.430 μm and 0.662 μm) and b (blue green; absorbs at 0.453 μm and 0.642 μm), assessory pigments (e.g., carbon-hydrogen rings of Beta carotene, lycopene; absorbs between 0.460 μm and 0.550 μm), nitrogen, lignin (cell wall polymer), cellulose (40-60% of cell walls), and open pore space. Thus, there has been voluminous research over the past three decades to find remote-sensing methods to accurately estimate these constituents in the hope that they will provide a quantitative tool for mapping vegetation type. Recent research has determined the following.

1. There is a strong linear correlation between chlorophyll (a+b) and the ratios 0.750 μm/0.700 μm and 0.750 μm/0.550 μm and the green vegetation index (Gitelson and Merzlyak (1997), the 0.700 μm and 0.735 μm reflectance and band ratio (Gitelson et al., 1999), the first derivative of the green vegetation index (Elvidge and Chen, 1995), the perpendicular vegetation index (Richardson and Wiegand, 1997), the first derivative of the 0.721 μm band (Blackburn et al., 1999), and the band ratios 0.836 μm/0.817 μm and 0.969 μm/0.931 μm, the first derivative of the 0.750 μm band, and the second derivative of the 0.753 μm band (Blackburn and Steele, 1999). Blackburn and Steele (1999) also found good correlations between their

wavelength band ratios and derivatives and the carotenoid content; Blackburn et al. (1999) found that the derivative of 0.721 μm band correlated well with total chlorophyll, chlorophyll a, and chlorophyll b, but not so well with carotenoid content.

2. Penuelas et al. (1997) found some relation between the 0.900 μm/0.970 μm band ratio and plant water content, but it was very weak. Also, Hardy and Burgan (1999) did not find a good correlation between NDVI and plant moisture.

3. Kokaly and Clark (1999) found good correlations between spectral reflectance centered at 1.730 μm, 2.100 μm, and 2.300 μm with nitrogen and cellulose, but not with lignin.

4. Spectral reflectance from vegetation is effected by soil and litter cover, illumination angle, and shadows and methods have been devised to mitigate these effects (Lee and Marsh, 1995; Garcia-Haro et al., 1996; Todd and Hoffer, 1998; Blackburn, 1999; Pinder and McLeod, 1999; Yu et al., 1999; and Quackenbush et al., 2000).

5. Good vegetation classification results (>80% accuracy) can be obtained using remotely sensed data (Butt et al., 1998; Purevdorj et al., 1998; Coulter et al., 2000), use of seasonal data improves classification for deciduous vegetation (Grignetti et al., 1997; Mickelson et al., 1998), additional and narrower wavelength bands increase classification accuracy (Elvidge and Chen, 1995; May et al., 1997; Green et al., 1998), and airborne imagery provides better accuracy than spaceborne imagery due to higher resolution (Rowlinson et al., 1999; Zhu et al., 2000).

All of this research points to the distinct possibility that terrestrial vegetation mapping can become more automated, extensive, and less expensive using remotely sensed data and existing image-processing algorithms than it is at the present time. A crude demonstration of this potential is shown by taking a digital CIR image (Figure 6) and performing a simple NDVI analysis of the red and near-infrared bands to produce a map that displays all areas with vegetation (Figure 7), based on the dramatic increase in reflectance from the red wavelength to the near-infrared wavelength that is distinctly characteristic of most vegetation (Figure 5). This analysis took just 10 minutes. A regional analysis, even as simple as NDVI, requires calibrated image data, otherwise the analysis could take hours to complete to compensate for changes in vegetation signature between image frames.

Ecological Models

Even though Korman and Walters did not intend on their model system to be used for detailed, quantitative predictions of the effects of particular unnatural and natural events within the Grand Canyon, it is very tempting to consider this software system as a ecological predictive tool. Even though the ultimate goal of the program was to develop management experiments, in the process of improving the model with additional, more regional or system-wide results that can be obtained by an expanded remote sensing program, the model may become the single most powerful tool for testing integrated cause/effect relations of dam operations.

Cultural/Socio-Economic Resources

<u>Objectives:</u>

The primary goal of the Cultural/Socio-Economic Resource Program is to monitor cultural and socio-economic resources with respect to Glen Canyon dam operations, so that ultimately a model can be constructed and used for the prediction and possibly the mitigation of dam-operation effects on these resources. The resources for monitoring include: camping beaches, prehistoric and historic sites, and traditional tribal resources such as ethnobotanical, faunal and physical resources. The physical resources include springs, sediment deposits, and mineral deposits. Four specific objectives are: (1) to conserve downstream resources, (2) to design mitigation procedures where necessary, (3) to maintain physical access to cultural resources, and (4) to provide quality recreational resources that do not adversely affect natural/cultural resources. There are other socio-economic objectives associated with hydropower supply and water resources, but these are outside the realm of remote sensing and are not considered in this assessment.

Parameters Measured and Methods Employed:

Activities that are ongoing or will commence in the near future consist of the following: (1) Compiling known cultural data that has been collected by different agencies and groups, including Bureau of Reclamation, National Park Service and tribal authorities, which is primarily a record compilation and archival process; (2) Monitoring beach change by examination of temporal aerial photography and monitoring user preferences by interviews with boating guides; (3) Monitoring river-user preferences and attitudes during different flow regimes by survey forms; (4) Synthesizing camp-site changes through time associated with different flow regimes using historical aerial photography, which is to be completed in 2000; (5) Evaluating the effectiveness of new monitoring techniques for long-term assessment of camp-site change from different flow regimes; (6) Monitoring trout angler use and satisfaction during different flow regimes by survey forms; (7) Investigating the use of hydrodynamic models to predict resource change due to different flow regimes; and (8) Evaluating the effectiveness of vegetation and earth check dams in mitigating observed erosion and degradation on historic and prehistoric resources. The latter activity will commence in 2001; proposed approaches are currently under RFP review.

Socio-Cultural Models:

Both qualitative and quantitative approaches have been taken to assess, understand, and model the cause/effect relations between dam operation and cultural/socio-economic resources. An early approach was qualitative (Hereford et al., 1993) in which observational data were used to hypothesize that arroyo development and degradation of the particular cultural resources were an indirect result of the lower flow levels of the Colorado River in recent times. Recent dam operations have not produced the large, natural flow levels that historically scoured the arroyo fan deposits from the upper river terraces. Thus, as uninterrupted arroyo fan deposition reaches the edge of the terrace, the arroyo begins to downcut the terrace and move material toward and over prehistoric and historic resources that are present below the upper terraces. Recently, the Program requested Wiele to use his quantitative hydrodynamic models for selected resource areas to determine whether his model could be used to predict the observed adverse effects on cultural resources, but this effort has been curtailed for programmatic reasons.

Remote Sensing Recommendations:

Historical data analysis

One of the most difficult issues associated with the objectives in this program is separating natural effects from dam-related effects. The goal of other agencies working on this problem is generally the preservation of cultural resources, whereas the charter of the GCMRC cultural resource program is understanding the effects of the dam operations on the cultural resources and mitigating the effects where they are related to dam operations. As in the other two research programs, unraveling these effects for cultural resources requires the use of the historical image archive in mapping both the surface materials and the terrestrial topography. Such analyses in all three research programs would be faster, less expensive, and more accurate (reliable) if the historical data were converted to a digital format and orthorectified and if there was a ground control network (x, y, and z) on fixed point features equally spaced throughout the river system. The active cultural resource monitoring program differs from the other research programs in its areal coverage. The program considers hundreds of target sites that are scattered throughout the entire river system, hence the need for system-wide control. Some of the processes that affect cultural resources need to be examined hundreds of meters from the river and at upper river terrace elevations. Image data for these remote areas could be locally controlled in a relative sense for change detection, but could not be used for assessments of any absolute changes. In addition, future data that are well controlled will probably not register with the locally controlled data sets. This would require readjustments of the historical image data to match the better controlled future data. Such an adjustment will be much more difficult if only topographic data are being used in the analysis because recognition of coincident points in topographic data is much more difficult than in image data.

Monitoring small cultural resources

Some cultural resources are relatively small in areal extent ranging from less than 1 meter to a few meters (e.g., ethnobotanical, sediment, and mineral-mine resources). Monitoring the adverse effects of humans and dam operations on these small features can best be accomplished using radar image data if the effects are mostly physical in nature. Radar signals are very sensitive to physical changes in surface roughness, relief, water content, and vegetation, but are relatively insensitive to changes in composition. The scale of change that radar data can detect is about 2.5 cm change in roughness and a few mm (with IFSAR) of change in relief. Therefore, radar data can detect very small changes that manifest themselves as either a rougher or smoother surface, a vertical displacement, a change in moisture content, or the growth or removal of a small patch of vegetation. Exposed building (ruins) and even buried structures in unconsolidated alluvium can easily be seen and monitored or discovered using radar data (McHugh et al., 1988; Holcomb, 1992). In dry, unconsolidated alluvium L-band radar can penetrate down to and reflect from hard surfaces at a depth of 3 meters; the radar signal is reflected from the harder buried object and is attenuated in the surrounding alluvium (Schaber et al., 1986). There is good radar satellite-image coverage for all of the United States for historical and future analysis, but the highest spatial resolution is 10 meters. Airborne systems can provide 5-m resolution, but data acquisition is very expensive and has been for several years. Despite the relatively low resolution of available satellite radar data, this option should be explored because small changes within a radar pixel can be seen even if the change is smaller than the pixel dimension.

Springs and historic/prehistoric resources can also be monitored or discovered using thermal-infrared image data, which is sensitive to both physical and chemical changes in a surface or subsurface. The best time to detect a spring using thermal infrared depends on the temperature of the spring. A cold-water spring will appear better against the warm alluvium during the day, whereas a hot spring will appear better against the relatively cold alluvium during night time. Thermal infrared, in contrast to radar, is very sensitive to subtle differences (or changes) in composition, density, and grain size, all of which affect a material's conductivity and emissivity (Hussein, 1982; Johnson et al., 1998). Thus, minor disruptions of the surface (digging, breaking rock or a wall, making a new path) will change the surface's density and/or grain size which will be detected in thermal-infrared images (Johnson et al., 1998). Thermal infrared can also distinguish a degraded, buried ruin from its surrounding alluvium, as long as the ruin and the alluvium have either different compositions or different densities (Berlin et al., 1977; Nash, 1985; Berlin et al., 1990). One-meter resolution thermal infrared data can be acquire by low-flying airborne instruments, but problems with cooling the detector during the hot Summer months and the high cost for an overflight make this less appealing than the radar option.

Optical data can approach change detection of these small features, but because optical data are less sensitive to physical changes much higher spatial resolution are needed to detect changes that are mostly physical in nature. The resolution has to be near the size of the change in the surface. A combination of multi-band and stereo-image pair data at relatively high resolution (< 0.5 m) can be used to monitor surface changes in materials and topography. For a particular site, the cost for two optical multi-band data sets would be less than the cost for two radar images, if the optical data were acquired in during a wide-area data acquisition. Optical data will not however provide any subsurface information, but optical data at high spatial resolution (≤0.3 m) do provide more capability than radar image data (at 10-m resolution) for detecting and monitoring a change in a small object (e.g., a bush) that exists within a group or clump of objects. In order to use the optical or thermal infrared data for monitoring singular or small occurrences of a particular cultural resource, it would be necessary to determine that feature's spectral signature and to determine if that signature is unique relative to the surrounding features or terrain. This determination would require ground spectral sampling of the resource using a spectrometer with very narrow spectral band widths; such data have been acquired for some vegetation resources during two field trips in 2000 from the dam to Phantom Ranch, but many more spectrometer samples need to be acquired for all of the resources of interest.

Monitoring camping beaches and camp sites

The camping beaches and camp sites are relatively small areas, but there are hundreds of them. The most efficient method to monitor future changes in these features is to use low-altitude LIDAR and digital panchromatic image data. The LIDAR data should be processing to remove noise and possibly vegetation (depending on the vegetation algorithm used by the contractor) and should be delivered as point data. These point data can then be easily converted to a TIN and a DEM within minutes and digitally compared with previous data to determine changes in slope, height, and volume. The DEM can then be used to convert the point-perspective panchromatic images (using the images' GPS and IMU information) to an orthographic projection and the resulting image data can be directly compared with previous orthoimages to determine surface material and area changes.

Examining past changes in the camping beaches and camp sites is a more difficult task. One option is to use historical IFSAR data that provides 10-m spatial resolution, but also provides height change detection of a few mm. If a large number of beaches and camp sites are to be examined, IFSAR may provide a more cost-effective method because one image analysis yields a 45 km by 45 km data set. However, camp sites are relatively small and a camp site may only be represented by a single pixel in 10-m radar data. Thus, the radar option for camp sites may not be the best approach. The other option is to use the historical aerial photographic archive, most of which was acquired in stereo, to derive local topography and orthorectify the image data. In the absence of absolute ground control at all camp sites and camping beaches, the topographic data would have to be tied to stable ground points throughout the time frame. If such points exist at sites of interest, then a relative, quantitative change detection can be performed. Once an accurate orthophoto base map is produced for the entire river system, it can be used to historical image data, or at least check the accuracy of independent orthorectifications. The photogrammetric study by Blank (2000) using the GCMRC historical photographic library suggested that the camera parameters for some annual photographic data, which were provided by the aerial photographic firm, may be in error. A study by Barrette et al. (2000) found a 1.1 m difference between mapped unit boundaries for a wetland region using georectified (using control points) and orthorectified (using control point and a DEM) image data. Higher errors should be expected in using photographs with absolutely no rectification. The data used in that analysis were acquired at a scale of 1:7,200 and digitally scanned to provide about 15-cm resolution. That study also found that stereo imagery did not improve boundary delineation over that provided by orthorectified data. Whether a radar approach or an optical approach is used for camping beaches and camp sites, the change analysis should be automated as much as possible within pre-defined limits on accuracy.

Monitoring historic/prehistoric resources

One of the priorities for the cultural resource program in 2001 is evaluating the effectiveness of check dams at various historic and prehistoric resources in mitigating (by diversion) the adverse erosional effects of arroyo development and river flow stage. A more fundamental question for the power authority may be whether the low flow rates produced by current dam operations are the primary factor in accelerating or lengthening arroyo formation or is this occurrence just a natural aberration within a long-term geomorphic cycle. One way to separate these effects is to examine historical remote-sensing data, both before and after dam construction, for extended periods of time (in order to gather a statistically sound database) and to compare the effects on the cultural resources during periods of similar river stages and climatic conditions. The length of the historical record needed to address a natural process such as this may be significantly longer than can be provided by the existing GCMRC archives. One question that may be addressed by such a data analysis is: If very high river stages, produced by nature in the past, did in fact slow downslope arroyo development by removing arroyo fan deposits, was the slowing of arroyo-fan scouring more beneficial in the long term than the potentially adverse direct effects (water erosion, sediment deposition) of these periodic high river stages on the cultural resources ? The physical resource PEP (Wohl et al., 1999) recommended that both the presence and rates of terrace erosion be determined and that the process be modeled to enable prediction of the extent and rate of terrace erosion at culturally important sites.

Considering just the immediate task of evaluating the mitigating effects of check dams, as well as evaluating alternative mitigation procedures if the check dams prove ineffective, the data collected for this study must be able to detect both the small-scale and large-scale surface effects on or near the targeted cultural resources. In order to detect the subtle indications of an incipient process, the remotely sensed data must be sensitive to small changes in physical, chemical (mainly biochemical), and mineralogical factors. Physical changes would be the vertical and horizontal movement of material and a change (either an increase or decrease) in grain size. Chemical changes could include the exposure of fresh, unoxidized or unvarnished material and changes in vegetation, either removal or stress. Mineralogical changes might include the exposure, burial, or transport of alluvium, which may not be obvious in visible wavelengths, but can be detected at certain short-wave wavelengths. A system that satisfies almost all of these criteria would be a calibrated, multispectral CCD sensor that can collect at least four wavelength bands, but more wavelength bands may be needed, such as the six bands listed by Price (1997) and mentioned in the recommendations for the physical resources program. Some of the physical changes would have to be monitored by deriving topographic data that could detect a few cm of vertical change. The most efficient method to obtain such information would be high-resolution LIDAR acquired using a helicopter. In order to make the analysis rapid and accurate the image data would have to be collected with GPS and IMU data so that the data could be orthorectified using the topographic data with a positional at or better than 0.5 meters. This would require an image resolution of about 20 cm. Multiple periods of data acquisition would be required to monitor these changes, which will determine the majority of the cost for this study. A well calibrated imaging system is essential for monitoring subtle changes and for reducing time and cost in postprocessing.

Information Technology

Objectives:

The purpose of the Information Technology (IT) Program is to provide cost-effective tools for resource monitoring within the Grand Canyon. These tools or services include: remotely sensed data; a Geographic Information System (GIS) for efficient storage, retrieval, and analysis of data collected by all programs; a database management system (DBMS) for tabular data; ground surveying; and a library that houses all relevant hardcopy books, reports, maps, photographs, and video tapes, as well as remote-sensing data stored on CD and DVD. The primary objective of the remote-sensing aspect is to provide increasingly more cost-effective, resource-monitoring data that is increasingly less invasive, but increasingly more extensive in terms of its geographic and resource-component coverage. The primary objective of the GIS service is to provide efficient, reliable storage of all collected data in a format that allows for rapid search, retrieval, and analysis of these data (i.e., a database management system), and to provide the capabilities for map generation and spatial data analysis. The database management service is to house and manage all of the tabular and descriptive data that is collected by the resource programs. The surveying service provides the basic ground control (GPS) network within the Canyon, which is used by both ground and air surveys, and provides surveying support during particular resource monitoring campaigns. An on-going objective of the survey service group is to make the ground-control network system wide. The primary goal of the library service is to ensure the safe disposition and efficient search and retrieval of all hardcopy information that is provided to the library by the research and IT program activities. A current objective of the library service is the conversion of its existing ASCII database search engine to a web-based system that operates with graphical user interfaces so that document searches can also be performed using geographic parameters.

Methods Employed:

Remote Sensing Services - Table 2 lists the airborne remotely sensed data that have been acquired to date by GCMRC and its predecessor GCES. Until recently, most of the image data that have been acquired were aerial photographic film and prints using black-and-white or natural color film. Before calendar year 2000, these data were not collected using GPS or IMU instrumentation. The mapping camera was gyro-stabilized so that the camera was always pointing nadir (orthogonal to the surface geoid). The image data were always acquired with stereo (60%) overlap. Starting in calendar year 2000, aerial photography was acquired using color-infrared film and using GPS and IMU instrumentation, although the instrumentation did not always function properly. Digital image data were also acquired using a panchromatic CCD sensor, a 12-band line scanning sensor, and a 220-band hyperspectral sensor; all systems were equipped with GPS and IMU. The 12-band line scanner sensor was flown 1,200 feet above the ground and maintained lock on the GPS satellite systems, which proved that low-altitude flights in the Canyon can provide good georeferenced data. All the photographic image data that were acquired in 2000 are being digitally scanned at 14μm (1814 dpi) and stored on DVDs with GPS and IMU data (if available). LIDAR surveys of the terrestrial resources within the entire canyon system and within the first 100 river miles were conducted using different LIDAR spot spacings (4.0 and 0.5 meters, respectively) and using GPS and IMU. Within the last two years new aquatic mapping techniques have been employed to map channel bathymetry and the morphology and grain-size of channel sediment deposits. A goal for calendar year 2000 was the construction of a system-wide 1-m DEM and a system-wide, CIR orthophoto (1-ft resolution) mosaic that would serve as a the first well-controlled base map of the entire river system. This goal was only partially accomplished in terms of its accuracy specifications.

GIS Services - The GIS group is currently cataloguing and organizing the spatial databases that have been acquired or produced to date by the resource programs and the IT program. The GIS group decided on ERSI's Internet Map Server (ArcIMS) as the internet link to and access to all the data on a GCMRC data server, as well as any specified database that can be accessed through the internet in other agencies or universities. ArcIMS was used by the U.S. Geological Survey to construct the National Atlas™, which is being considered by the GIS group to be a model for the GCMRC internet archive/retrieval system. ERSI's Spatial Database Engine (ArcDSE) was selected as the database interface between the spatial databases within different formats (raster, vector) and the Oracle databases. ArcSDE also interfaces with ArcView and other ESRI data-analysis systems to provide integrated data analysis using all of these diverse databases. A powerful, dedicated server with terrabyte data storage has been installed. The GIS group has a comprehensive set of data standards that is revised when warranted.

Database Management Services - Oracle has been selected to house and manage the ASCII tabular and descriptive data that is collected or produced within the three resource programs. The DBMS personnel are locating data and downloading, transforming, or hand entering the data. Completion of this database will probably take 2-3 years.

Survey Services - The survey group maintains 4 permanent GPS stations on the canyon rim spaced about 60 km apart to support airborne remote-sensing data acquisitions and these are manned with Ashtech GPS receivers during the overflights. In addition, the survey group maintains permanent GPS sites at the main GIS sites where most of the resource monitoring occurs on an annual basis. The group is trying to establish a more widespread control net in anticipation of future system-wide resource monitoring. The survey group also provides survey support for field surveys within the resource programs; this is dominantly in support of the terrestrial and near-shore topographic mapping and the aquatic bathymetric mapping. All GPS data are currently referenced to the 1990 geoid and stored as geoid-transformed x, y, and z coordinates.

Library Services - The IT library currently catalogues all material using a system that was inherited from the GCES. This system is not similar to any of the catalogue systems used by government libraries. The library uses the OPAC (On-line Public Access Catalog) produced by Follet Corporation as a search engine. A prototype web-based system has been developed that is a map-referenced bibliographic search engine. This system allows either ASCII word searches or graphical-user-interface searches, which retrieves bibliographic titles for user-designated map areas within the Grand Canyon. Only the titles can be retrieved from either the OPAC or the map-referenced system. The librarian duplicates all delivered CD ROM or DVD so that there are two copies, one for general use and one for deep archive.

<u>Data Archives:</u>

An inventory of available digital and hardcopy archives provided the following list of items. These should be amended to include additional data and then used to ensure their safe archival in a central computer system.
Biologic Resources Databases:

1. Average ash-free dry mass (AFDM, g C/m^2 +1 se) of Cladophora glomerata from benthos collections at Lee's Ferry cobble bar 1991-1999 (Shannon et al)

2. Average ash-free dry mass (AFDM, g C/m^2 +1 se) of macroinvertebrates from benthos collections at Lee's Ferry cobble bar 1991-1998 (Shannon et al).
3. Average ash-free dry mass (AFDM, g C/m^2 +1 se) of Cladophora glomerata from drift collections at Lee's Ferry cobble bar 1993-1998 (Shannon et al).
4. Density of macroinvertebrates (1000 x no./m^2) in Glen Canyon reach 1993-1997 (AZ Game & Fish)
5. Average ash-free dry mass (AFDM, g C/m^2 +1 se) of Cladophora from benthos collections at RM 205 cobble bar 1991-1998 (Shannon et al).
6. Average ash-free dry mass (AFDM, g C/m^2 +1 se) of macroinvertebrates from benthos collections at RM205 cobble bar 1993-1998 (Shannon et al).
7. Number of backwaters between Lees Ferry and Diamond Creek 1995-1997 (Stevens and Hoffnagle)
8. Catch per unit of effort of flannelmouth sucker in Glen Canyon reach 1992-1998 (McKinney)
9. Large amount of data on population, distribution, reporductive success, movement, subspecies genetics, and survival of speckled dace species.
10. Trout condition factor (10,000 x length^3/weight) in Glen Canyon reach 1984-1998 (AZ Game & Fish)
11. Rainbow trout catch per unit of effort by size class in Glen Canyon reach 1991-1998 (AZ Game & Fish)
12. Proportional stock density (proportion of fish over 12 inches of quality size [16 in.] to anglers in Glen Canyon reach 1992-1997 (AZ Game & Fish).
13. Angler catch rate vs angler hrs and stocking rates in Glen Canyon reach 1984-1998 (AZ Game & Fish)
14. Relative volume (vol/total fish length) of macroinvertebrates in trout gut contents in Glen Canyon Reach 1992-1997 (AZ Game & Fish)
15. Number of wet marsh patches along CO River from Lees Ferry to Diamond Creek 1965-1998 (Stevens)
16. Area (ha) of wet march patches from Lees Ferry to Diamond Creek 1965-1998 (Stevens)
17. Kanab Ambersnail habitat changes at three stage elevations 1995-1999 (Stevens)
18. Kanab Ambersnail estimated population size at three stage elevations 1995-1998 (Stevens)
19. Mean modeled body mass of 300-mm long male humpback chub in lower LCR during spring spawn (May) 1978-1998 (AZ Game&Fish and USFWS)
20. Number of breeding SW willow flycatcher pairs detected from RM46-72 1982-87 and 1991-99 (Sogge, Spence)
21. Number of Willow Flycatcher nests from RM46-72 1982-87 and 1991-99 (Sogge, Spence)
22. Phantom Ranch Air Temperature 1988-1997 from NOAA
23. Phantom Ranch Precipitation - 1988-1997 from NOAA
24. Long-term climate station data from NOAA at Ashfork, Cameron, Desert View Ranger Station, Flagstaff, Grand Canyon National Park, Lees Ferry, Mt. Trumbull, Seligman, Tuweep, Williams
25. Daily streamflow at Lees Ferry 1920-present from USGS
26. Daily minimum/maximum streamflow at Lees Ferry 1996-1998 from USGS
27. Daily minimum/maximum ramping rates (cfs/hr) 1996-1998 from BOR SCADA
28. Daily minimum/maximum flows below Glen Canyon Dam 1989-1993 from USGS
29. Daily discharge in Paria River above Lees Ferry 1923-1998 from USGS
30. Daily discharge and minimum/maximum flow in Little Colorado River near Cameron 1924-present from USGS
31. Daily discharge and minimum/maximum flow in Little Colorado River above mouth of Desert View 1990-1993 from USGS
32. Daily discharge and minimum/maximum flow in Bright Angel Creek near Grand Canyon 1923-1974 and 1990-1993 from USGS
33. Daily discharge and minimum/maximum flow in Kanab Creek above mouth of Supai 1990-1993 from USGS
34. Daily discharge and minimum/maximum flow in Havasu Creek above mouth near Supai 1991-1997 from USGS
35. Daily discharge and minimum/maximum flow in Diamond Creek near Peach Springs 1993-present from USGS
36. Daily discharge and minimum/maximum flow in Spencer Creek near Peach Springs 1998-present from USGS
37. Fill history of Lake Powell 1965-1998 (S. Hueftle)

38. Lake Powell Reservoir and GCD tailwaters sampling stations
39. Temperature, conductivity (reflection of salinity), and dissolved oxygen in forebay of GCD 1964-1998 (S. Hueftle)
40. Chlorophyll a and secchi depth in main channel of Lake Powell 1991-1999
41. Temperature (°C), specific conductance (µS/cm), turbidity (NTU), dissolved oxygen (mg/l), pH, DO saturation (%), and water density (kg/m^3) in main channel of Lake Powell 1999 (S. Heuftle).

Physical Resources Databases:

42. 10-year average sediment inputs from ungaged tributaries below Glen Canyon Dam (Webb et al., USGS)
43. Tributary debris-flow potential from ungaged tributaries below Glen Canyon Dam (Griffiths et al., USGS)
44. Time series channel-bed grain-size data for main channel of Colorado River (Topping et al., USGS)
45. Channel sand storage above RM 61 1991-1998
46. Sand inputs from Paria and Little Colorado Rivers 1990-1998
47. Sand bar volume and area upstream and downstream from Little Colorado River 1990-1998
48. List of sites where main channel geomorphology was impacted by debris flows 1872-present
49. Historical time-series data on changes in sand bars and main channel streamflow and sediment transport between Lees Ferry and Phantom Ranch (Schmidt and Topping, Utah State)
50. Side-scan sonar images of bed substrates (Anima and Rubin, USGS)
51. Multi-beam hydro-acoustic bathymetry

Cultural Resources Databases:

52. Number of river rafters per year 1869-1998 (GCNP)
53. Mean hourly power production (Mw/hr) 1997-1998 (BOR SCADA)

Remote Sensing Databases Applicable for all Programs:

54. 1998 LIDAR (10 m along track, 5m across track, vertical accuracy 1m) - had a 1,600 ft swath width, too narrow for complete coverage of Old High Water Zone. 83% of data had accuracy within 1 m. 12% within 1-2 m due to (1) LIDAR saw roughness (boulders) that photogrammetry ignored; (2) did not penetrate dense vegetation as purported; (3) severe changes in surface slope, could be overcome using breaklines; (4) changes between photogrammetry and LIDAR; (5) shadowed areas not seen by photogrammetry, but seen by LIDAR.
55. 2000 LIDAR data (4.0-m across- and along-track spot spacing) from Glen Canyon dam to Lake Mead.
56. 2000 LIDAR data (0.5-m across-track spot spacing, 1.0-m along track spot spacing) at 4 river reaches within first 100 river miles of Glen Canyon dam (RM 0.9-2.9; RM 29-32; RM 42-45; and RM 59.5-65.0) and 20 camping beaches (at RM 11.8, 20.4, 38.3, 71.9, 76.6, 84.0, 84.4, 91.6, 98.0, 114.5, 120.0, 133.0, 134.6, 136.2, 137.0, 145.6, 148.4, 155.7, 206.6, and 208.8) before the September 5, 2000 high flow spike.
57. 2000 LIDAR data (2.0-m across- and along-track spot spacing) for first 100 river miles from Glen Canyon dam both before and after the September 5, 2000 high flow spike.
58. 2000 LIDAR data (0.5-m across-track spot spacing, 1.0-m along track spot spacing) at 4 river reaches within first 100 river miles of Glen Canyon dam (RM 0.9-2.9; RM 29-32; RM 42-45; and RM 59.5-65.0) after the September 5, 2000 high flow spike.
59. 2000 photogrammetric contour maps and digital terrain models for two river reaches (RM 59.5-61.6 and RM 44.5-46.9) at 0.25-m, 0.50-m, 0.75-m, and 1.0-m contour intervals.
60. 1998 HYDICE data (1.5m) for Badger Rapids to Glen Canyon Dam for selected reaches resides at GCMRC in RAW form only.
61. GPS (GCMRC)
62. Topographic maps between 5,000 and 300,000 cfs for GIS sites established by GCES (a few percent of river).
63. Topographic maps for areas below 5,000 cfs for less than 3% of river system.

64. Photographic and digital imagery:

Table 2. Inventory of all aerial photographic and digital imagery that have been collected for GCMRC.

Year Acquired	Type	Format	From RM	To RM	Scale	Quantity	Known Missing
1935	B&W	9" print	-19.3	239.8	unknown	54	6, but retrievable
1952	B&W	18" print	-13.5	3.5	7,920	6	
1965	B&W	9" print	not listed	not listed	12,000*	652	8
06/17/73	B&W	9" print	not listed	not listed	14,400*	50	
08/08/79	Color	9" print	-1.5	16	3,000*	100	
06/27/80	CIR	9" print	GCD	211	3,600*	400	
07/11/80	CIR	9" print	House Rock	220	3,600	200	
10/20/80	B&W	9" print	various	segments	4,800	100	
06/09/82	Color	9" print	segments; 34	182	32,000 37,000	51	
06/09/82	B&W	9" print	rapids	survey	32,000 37,000	37	
10/22/84	B&W	9" print & film	-15.5	260	3,000	600	
06/08/85	CIR	film	-15.5	260	4,800	7 rolls, about 1,000	
06/13/86	B&W	9" print	Hermit Mon. Lava	Badger Creek	8,000*	90	
06/13/86	B&W	9" print	segments; Lees Ferry	Diamond	8,000*	80	
05/20/87	CIR	9" print & film	73	47	9,600*	104	22
05/28/88	CIR	film	-15.5	280 + LCR	4,800	1,000	

Year Acquired	Type	Format	From RM	To RM	Scale	Quantity	Known Missing
10/08/89	B&W, some color	9" print & film	-15.5	280	6,000	700	
06/02-06/90	CIR	9" print	-15.5	280	4,800	760	Sent to BOR, cannot find film
06/02-06/90	B&W	9" print and film	AREA 1	AREA 2	7,200 & 14,400	99	
06/02-06/90	B&W	9" print and film (roll HI 1234)	AREA 3	AREA 5	7,200 & 14,400	105 @ 7,200	
06/30-07/01/91	B&W	9" print and film (rolls HI 1334-35)	AREA 6	AREA 13	7,200 & 14,400	100 @ 7,200	
10/11-13/92	Color	9" print and film (rolls 1-8)	-15.5	280	4,800	800	
10/10/92	B&W ortho	9" print and film (roll HI 1539)	AREA 14	AREA 15	6,000 & 14,400	60 @ 6,000	
05/30-06/02/93	Color	9" print and film (rolls 4-10)	-15.5	267 + LCR	4,800	1,730	
05/29/93	Color	9" print and film (roll 1)	AREA B		25,000	297 (for all 1993 photos)	
05/29/93	Color	9" print and film (roll 1)	AREA C		3,000		
05/29/93	Color	9" print and film (roll 1)	AREA D		8,000 & 10,000		
05/29/93	Color	9" print and film (roll 2)	AREA E		15,000		

Year Acquired	Type	Format	From RM	To RM	Scale	Quantity	Known Missing
09/02/93	Color	9" print and film (roll HI 1478C)	F1		25,000		
05/28-29/94	Color	9" print and film (roll 1-10)	-15.5	281 + LCR	4,800	1,730	
05/28-29/94	B&W	9" print and film (roll 1-10)	AREA 16	AREA 17	6,000 & 14,400	152	
05/29-31/95	Color	9" print and film (roll 1-9)	-15.5	281 + LCR	4,800	1,730	
03/24/96	Color	9" print & film (roll unknown)	9 MILE DRAW		4,800	10	
03/24-26/96	B&W	9" print & film (roll 1-8)	-15.5	281 + LCR	4,800	1,730	
03/31/96	B&W	9" print & film (roll HI 1823)	TOROWEAP & PROSPECT		14,400	23	
04/04-07/96	B&W	9" print & film (roll 1-8)	-15.5	281 + LCR	4,800	1,730	
09/01-03/96	B&W	9" print & film (roll 1-9)	-15.5	281 + LCR	4,800	1,730	
09/01-03/96	Color	9" print & film (roll 7)	select areas		4,800	160	
08/31-09/03/97	B&W	9" print & film (roll 1-7)	-15.5	281 + LCR	4,800	1,730	
08/31-09/03/97	Color	9" print & film (roll 1)	select areas		4,800	160	
09/05-07/98	B&W	9" print & film	-15.5	281 + LCR	4,800	1,730	

Year Acquired	Type	Format	From RM	To RM	Scale	Quantity	Known Missing
		(roll 1-7)					
09/09/98	Color	9" print & film (roll 1)	select areas		4,800	160	
09/05/99	B&W	9" print & film (roll unknown)	-15.5	281 + LCR	4,800	1,730	
09/05/99	Color	9" print & film (roll unknown)	select areas		4,800	160	
16 intervals between 1990-91	B&W from helicopter	2" film negs	select areas (Brian Cleur's Beach Sites)		unknown, could be variable	2,000	
03/26-04/03/00	CIR	9" print, film, and 14-micron digital scans	-15.5	281 + 5 confluences	20,000	625	
03/26-04/03/00	B&W	digital	-15.5	281 + 5 confluences	20,000 1.0 foot resolution, 4096 pixel swath	estimated 1,500	
07/04-06/00	CIR	film and 14-micron digital scans	-15.5	281 + 5 confluences	4,800	1,730	
07/25/00	Daedalus 1268 ATM 12 channel	digital	30	74	1.0 meter resolution, 640 pixel swath	continuos, 12 -band data strip centered on river	
07/26/00	Daedalus 1268 ATM 12 channel	digital	51.5	53.5	one meter resolution, 640 pixel swath	continuos, 12-band data strip	

Year Acquired	Type	Format	From RM	To RM	Scale	Quantity	Known Missing
	predawn thermal infrared					centered on river	
08/29-31/00	B&W	digital	-15.5	103	0.6 foot resolution, 4096 pixel swath	940	
09/02/00	B&W, high gain	digital	-15.5	0	0.6 foot resolution. 4096 pixel swath	168	
09/04/00	Color	9" print & film	44 59	47 62	both river segments at three scales: 12,800, 6,400, and 4,000	23 33 48	
09/06/00	CIR (overcast)	9" print, film, and 14-micron digital scans	-15.5	103	1 foot resolution 1:20,000	181	
09/15-18/00	B&W	digital	-15.5	103	0.6 foot resolution, 4096 pixel swath	1080	
09/05/00	B&W, high gain	digital	-15.5	0	0.6 foot resolution, 4096 pixel swath	223	

GCMRC Library Databases:

65. Published and unpublished reports related to GCMRC are catalogued as far as author, title, library call number, and year, but not indexed with respect to location, subject, key words, etc. The library OPAC catalogue allows limited search capability. The web site for searching for reports on the GCMRC study area is a good concept, but should be integrated with the on-line database archive.
66. Ground photographs - exist as slides; some have dates, too few have locations, and some have neither. There is no centralized index for the slides.
67. Videography - exists mostly as master broadcast tapes that require a special device for viewing. A limited number of tapes are the small-format cam recorder tapes. Film dates include: 1984, 1985, and 1990 through 1997. These tapes are not rewound periodically, nor are they copied. Deterioration is inevitable and might have commenced already. Users say these videos look blurred relative to aerial photos and generally do not use the videos.
68. Maps - published USGS 7.5 minute, 15 minute, and 1:250,000-scale topographic sheets. Maps showing flight lines for selected aerial photographic flights. Some topographic maps and orthophotos produced by Horizons Corporation.

Information Technology Recommendations:

Remote Sensing Services

Future remote sensing data must be acquired digitally in order to eliminate the ambiguities associated with the scanning of photographic film and processed as orthorectified to make the data immediately useable by the cooperators. Imaging sensors must be also be calibrated so that their digital data can be used system wide in more automated data analyses. Although CIR data are an improvement over natural-color and black-and-white photography, more wavelength bands will be necessary to approach the wide range of protocols within the resource programs. The number and wavelength positions of the bands will be assessed during 2001 using available hyperspectral airborne and field spectrometer data. At least one of the bands will probably be used for channel water sensing for both bathymetry and substrate mapping. A survey of all available sensors and their characteristics is included as an Appendix in this report. The most appropriate sensor can be selected from that list, once a set of optimum sensor requirements are defined by detailed analyses of available test data. Every effort should be made within the next two years to obtain a well-controlled, system-wide orthophoto mosaic so that historical and, where necessary, future image data can be geographically controlled. The optimum time for image data acquisition, considering all of the various resource protocols, would be near the Summer solstice in June, when vegetation is in bloom, shadows are minimal, and sediment input from tributaries is minimal for water penetration. This time period may miss the maximum bloom for some terrestrial vegetation.

As mentioned in previous recommendations for the physical and biological resource programs in this report, some of their high-frequency survey needs may be approached by the procurement of a CCD imaging system that provides selectable wavelength bands, that can be mounted on local aircraft, that can record GPS and IMU data, and that provides the spatial resolution required for resource protocols. One instrument that appears to satisfy these requirements is the DuncanTech 3-CCD cameras. However, this CCD camera system has only 1392 rows and 1040 columns within its CCD arrays. As stated in one of the previous recommendations section, Mostafa and Schwarz (2000) found that positional and vertical accuracies decrease with decreasing size of CCD image array. For 15-cm data acquired with a 1500 x 1000 CCD array camera, comparable to the DuncanTech CDD, they determined the positional accuracy to be 90 cm and the vertical accuracy to be 1.8 m, whereas a 15-cm data acquired with a 4096 x 4096 CCD array camera produced a positional accuracy of 40 cm and a vertical accuracy of 0.5 m. Even though the cost for a small format sensor (such as DuncanTech) is only $9-11,000, such sensors may not provide the horizontal or vertical accuracies desired or required by GCMRC resource protocols.

A LIDAR alternative to photogrammetry and land-based terrestrial topographic mapping needs to be fully evaluated to determine if the LIDAR return signal can accurately discriminate vegetation from bare ground. This effort should first focus on the use of the LIDAR's power return and thus only LIDAR sensors that can record power should be considered in near-term (2001) assessments. [Note: SHOALS may have been successful in this regard because it uses both a green and a near-infrared laser; the ratio of the power returns from the near-infrared and the green lasers could indicate a vegetation target. However, the gain on the SHOALS near-infrared laser is set so high for water-surface reflection that it is saturated on hard surfaces. The sensor gain cannot be reset for hard surfaces.] There is no advantage to acquiring LIDAR data or any topographic data for vegetated terrestrial resources during the Winter "leaf-off" period. The tamarisks are the most extensive and tallest ground cover and they do not shed their senescent leaves unless there is a period of very strong wind. Otherwise, the dead leaves are merely pushed off by the Spring bloom (Mike Yard, personnel communication, 2000). If the LIDAR power return approach does not prove reliable, then an alternative image-based approach for this discrimination needs to be explored. Only the processed LIDAR points should be a deliverable, if LIDAR proves to be a reliable remote-sensing protocol for topography; contour lines are not used by cooperators or in digital analyses and LIDAR point data can easily be converted to a TIN and DEM using most commercial image-processing software.

The IT program manager needs to work closely with the contract officer within the U.S. Geological Survey for future remote-sensing surveys to ensure that the statement of work and specifications are constructed in a manner that will be enforceable. In addition, all future data acquisitions need to be preceded by a careful, joint USGS-contractor review of the statement of work and data standards, just after contract award, so that the contractor understands completely the expectations and requirements for that flight data.

The volume of remote-sensing data is growing rapidly within GCMRC; the need for access to these data overlaps many of the protocols within the resource programs is increasing due to the trend towards more integrated analyses. Degeneracy of the historical data is a product of normal processes: aging of paper and film products, cumulative use (handling, machine reading) by humans, and misplacement. Other disadvantages to hardcopy print or film data storage include (1) large storage area, (2) use of archaic and possibly erroneous processes for their duplication and analysis (photocopy machines create geometric distortion), (3) access is limited by physical location, and (4) laborious search and retrieval methods. The historical records need to be converted to a digital format and stored on stable, long-term media as soon as possible for their preservation and to make these data much more accessible and useful to resource projects, managers, and administrators. This will also greatly reduce their storage space and greatly reduce or eliminate librarian management time. This recommendation reiterates that of the National Research Council (1999) which stated that a high priority should be given to data archiving.

Although many of the original film rolls of the historical aerial photography reside at Horizons, the cost of reproduction of the entire photographic print collection (over 34,000 images) would be well over $200,000. Currently, the GCMRC aerial photographic print collection is neither waterproof nor fireproof. In order to preserve the full 5.8 cm resolution of the aerial photographs, they would have to be scanned at about 12 microns (2117 dpi). A survey of reliable companies that scan aerial photographic film (Table 3) shows that the cost for scanning the entire photographic film library at just 20 microns would be in the range of $500,000 to $600,000.

Table 3. Dollar cost for scanning various photographic products at 20 microns per pixel (1,270 dpi).

Company	B&W photograph	Color photograph	Film	Each CD ROM
Photogrammetric Engineering	13.00			1.50
Admap	12.50	20.00		2.50
Airphotographics	20.00	86.00		10.00
Image Scans	10.00	20.00	22.00-25.00	included
Precision Photo & Imaging	15.00-20.00			15.00

Horizons	NO	NO	25.00	

An alternative approach is to purchase a scanner and a cpu to run the scanner, and to use two temporary employees to digitize the photographic library. The full resolution of the aerial photographic film (5.8cm at 4800 scale) can be captured using a 12 micron (2,117 dpi) scanner. All existing scanners on the market were reviewed given the basic requirements of (1) scanning at a minimum true resolution of 2,117 dpi (12 microns/pixel), (2) able to scan 9"x 9" products, (3) scan at least in 8-bit, and (4) able to scan hardcopy and transparencies in color and B&W. The lowest cost scanner that satisfies all of these requirements is the AgfaScan T5000 Plus. This scanner has a true maximum scan resolution of 5,000 dpi (5.1 microns/pixel; scan resolution can be set to any value ≤5,000), is a flatbed scanner with an effective scan area of 12" x 17" (305 mm x 432 mm), has 13-bit density resolution (which can be reduced to 8 bit if the data warrant for storage purposes), and scans an average of 12 images per hour. Certain scanners and scanning practices can induce noise in a scanner's output file, which seriously limits data compression and reduces data quality. Test scans of some GCMRC aerial CIR prints using the AgfaScan T5000 at 1250 and 2500 dpi show no noise induction (Figures 8-10). Before starting such a production process it would be necessary to: (1) test and calibrate scanner for geometry; (2) test and calibrate scanner for color fidelity; (3) establish a procedure that places the side of a photo orthogonal to the scan direction; and (4) establish data compression, metadata, and storage procedures. All of these issues, as well as the procurement of the scanner, can be set aside if another group with similar needs would procure, calibrate, and operate the scanning system. The Astrogeology Team is seriously considering doing just that; they should be contacted about a possible time-share agreement.

Scanning a B&W aerial photograph at 12 microns produces an image file that is 368 Mbytes. With 25% compression two images could fit on a CD ROM, but a three-band color image could not. DVD technology is progressing quickly to replace CD ROM as the common storage medium, now that a common DVD format has been decided by the international DVD Forum. DVD readers can read CD ROMs and most DVD writers can write both digital data and video (which may be relevant if historical GCMRC videography is to be preserved). A single-sided DVD holds 4.7 Gbytes, a double-sided DVD holds 8.5Gbytes, and projections indicate that future (2005) capacity will be 50Gbytes per side and that within 2 years DVD readers will surpass CD ROM sales for PCs.. Unfortunately, each DVD disk currently costs $30 (comparable storage on 7 CD ROMs would cost $7). However, DVD prices will decrease with more widespread use, as was the case for CD ROMs. As far as the GCMRC photographic archive, 2,886 DVDs would be required to store the existing color and B&W photographs, if scanned at 12 microns. The projected costs for digital conversion of the existing photographic archive as DVD and CD ROM are listed in Table 4.

Table 4. Estimated costs for digital conversion of the entire GCMRC photographic library at full spatial resolution (12 microns/pixel scan or 5.8 cm/pixel).

Item	Cost
1. AgfaScan T5000 Plus scanner	22,500
2. Computer with adequate disk storage with DVD/CD reader and 8mm tapedrive	10,000
3. DVD writer	4,995
4. 2,886 write-once DVDs @ $30 each	86,580
5. 2 yrs x 2,080 hr/yr x $6.00/hr for operator	24,960
total	**149,035**
CD alternative to items 3 and 4:	

Item	Cost
3a. CD writer	400
4a. 22,427 CD ROMs @ $1 each	22,427
total	**80,287**

The idea of housing and managing over 22,000 CD ROMs, just for the current image archive, is overwhelming considering the fact that there should be two copies of each CD as a backup for possible loss. [NOTE: Any option selected should include a provision for a duplicate set of copies for deep archive in case of loss or damage.] An alternative option is to temporarily store the scanned data on high-density, 8-mm (or 4-mm) tapes and transfer the tape data to DVD when DVD prices approach $4 in the future. Tape storage costs about the same as the CD ROM option (Table 5) and only produces 622 tapes for all of the archived images, but the short life of tape data (both from shelf age and usage) makes the tape option less desirable than managing large volumes of CDs or DVDs and their cost of production. Another option is to scan every other photograph in the stereo image library, which would retain complete areal coverage and lower overall DVD archiving costs to about one-third that shown in Table 4, but this process would not preserve the full stereo capability of the present archive, which needs to be maintained for some historical analyses. Another option is to reduce the scanning resolution to 24 microns (about 1.050 dpi that results in a 11.6 cm pixel resolution). Test scans of CIR aerial photography at 20 and 10 microns/pixel showed only a small degree of degradation in image detail between 10 and 20 microns (Figures 8-10). Thus, 24 microns could be used on the library and still retain almost all information. Under this scenario data volume and storage media reduces by about a factor of four (e.g., 5,168 vs 22, 427 CDs or 673 vs 2,886 DVDs) and the total cost for the DVD option (shown in Table 5) is reduced by one-half the costs for 12 micron scanned library (shown in Table 4). Furthermore, the total cost can be reduced to $45,000 (just items 4 and 5 in Table 6) for the DVD option, if GCMRC can get a cooperative agreement with Astrogeology who is considering the procurement and operation of such a scanning system.

Table 5. Estimated costs for digital conversion of the entire GCMRC photographic library at reduced spatial resolution (24 microns/pixel scan or 11.6 cm/pixel).

Item	Cost
1. AgfaScan T5000 Plus scanner	22,500
2. Computer with adequate disk storage with DVD/CD reader and 8mm tapedrive	10,000
3. DVD writer	4,995
4. 673 write-once DVDs @ $30 each	20,190
5. 2 yrs x 2,080 hr/yr x $6.00/hr for operator	24,960
total	**82,645**
CD alternative to items 3 and 4:	
3a. CD writer	400
4a. 5,168 CD ROMs @ $1 each	5,168
total	**63,028**
Tape alternative to items 3 and 4:	

Item	Cost
3a. Tape drive	included in #1
4b. 156 20Gbyte tapes @ $40 each	6,240
total	**63,700**

GIS Services

All GCMRC data should be centralized and logical, and tied to a spatial reference base for easy search and retrieval using geographic maps and key search words. The data archives can allow selective proprietary restraints on access. The National Research Council (1999) recommended that a high priority be given to accelerating data archival and delivery through the internet. Currently, access to data on the GCMRC ftp site is almost as awkward as using DOS to run a computer program. The user has to worm through multiple directory levels and has to know the file name of the desired database and specific tile name (number) for an area in order to retrieve it. A database management system and a search engine with a reference map are absolutely critical. The GIS group has ordered such software that has been used by other groups with similar requirements. Assuming there is adherence to metadata standards by data providers, there are some fundamental requirements that should be met by an integrated data archive:

1. The metadata must be stored in a searchable database that contains pointers to the actual data.
2. The actual search and retrieval system must have the following characteristics:
    a. Operate on a variety of computer platforms.
    b. Internet accessible user interface.
    c. User access to a search specifications page used to define the search.
    d. Searchable by a variety of characteristics, including type of data (e.g., image, graphics, tabular, Arc coverage), category (e.g., flora, fauna, hydrologic, geologic, cultural, weather); parameter (e.g., sediment load, grain size, chemistry, temperature, area, volume, species, topography, bathymetry); date of acquisition; location (defined by rectangle on index map); and source of data (e.g., person, method of measurement).
    e. Provides a list of the recovered databases, a brief description, and a general map of the recovered data's distribution (if desired, understanding that the map generation will slow the process).
    f. Allows extraction of additional details about any of the listed databases, including browse images or quick-look graphics.
    h. Sufficient disk space for maintaining all data or temporary storage space for CD ROM, DVD, or tape transfer from a juke box.
    i. Download link button to allow users to transfer data from archive to their own platforms.

Constructing such an archive and retrieval system is not simple because the archive needs to meet the different needs, desires, and capabilities of a diverse user group. Instead of trying to satisfy everyone's desires immediately, it would be most advisable to proceed with a rudimentary implementation and allow users to express their joy, frustration, and desires by actually using a prototyped system. The ESRI Arc tools that the GIS group has ordered have been shown to be adequate for large, diverse databases that are served through the internet. One such group is located at the EROS Data Facility that produced the National Atlas™. Their Arc code should be available at no cost to anyone within the U.S. Geological Survey; obtaining the code should be explored because the shell code should only require modification for appearances and for database interfaces.

Standards for submission of data and their associated metadata do exist and must be enforced. These standards rely on existing standards for the federal government and are adequate for GCMRC needs. The standards are not that difficult to understand. Currently, submitted data are reviewed only by the GIS manager to determine its compliance to these standards. This is not sufficient for permanent science data. Instead, all submitted data should be reviewed by the appropriate resource manager and 1-2 resource cooperators to determine acceptability of format, metadata, and content of each submitted database. Updates to existing databases would merely be checked for conformity. The review process for data submitted to NASA archives consists of a chief reviewer and 1-2 knowledgeable peer reviewers, all of whom verify the accuracy, dependability, and usefulness of the scientific data, and of the archive manager who verifies the metadata's compliance by test loading the submitted metadata into the archive system and performing various searches with different parameters. The science review recommends major and minor corrections, if necessary, and the chief reviewer ensures that at least major corrections are made before final submission to the archive. If any disagreement between reviewers and submitting scientist cannot be resolved, then the partially revised data are archived with the chief reviewer's comments on the disagreement. This system should be used by GCMRC.

The advantage of digital data over hardcopy data is that digital data occupies less physical space, is preserved for longer periods of time, and allows easier quantitative analysis and construction of various types of displays. However, data volume is a matter for concern in moving towards digital data collection and storage, especially with respect to access. It would be better to have final processed data as mosaic tiles whose boundaries conform to commonly used maps, such as the 7.5-minute quadrangle maps. However, a single-layer, 0.3-m-resolution database for a 7.5-minute map quadrangle occupies 1.678 Gbytes; if that quadrangle database was a color orthophoto mosaic, it would occupy 5.034 Gbytes per 7.5-minute map tile. Current computer platforms have 32-bit processors which means that the largest address that software can use (understand) for accessing any type of dimensional data is (2^{32}-1) or 4.295 Gbytes. Thus, quarterquads will have to be employed in the disk storage and access system for either high spatial density data or multi-band image data. This problem may diminish for on-line storage and access when 64-bit computers are available, but it may not disappear altogether for multi-band image data.

In order to store the vast volumes of data that are being collected and that will be generated if the historical image data are converted to a digital format, data compression techniques need to be considered. Desirable archival data compression systems use lossless algorithms and have a high probability of surviving changes in technology. The following general rules are also provided by Eric Eliason, who is manager of NASA's Planetary Data System Imaging Node.

1. Data collections that are small in volume should not be compressed. Compression can act as a barrier to the data.
2. Tabular data should be organized in ASCII form whenever possible. Binary storage has problems with floating point conversions, byte-order, etc.
3. Digitally acquired data should only be stored in 'lossless' compressed form.
4. Scanned images of photographic prints may use 'lossy' compression methods, such as JPEG. The JPEG compression rates should be carefully chosen to reflect the MTF (modulation transfer function) of the photographic emulsion as well as the digitizing system. This does not refer to high-quality photographic film.
5. Any compression scheme used to store data must be non-proprietary and be widely and freely available to the general user. The archiving institution should avoid the task of maintaining and providing software for decompressing data in its archive. Avoid the use of "GIF" format for image files because of CompuServe's recent aggressive stand on community use of its proprietary software.

Investigation of various types of compression algorithms showed that all lossless algorithms use run-length encoding (RLE) for their primary data reduction. RLE looks at the change in numbers along a line and replaces strings of the same number with the value of the number and the frequency of its occurrence. There has been little progress in data compression algorithms within the past five years. A new compression technique (MrSID) provides a range of compression factors. This patented software purports to "encode large, high-resolution images to a fraction of their original file size while maintaining the original image quality and ... without compromising integrity" (LizardTech Internet Web Site). This claim was tested using a 20X and a 100X compression ratio on a scanned CIR aerial photograph. Visual comparison of the original CIR image and the 100X compressed CIR image suggests that the two images are identical (Figure 11). However, subtracting the digital numbers (DN) of the restored 20X- and 100X-compressed images from the DN of the original image for each of the three color bands shows that even the 20X compression ratio does not maintain the DN of the original image (Figure 12). [Digital

number simply refers to the a pixel's number value; in 8-bit data the DN range from 0 to 255.] This can be seen spatially by examining the color images in Figure 13, formed by compositing the difference images produced for the red, green, and blue bands of the CIR image both for the 20X and the 100X compression ratios. If the 20X compression was lossless, its color difference images would be entirely black. MrSID might just shift the DN during compression, which would alter the true DN but maintain the relative changes in color within the image. If so, the ratio of the DN in the compressed image to the DN in the original image for each color band should be 1.0 everywhere. Examination of color composite images of the 20X and 100X ratios for the red, green, and blue bands (Figure 14) shows that indeed MrSID performs some type of shift because much of the 20X and 100X ratio composite images are gray, which is why the 100X compressed image looks much like the original. However, water areas show anomalous shifts in image DN in the three color bands, which is detrimental to temporal analyses of water areas. Thus, MrSID should not be used for archiving data that are to be used for quantitative analysis. However, MrSID's ability to compress image data significantly while maintaining most of the relative color differences suggests that this method would be useful to produce quick-look, browse images for the web-based data archive. The remote-sensing PEP recommended that a complete catalogue of reduced-resolution, browse images be constructed and be made available on the ftp or web site (Berlin et al., 1998).
In terms of lossless compression, the most efficient lossless compressor that is nonproprietary and works on any the main computer operating systems (i.e., it is portable) is GZIP. GZIP is recommended for all lossless data compression for GCMRC.

The remote-sensing PEP (Berlin et al., 1998) recommended that the IT program invest in image processing and topographic modeling software. This assessment reiterates that panel's recommendation and suggests that Research Systems Incorporated (RSI) be seriously considered to meet these needs. RSI provided the most powerful image processing system and the most powerful and easy programming environment to construct user-specific applications.

Database Management Systems

The National Research Council (1999) recommended that the IT program proceed as soon as possible with the construction of a DBMS, even without carefully formulated design, because too much time could be taken in the design phase producing an implementation that is too late to be useful. Given the fact that Oracle has been selected as the database engine, data should be entered as fast as possible so it can be used. The final appearance of the Oracle database can be determined and implemented at any time without jeopardizing the stored data. Some of the resource surveys are still recording field data in hardcopy format. Conversion of these cryptic logs to digital format is extremely difficult and time consuming. Given the costs of small palm pilot computers, this study strongly urges all resource programs to mandate digital data collection or recording as soon as possible.

Survey Services

The remote sensing PEP recommended that the survey group should develop system-wide ground-control points that are identifiable on image data for use by field crews. This recommendation is correct. Such system-wide ground control is lacking and is also essential for the airborne remote sensing data acquisitions, at least until GCMRC is comfortable with contractor ability to obtain good airborne GPS and IMU information. A system-wide orthophoto image mosaic would also help in this regard; it would provide control for historical image data analyses where control is lacking. However, such a orthophoto base map should not have a positional accuracy in excess of that required by most resource protocols because rectifying other image data to the base map will always produce more positional error than exists in the base map. The positional error of this base map should not exceed 50-60 cm, based on the current resource protocols.

All field collections are georeferenced using the 1990 geoid of the National Geodetic Survey. Airborne remote-sensing data are being collected and referenced to the 1996 or 1999 geoid. Because of this inconsistency it difficult to compare ground and airborne data or to use both in an analysis. All field survey data collected to date should be stored with respect to a map datum and not be carried to the geoid level until a cooperator wants to use the data. At that time, the cooperator can decide which geoid to use. This issue must be addressed in the statement of work for every data acquisition of remotely sensed data so that data are delivered in a useful, common form.

Library Services

The National Research Council (NRC, 1999) commented on the deterioration in the cataloguing and loan recovery process since the GCES transition to GCMRC. The status of the library has improved somewhat since that report, but there is still room for improvement. All recent and future reports and data provided to the library should be required to be submitted in both digital and hardcopy formats. The web-based bibliographic search and retrieval system looks very useful and should be carried to completion. The present cataloguing system is awkward and should be replaced with a more widely used and more logical system, such as one of those actually used in U.S. Geological Survey libraries. The current search and retrieval system (OPAC) should be removed as soon as the map-referenced bibliographic engine is working with all the information contained within OPAC. One consideration for the near future is scanning the abstracts of all previous reports and having them, and future digital abstracts, visible through the search engine so users can better determine whether they actually want to check or copy the reference. This proves very useful within the GeoRef™ system that the U.S. Geological Survey uses.

SUMMARY OF REMOTE SENSING RECOMMENDATIONS

This report has reviewed the parameters being measured and the methods currently used to make these measurements within each of the three resource programs, as well as the types of remote-sensing data that are currently being collected and the methods being used to archive all data by the Information Technology program. For each aspect of these programs, alternative methods of data collection and analysis have been discussed where improvements over current technologies appeared possible with respect to remotely sensed data. This section condenses, and in certain cases expands on, the various recommendations made in this report, but does so more in terms of possible integrated remote-sensing approaches.

1. **General comments** - Based on the information presented in this report there is a high likelihood that the collection and analysis of more advanced remotely sensed data can, at a minimum, directly address two recommendations that have been repeated by three recent scientific review panels (Berlin et al., 1998; National Research Council, 1999; Wohl et al., 1999); those recommendations being the need for more integrated studies and the need for more system-wide analyses. This viewpoint is based on several observations: (1) One of strengths of a remote sensing approach is its areal perspective, which, if the data are used correctly, can extend site-specific, *in situ* observations to very large areal extents. (2) Many of the parameters being measured by the resource programs are interrelated spatially and genetically (e.g., the distribution of vegetation habitats and of terrestrial geomorphic units, the occurrence of terrestrial sediment deposits and their stabilizing vegetation, the distribution of aquatic fauna and turbidity); some parameters are actually the same (e.g., turbidity, the distribution of cobble deposits, distribution of certain terrestrial geomorphic landforms). (3) Some of the resource parameters that are being measured have similar physical and/or chemical characteristics, and as such, can be approached using similar remotely sensed data and methods of analysis. (4) Many of the resource parameters being measured in different programs occur within the same environment and, as such, the spectral characteristics are interrelated and need to be approached in an integrated analysis. (5) The remotely sensing image data that have collected to date are quite conventional; relatively crude compared to the current inventory of available sensors (see Appendix). and (6) Many current analyses of collected remotely sensed image data are employing manual techniques on uncalibrated hardcopy products and, for the most part, do not employ spatial GIS technology that is easy to use and so much more powerful than manual techniques. The benefits that can be realized from a more rigorous remote-sensing program include (1) measurements that are more areally extensive and thus more representative by providing a larger statistical sample base, which can translate into better formulation of ecological models; (2) measurements that are more cost effective per unit area; and (3) monitoring that is less invasive of the environment. The recommendations within this report can be placed into two categories, in which alternative remote-sensing technologies can either (1) augment or extend current *in situ* measurements or (2) largely replace current methods of *in situ* measurements.

2. **Current *in situ* measurements that may be augmented or extended by alternative remote-sensing technologies**

a. Water and aquatic foodbase studies - Use ground-based radiometer to monitor relations between radiance and water property, and use observed relation to derive parameters from airborne wide-area coverage. Spatial resolution can probably be less than required for other purposes thus this application will not set the minimum resolution required. One problem here is timing - data are taken in intervals of every few minutes at the gaging stations and to every three months by sample collections, but what is the period of time that seems to be useful? This might be seasonal and high frequency monitoring may only be an issue during high tributary discharge. What could periodically provide areal data - a GCMRC sensor, but they can be expensive if more than 3-4 bands, their spatial accuracy is not great but could be acceptable for water properties. An alternative is to use remote sensing data to determine where water monitoring should be performed during a particular season or year. What has potential for being reliably monitored? Total suspended load, turbidity, chlorophyll (a, b, and total), total dissolved solids (specific conductance), algae, organic matter (vegetation flotsum, surface drift, phytoplankton), and near-surface radiant temperature (esp for Lake Powell and shoreline). Here, the first-order objective of an airborne remote-sensing approach is to extrapolate site-specific data to wide-area coverage of entire reaches or possibly the entire river system. The unknowns are the numbers and wavelength positions of the bands to use in this process. The bands that have been shown useful have been narrower and some at different wavelengths than the bands currently employed by the Chavez radiometers. That "calibration" radiometer should be replaced by a spectroradiometer that records between 0.420 µm and 0.920 µm at ≤10 nm intervals. Pat Chavez has purchased such a spectroradiometer that records between 0.325 µm and 1.075 µm at 3.5 nm wavelength intervals. It is strongly recommended that the applied research of Pat Chavez be expanded from its current turbidity/suspended load aspect to include all of the above water parameters and that he work with the Water Resources personnel that perform the water sampling in order to develop spectral-reflectance approaches that can provide wide-area information on water properties.

b. Aquatic and terrestrial faunal habitat studies - Although there have been instances where very high resolution remotely sensed data have detected the presence of fish schools, it is not recommended that remotely sensed data can used to detect the presence of individual mammals as small as those that are monitored within the Grand Canyon. However, the habitats that fish, birds, snails, and other small mammals tend to prefer can be detected, mapped and used to monitor the presence (or removal) and condition of the different habitats. In the case of fish, these habitat characteristics include the presence of cobbles, underwater (near-shore) vegetation, a foodbase component, and the presence (chub) or absence (trout) of turbid water. In the case of birds, the characteristics include the presence backwaters (for water fowl), tree area and volume, tamarisk area and volume, and new-high-water-zone area. The different Ambersnails also prefer a distinct set of vegetation collections. Although the mere presence of a known habitat does not mean that fauna are present, the annual changes in habitat availability may be correlated with, and used to infer, a fauna's population in any given year. The most suitable remote-sensing data to map these types of habitats is multispectral optical imagery because these data can map most of the listed aquatic and terrestrial characteristics, can be used to estimate and map vegetation height, area, and volume, and can perform these tasks in a fairly autonomous manner. The combination of LIDAR and optical image data would be more accurate than the use either data alone for mapping the terrestrial habitats. However, neither aquatic nor terrestrial habitat mapping would be a separate task for remote sensing analysis because all of the habitat characteristics for the aquatic fauna would be derived remote-sensing analyses for water and aquatic foodbase, channel bathymetric and substrate geomorphologic mapping, and marshes and backwater surveys (each of which are addressed in this summary section). Likewise, the characteristics for the terrestrial fauna would be derived under other remote sensing analyses, such as terrestrial geomorphologic mapping, terrestrial vegetation surveys, and marsh and backwater surveys (also addressed separately in this summary section). Thus, assuming digital maps of these different characteristics are derived from remotely sensed data, it is a very small step to import the map databases and the faunal population data into a GIS system (such as ArcView, Spatial Analyst, or Map Analyst) and to determine dependent variables and correlations, perform change analyses, and examine cause/effect analyses using dam water release records. Timing is an issue - 3-6 times a year, but since this is not detecting fauna not big problem.

c. Historic/prehistoric resource monitoring for mitigation - The types of surface change that may be associated with river-flow or arroyo degradation of the historic/prehistoric resources were listed and discussed in the Remote Sensing Recommendations section for the Cultural Resource program. The best approach to monitor these processes around cultural resources will depend on the dominant type of surface manifestation for these erosional/depositional processes. If the dominant change is physical in nature (e.g., movement of material, change in grain size), then radar image data would better monitor the overall process. C-band radar has a 2.5-cm wavelength, which means it can detect changes in surface roughness at that scale. On the other hand, optical data can detect changes in surface roughness that are near the pixel spatial resolution, which therefore would require extremely high-resolution optical data to detect 2.5-cm roughness. Although the spatial resolution of satellite radar data is only 10 m at best, the data can detect physical or vegetation changes that occupy only a fraction (≤1% of the area) of the pixel. In addition, IFSAR image-pair data can detect vertical changes in a surface of a few mm. At $4,500 per radar image, it would cost $45,000 to cover the Canyon with a single set of radar images. If the more indicative and predictive changes of these processes are chemical and/or mineralogical in nature (e.g., exposure, burial, or transport of chemically or mineralogically different materials), then multispectral image data would be a more appropriate monitoring tool. To adequately monitor such chemical and mineralogical changes would require one or two short-wave infrared wavelength bands, in addition to some visible and near-infrared bands, to detect changes in commonly occurring minerals and iron oxidation. Such image data would have to be acquired with a digital camera system, be calibrated with respect to their recorded radiance values, and preferably be orthorectified on delivery. Spatial resolution of the image data should be on the order of the lateral dimension of the change that needs to be detected. One reason this program protocol is list under the augmentation or extension category is that the surface effects that will probably be examined may have a small lateral extent, possibly less than the positional accuracy that can be achieved using 20-cm resolution image data, which is 50-60 cm. Thus, regional analyses of even orthorectified image data sets may not be possible. If the scale of the changes that are to be examined is as small as 50-60 cm, then the data will have to be locally controlled to surface points that remain fixed throughout the study period. With any approach taken the cause/effect relations should be stored and analyzed within a spatial-data analysis (GIS) environment.

d. Small, non-vegetation cultural resource monitoring - The features considered in this section include the natural springs and mineral deposits (e.g., salt and hematite mines) that have Native-American significance. These features generally occur on the canyon walls; the mines are generally wall adits. The resources are monitored to detect adverse effects due to visitors and river flow. These resources present one of the most difficult tasks for a remote-sensing approach because the features have relatively small areal extent (considering a possible positional accuracy of image data on the order of 50-60 cm or worse) and their adverse effects may be hidden (within adits) or of a similar nature to the resource (in the case of a spring). As stated for the above cultural resource monitoring the most appropriate sensor data for these resources will depend on the nature of the dominant form of disturbance of each resource. Physical effects will be best detected by radar data but spatial resolution and cost are two opposing issues with radar data. Chemical and mineralogical effects can be detected by optical or thermal infrared image data but field spectroradiometer data should be acquired for the effects to determine the number and positions of the most appropriate wavelength bands. If resources are a high priority, then field examination and aerial test would have to be performed to decide on the best approach.

3. **Current *in situ* measurements that may be largely replaced by alternative remote-sensing technologies**.

a. Channel bathymetric and terrestrial topographic mapping - The most effective and straightforward method to obtain both bathymetry and terrestrial topography is using the SHOALS LIDAR instrument. This instrument has now been modified so that it can derive terrestrial elevations using its green laser, which provides continuous topography mapping of the entire ecological system. However, green wavelengths do not penetrate canopies as effectively as do near-infrared wavelengths, but this should be determined with actual data for tamarisk areas that have been topographically mapped. Another disadvantage of SHOALS is that its spot spacing at a 400 m AGL is only 4 m, which is probably too sparse for terrestrial and bathymetric mapping in the Grand Canyon. The AGL can be reduced to increase spot spacing; the cost for a low AGL flight needs to be determined this Spring. The cost is probably less than flying two LIDAR systems, the SHOALS and a normal near-infrared LIDAR. The most appropriate spot spacing for both bathymetry and terrestrial topography needs to be determined. The terrestrial factor will be assessed this Spring using previously acquired coincident topographic data from LIDAR, phtotogrammetry, and land-based surveys for two river reaches in the Grand Canyon. The other options both include optical image data (the dual-band approach and the stereo-pair photogrammtric approach), but these approaches are more indirect, probably less accurate, and more expensive (for photogrammetric approach) than the SHOALS approach. The timing for data acquisition needs to coincide with a period of minimum turbidity and therefore should be in the May-June time frame before the monsoonal season begins. Even under low turbidity conditions there still may be some small areas that have turbidity levels that preclude light penetration to the substrate, but a SHOALS survey can cover 100 miles in 1-2 days versus many weeks by the hydro-acoustic method.

b. Channel geomorphologic mapping - The most efficient and cost-effective method to map the geomorphic units on the channel substrate is the use of multispectral image dat using wavelength bands in the visible region that provide both maximum depth penetration in water and maximum discrimination of various substrate materials. The exact wavelengths for these bands will need to be determined using test data (either existing hyperspectral data or multispectral data acquired during calendar year 2001. Such data cannot distinguish between the very fine-grained substrate units (clay, silt, and sand deposits), but these data can distinguish and map areas of fine sediment, cobbles (and boulders), vegetation, and algal mats. The multispectral image approach will produce less uncertainty in this mapping than the single-band approach; both image approaches can produce higher positional accuracies than that resulting from current side-scan surveys and can map large areas in a shorter time frame than the side-scan approach. Processing calibrated multispectral image data to produce a substrate classification map for 100 river miles would take about a week if the data were already orthorectified, which is a much shorter time frame than that required by the side-scan sonar. There may be areas of turbid waters that would not be classified using a multispectral approach, but if the data were acquired during periods of minimum turbidity (May-June) the proportion of such areas may be small relative to the entire surface area covered by the airborne survey. The spatial resolution of these image data would be the same as that used for the terrestrial mapping (20-30 cm), which is close to the spatial resolution of the panchromatic image data that were acquired during calendar year 2000 under high-gain sensor conditions. Preliminary examination of that panchromatic data suggests that this resolution may be adequate for channel substrate mapping (Pat Chavez, personal communication, 2000), but his will have to be verified by more detailed analysis during calendar year 2001.

c. Terrestrial vegetation and cultural ethnobotanical surveys - The most efficient and cost-effective method for mapping the terrestrial vegetation is the use of multispectral image data that have the appropriate wavelength bands for the vegetation species of interest, are calibrated so that spectral reflectance values within these bands remain consistent over the entire study area, and are orthorectified to automatically obtain reliable estimates of stand area. Field spectroradiometric data have been acquired for all of the vegetation species of concern to the biological resource program during calendar year 2000. These data will soon be examined to determine the positions and number of wavelength bands that are necessary for accurate vegetation mapping. The results will be tested using hyperspectral HYDICE data that were acquired for parts of the Grand Canyon in 1998. Given appropriate multispectral data, a computer algorithm can be constructed that considers spectral reflectance and surface texture to automatically map the vegetation stands much the same way in which manual image interpretations are currently performed, but the computer algorithm will perform the mapping at a fraction of the time and cost of the current manual technique. Normally, unsupervised vegetation classifications produce accuracies near 80%. However, the use of stable “ground truth” vegetation sites within the Canyon can be used to produce accuracies approaching 100%. This approach would better ensure that changes in vegetation spectral signatures with stages of senescence were factored into the classification. The influence of ground reflectance is always an unknown in mapping vegetation, but mixing models using ground truth areas for both vegetation and bare ground can compensate for the contributions of the soil or alluvium in the classification of each pixel. Height estimates of vegetation stands can also be obtained either using LIDAR or the optical image data. The most appropriate LIDAR technology for determining the physical attributes of vegetation is the SLICER system, but its configuration will not produce detailed bare-ground topography, which would then require separate LIDAR surveys for vegetation and bare-ground topography. Normal LIDAR using smaller spot diameters will produce laser first returns which may be sufficient for height and volume estimates, but this needs to be determined using the LIDAR data that was acquired over river reaches during calendar year 2000 where vegetation surveys were conducted. An alternative approach using shadow-height measurements obtained from the optical data might be less accuracy than this latter LIDAR approach, especially under high-sun conditions, but this too needs to be evaluated. Normally, the vegetation surveys are conducted during September, but it would be better for the optical image classification to acquire the image data near Summer solstice to minimize shadowing from steep canyon walls. Some reaches within the Canyon provide very limited daytime viewing in September where there are no shadows cast by the canyon walls. However, if September surveys are necessary the flights can accommodate these narrow flying windows for specific reaches, but if data were also acquired during the Summer solstice for other requirements then acquisition costs would double. Regardless of the exact methods that are used to derive the vegetation classification maps, the derived data should then be permanently stored within a GIS environment for rapid annual analysis and for rapid change-detection analysis.

d. Terrestrial geomorphologic mapping and marsh and backwater surveys - There are several general inherent characteristics of the different types of sand bars, the cobble bars, the debris flows, and the marshes and backwater areas that are used for visual identification of these features . They include surface brightness, surface color (and spectra as a whole in the case of debris flows), texture, density and type of vegetation, elevation (river stage), and presence of water. Geomorphic type of sand bar features are identified on the basis of their spatial relations to the river bank, but this characteristic is contextual, not inherent, and is the most difficult to implement in a computer algorithm, but it can be accomplished given some logic and a map of all of the basic land features or water areas listed above that can be identified by inherent characteristics. All the inherent surface characteristics can be derived from remotely sensed image and LIDAR (topography) data in a simple, direct manner. The type of multispectral data that can detect all of these inherent characteristics is multispectral image data, but LIDAR can provide elevation in a much more straightforward and less-expensive manner. A computer classification algorithm can be constructed, given the appropriate wavelength band data, that could map the distribution of the basic units. Separation of the sand bar unit into its geomorphic categories would then require either manual editing of the classification map or producing a computer algorithm that can simulate a human's contextual reasoning. In either case, the contextual analysis should be performed in a GIS environment. Such an autonomous mapping scheme, which would be visually verified, could produce a classification map for a 100 mile segment of the river in less than 3 days using multispectral data with 20-30 cm resolution and LIDAR elevation data. One critical requirement for this process is that the image data be calibrated so that spectral information along the entire corridor is consistent and therefore predictable. Such calibrated, multispectral sensors exist (see Appendix). The acquisition of the image data should be near the Summer solstice in order to minimize shadows.

e. Camping beaches and camp site monitoring - The primary attributes of camping beaches (and their associated camp sites) that are surveyed are the surface area (and possibly height and volume) of shoreline sand deposits that are available for camping and the degree of vegetation encroachment on the potential camping beaches. Both of these attributes can be automatically mapped system-wide using either radar or optical image data. Both types of remotely sensed data can detect the water's edge, the presence of fine-grained, smooth sand deposits, and the presence of vegetation. The highest resolution satellite radar data have only 10 m spatial resolution, and higher resolution aerial radar data are much more expensive than the satellite data and are acquired using DC-8 jet aircraft that acquires 5-m resolution data at a flight elevation of 8,000 feet (which may present an airspace problem). However, it does not require very sophisticated optical data to map the presence of camping beaches and the encroachment or presence of vegetation. This can be accomplished using color-infrared image data, but automated regional analysis for the above attributes will require calibrated, digital CIR image data that are orthorectified. These requirements are also reiterated for every other program recommendation made in this section. The near-infrared wavelength band will be sued to detect the water's edge; the combination of brightness (albedo), three-band spectral signature, and texture (which is automatically determined with spatial filters) for a surface pixel will uniquely identify a bare sand surface; and the near-infrared/red or near-infrared/green band ratio for a pixel will uniquely identify the presence of vegetation. A application of a computer algorithm to look for these criteria and classify a surface pixel as bare sand, vegetated, or water will be extremely rapid, especially if the outer areal limits for operation of the classifier are established as a system-wide polygon, which is simple to establish. The areas of each unit's polygons can then be determined within minutes using simple commercial GIS software. If LIDAR data are also acquired for the same region of analysis, height and volume of camping beaches and camp sites can also be derived within minutes. Having these basic databases (classification map and topography) within annual databases will provide total flexibility in terms of the type of analysis and of the specifications desired for each parameter in an analysis.

4. **Information Technology services**

a. <u>Remote-sensing services</u> - There are several issues that need to be addressed with respect to the acquisition of remotely sensed data regardless of the application. The following lists and then discusses these main issues.

1. Contracting practices - the need for improvements.
2. General rules for image and LIDAR data acquisition - regardless of the specific objectives for the data.
3. LIDAR bathymetric and topographic mapping - capabilities and vegetation vs bare ground problem.
4. Timing and frequency of data collection - optimal conditions for most applications.
5. Spatial resolution and accuracy of data collection.
6. Number and wavelengths of image bands.
7. System-wide image mosaicing - consistency of surface reflectance under different solar conditions.

1. *Contracting practices* - Better contracting practices are needed in order to overcome two problems that have been encountered in all seven commercial flights that have occurred during calendar year 2000. First, only one contractor paid enough attention to the details within the statement of work to ask for clarifications. All other contractors either overlooked or misinterpreted various specifications. Because the contract officers did not understand the basis for the specifications in the statement of work, they were more detrimental than helpful in the execution phase of some projects. Second, no contractor carefully read the data standards completely and therefore all initial deliverables did not meet data standards. This problem resulted in increased data quality control and contractor interaction by GCMRC personnel and in extensions of final delivery dates by at least 30%. These problems can hopefully be largely overcome by two steps. Step 1 entails working closely with contract officers so that they understand the significance of the specifications, which should result in a statement of work and description of deliverables that clearly describe full performance and can be enforced if necessary. Step 2 should be initiated immediately after the award of a contract and consists of a face-to-face meeting of GCMRC staff and the contractor in which all requirements, expectations, and data standards are reviewed line by line.

2. *General rules for image and LIDAR data acquisition* - General specifications for future data acquisitions can be made at this time, regardless of the instrument that collects the data. They are as follows:

a. All data need to be acquired, and of course delivered, in digital form and preferably using a large format (4096x4096 or larger), charge-coupled devices (CCD). Line scanner systems cannot acquire stereo imagery and present more data processing issues than CDD-array data. The larger format provides better x, y, and z accuracies and involves fewer images to cover an area and thus less effort in the creation of a mosaic than smaller format cameras.

b. All acquisition systems need to use GPS and IMU instrumentation that can meet the accuracy standards for horizontal and vertical data in order to overcome the limitations of gyro-stabilized platforms during turbulent air conditions.

c. All imaging systems used by GCMRC need to be radiometrically calibrated such that data within each image frame are consistent in terms of their radiance values. Evidence of the calibration, as well as their methods for applying the calibration, should be provided by all RFP responders.

d. Image data should be delivered as orthorectified final products, which allows immediate access to the data, more reliable analyses of the data, and less annual expense for individual resource programs.

e. Topographic point data produced by a LIDAR system should be delivered as processed LIDAR points with appropriate breaklines. Processing such point data further to produce a TIN or DEM is elementary and should not require contractor fees, although the contractor will need to produce a TIN to determine the need for and locations of breaklines. This statement especially pertains to the generation of contour lines, which are more esthetic than useful for analysis of resource protocols.

A side issue that is related to image data is the historical aerial photography. There are several reasons to proceed with conversion of this library to digital format: (1) to make the data readily available for use and to allow more extensive use of the data, (2) to reduce the annual cost to resource programs associated with cooperators digitally scanning the data for their research, and (3) to store the data on reliable media for data preservation. This process can be phased over a period of years and can be driven, and partly funded, by the immediate needs of the resource programs. The funds that would be provided to a research effort that entailed digital conversion of photographs during any given year could instead be directed to IT, who would scan an entire annual set of photographs instead of just a selection. Regardless of the final decision on this recommendation, the camera characteristics (calibration) for each year's data acquisition need to be obtained from Horizons Corporation and stored before it is lost. The camera calibration is necessary for removal of geometric distortions and for photogrammetric analysis of the data. If scanning is pursued, it is recommended that the process be coordinated with the Astrogeology Group (U.S. Geological Survey, Flagstaff) who is considering the procurement and operation of an appropriate scanner and who would therefore incur the initial costs of the equipment and its calibration.

3. *LIDAR bathymetric and topographic mapping* - There are three uncertainties that need to be addressed with respect to the potential use of LIDAR for bathymetry and topography. First, a method needs to be devised that can unambiguously determine whether a LIDAR last return hits vegetation or bare ground. There are two possible approaches: one approach uses the power return or full power spectrum of the LIDAR return, while the other approach uses vegetation signatures in image data. These approaches need to be evaluated. Second, an assessment of LIDAR-derived and land-surveyed topography needs to be made to determine if LIDAR can provide an acceptable level of accuracy in wide-area, sediment-volume measurements even though the LIDAR data may miss some understory undulations on sand bars. This assessment will be made during the first half of calendar year 2001 using LIDAR, photogrammetric, and land-surveyed topographic databases that were acquired in September, 2000 for selected vegetated sand bars. Third, an assessment is needed of the accuracy of a green-wavelength LIDAR system for obtaining bathymetry data within the Colorado River and for obtaining topographic data for vegetated sand bars. With respect to bathymetry, the primary issues that need to be addressed are (1) the water conditions under which reliable bathymetry data can be obtained and (2) the spot spacing required to meet GCMRC resource objectives. With respect to terrestrial topography, the only issue is the level of performance of a green-wavelength laser versus a near-infrared-wavelength laser for vegetated terrain. The first and third LIDAR uncertainties can be addressed by carefully structuring the remote-sensing flights for calendar year 2001.

4. *Timing and frequency of data collection* - Two issues related to the timing of image data acquisition include the time of year that data should be acquired and the frequency of data acquisition within a year and between years. The optimum time of year to acquire optical image data is either (1) near the Summer solstice when the Sun is high and therefore minimal shadows and when turbidity levels are the

lowest, or (2) during a period of total overcast when shadows are practically non-existent. The latter conditions were used by necessity during the September 6, 2000 spike flow and the resulting CIR image data are of higher quality in terms of surface contrast and absence of shadows than CIR image data acquired during clear, high solar-elevation conditions. Relying on total overcast conditions for extensive (week long) data collections has a much higher risk than relying on a period of clear sky conditions in northern Arizona. Cloud cover even during the monsoonal period is very transient and scattered. Considering both the aquatic and terrestrial resource objectives, image data acquisitions would be better performed around the Summer solstice when the river is less turbid in order to map both the channel substrate and the terrestrial resources. This also applies to LIDAR bathymetric surveys. A Summer acquisition may not be optimum for certain terrestrial vegetation species that come to full bloom later in the year, but the presence of those vegetation species may still be detected in image data during the Summer months. The biological resource program currently has the highest frequency of data measurements within GCMRC with sample intervals ranging from hours to months for various water parameters because the characteristics of the water, as well as sediment distribution on the channel substrate, can change within short time periods. Monitoring the aquatic environment, even on a monthly basis, using commercial services would greatly exceed the total IT budget due to commercial mobilization costs as well as data acquisition costs. An alternative approach for the aquatic ecosystem is the procurement of an imaging systems that is flown locally on an as needed basis. Several U.S. companies produce CCD detector systems (e.g., SensyTech [was Daedalus], DuncanTech, Geophysical Environmental Research Corporation) with a range of capabilities and costs. However, more research needs to be conducted to determine the number and wavelengths of bands and the procedures that can produce reliable resource data (i.e., proof of concept) before procurement of a sensor should be seriously considered. Also, technology is advanced quickly; better and less expensive instruments will follow. As an example, DuncanTech recently received a grant from the Stennis Space Flight Center to develop an advanced multispectral imaging system for marine and coastal remote sensing (www.duncantech.com/NASASBIR). It appears as though the terrestrial resources can be effectively monitored by singular, annual data acquisitions because the vegetation and ground features do not change that much year to year unless there is an anomalously high flow rate. Terrestrial topography can be obtained using LIDAR at almost anytime during the year because LIDAR is an active system (it provides it own illumination). However, it would be less expensive to acquire both bathymetry and topography at the same time, if a green-wavelength LIDAR system can provide both datasets with acceptable accuracies.

5. *Spatial resolution and accuracy of data collection* - The accuracy that can be obtained by image data is determined in part by the spatial resolution of the image data, as stated previously in this report. The smallest physical parameter being monitored by GCMRC is the size composition of aquatic and terrestrial sediments. Discrimination of particles that are in the range of clay through sand sizes is extremely difficult using reflected-optical or emitted-thermal image data because a number of physical, chemical, and mineralogical factors combine to produce an energy signal from a surface, some of which counteract the effects of other factors. Excluding fine-grained sediment from consideration, the next largest feature measured by GCMRC consists of individual bushes (≥ 0.5-m in diameter) or cobble-sized (7-26 cm) particles. One of the smallest scale measurements made by the biological resource program is the volume of vegetation using a sampling diameter of 20 cm. A terrestrial biologist that maps the vegetation within the Grand Canyon believes that a spatial resolution of 10-15 cm would be adequate for vegetation surveys (Mike Kearsley, personal communication, 2000). This resolution is close to the mean diameter (16 cm) defined for cobbles. A recent field investigation was conducted in the Lee's Ferry reach to evaluate the use of CIR orthophoto images for locating and detecting individual bushes. The investigation found that individual bushes could easily be detected, located, and mapped using the 25-cm resolution of the CIR imagery. Cobble bars could also be detected because the average diameter of the cobbles was within the upper size range for cobble particles. Thus, a conservative estimate of the spatial resolution for GCMRC resource requirements would be 15-20 cm (three to four times lower resolution than previously acquired). Recent image data of the channel substrate that was acquired under high-gain sensor conditions at 18-cm resolution showed obvious textural differences among channel substrate units, even though the resolution was somewhat degraded by normal refraction in the water. A spatial resolution of 15-20 cm results in a

positional accuracy of about 39-50 cm, which is close to the positional accuracies of the better controlled resource surveys. Although this accuracy is an order of magnitude lower than that provided by the terrestrial sediment surveys, the 3-cm accuracy in location that is reported for those surveys is not required for area and volume measurements which have 2-3% error levels. This recommended spatial resolution and positional accuracy may be further relaxed in the future after more detailed analysis of data acquired at this new spatial resolution.

In terms of LIDAR resolution, there is not yet a good understanding of the accuracies of area and volume calculations associated with different LIDAR spot spacings, especially for vegetated terrain. The LIDAR simulation data presented in the physical resources section (Figure 1-3) provides some guidance. That analysis suggests that a small error (3%) in volume estimate can be achieved using a LIDAR spot spacing that is equal to the wavelength of the smallest mappable terrain undulation in areas of relatively moderate relief that have no vegetation. [The more topographically subdued a region is, the larger the LIDAR spot spacing can be and still achieve a 97% accuracy in volume estimate.] For example, if volume estimates are based on a DEM that is generated from a topographic map with a 0.25-m contour interval, then the smallest undulation that can be represented by the map would have a wavelength (basal width) of 0.5 m. Application of the "theoretical" rule derived from the simulation data would therefore suggest that LIDAR could capture about 97% of the topographic data represented by that topographic map using a spot spacing of 0.5 m. This "theoretical" rule is more stringent than the "rule of thumb" that is employed by all commercial LIDAR companies, which states that an average LIDAR spot spacing equal to four times a desired map contour interval will produce that contour map with the accuracy dictated by national map accuracy standards. The issue of LIDAR resolution needs to be addressed using data collected over vegetated sand bars in the Grand Canyon. Such data now exists for several reaches at a spot spacing of 0.5 meters; these data will soon be carefully compared with other topographic data produced by land surveys and photogrammetry, but a conclusive recommendation may require higher resolution LIDAR data if the existing data produce ambiguous results. An evaluation of LIDAR bathymetry should also be performed during calendar year 2001 in order to determine LIDAR's potential (and limitations) for both the Aquatic and terrestrial environments. The positional accuracy of the LIDAR data should be no worse than that for the image data; most LIDAR systems provide 15-30 cm positional accuracies. In term of the vertical accuracy of LIDAR, most LIDAR systems can obtain 15 cm accuracies, but this is far below the levels of annual change in height (a few cm) that is observed on terrestrial sand bars. However, local adjustments of the LIDAR elevations could be made for sand bars using the stable topographic areas that occur further up slope within or above the Old High Water Zone.

6. *Number and wavelengths of image bands* - Previous remote-sensing research has indicated a range of wavelength bands and different numbers of the bands as possible approaches to ecological monitoring of aquatic and terrestrial environments. Many of the more recent approaches have used high spectral resolution data in the hope that more complex analysis of such data will increase capability, accuracy, or both. As yet, there is no a clear indication from the published results that the full range of bands used is warranted for monitoring. As the remote-sensing PEP stated in their review, there is a difference between remote sensing for research and remote sensing for monitoring (Berlin et al., 1998). At this point, GCMRC is performing mostly remote sensing for monitoring, but possibly not monitoring most effectively or efficiently. In order to achieve a higher level of effectiveness and efficiency, it is necessary to perform some remote sensing for research and some of the remote-sensing issues above recommend that. One of the more important issues that needs to be addressed for more efficient and cost-effective remote sensing is type of image data that needs to be acquired. This issue needs to be addressed through a process of testing and verification using complex data that can be spectrally degraded and dissected to produce lower order image data for wide-area testing for each resource parameter (a similar approach to that suggested for the water parameters using a high spectral resolution spectroradiometer). For the terrestrial resource parameters, this approach will be applied to hyperspectral (HYDICE, and possibly AVIRIS) data during 2001 to determine a minimum configuration of bands that can accurately map these resources . A similar approach needs to be applied using appropriate test data for the aquatic environment, which is best approached by Pat Chavez. The decision on these issues should be based on a cost-benefit analysis, where

benefit consists of increased capability in terms of the areal coverage and/or the new and useful parameters that can be measured at an acceptable level of accuracy. For example, if it is determined that the number bands necessary to accomplish most resource needs is such that only scanner systems can acquire these data, the cost of data processing will increase. Scanner systems use a rotating mirror that collects all the band data for each ground pixel as the mirror scans the terrain. Thus, the view angle of each pixel is different and that difference must be corrected in order to produce a consistent set of pixel radiance values across the entire line of image data. A scanner system cannot collect stereo imagery, which may not be a large sacrifice if LIDAR topography is also acquired. At this time a preliminary configuration of a multispectral sensor system would include a blue- and a green-wavelength band with high gain to provide maximum water penetration, a few other visible and near-infrared bands for water parameters and for terrestrial vegetation, and possibly one or two short-wave infrared bands, which together with the visible and near-infrared bands, would provide good discrimination of various terrestrial inorganic materials and might also enhance vegetation discrimination. The inclusion of short-wave infrared bands would, however, require separate detector for that wavelength region and that might increase the cost of data acquisition.

7. *System-wide image mosaicing* - One of the largest hurdles to overcome in producing a system-wide, calibrated digital orthophoto mosaic of the Canyon is compensating for the variations in phase angle that results from variations in the solar elevation angle during a system-wide data acquisition. This is particularly critical if system-wide, computer analysis of the data is a desired goal. This has not been a problem for satellite image data because most satellite systems have sun-synchronous orbits, which results in images taken at the same local time and thus same solar-elevation angle (and therefore same phase angle which is the angle between the Sun and the sensor). However, even with a constant phase angle dramatic changes in topography produce different surface reflectance values for the same surface material, because local phase angle is affected by local slope (which is one reason why aerial photographs display opposing dark and bright sidewalls in the Canyon). In order to produce consistent surface reflectance values for all pixels within an image of rugged terrain most scientists have used a surface photometric function and a DEM to produce "normal albedo" images; normal albedo is the reflectance along the surface normal vector of a pixel (Kowalik et al., 1982; Teillet et al., 1982; Civco, 1989; Duguay and LeDrew, 1992; Kennedy et al., 1997). Most of these approaches are theoretically based, but some are empirical and may not be applicable to different terrain or changing solar conditions. These approaches are applied on a pixel-by-pixel basis, which requires large computation times. Dozier and Frew (1990) proposed a method of approximation and look-up tables that significantly reduces that time. Gu et al. (1999) and Gu and Gillespie (1999) found that such single pixel solutions produces local anomalies. They developed a method that considers the neighborhood of a pixel (the contextual information) in its solution, which results in better solutions for the image as a whole. Although all of these approaches were designed to normalize the effects of topography, the same approaches can be applied to a set of image data with varying solar elevation angle because the real issue is changing phase angle in either case. However, in order to normalize the sun elevation angle most effectively will require a DEM for the area under consideration. The most promising of these approaches should be tested on Grand Canyon data as soon as a DEM and digital imagery of the same area that were acquired with different solar elevations are available.

b. Geographic Information Systems - The most critical tasks for GIS services are the organization of existing databases on a central server, and the implementation of the database access, archive, and retrieval system. Appropriate software has been ordered for the last critical task. It is the same software used by EROS Data Center to construct their National Atlas™ archive. That EROS archive appears to have all the capabilities needed for GCMRC. An attempt should be made to acquire the software code from EROS. If possible, the code could be modified for specific GCMRC needs and appearances and be operational in a short time frame.

c. Database Management Services - Entry of field data into the Oracle database needs to proceed without hesitation because of the large size of the task. In addition, in order to make this task manageable within a few years, all future field data should be recorded digitally in the field, or at least provided digitally to the DBMS manager in digital form. The technology for field recording now exists in the form of palm-sized computers.

d. Surveying services - The GPS data that is acquired and stored for all ground surveys should be stored within the GCMRC archive just referenced to the map datum, not the geoid, especially not the 1990 geiod that is currently used. The National Geodetic Survey updates their geoid periodically and it would be better to reference all integrated *in situ* and remote-sensing data analyses to the same geoid at the time of analysis. This would require some effort to convert present databases to a map datum and to store the resulting data in a format that allows easy conversion to a reference geoid, but this would also make data analyses more accurate. In addition, a system-wide control network of physically fixed points are needed for a few reasons. First, there is a wide range in the accuracies that commercial remote-sensing firms can provide using just airborne GPS and IMU information. The network would allow adjustments to be made to these data before final delivery. Second, the network would allow accuracy assessments to be made of commercial products throughout the Canyon. Currently, such an assessment is limited to the Lee's Ferry area. Third, the control network would provide absolute positional information to studies that may need to locally control wide-area data in order to monitor very small resources. Fourth, the network would provide valuable control for historical data, which were not acquired with airborne GPS and IMU instrumentation.

e. Library - Regardless of the cataloguing system used by GCMRC, it would be extremely useful to have a web-based search engine like the prototype on the GCMRC web site for the library. It would also be good to have the abstracts of GCMRC reports on-line in that engine so that the searcher could better determine the content of a holding, thus it would be useful if all reports submitted to the GCRMC library be required to also submit a digital version of the abstract. In addition, all permanent media (CD or DVD) containing scanned photographic film produced by GCMRC or containing data that are delivered by future contractors should be copied and the copies should be stored in a fireproof container that are only accessed if the shelf copy is destroyed or lost. This second stored copy of the archive is referred to as the deep archive in many government facilities.

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FIGURES

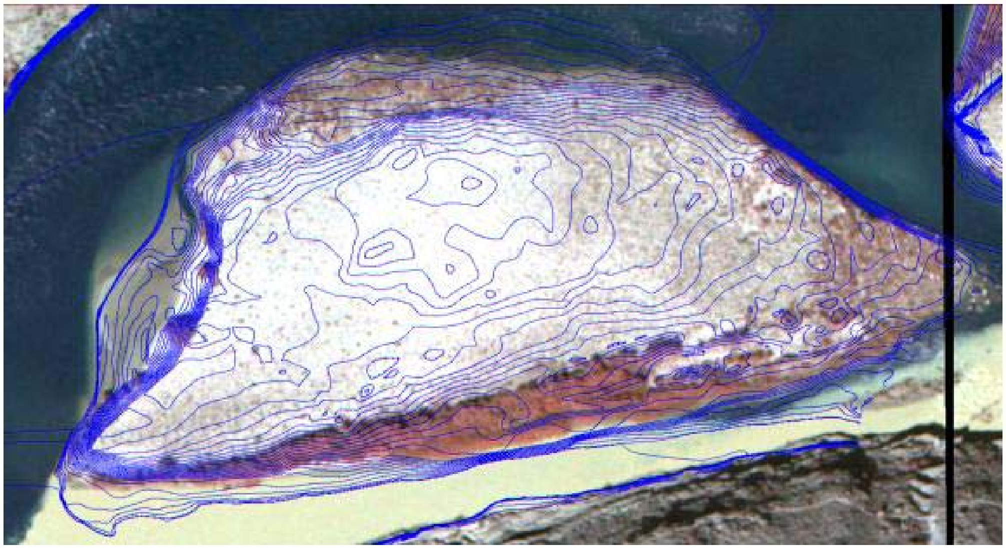


Figure 1. Photogrammetrically derived topographic contour data for the sand bar at the Little Colorado River confluence. Data derived from aerial photography acquired September 4, 2000 at a flow rate of 8,000 cfs. Contour interval is 0.25 meters. Contours have been overlain on a color-infrared orthophoto image.

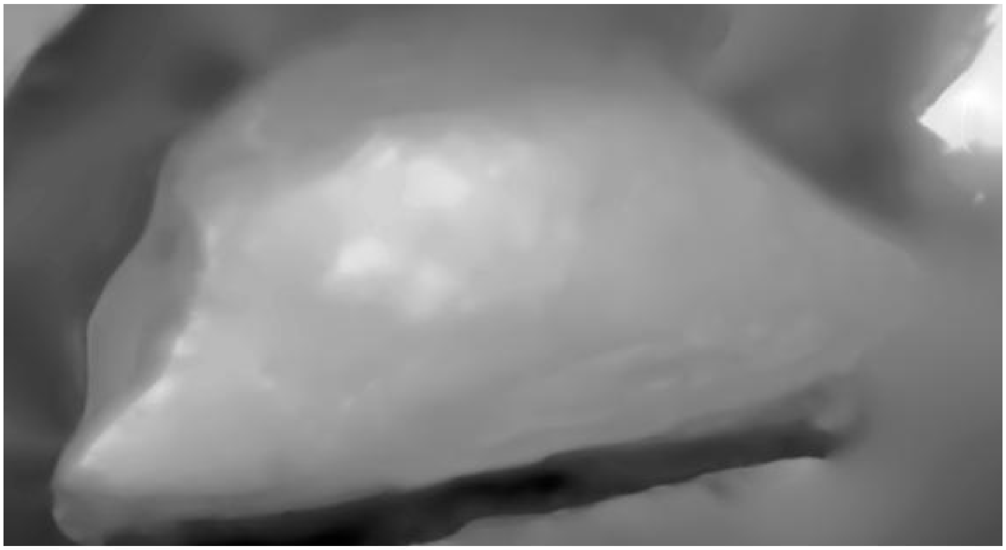


Figure 2. Digital elevation model (DEM) generated from the photogrammetric contour data shown in Figure 1. The contour data were sampled (interpolated) at a 0.3 meter interval to produce the DEM.

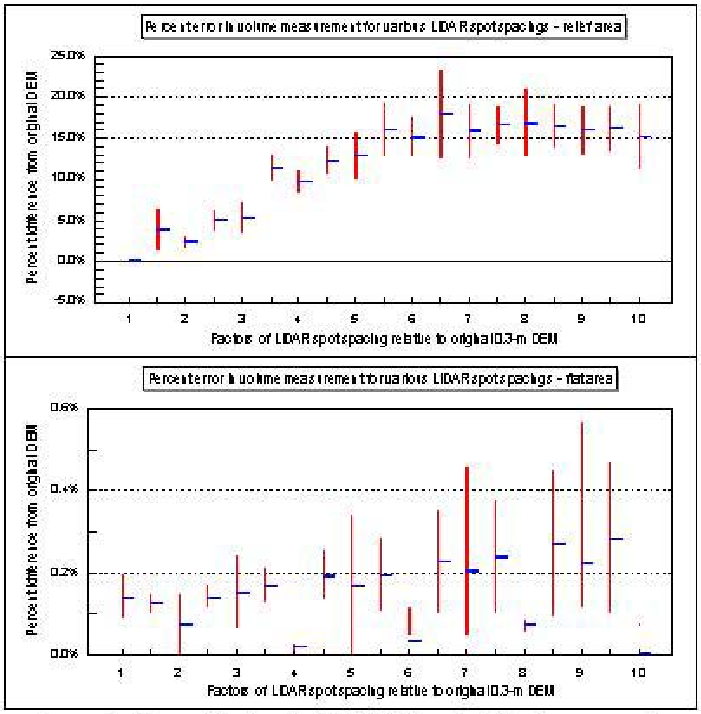


Figure 3. Comparison of errors in volume estimates using LIDAR data with different average spot spacings. The spot-spacing values are factors of the original 0.3-m spacing of the DEM database. The "flat area" (bottom graph) is for the sand bar pictured in Figure 2; the "relief area" (top graph) is for the west-bank riparian area just west of the "flat area." Blue dash and red line represent the average and standard deviation, respectively, of 10 different flight orientations for each LIDAR spot spacing.

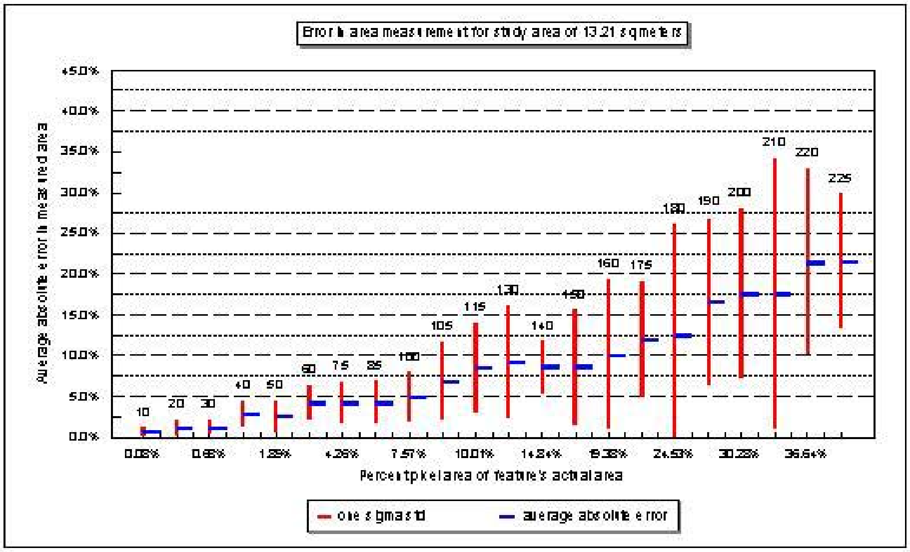


Figure 4. Calculated average error in accuracy in land area measurements using hypothetical digital image data with different pixel sizes. Pixel sizes are expressed as percent pixel area (x axis) of the land feature's actual area and as absolute dimension (indicated in centimeters above each data point).

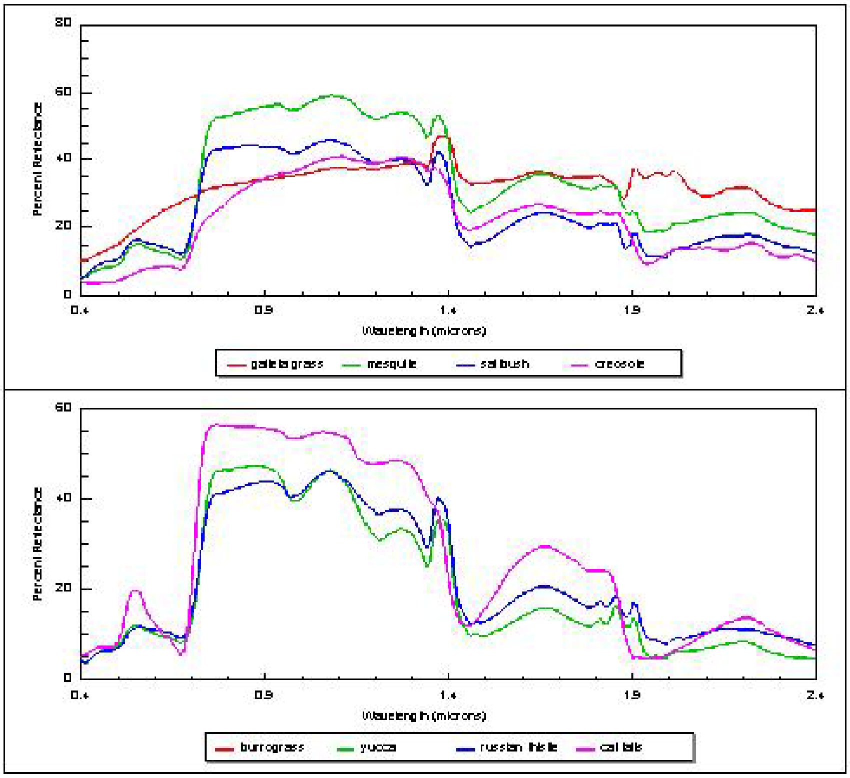
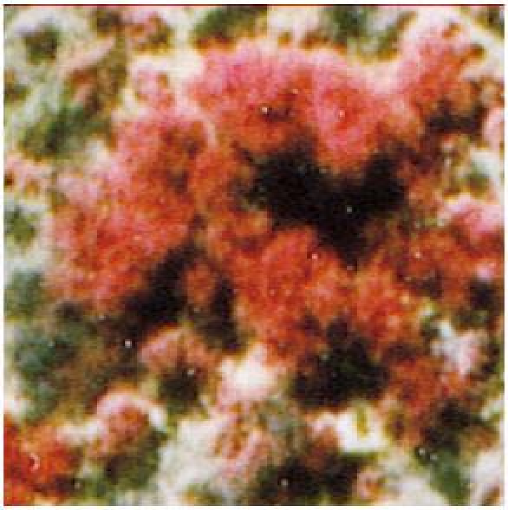


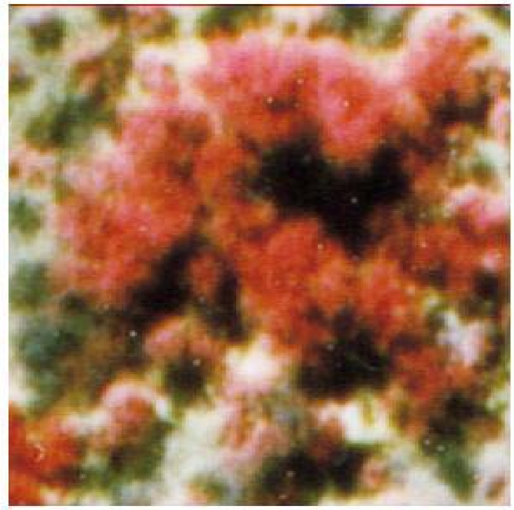
Figure 5. Spectral reflectance curves for vegetation common to the southwestern U.S. The range in wavelength covers that of most commercial remote sensors; only hyperspectral sensors provide the fine spectral resolution shown by these curves.

Figure 6. Portion of a digitally scanned CIR photograph, acquired under overcast conditions, whose three color bands have been linearly stretched by 1% on both ends of their 8-bit range. CIR is especially useful for discriminating vegetation, as Figure 7 shows.

Figure 7. Color coded map of the Normalized Difference Vegetation Index (NDVI) that was generated from the red and near-IR wavelength data provided by the CIR image in Figure 6. Ranges of the resulting index values were color coded to show vegetation (greens, blues, and yellow) and alluvium and water (white, orange).



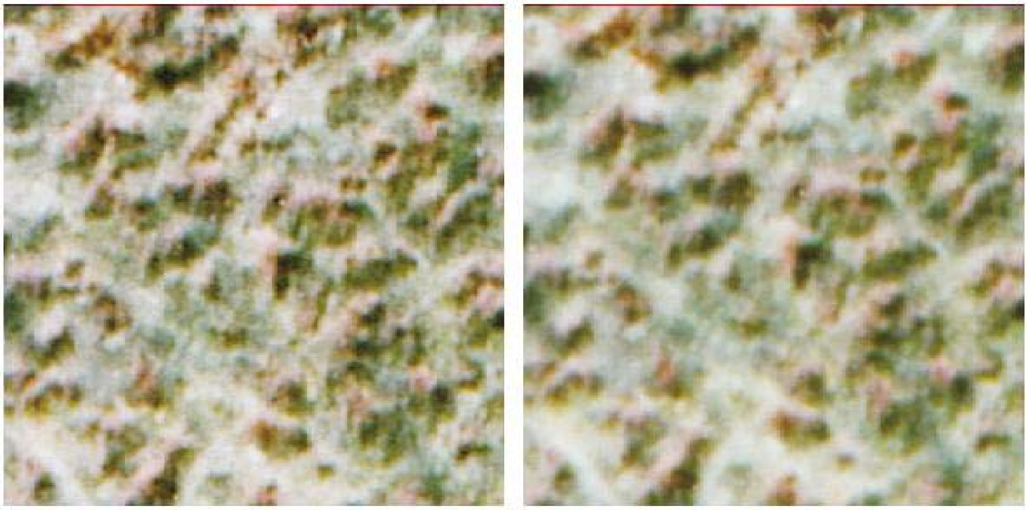
2500 dpi (10 micron) scan of vegetation



1250 dpi (20 micron) scan of vegetation

Scale: width and height of images are 19.5 meters

Figure 8. Comparison of a vegetated area on an aerial photograph (1:4800 scale) that has been digitally scanned at 2500 dpi and 1250 dpi. The 2500 dpi image preserves the full 5.8 cm resolution of the aerial photograph.



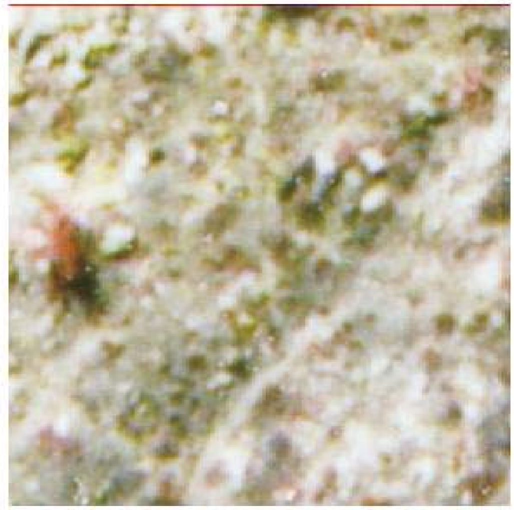
2500 dpi (10 micron) scan of rocky area with scattered grasses

1250 dpi (20 micron) scan of rocky area with scattered grasses

Scale: width and height of images are 19.5 meters

Figure 9. Comparison of a grassy cobble area on an aerial photograph (1:4800 scale) that has been digitally scanned at 2500 dpi and 1250 dpi. The 2500 dpi image preserves the full 5.8 cm resolution of the aerial photograph.

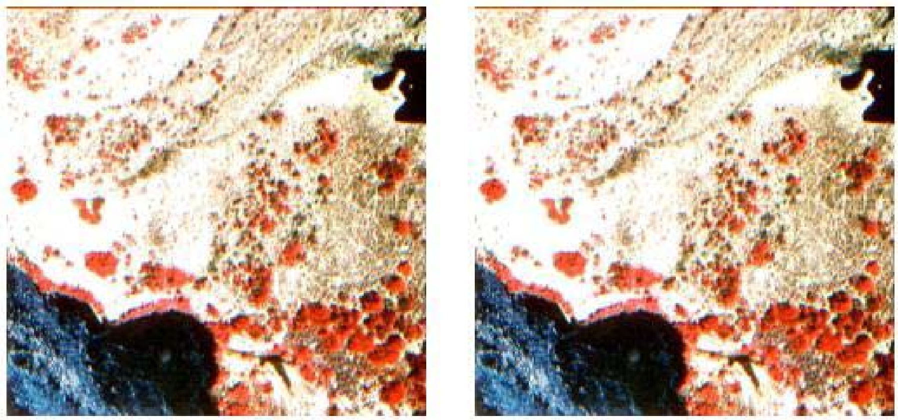
2500 dpi (10 micron) scan of talus with little vegetation



1250 dpi (20 micron) scan of talus with little vegetation

Scale: width and height of images are 19.5 meters

Figure 10. Comparison of a very sparsely vegetated talus area on an aerial photograph (1:4800 scale) that has been digitally scanned at 2500 dpi and 1250 dpi. The 2500 dpi image preserves the full 5.8 cm resolution of the aerial photograph.



Non-compressed digital CIR image

Restored digital CIR image after 100x compression by MRSID.

Figure 11. Comparison of an original digitally scanned aerial photograph with that same digital photograph that had been compressed by a factor of 100 and then uncompressed.

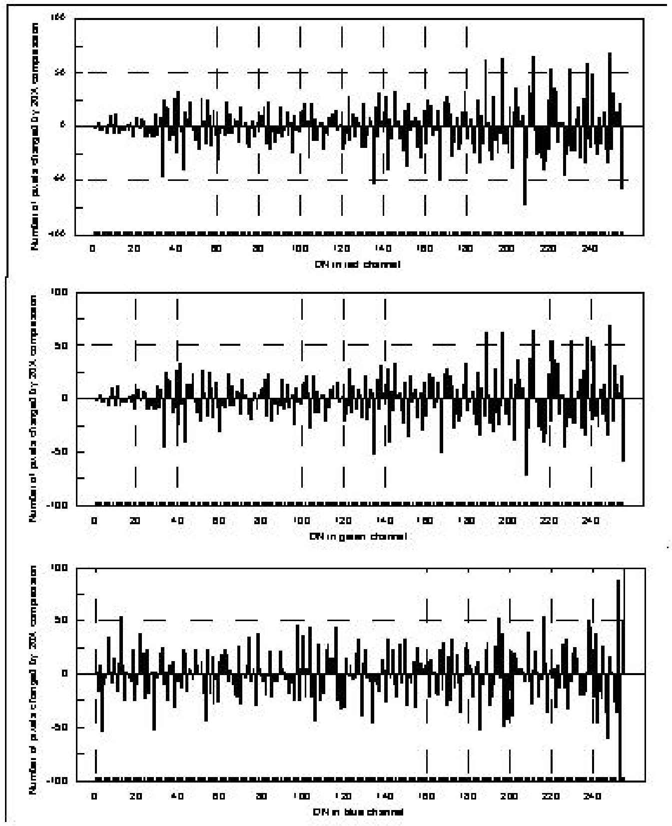


Figure 12a. Plots showing the number of pixels that changed for each amount of digital number (DN) change between the original CIR red, green, and blue bands and the compressed (20x) MRSID red, green, and blue bands.

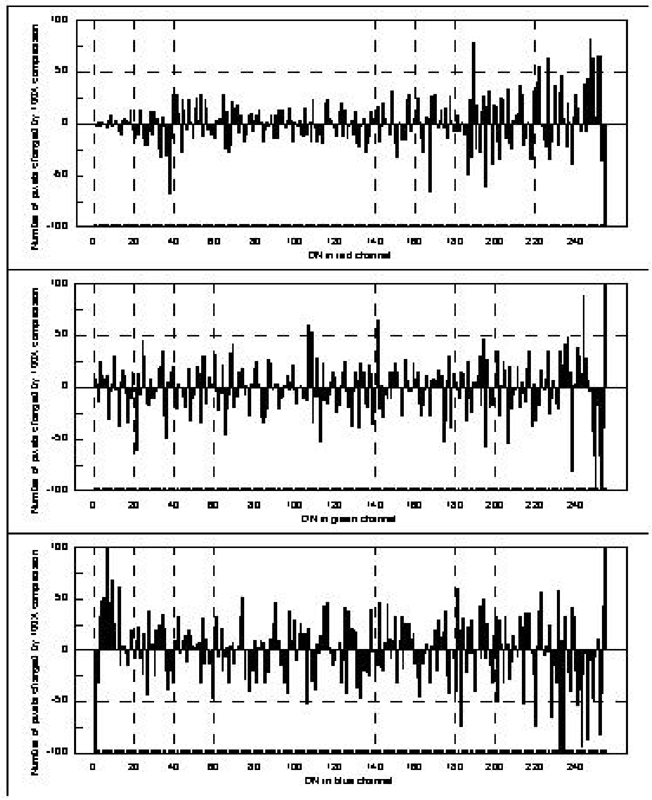
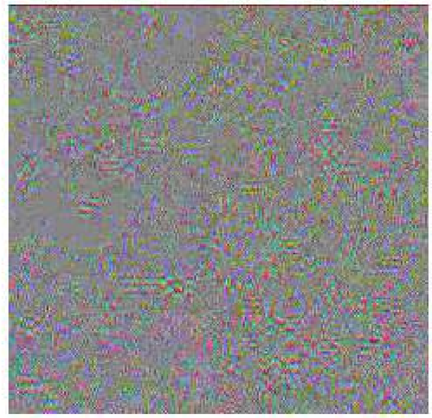


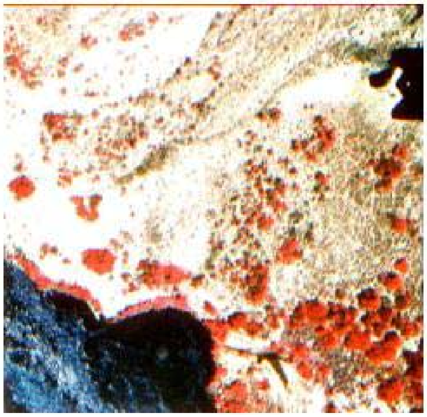
Figure 12b. Plots showing the number of pixels that changed for each amount of digital number (DN) change between the original CIR red, green, and blue bands and the compressed (100x) MRSID red, green, and blue bands.

20x compression - difference image of compressed minus original DN

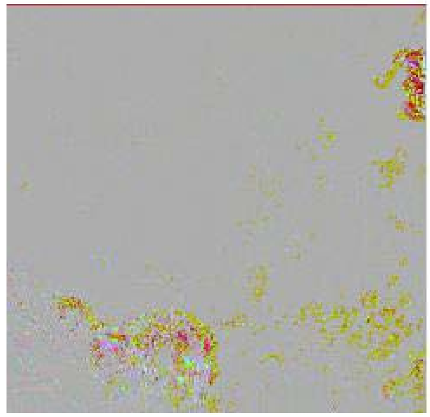


100x compression - difference image of compressed minus original DN

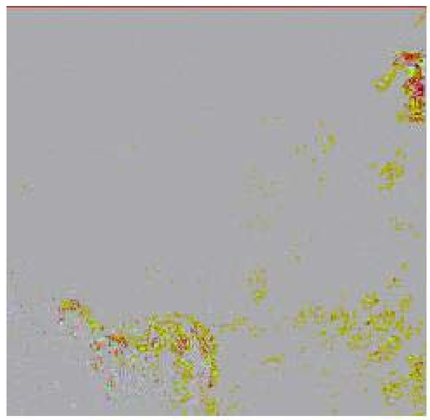
Figure 13. Color composite images of the red, green, and blue DN difference images for a MrSID compression factor of 20 (left-hand image) and 100 (right-hand image). The three color files used to make each color composite was produced by subtracting the compressed DN by the original DN on a pixel-by-pixel basis for each of the red, green, and blue bands.



Non-compressed digital CIR image



Three-color ratio image formed by compositing the quotient files produced by dividing the compressed (100x) DN by the DN of the original image for each color band.



Three-color ratio image formed by compositing the quotient files produced by dividing the compressed (20x) DN by the DN of the original image for each color band.

Figure 14 Color composite images of the red, green, and blue DN ratio images for a MrSID compression factor of 100 (top-right image) and 20 (bottom right image). The three color files used to make each color composite were produced by ratioing the compressed DN by the original DN on a pixel-by-pixel basis for each of the red, green, and blue bands.

APPENDIX: AVAILABLE SENSORS FOR USE

This Appendix lists all the available spaceborne and airborne sensors that can provide visible, near-infrared, short-wave infrared, thermal infrared, microwave (radar), and LIDAR data. The sensors are not limited to the United States, but contracting with foreign companies would be more expensive than domestic companies. The following characteristics for each sensor are provided.

Type of sensor - sensors are divided by the number of bands they provide or by type of data. Optical and thermal infrared sensors are subdivided by the total number of bands that they provide: panchromatic data offers a single band, multispectral data ranges from 3 to 30 bands, hyperspectral data ranges from 31 to 100 bands: and ultraspectral provides more than 100 bands. Radar (microwave) and LIDAR are separate categories because they are based on different physics principles.

Name of sensor - both the acronym and the full name are provided.

Resolution - This is the ground spatial resolution provided by the sensor. In some cases both milliradians and spatial dimension are provided. Milliradian is the optics viewing angle and can be roughly converted to distance for a particular flight height by the equation: ground resolution = radians x flight height ÷ 3.25.

Bands - This shows the number of bands within each wavelength region covered by the sensor and the width of each band within that wavelength region.

Airborne or spaceborne - self explanatory.

Repeat cycle - Indicates the number of days between image acquisition of the same spot on Earth. This is only relevant to spaceborne sensors.

Image x dimension - This is the across-track dimension of the image in either number of pixels or in kilometers. If value is given in pixels, the dimension in kilometers can be derived by multiplying the spatial resolution of the sensor by the number of pixels.

Image y dimension - This is the along-track dimension of the image in either number of pixels or in kilometers. If value is given in pixels, the dimension in kilometers can be derived by multiplying the spatial resolution of the sensor by the number of pixels.

Bit per value - This is number of bits that each pixel's radiance is recorded. An 8-bit number range is 0-255; a 16 - bit number range is 0-32,767. The higher the bit size, the more detailed the recording of the surface signal.

Stereo or interferometric capability - This indicates whether an optical or thermal-infrared sensor system is capable of acquiring stereo image pairs or a radar system is capable of acquiring interferometric image pairs.

Contractor - Indicates the government or commercial operator of the instrument. In some cases there can be more than one contractor that operates a sensor, but only the major contractor is listed.