Practical Paper

Image Enhancement of Landsat Thematic Mapper Data and GIS Data Integration for Evaluation of Resource Characteristics

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ABSTRACT: Landsat Thematic Mapper (TM) digital data have been enhanced to provide an understanding of the hydrological character of water bodies, stream channels, and glacial ice within Glacier National Park, Montana. A USGS digital elevation model (DEM) was processed to further augment the hydrological database for the park. The enhanced TM and DEM data were merged within a geographic information system (GIS) framework to facilitate their comparison and utility as hydrologic thematic overlays. The approach of integrating enhanced digital satellite data and DEM data in a GIS framework proved to be valuable in understanding the hydrologic processes in complex and rugged topography.

INTRODUCTION

THE GEOMORPHIC NATURE of Glacier National Park has been strongly affected by the hydrologic processes observable in the present and evident in the past. Snow, ice, and flowing water have sculptured a landscape of tremendous variability. The interrelationships of geology, soils, climate, vegetation, geomorphology, and hydrology form an earth-science system of significant complexity that requires an integrated spatial investigation of both natural and anthropogenic features. The necessity for the spatial integration of biophysical factors in the analysis, and the difficulties of field efforts in such a formidable environment, create an opportunity to evaluate the capabilities of the combined remote sensing and GIS approach.

Traditionally, the link between remotely sensed data and GIS has been perceived as unidirectional, with remote sensing data being used as an input into the GIS. The use of GIS thematic overlays as an aid in the interpretation of remotely sensed data is not widely utilized, though its application has great potential. Geographic data, represented in the form of maps or digital files, can serve as baseline measures of phenomena from both a spatial and landscape-attribute perspective. With this approach in mind, remotely sensed data were employed in order to detect changes within the study area and to validate enhancements of landscape elements. DEMs were used to evaluate topographic conditions that favored or limited the recognition of hydrologic elements through TM digital enhancements.

BACKGROUND

Digital elevation models have become an important source of ancillary information for integrating processed satellite data and for integration within an enhancement and/or classification process. Goodenough (1988) integrated GIS and remotely sensed data for various resource management scenarios. He reported that such a technique can be used to guide the selection of classification training areas, and to update databases for the assessment of spatial and temporally dynamic phenomena. Transformations (format, scale, and projection, etc.) of data contained within a GIS database can introduce data quality and accuracy considerations to confront and solve prior to the data integration and analysis process.

The topographic influence on spectral responses in satellite data has been well documented (Hoben and Justice, 1980; Justice *et al.*, 1981; Karaska *et al.*, 1986; Walsh, 1987). Cibula and Nyquist (1987) have recently demonstrated the utility of incorporating DEMs and climate models in digital classifications of land cover employing GIS technology. Another application is to use DEMs to stratify the landscape prior to the classification of land cover, and to merge DEM derivatives such as slope angle, slope aspect, and elevation together with the classification. A unique spectral and spatial pattern of phenomena correspond to unique landscape attributes. Hence, a blending of spectral enhancements and terrain "enhancements," achieved through the processing of remotely sensed and digital terrain information, respectively, can yield a description of landscape units difficult to achieve through other means.

Franklin (1987) has used DEMs to document the nature of the relationship between spectral response patterns and surface elevation and geometry. He also determined the landscape structures for supervising the classification of remotely sensed data. In this study, digital terrain information was used to visualize topographic conditions that might suggest hydrologic processes and resulting landforms.

In addition to DEM data, remote sensing inputs are a necessary compliment to landscape analysis. Visible and infrared wavelengths are vital in defining and understanding differences in vegetation and hydrologic conditions associated with arctic landforms and alpine environments (Dean and Morrissey, 1988). Trolier and Philipson (1986) reported that Landsat TM channels 3, 4, and 5 or the compositing of such wavelength combinations were superior to the other TM spectral regions for defining hydrologic related land-use and land-cover characteristics.

The combination of DEM and remote sensing data is further augmented with information on drainage patterns. Drainage patterns, produced through a unique combination of topography, geology, soil, vegetation, and physical and chemical processes, are indicative of histories and current processes at work on the landscape. Further, drainage patterns suggest future landscape scenarios as a product of drainage shape, form, pattern, orientation, and spatial correspondence with related physical and cultural phenomena.

Árgialas *et al.* (1988) have described drainage networks by their topology and geometry by incorporating structural relationships within an automated description and classification process. Enhancement of such hydrologic spatial relationships

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through image processing techniques, blended with variables contained within a GIS, can potentially improve our capability to understand the landscape. This will be achieved by clarifying information revealed by drainage patterns.

The objectives of this study were to (1) conduct a preliminary investigation of the hydrologic character of a portion of Glacier National Park that encompassed a combination of glaciers, lakes, and rivers within a varying physical environment; (2) evaluate the capabilities of enhanced Landsat TM digital data in discerning hydrologic characteristics; (3) appraise the use of 1:24,000-scale DEMs for defining elevations, slope angle, and slope aspect within alpine environments; and (4) validate the appropriateness of each technique by comparison to ground information contained within a GIS.

METHODS

Glacier National Park is separated into two nearly equal portions by the Continental Divide. Relief within the park is approximately 2,500 m with many peaks along the Divide rising to nearly 3000 m above mean sea level. Topography plays an important role in both glacial and vegetation landscape units. The vegetation within the park is complex owing to the topographic variability and the corresponding climatic regimes that dominate the respective regions of the park. Figure 1 shows the specific region selected for this study, which lies within the Mount Cannon 7 1/2-minute USGS topographic map.

During the summers of 1987 and 1988, field data were gathered, and terrestrial photographs were taken to document hydrologic, vegetation, and geomorphic elements of the landscape. An 6 August 1986 TM data set (ID No. 508891746) was selected for analysis because it most closely matched the seasonal time period in which field data had been gathered.

The TM data were preprocessed to remove biases, distortions, and degradation of the data introduced by geometric and radiometric considerations. Image restoration produces an image geometrically and radiometrically corrected as close as possible to the radiance characteristics of the original scene (Estes *et al.*, 1983). Ground control points were selected and compared to the location of the sample points on the TM data. A 0.46 root mean square error (RMSE) was achieved for the geometric registration. Histograms of each TM channel were studied to determine if a histogram adjustment was warranted to reduce the effect of atmospheric biasing of the data. Correction coefficients (LMIN λ and LMAX λ for specific TM channels and processing dates and systems) were utilized to convert TM digital counts to absolute radiometric units (spectral radiance ($L\lambda$), therefore, $L\lambda = L\lambda$ target + $L\lambda$ path radiance), and to detect and remove any detector-to-detector striping of the data (EOSAT, 1986). "Radiometric calibration of TM scanners is accomplished by rescaling the raw digital data transmitted from the satellite to calibrated digital data, which have the same post-calibration dynamic range for all scenes processed on the ground for a specific period of time" (EOSAT, 1986, p. 3).

Following the preprocessing, the TM data were enhanced through ratio, principal components analysis, and spatial filtering. The products of the digital enhancements were integrated with disparate information contained within a GIS framework. The ERDAS image processing software was utilized for this portion of the analysis. ERDAS was resident on a DEC Microvax II computer, and images were displayed and analyzed on a Gould FD5000 image processor. A Compaq 386/25 workstation also was used for image processing within the ERDAS environment. Figure 2 shows a conceptual overview of the analysis strategies employed and the data types utilized in this study.

Surface hydrography has been encoded from the Mt. Cannon quadrangle. In addition, geology was captured from a 1960 USGS map of the park produced at a scale of 1:125,000. The hydrography and geology maps were co-registered and utilized as separate GIS thematic overlays. Both maps were encoded through use of a graphic digitizer.

A digital elevation model from USGS also was acquired for the Mt. Cannon quadrangle. The 1:24,000-scale base-level digital product was processed through the Triangulated Irregular Network (TIN) approach offered within the ARC/INFO GIS software package. Elevation, slope angle, and slope aspect thematic overlays were generated from the DEM data.

RESULTS

Ratio Enhancement

Transformations of remotely sensed data can be performed to reduce the effect of shadows, seasonal changes in solar angle

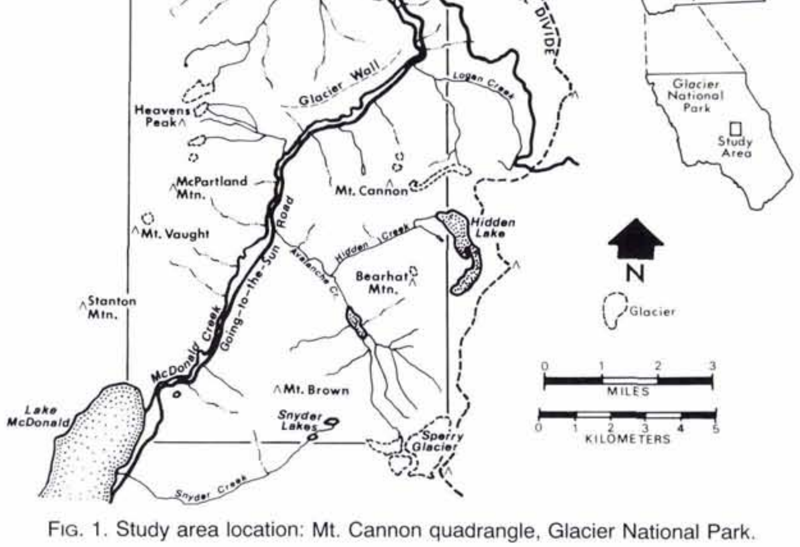

FIG. 1. Study area location: Mt. Cannon quadrangle, Glacier National Park.

and intensity, and fluctuations in sensor-surface geometry caused by topographic orientations (Jensen, 1986). In rugged and complex topography, shadows can obscure and mask spectral differences that characterize various vegetation units that otherwise might be sufficiently different to be separated by spectral comparisons. Ratioing spectral channels for feature enhancement or merging of ratioed spectral channels with raw spectral channels within the classification process can improve land-cover differentiation in such complex environments.

A variety of TM spectral channel combinations were ratioed. The thermal infrared channel (10.4 to 12.50 micrometres) was excluded from the analysis because of the difficulties associated with the exporting of diurnal and seasonal thermal signatures to other locations. Ratio combinations were identified either because of (a) low correlation between corresponding channel pairs indicating non-redundant information; (b) published literature documenting specific channel combinations (Chavez and Bowell, 1988; Sheffield, 1985; Chavez *et al.*, 1982); and (c) hypothesized spectral/biophysical relationships within the study area. The following band combinations were ratioed: TM5/TM3, TM4/TM1, TM5/TM2, TM7/TM3, TM5/TM1, TM4/TM3, TM7/TM1, TM4/TM2, TM7/TM2, TM7/TM4, and TM7/TM5.

The channel combinations of TM4/TM2 and TM4/TM3 enhanced the location of hydrologic characteristics—streams, lakes, and ponds. Glaciers, however, were not very well delineated. Topography and geologic structure were suppressed in the data, thereby increasing the ease of identifying structure-related intermittent streams. While water bodies were readily delineated, very little variability within the water bodies was apparent, but good vegetation discrimination assisted in defining stream channels.

TM4/TM1 revealed slightly more topographic structure than did either TM4/TM3 or TM4/TM2. Again, a good land/water interface was maintained. Glaciers were shown along with other hydrologic features, but without any satisfactory phenomena differentiation.

TM5/TM3 highlighted the location of glaciers and sediment within the water bodies, geologic structure was suppressed, and dominant stream channels were outlined. This was accomplished by highlighting the change in material and vegetation composition related to hydrologic features regardless of the condition or state of the water. Glaciers, streams, lakes, and ponds were readily revealed, but any discrimination as to feature variability was limited.

TM7/TM3 highlighted glaciers and did show variability within water bodies related to possible turbidity differences. TM7/TM5 was not very useful for identifying glacial ice or free-flowing water. Geologic structure was suppressed or "flattened", which reduced topographically-induced shadows but did little to highlight hydrologic features related to structure.

TM5/TM2, TM5/TM1, and TM7/TM1 showed a good land-water interface on all hydrologic features evaluated. All glaciers, lakes, and rivers were identified and highlighted, but no feature variability was apparent regardless of depth or basin/channel morphology of the features. TM5/TM2 did show more spectral variability among similar hydrologic parameters than did either TM5/TM1 and TM7/TM1. TM7/TM3 highlighted snow and ice and did a fair job of discriminating between water bodies of different depths and relative sediment differences.

TM7/TM2 and TM7/TM4 were similar in that they both showed a good land/water interface, topography is somewhat suppressed, and rock formations are well discriminated. TM7/TM4 provided a sharper and more intensity separation between land and water than did TM7/TM2. Little variation in water conditions was revealed by either of the two ratios. Glaciers were not highlighted beyond a general indication of location with boundaries only suggested.

The resultant products of the ratios were displayed on an image processing system and colored in various shades of red, green, and blue for interpretations. Table 1 provides a general summary of the relative value of TM channel ratios for the identification of glaciers, water bodies, rivers, and streams, and for reducing the topographic impact on feature identification. Channel combinations were composited by assigning three selected ratios to one of the three color guns of the image processor. The most useful composite for overall use associated with hydrologic analyses was TM4/TM3, TM5/TM2, and TM7/TM3 (Figure 3).

The composite of TM4/TM3, TM5/TM2, and TM7/TM3 highlighted the land/water interface, vegetation, glaciers, and low-order streams. This composite combination satisfactorily enhanced all features under study, thereby serving as the best overall ratio composite for hydrologic purposes in this application.

Principal Components Analysis

Principal components analysis (PCA) transforms the highly correlated TM data into statistically independent orthogonal axes on which the original satellite data are reprojected.

The results of the PCA (Table 2) show that the first principal component accounts for 80.1 percent of the variance within the entire TM data set. Components 2 and 3 account for 10.7 percent and 7.8 percent of the remaining variance, respectively. Approximately 98.6 percent of the total variance of the six TM channels (excluding the TIR channel) was explained by the first three principal components (Figure 4).

Channels 5 and 7 (middle-infrared) accounted for the highest factor loadings for the first principal component. Component 2

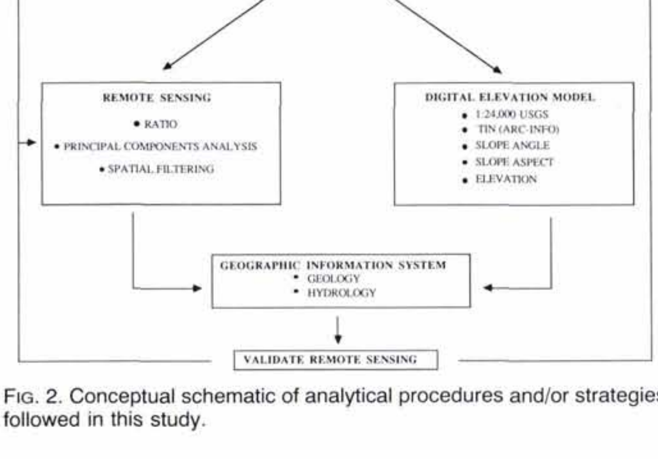

FIG. 2. Conceptual schematic of analytical procedures and/or strategies followed in this study.

TABLE 1. SUMMARY OF TM CHANNEL RATIOS: GOOD, FAIR, AND POOR.

TM Channel Ratio	Glaciers	Lakes/ Ponds	Small Streams	Rivers	Topography
TM5/TM3	fair	good	good	good	good
TM4/TM1	poor	good	good	good	fair
TM5/TM2	good	good	good	good	good
TM7/TM3	good	good	fair	good	fair
TM5/TM1	good	good	good	good	good
TM4/TM3	poor	good	good	good	good
TM7/TM1	good	fair	good	good	fair
TM4/TM2	poor	good	good	good	good
TM7/TM2	fair	fair	fair	fair	fair
TM7/TM4	poor	good	good	good	fair
TM7/TM5	poor	fair	poor	fair	good

FIG. 3. Composite image of ratioed TM data that proved to be the most effective for assessing selected hydrologic characteristics: TM4/TM3; TM5/TM2; and TM7/TM3.

TABLE 2. PRINCIPAL COMPONENTS ANALYSIS: LANDSAT TM SPECTRAL CHANNELS, EXCLUDING TIR.

Component	Eigenvalues	Variance (%)	Total (%)
1	3331.009	80.096	80.096
2	445.856	10.721	90.816
3	322.373	7.752	98.568
4	51.525	1.239	99.935
5	5.304	0.128	99.935
6	2.723	0.065	100.000

Eigenvector Matrix

	Principal Components					
TM Channels	1	2	3	4	5	6
1	0.143	0.417	−0.115	0.120	0.880	−0.069
2	0.188	0.597	−0.124	0.181	−0.385	−0.670
3	0.220	0.539	−0.187	0.099	−0.275	0.734
4	0.156	0.209	0.845	−0.457	0.054	0.075
5	0.659	−0.337	0.293	0.604	0.005	−0.048
7	0.662	−0.153	−0.412	−0.607	−0.007	−0.009

TABLE 3. MASKS UTILIZED IN THIS STUDY.

MASK 1	−1	−2	−1	MASK 2	−1	−1	−1	MASK 3	−1	−2	1
	−2	13	−2		−1	9	−1		−2	5	−2
	−1	−2	−1		−1	−1	−1		1	−2	1
MASK 4	0	−1	0	MASK 5	−1	−1	−1	MASK 6	0	−1	0
	−1	4	−1		−1	8	−1		−1	5	−1
	0	−1	0		−1	−1	−1		0	−1	0

was more representative of the visible portion of the spectrum within the TM wavelength range. The near infrared spectral regions of TM were associated with the third principal component.

The results of the PCA were viewed on the image processing system with color assignments of the first three components to the three color guns of the system. Components were studied as individual images and as composite images. Fung and LeDrew (1987) point out that the PCA is a scene dependent technique that requires a visual inspection of the image to assign specific landscape elements to specific components, and, therefore, renders the technique difficult to use for most practical evaluations where transferrability of quantitative results is the objective. This assignment process necessitates an understanding of the area under investigation: its vegetation, hydrography, and geomorphic character.

The first principal component identified the dominant trend within the data that accounts for the primary magnitude of the scene variance. Structure, topography, shadows, bare soil and rock faces, and water bodies were the highlighted phenomenon within the image. Gullies could be distinguished by surrounding variations in vegetation type, and the location of intermittent streams could be identified through certain geomorphic features oriented in specific directions that were suggestive of intermittent stream locations. Lakes and shadows were difficult to discriminate in the first principal component, particularly in areas of high structural contrast. Glaciers were not clearly distinguishable and low order streams and intermittent streams were only poorly represented.

The second principal component suppressed shadows and provided only a moderate representation of vegetation. Snow fields and glaciers were very well enhanced through a relatively sharp outline of their boundaries and thereby their areal extent. Shorelines and perennial streams were highlighted, particularly their boundaries. Poor representation of shadows, vegetation, and geologic structure introduced difficulties in recognizing intermittent and lower order stream channels.

Component 3 provided superior vegetation discrimination and good land/water interface discrimination. Glaciers, however, were not clearly outlined. Snow avalanche paths were highlighted due to their rather distinctive spatial organization and the good spectral contrast between brush in their paths and the residual undisturbed timber of unaffected slopes. Even when the snow avalanche paths were smaller than the spatial resolution of the data, their presence could be observed due to their unique appearance and vegetation composition.

SPATIAL FILTERING

High frequency spatial filters were constructed to emphasize directional and non-directional differences in brightness values summarized through a 3- by 3-pixel kernel. The size of the kernel was related to the complexity of the terrain (Chavez and Bauer, 1982) and to the resolution of the sensor in relation to the topography and the landscape features under consideration. Filters of 5 by 5 and 7 by 7 matrices were calculated and passed over a portion of the study area to confirm that the 3 by 3 kernel was most appropriate for this research.

The size, shape, location, orientation, and "character" of glaciers, rivers, and lakes were the characteristics to be extracted by filtering. Six filter masks were applied to the TM data for enhancement of the hydrography throughout the study area. The masks utilized in this study are indicated in Table 3.

Masks 1, 2, and 3 are high-pass filters which accentuated overall detail (Figure 5). Masks 4 and 5 are Laplacian non-directional edge enhancements, which reduced to zero all pixel values except those associated with edges in the data; Mask 6 is a Laplacian enhancement re-applied to the original image (Bernstein, 1983), which preserved a resemblance to the original data values, but with additional subtle information highlighted (Figure 6).

Directional filters were not utilized because of the rugged and complex environment that produced slopes of varying slope aspects and slope angles. Dominant slope orientations could have been determined and directional filters applied, but this study sought

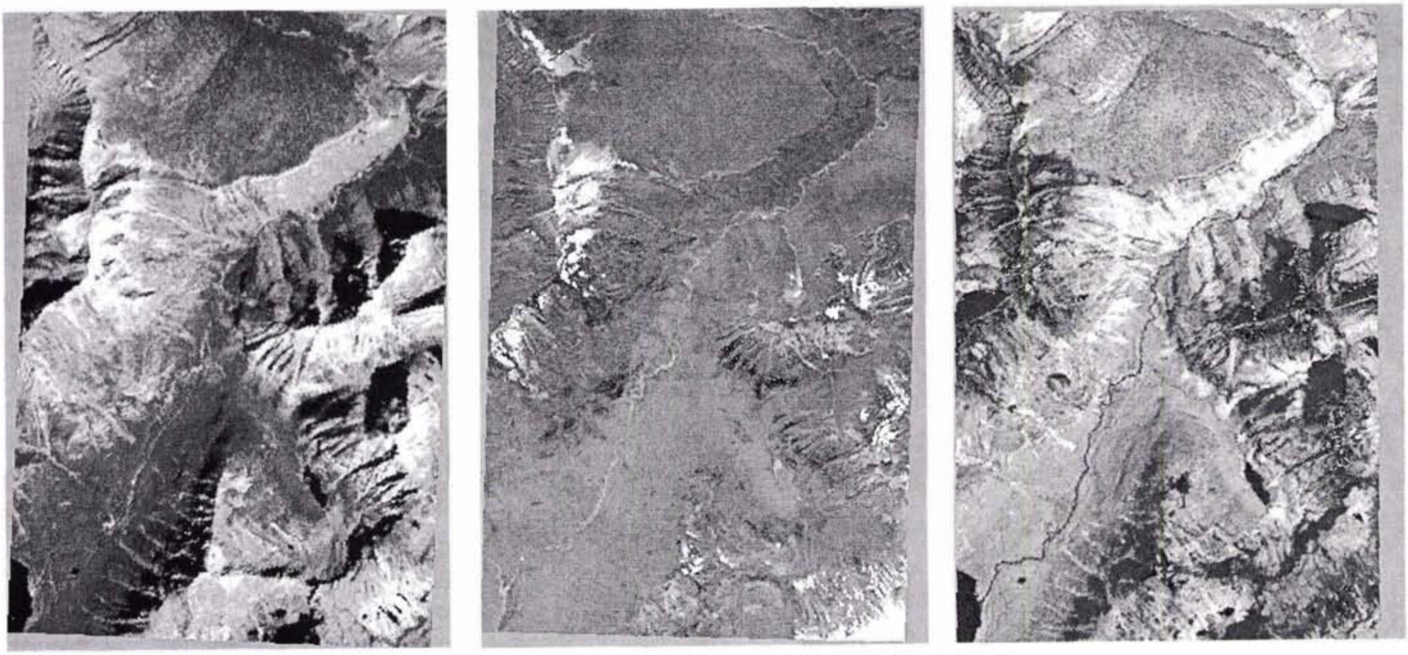

FIG. 4. Principal Components 1, 2, and 3 presented as individual digital images.

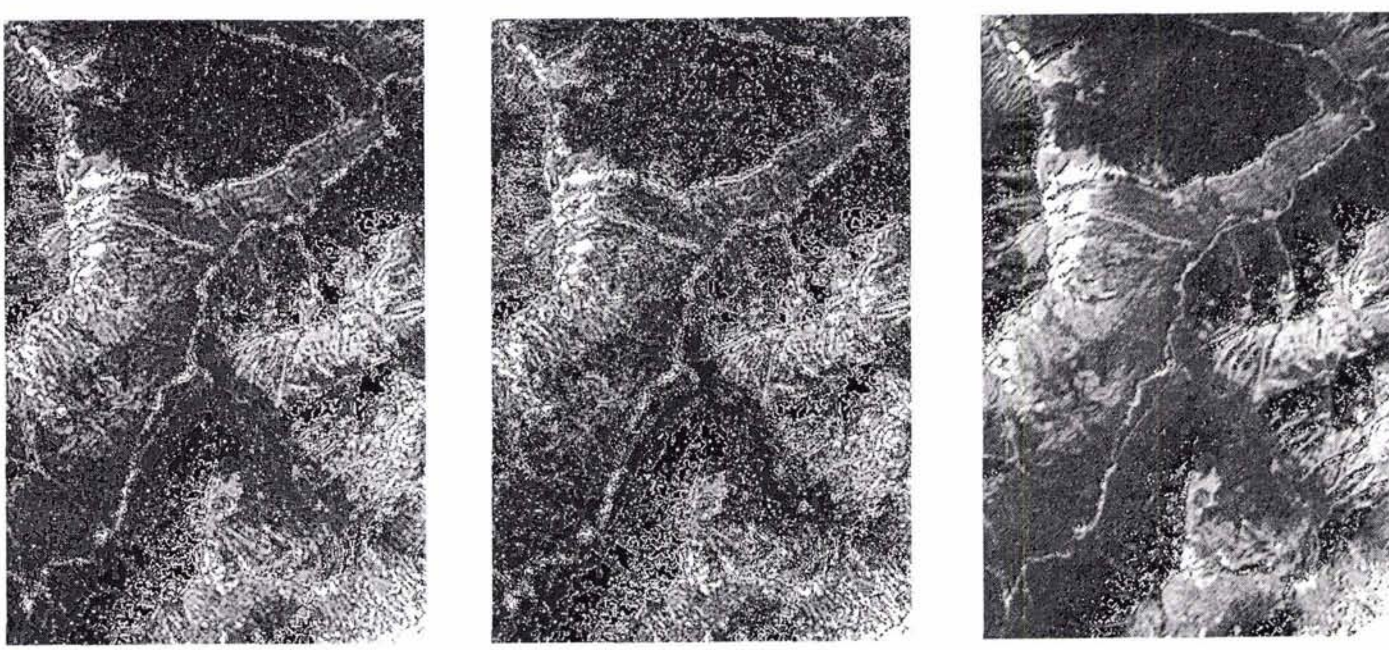

FIG. 5. Digital filters: masks 1, 2, and 3.

to detect larger scale landscape attributes that varied considerably from the dominant trend of the overall mountain system.

Because of the high degree of terrain complexity, a low pass filter was utilized prior to the application of the high pass filters. The low pass filter reduced the large amount of noise in the data, resulting in a moderately smoothed surface prior to subsequent high pass filtering. The objective of any study certainly dictates the strategies to be employed in the possible use of high pass, low pass, or a combination of the two filters in the analysis.

Masks 1, 2, and 6 were found to be best for identifying stream location. Mask 3 was marred by noise that remained in the image, while Masks 4 and 5 highlighted only the larger, perennial streams and streams in areas of high relief where gullies were severely eroded. Low order perennial streams occurring on gently sloping terrain were difficult to detect. Several strong edges were indicated in the data which resembled stream courses, but were determined to be shadow boundaries when compared to control information.

Masks 1, 2, and 6 were found to be virtually equal in their ability to identify streams. Large water-courses and streams in sharply etched gullies and subtly sloping streams, that were overlooked by the other masks, were identified by use of these filters. All but three of the perennial streams and two-thirds of

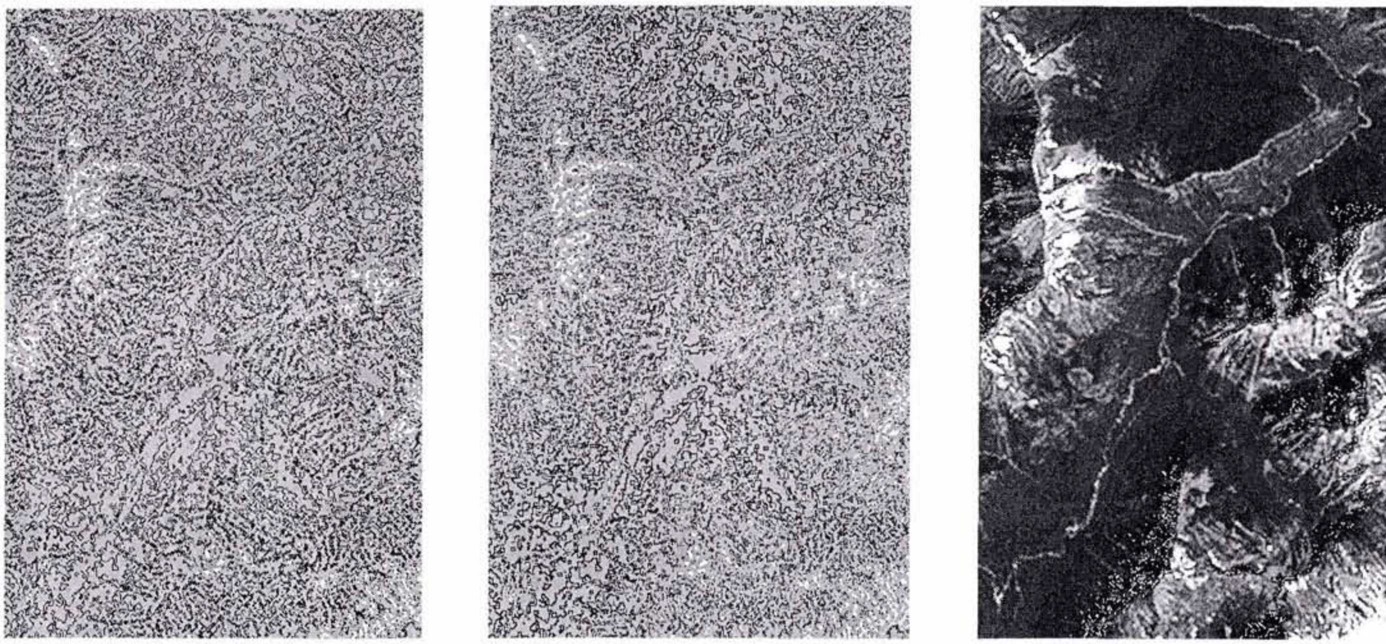

FIG. 6. Digital filters: masks 4, 5, and 6.

the intermittent streams were correctly identified through use of masks 1, 2, and 6.

DATA INTEGRATION THROUGH GIS

Figure 7 shows a generalized digital representation of a portion of the region under study that was generated from digital topographic information. Such views of the landscape are useful as thematic files for terrain analysis, and can be applied to the validation of satellite enhancements in which terrain factors play a role.

The geology and hydrography overlays digitized for the study area were interfaced with the slope angle, slope aspect, and elevation data from the DEM, and the remotely sensed digital enhancements within the GIS environment. Thematic overlays were superimposed and studied as composite images. For example, streams, rivers, and glaciers, digitized from the 1:24,000-scale topographic map and contained within the GIS, were color coded by slope angle and slope aspect classes. This was accomplished using the DEM to determine their topographic orientation and, thereby, to indicate their flow direction, gradient, and stream order.

A useful technique applied to the enhancement validation process was to split the screen into halves or quarters in order to view multiple enhancements and selected GIS overlays simultaneously but without direct compositing. Satellite enhancements were validated by superimposing and by viewing as split screens and as composite images the digital enhancements and the hydrography and/or geology overlays contained within the GIS. In this way, breaks in stream courses that were the result of problems in the digital enhancements were identified; misrepresentation of shorelines and stream courses were located; stream orders correctly identified by each enhancement were assessed; and the impact of geology, terrain, and the spatial position of target features were evaluated as to their propensity for being correctly identified through various enhancement procedures.

Figure 8 shows a GIS product in which all water bodies, stream courses, and glaciers were coded by slope aspect classes. Areas within a 300-m terrain buffer of water bodies, streams, and glaciers were analyzed through graphic display of slope angle classes that border the hydrologic phenomena. Digital

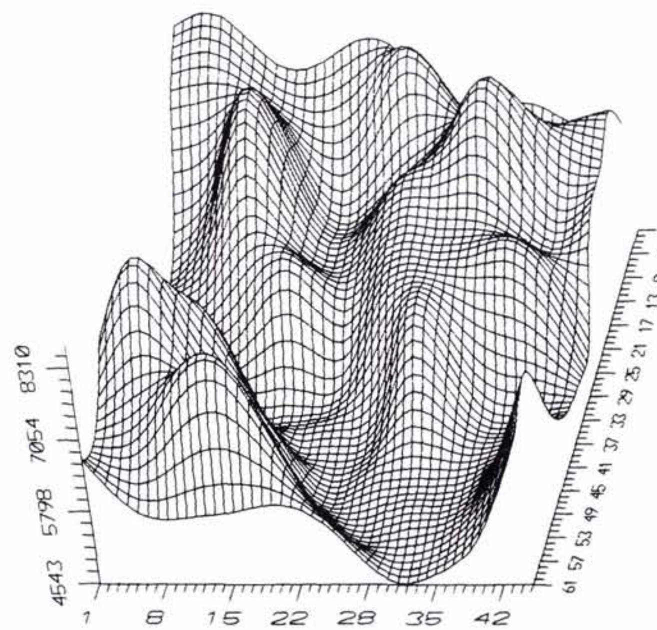

FIG. 7. Three-dimensional perspective diagram of a portion of the study region generated from digital terrain information: 15-degree direction of view with a 35-degree angle of tilt.

enhancements were then evaluated by observing the correct location of hydrologic features digitized from the USGS topographic maps, and the orientation of the hydrologic features and their surrounding terrain. GIS thematic overlays and composites of overlays can be merged with the digital enhancements through image differencing techniques to identify, for example, stream courses that occur on the topographic map but were not delineated through a digital enhancement technique.

This approach permitted evaluation of the quality of satellite data for identification of terrain and landscape units. In addition,

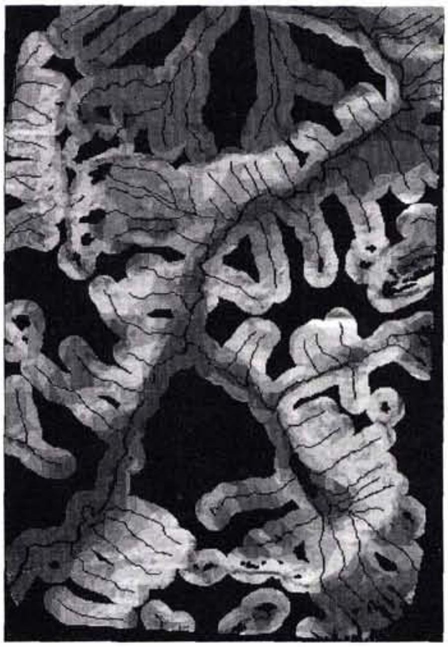

FIG. 8. Slope angle map of terrain surrounding or bordering hydrography processed for enhancement validation.

a preliminary understanding of the hydrologic character — size, shape, orientation, location, and condition — of the study area was acquired by visualizing terrain on hydrologic processes and on the spatial arrangement of the landscape.

Spatial modeling and image processing techniques were capable of providing further insight into hydrologic processes within the park and their geomorphic and vegetative responses. Composites of thematic overlays on the remote sensing enhancements were useful in discerning the spatial pattern of known phenomena. Also, such techniques were useful to examine phenomena and specific attributes of phenomena not appearing on the GIS overlays or only suggested from the overlays, but readily apparent on the satellite digital images.

CONCLUSIONS

Ratio processing, principal components analysis, and spatial filtering were useful techniques for appraising the hydrologic character of a portion of Glacier National Park. Changes in streams, ponds, lakes, and glaciers were assessed on a spatial basis by landscape attributes, through comparison to the 1968 USGS topographic map and derived data sets and remote sensing data. DEMs were important data sources for hydrologic analyses because they aided the interpretation of satellite digital data and served to characterize the distribution of landscape elements. Thematic overlays contained within the GIS served as a reference source for defining the spatial location of phenomena, and for comparing such phenomena against features identified employing the digital processing of satellite data.

Each of the digital enhancement techniques provided unique and useful information. They provided a representation of the study area not apparent in any single enhancement technique. The merging of GIS thematic overlays increased the interpretative power of the analysis and validated the interpretations completed for each enhancement technique by serving as "control" data from both a spatial and non-spatial, attribute perspective. Combinations of lithology, vegetation, topography, and hydrography, that hindered and/or facilitated the successful digital enhancement of certain landscape units or landscape segments, could be identified. Through the integration of remote sensing digital enhancements and selected thematic overlays integrated within a GIS, digital enhancements were appraised with greater capability than by use of remote sensing or GIS data alone.

REFERENCES

Argialas, D. P., J. G. Lyon, and O. W. Mintzer, 1988. Quantitative description and classification of drainage patterns. *Photogrammetric Engineering and Remote Sensing*, 54(4):505–509.

Bernstein, R., 1983. Image geometry and rectification. *Manual of Remote Sensing*, Chapter 21 (R. N. Colwell, editor), American Society for Photogrammetry and Remote Sensing, Falls Church, Virginia, p. 888.

Chavez, P., and B. Bauer, 1982. An automated optimum kernel-size selection technique for edge enhancement. *Remote Sensing of Environment*, 12:23–38.

Chavez, P. S., and J. A. Bowell, 1988. Comparison of the spectral information content of Landsat Thematic Mapper and SPOT for three different sites in the Phoenix, Arizona Region. *Photogrammetric Engineering and Remote Sensing*, 54(12):1699–1708.

Chavez, P. S., G. L. Berlin, and L. B. Sowers, 1982. Statistical method for selecting Landsat MSS ratios. *Journal of Applied Photographic Engineering*, 8:23–30.

Cibula, W. G., and M. O. Nyquist. 1987. Use of topographic and climatological models in a geographical database to improve Landsat MSS classification for Olympic National Park. *Photogrammetric Engineering and Remote Sensing*, 53(1):67–75.

Dean, K. G., and L. A. Morrissey, 1988. Detection and identification of Arctic landforms: An assessment of remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, 54(3):363–371.

EOSAT, 1986. *Landsat Technical Notes*, No. 1:3–5.

Estes, J. E., E. J. Hajic, and L. R. Tinney, 1983. Fundamentals of Image Analysis: Analysis of Visible and Thermal Infrared Data. *Manual of Remote Sensing*, Chapter 24 (R. N. Colwell, Ed.), American Society of Photogrammetry and Remote Sensing, Falls Church, Virginia 1:1039–1040.

Franklin, S. E., 1987. Terrain analysis from digital patterns in geomorphotometry and Landsat MSS spectral response. *Photogrammetric Engineering and Remote Sensing*, 53(1):59–65.

Fung, T., and E. LeDrew, 1987. Application of principal components analysis to change detection. *Photogrammetric Engineering and Remote Sensing*, 53(12):1649–1658.

Goodenough, D. G., 1988. Thematic Mapper and Spot integration with a geographic information system. *Photogrammetric Engineering and Remote Sensing*, 54(2):167–176.

Holben, B. N., and C. O. Justice, 1980. The topographic effect on spectral response from nadir-pointing sensors. *Photogrammetric Engineering and Remote Sensing*, 46(9):1191–1200.

Jensen, J. R., 1986. *Introductory Digital Image Processing: A Remote Sensing Perspective*. Prentice-Hall Publishing Company, Englewood Cliffs, New Jersey.

Justice, C. O., S. W. Wharton, and B. N. Holben, 1981. Application of digital terrain data to quantify and reduce the topographic effect on Landsat data. *International Journal of Remote Sensing*, 2:213–221.

Karaska, M. S., S. J. Walsh, and D. R. Butler, 1986. Impact of environmental variables on spectral signatures acquired by the Landsat Thematic Mapper. *International Journal of Remote Sensing*, 7(12):1653–1667.

Sheffield, C., 1985. Selecting band combinations from multispectral data. *Photogrammetric Engineering and Remote Sensing*, 51(6):681–687.

Trolier, L. J., and W. R. Philipson, 1986. Visual analysis of Landsat Thematic Mapper images for hydrologic land use and cover. *Photogrammetric Engineering and Remote Sensing*, 52(9):1531–1538.

Walsh, S. J., 1987. Variability of Landsat MSS spectral responses of forests in relation to stand and site characteristics. *International Journal of Remote Sensing*, 8(9):1289–1299.

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