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MAY 1977

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Remote Sensing Inputs to Landscape Models which Predict Future Spatial Land Use Patterns for Hydrologic Models

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Craig Tom
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Landscape modeling organizes and overlays data from existing maps, analysis of remote sensing imagery, and tabular data into a computer framework. This provides a multivariate representation of the landscape much as a topographic map represents a three-dimensional model of the physical land surface. The overlays of map- and image-derived data in this model provide a basis for computer simulation or modeling of the future spatial behavior of the "stored" landscape to anticipated natural or man-made stimuli. A typical application of such a procedure to hydrology is the prediction of the future spatial evolution of land use patterns of an urban area as input into the simulation of the urban hydrograph. The application of a landscape modeling to the Denver metropolitan area in Colorado provides an illustration of this application. Modeling of the hydrologic implications of the alteration of more natural watersheds is also important. Landscape models of natural watersheds subject to future change due to natural (e.g., drought) or man-made (e.g., forest cutting) alteration also yield map-like projections of the future distribution of each land use or cover. A tropical forest area of Northern Thailand provides a test case of the application of the approach in more natural surroundings.

Remote sensing imagery subjected to proper computer analysis has already been clearly shown to be a very useful means of collecting spatial data for the science of hydrology. Remote sensing products provide direct input to hydrologic models and practical data bases for planning large and small-scale hydrologic developments. Combining the available remote sensing imagery together with available map information in the landscape model provides a basis for substantial improvements in these applications. Coincident, registered overlays of the map information upon multispectral remote sensing imagery of LANDSAT provide a basis for marked improvement in the accuracy of the computer interpretation of land use and land cover maps. These improved, automatically interpreted maps may be used directly in hydrologic analysis. They also "feedback" into the landscape model to provide a timely measure of past and present dynamic tendencies for change of the land use/land cover. Detailed airphoto interpretation of past and present low-altitude airphotos provided the maps of the land use/land cover on successive dates as measures of change for

the Denver and Thailand studies. LANDSAT imagery has been available since 1972. Accurate computer analysis of the temporal changes in land use/land cover with this imagery will provide more direct input to the landscape models and their subsequent projection of future land use/land cover patterns.

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INTRODUCTION

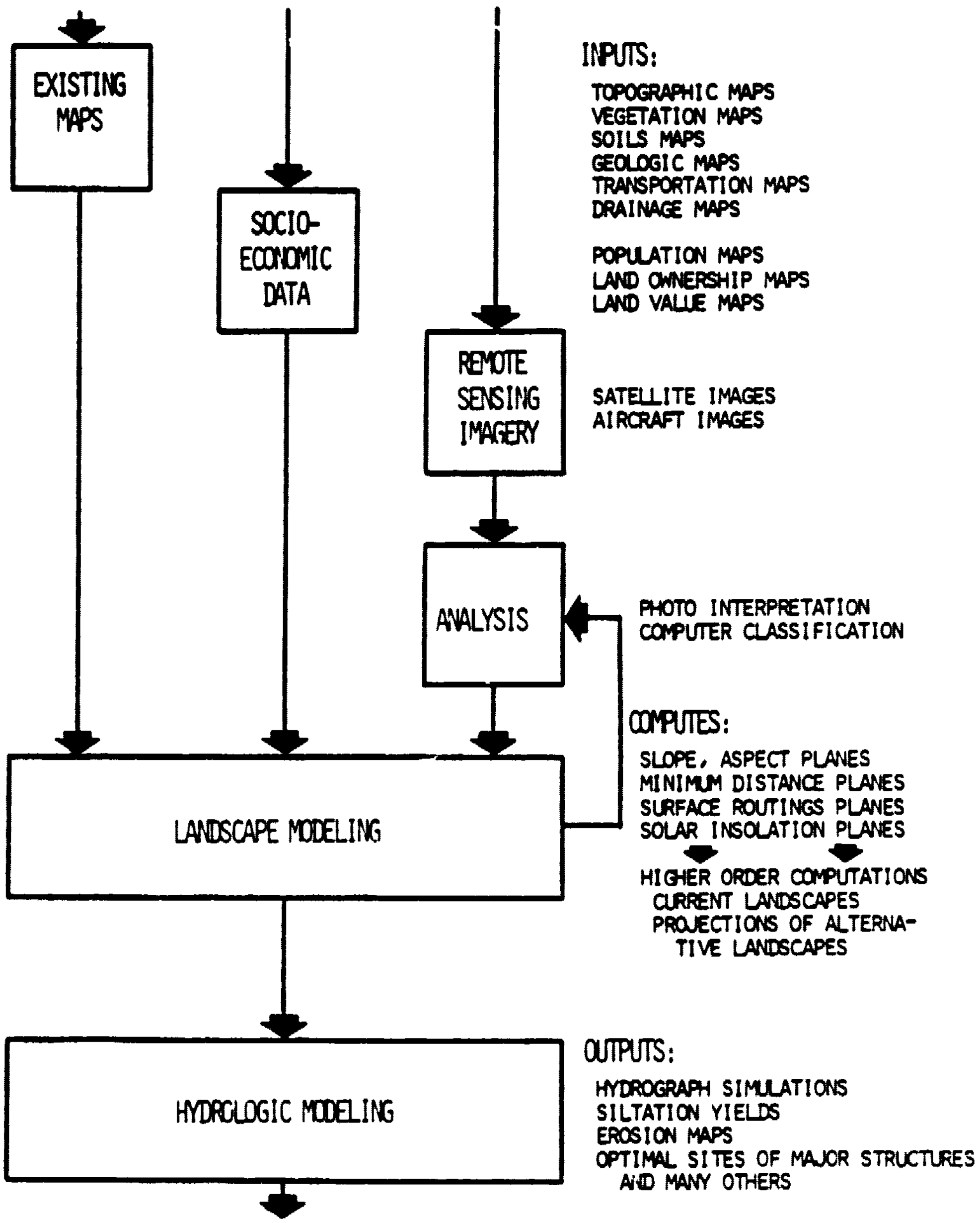
What is Landscape Modeling?

Landscape modeling organizes and overlays information from existing maps, tabular sources, and the analysis of remote sensing imagery into a computer framework (Table 1). This assemblage provides a multivariate, multitemporal mathematical model which represents the landscape much as a topographic map represents a three-dimensional model of the physical land surface. Coupled with this composite of data overlays is a collection of computer techniques which allow meaningful simulation of the spatial or map-like behavior of this landscape to natural and man-induced alteration and control (Tom and Miller, 1974). The current thrust of landscape modeling is the projection and display in a map form of the future landscape which would result from the continuation of current land management practices or the lack thereof. Success in this short-run objective has enabled contemplation of the computer techniques needed to predict how the landscape will evolve in a spatial sense to various scenarios of anticipated alternatives. The scenarios evaluated could include diverse objectives, such as various new zoning patterns for urban land planning, alternate sites for a new power plant, or the environmental impact of siting a new dam. Land management and planning in general, and hydrologic engineering and modeling in particular, would improve substantially if the future spatial implications of a contemplated action could be modeled before any commitment to a fixed course of action.

How Does Landscape Modeling Relate to Remote Sensing?

Computer analysis of remote sensing imagery is symbiotic with the process of landscape modeling. It provides the important current and past land cover inputs to the landscape model. In turn, the accuracy of the computer interpretation of the remote sensing imagery is substantially improved by including landscape variables, such as topographic elevation. Combining the available remote sensing imagery together with map information in the landscape model provides a basis for substantial improvements in both activities. Coincident, spatially registered overlays of readily available map information upon the multispectral imagery of LANDSAT has provided a basis for marked improvement in the accuracy of its computer interpretation to provide current land use or land cover maps. These improved, automatically interpreted maps of land use or land cover are of direct use in hydrologic analysis. They also "feedback" directly into the landscape model to provide a timely measure of past and present dynamic tendencies for change in the land use or land cover. Detailed interpretation of low-altitude airphotos provided the maps of the land use on various dates which were used as quantitative measures of change in the case studies to be discussed here. LANDSAT imagery has been continuously

TABLE 1. SIMPLE SCHEMATIC REPRESENTATION OF THE LANDSCAPE MODELING CONCEPT. Spatially referenced data from a variety of sources is overlaid in the landscape model. A symbiotic relationship exists between landscape modeling and remote sensing image analysis. Current and projected landscape scenarios provide new inputs to the hydrologic modeling and decision-making processes.



obtained since 1972. Thus, accurate computer analysis of land use or land cover with LANDSAT imagery of various dates will provide a more economical, timely, and direct measure of land change for landscape models and their projections of future land use patterns.

How Does Landscape Modeling Link Remote Sensing to Hydrology?

Landscape modeling provides the missing link between the data collected by remote sensing methods, tabular data, and existing maps and its interface to the hydrologic modeling process (Oliver and Miller, 1971). Remote sensing imagery and associated interpretations at various levels of sophistication have already been widely accepted as a means of collecting the spatial input needed for hydrologic analysis. Remote sensing products already provide direct input to hydrologic models and the data bases for planning large- and small-scale hydrologic developments. It is the purpose of this paper to show how the heretofore omitted, intermediate step of overlaying and analyzing all the known spatial data about a landscape can provide higher-order inputs to hydrologic analysis. The concept of landscape modeling with attendant inputs from remote sensing will be illustrated by two case studies. The first is a typical application of the procedure to predict the future spatial evolution of man-induced land use patterns of an urban area which, in turn, can provide input into the simulation of future urban hydrographs. The application of landscape modeling to the Denver, Colorado urban area provides this illustration. The second application, although not complete, should illustrate how landscape modeling is applied to more natural watersheads to provide the basis for analysis of the hydrologic implications of the alteration of their land cover. Primitive watersheds subject to change due to natural (e. g., drought) or man-made (e. g., forest cutting) alternation can be modeled to yield map-like projections of the future distribution of each land use or cover. A tropical forest site in Northern Thailand provides a demonstration of how the approach is being applied in a natural environment.

DENVER URBAN AREA CASE STUDY

Background

The Denver, Colorado metropolitan area was selected as a site to construct a landscape model typical of a rapidly urbanizing area (Tom, Miller, Krebs, and Aukerman, 1974). Considerable land area in Denver is being converted from more natural land uses and cover, such as pasture and agricultural land, to higher-order uses dominated by low infiltration rates, such as single- and multiple-unit residential, shopping center, and commercial uses. The total water system of this large metropolitan area subsequently drains into the South Platte River. The effects of the gradual "paving over" or sealing of a good portion of this urban watershed directly affects the storm hydrograph and the subsequent design of storm drains and other hydrologic works. (Root and Miller, 1972). Accurate, timely, current maps of the distribution of each land use and land cover would provide improvement in the planning of the hydrologic works for this dynamic urban area. Projection of the future spatial evolution of the land use and land cover of the area provides a new type of input for more accurate projections of future hydrologic engineering requirements.

Site Description

The urban landscape model covers an area of 24 by 24 miles or 576 square miles centered on the city of Denver (Figs. 1 and 2). Most of this site has relatively low relief except for about five percent of the western edge which includes the eastern foothills of the Rocky Mountains. Denver is a rapidly expanding, large city of approximately 1,500,000 people with future expectations for continued growth.

Construction of the Landscape Model

A complete inventory was prepared of all available maps, spatially referenced tabular data, and remote sensing imagery ranging from the early low altitude, black-and-white airphotos of the mid-1930s to the current LANDSAT images. Unfortunately, such information has been collected with diverse techniques and map scales by a wide assortment of public and private organizations. The landscape model provides a depository for interrelating all of this diverse information in a common format. A model variable or data plane is one overlay of the interrelated spatial data in a uniform cellular fashion upon all other data planes or variables in the model (Fig. 3).

The simplest way of incorporating each map into the model requires the overlay of a dot pattern representing a selected cell size upon the map (Miller, 1973). The input value of each cell is estimated from the map at the position of the sample dot; for example, the elevation of each cell is tabulated from the contour map. These sample values are keypunched, input into the computer, and organized into a data plane. Very careful procedures are maintained to insure that the common cell pattern overlaid on each new map or set of maps provides a data plane which registers exactly upon all previously created data planes. The hand tabulation of all the map data input in this fashion for this analysis was very laborious but was more accurate for these initial research efforts in landscape modeling. Once the basic principles of the approach are better understood the production landscape modeling efforts can input the data with a variety of sophisticated map digitizing procedures. Most earlier studies of landscape modeling have dealt with sophisticated machine entry of map data into the computer and have expended little effort on doing anything with it. Certain

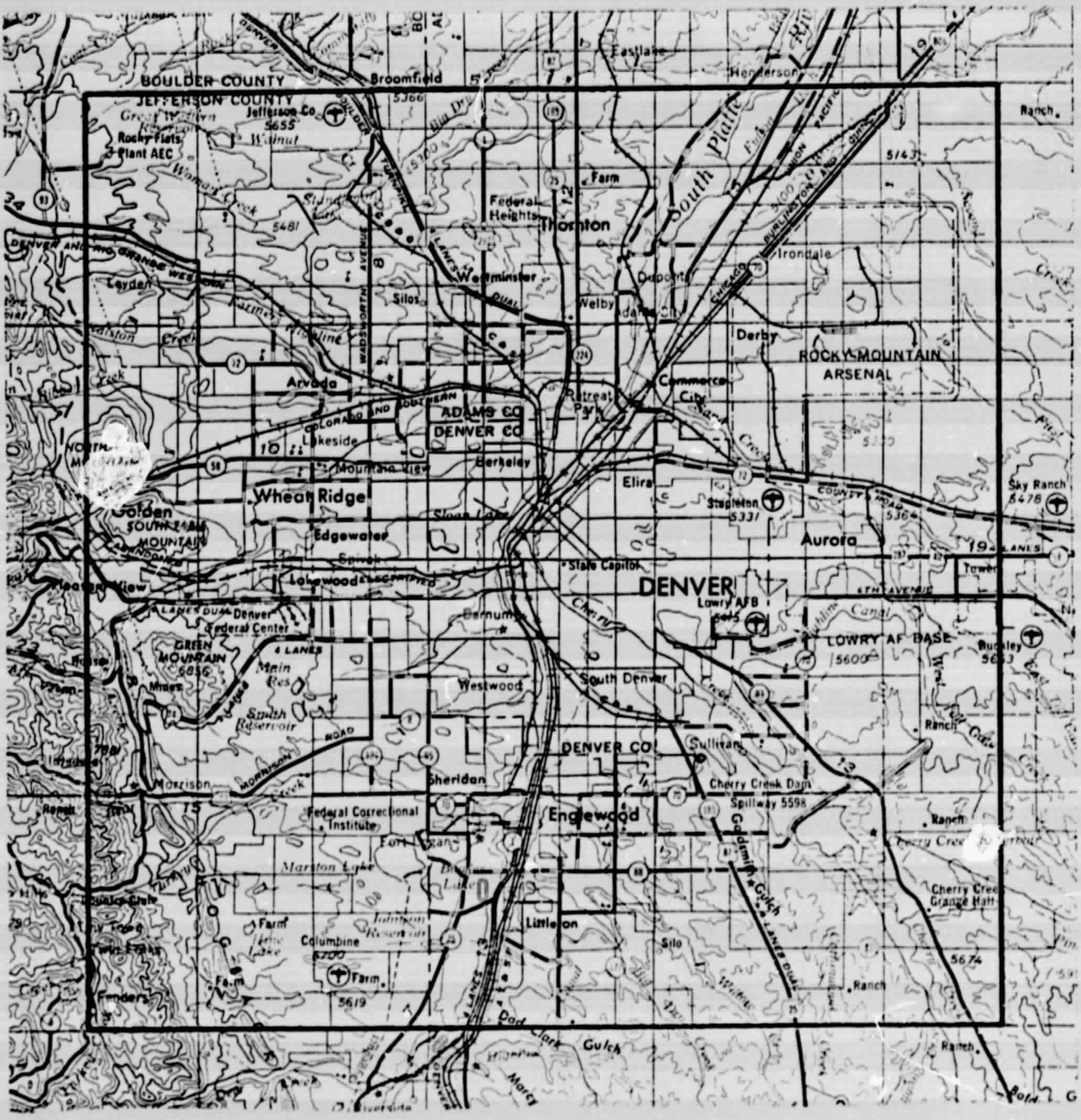


FIGURE 1. REFERENCE MAP FOR THE DENVER URBAN AREA LANDSCAPE MODEL. Scale 1:250,000. The outer boundary is a square of 24 miles by 24 miles (576 square miles). This area corresponds with each data plane digitized at a ten-acre cell size yielding 36,864 cells.

FIGURE 2. LANDSAT MSS BAND 7 IMAGE OF THE DENVER URBAN AREA. Scale 1:250,000. Graymap of the August 15, 1973 image showing 576 by 576 image cells exactly as they are overlaid onto the landscape model. This image is geometrically rectified from the LANDSAT computer compatible tapes and resampled to yield 1.11 acres per square cell. A three by three square array of these image cells of exactly ten-acres is overlaid upon the ten-acre square cells of the landscape data planes.

5 TRANSPORTATION SUBMODEL VARIABLES:
- Minimum Distances to Low-Capacity Minor Roads
- Minimum Distances to High-Capacity Major Roads
- Minimum Distances to Freeways
- Minimum Distances to Freeway Inter-Changes
- Minimum Distances to Fully Developed City Streets

17 SOCIO-ECONOMIC SUBMODEL VARIABLES:
- 5 Population/Family/Housing Unit Totals
- 1969 Mean Family Income
- Median Housing Unit Value/Rent
- 1, 2, 3, 3+ Car Families
- Census Tract Acreages
- 4 Population/Housing Densities per Acre
- Average Number of Cars per Family

7 LAND USE SUBMODEL VARIABLES:
- 1963 Photo Interpretation of Land Use
- 1970 Photo Interpretation of Land Use
- 1973 USGS Photo Interpretation of Land Use
- 1963 Land Uses Lost to 1970
- 1970 Land Uses Gained from 1963
- 1963-70 Alphanumeric Land Use Change

5 PHYSIOGRAPHIC SUBMODEL VARIABLES:
- Topographic Elevation
- Topographic Slope
- Topographic Aspect
- LANDSAT Image Insolation
- Surficial Geology

14 LANDSAT IMAGERY VARIABLES:
- MSS-4 Visible Green
- MSS-5 Visible Red
- MSS-6 Solar Infrared
- MSS-7 Solar Infrared
- 6 MSS Channel Ratios
- 4 MSS Ratios to Insolation

FIGURE 3. CONCEPTUAL DIAGRAM OF THE FOUR LANDSCAPE SUBMODELS OVERLAYING THE LANDSAT IMAGERY FOR THE DENVER URBAN AREA. The multivariate landscape modeling program was used to model future spatial land use changes with the 34 landscape variables. Significantly improved, automated LANDSAT image classification of land use was achieved when these landscape variables were used as collateral or ancillary data planes.

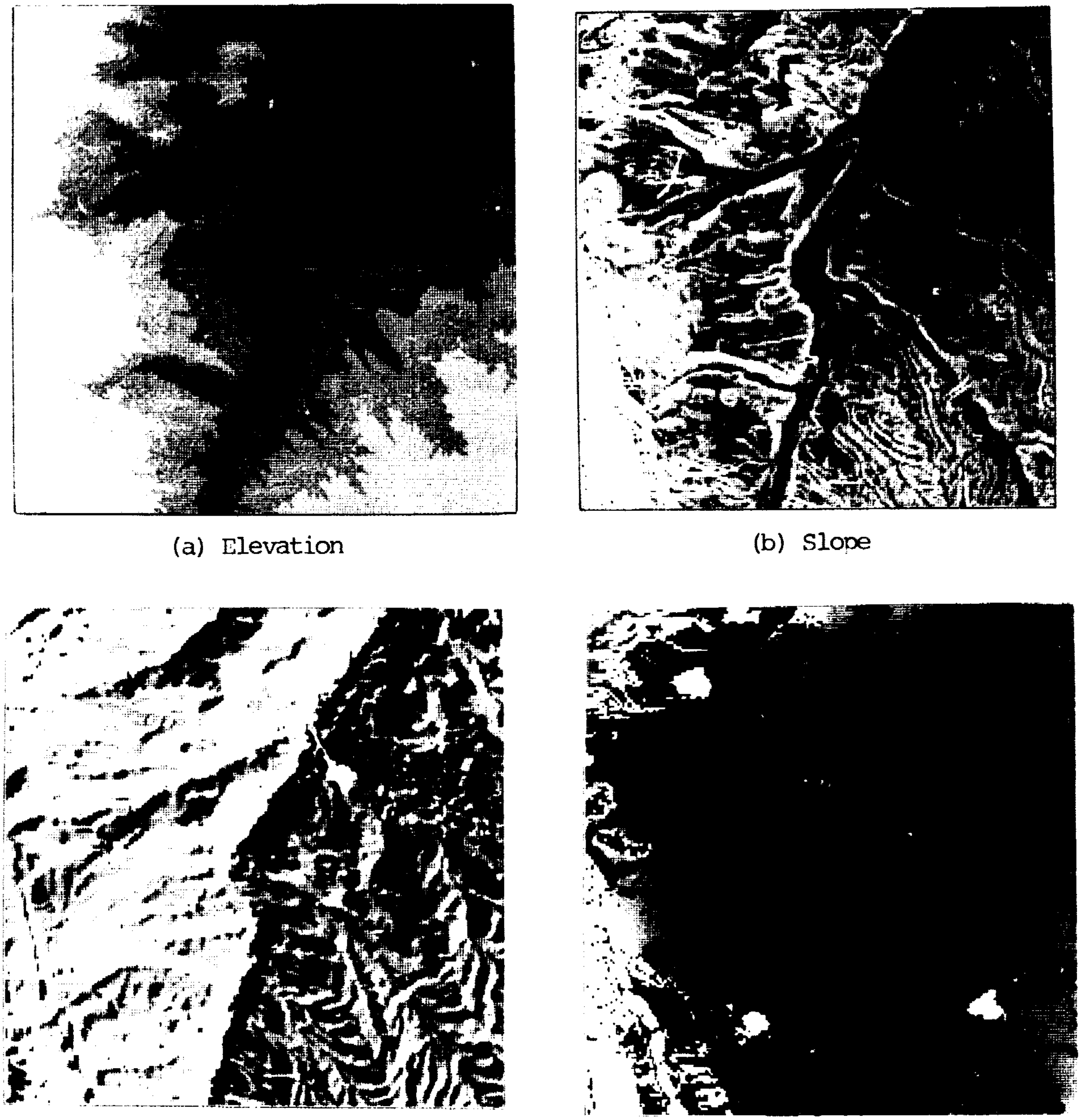
types of spatial data of the Denver area were initially identified as important to the landscape modeling process but were not available (e.g., a soils map) or were too diverse (e.g., land ownership and parcel size) to allow their collation and overlay.

A selection of the numerous available maps and spatially referenced tabular data must be made for inclusion in the model. Growing experience with the sensitivity of the landscape modeling process to the input variables provides a basis for this selection. Forty-eight landscape and image data planes were overlaid and registered in the Denver urban area model. Each data plane represents continuously variable, spatial information at a ten-acre square cell resolution for the 576 square miles. Thus each data plane spatially represents the determination of a landscape variable at 576 square miles times 64 cells per square mile, yielding 36,864 individual cells. A ten-acre square cell size or resolution was selected for each landscape data plane as it represents the smallest individual area which could be adequately sampled from the majority of the available maps. LANDSAT imagery in the digital form is available with a rectangular picture element resolution of approximately one acre. It is geometrically corrected and resampled to overlay the landscape model with a square cell resolution of 1.11 acres which nests a three by three array of square LANDSAT cells exactly into ten acres.

Area Planes and Their Transformations

Area planes such as topographic elevation were sampled directly by the 36,864 cell sample dot pattern. The elevation of each cell was estimated to the nearest ten feet from the contours of sixteen 1:24,000 scale topographic maps. After assembly this topographic elevation data plane was displayed from the landscape model on a computer microfilm plotter in a cell-by-cell or map fashion. Each ten-acre cell was represented by a gray level corresponding with elevation (i.e., magnitude of the variable) (Fig. 4a). Only five to ten meaningful gray levels can be displayed on a microfilm plotter and readily distinguished by the human eye. Thus these graymaps cannot directly display each of the ten-foot intervals of elevation actually recorded in the data plane, and each gray tone was assigned to a much grosser 500-foot interval in the display. All the data planes must be similarly quantified and grouped into much coarser categories when displayed. Thus, all the variables stored in the data planes are much more finely resolved than shown upon the respective graymaps.

Additional computations upon the original input data planes provide very useful "derived" data planes. Topographic slope and aspect data planes are accurately derived by computation from the topographic elevation data plane. This is accomplished by fitting a regression least-squares plane to the elevations of a three by three array of cells, determining the slope and aspect of that surface, and assigning them to the center cell of the array (Tom, 1975). Repeating the process over the whole elevation plane provides the slope and aspect



(a) Elevation

(b) Slope

(c) Aspect

(d) Surficial Geology

FIGURE 4. SAMPLE DATA PLANES FROM THE PHYSIOGRAPHIC SUBMODEL OF THE DENVER URBAN AREA. Scale 1:500,000.

(a) Topographic elevation data plane emphasizing lowest areas in black.

(b) Topographic slope data plane emphasizing shallowest slopes in black. Computed from the elevation data plane (a).

(c) Topographic aspect data plane emphasizing northwest-facing areas in black. Computed from the elevation data plane (a).

(d) Surficial geology data plane emphasizing alluvial deposits in black.

of all cells in the model, yielding the slope and the aspect data planes (Figs. 4b and 4c).

Point and Linear Planes and Their Transformations

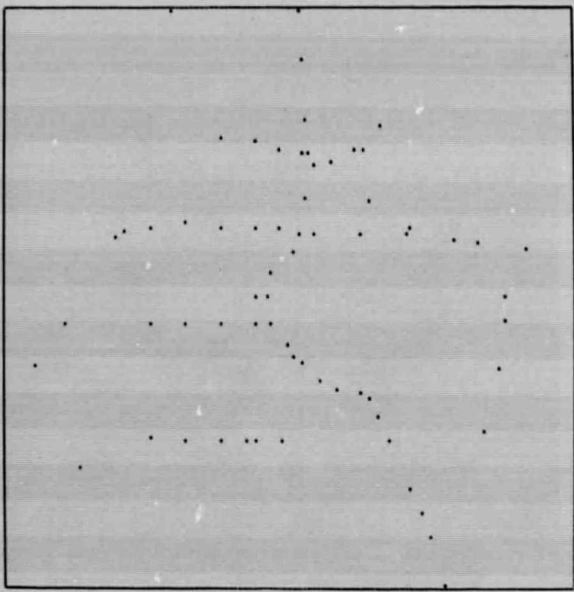
Various types of point and linear maps, representing transportation and communication routes, were overlaid upon the model. These planes were transformed to area planes before they were input into the landscape model. The locations of freeway interchanges are typical point features which have an important impact on changes in the land use surrounding them. This impact is a function of the distance away from the interchange. The impact of freeway interchanges is thus best input to the model as a minimum distance plane. Initially, the freeway interchanges are tabulated into a point-type data plane which records their location in the nearest ten-acre cell (Fig. 5a). This temporary data plane is subjected to computation so that the minimum distance in an east-west and/or north-south sense is computed for every cell in the plane to the nearest cell occupied by a freeway interchange. This transforms the point plane into a useful minimum distance area plane (Fig. 5b). Similarly, the initial data planes representing roads or other linear features (Fig. 5c) are computationally converted to area planes for overlay in the model (Fig. 5d).

Spatially Referenced Socio-Economic Data

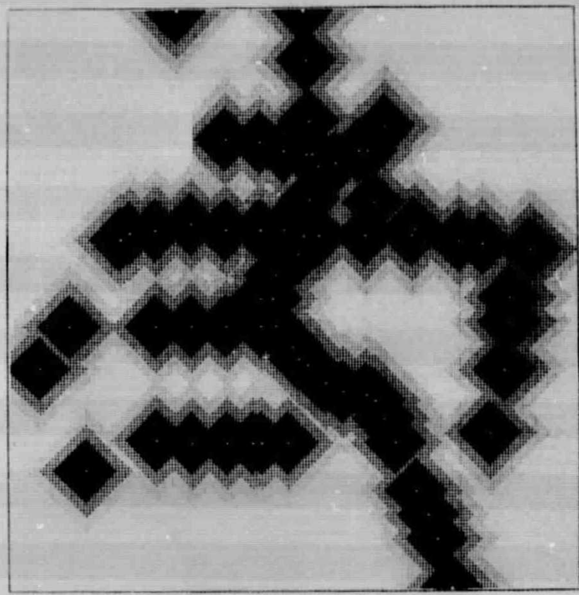
Socio-economic data for the United States is tabulated by census at ten-year intervals. This information is reported in a tabular form referenced to maps of the census tracts or other smaller spatial tabulation units called enumeration districts. These reference maps were sampled by a dot pattern so that each ten-acre cell was assigned to a specific census tract. This procedure allows the tabular statistics to be projected into area-type, socio-economic data planes, representing such variables as population density, mean family income, etc., for overlay into the model (Fig. 6). Unfortunately, the basic reference map of census tracts is far coarser than the ten-acre resolution of the model, and thus these data planes are not as highly resolved as desired in a spatial sense but do produce reasonable results. The repreparation of these data planes using the smaller enumeration districts employed for the census of densely populated areas would improve this resolution by a factor of about five.

Current and Historical Land Use Planes

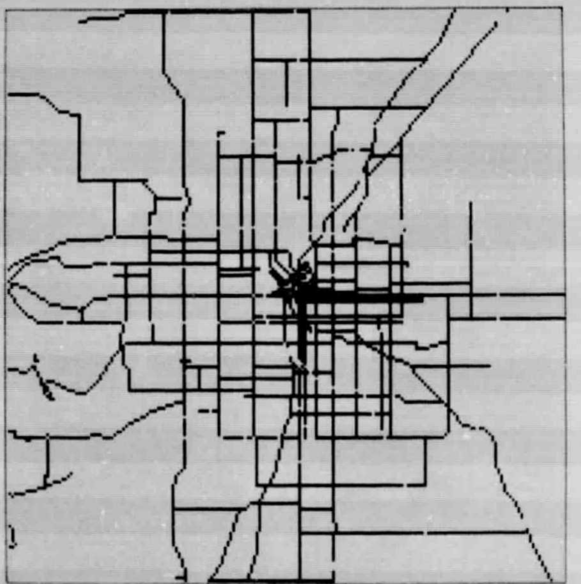
Projections of the future land use of the urban area were based upon observations of the changes which occurred in the area in the recent past. This requires the overlay onto the landscape model of accurate, detailed, current and past land use patterns. Photographic remote sensing imagery with accurate interpretation provides this data which drives the landscape modeling process.



(a) Freeway Interchanges



(b) Minimum Distance to Freeway Interchanges

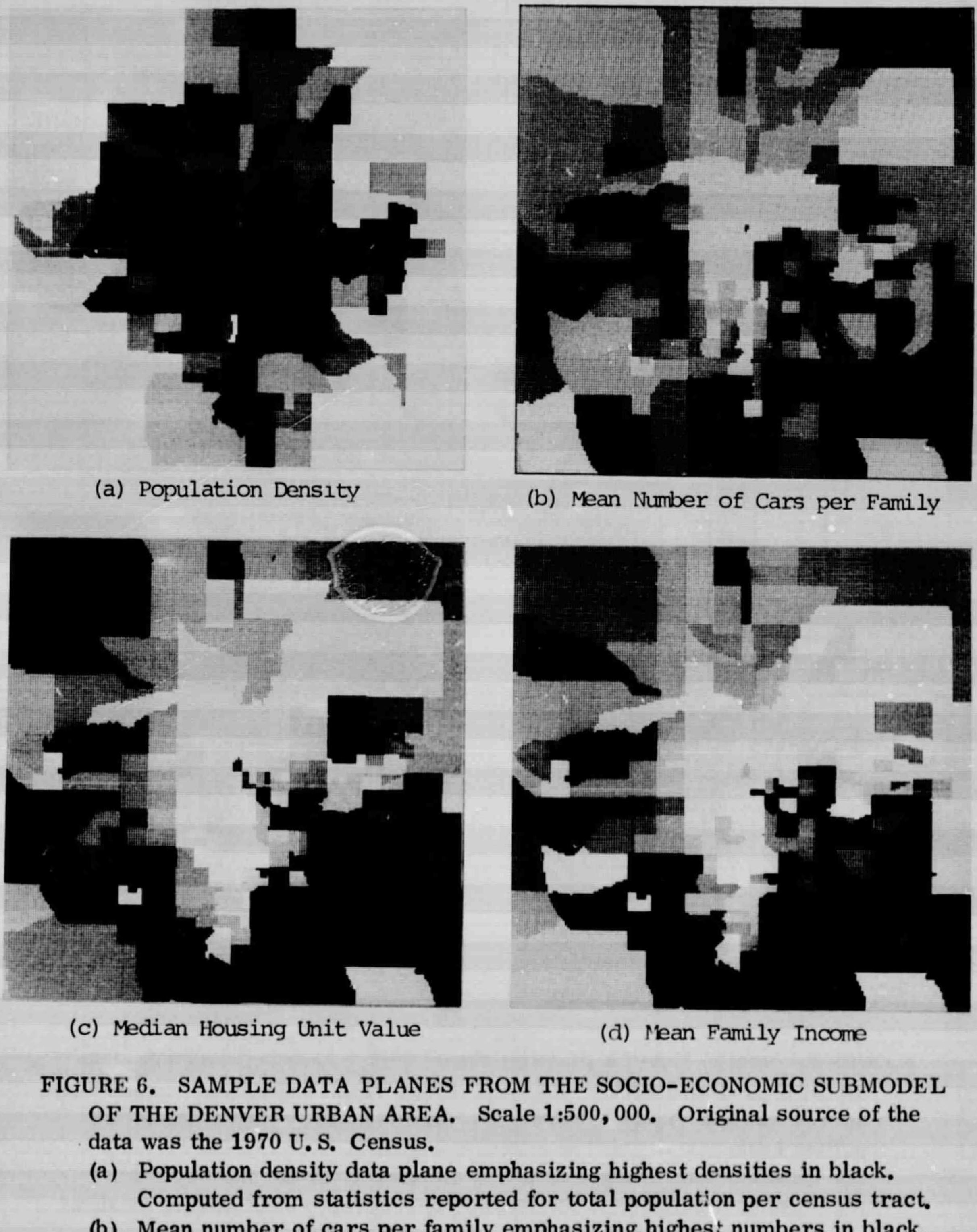


(c) High-Capacity Major Roads

(d) Minimum Distance to High-Capacity Major Roads

FIGURE 5. SAMPLE DATA PLANES FROM THE TRANSPORTATION SUB-MODEL OF THE DENVER URBAN AREA. Scale 1:500,000. Original data source was a 1971, 1:45,000 scale Colorado highway map of the metropolitan area.

(a) Freeway interchanges manually sampled from the highway map.
(b) Minimum distance to the freeway interchanges emphasizing smallest distances in black. Computed from (a).
(c) A high-capacity major road class composited from the highway map to represent major roads, principals, and expressways.
(d) Minimum distance to the high-capacity major roads emphasizing smallest distances in black. Computed from (c).



(a) Population Density

(b) Mean Number of Cars per Family

(c) Median Housing Unit Value

(d) Mean Family Income

FIGURE 6. SAMPLE DATA PLANES FROM THE SOCIO-ECONOMIC SUBMODEL OF THE DENVER URBAN AREA. Scale 1:500,000. Original source of the data was the 1970 U.S. Census.

(a) Population density data plane emphasizing highest densities in black. Computed from statistics reported for total population per census tract.

(b) Mean number of cars per family emphasizing highest numbers in black. Computed from statistics reported for the number of 1, 2, 3 and 3+ car families per census tract.

(c) Median housing unit value emphasizing highest value in black.

(d) Mean family income emphasizing highest income in black.

It will be subsequently shown how these inputs might be obtained and overlaid in a timely, accurate fashion by computer analysis of LANDSAT multispectral digital images. The initial testing of the landscape modeling process employed very carefully prepared and accurate maps of urban land use interpreted from low-altitude, black-and-white airphotos for a current (1970) and a past (1963) date. A uniform land use classification scheme covering 24 land uses was first adopted (Table 2) (Anderson, Hardy, and Roach, 1972). A single photo interpreter interpreted the large collection of airphotos for each date annotating the location of each of the 24 land uses to a ten acre resolution. The two land use interpretations on the airphotos for 1963 and 1970 were next transferred to the sixteen 1:24,000 scale topographic maps covering the site. The ten-acre dot patterns were imposed on these maps and the 24 class land use maps for both dates were tabulated and overlaid onto the landscape model (Fig. 7).

Projection of Future Land Use Patterns

Visual Display of Land Use Changes

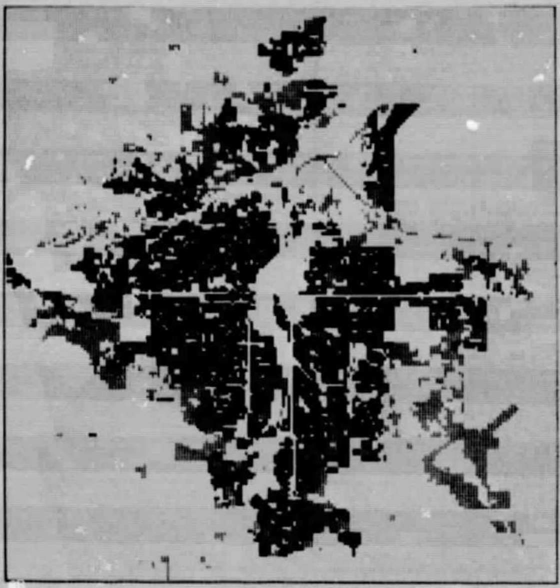
Recent changes in land use can be computed and displayed from the land use data planes overlaid in the model. A cell-by-cell comparison of the 24 land uses interpreted for the two different dates provides a visual display of the areas of gain or loss of each land use (Fig. 8). A summation of the cells which have changed between the two dates for each of the 24 land uses provides insight into those categories which are rapidly evolving (Table 3). The detailed cell-by-cell comparisons of the land use type for each of the 36,864 cells of each date provide a matrix which contains the number of ten-acre cells of each of the 24 land uses of the earlier date (1963) which had converted to another land use by the second date (1970). This tabular cell count matrix cross indexes the amount of each change in land use which occurred in the recent past. A probability transition matrix is prepared from the tabular matrix of cell changes. This new matrix contains the probabilities that each of the 24 land uses will remain the same or change to some other land use over the time interval represented by the dates of the two input land use data planes (Table 4).

Markov Trend Model

The assumption that future changes in land use can be measured in terms of those which occurred in the recent past allows a simple projection to be made of the future trends in land use (Miller, 1976). This assumption does not truly represent the evolution of real-world land use, which is constantly subjected to new, unanticipated stimuli. However, the techniques for projection of future land use, assuming no change in practices from the past, must be perfected before the impact of new, unmeasured, unobserved trends can be incorporated into the process.

TABLE 2. HIERARCHIAL LAND USE CLASSIFICATION SCHEME USED FOR THE DENVER URBAN AREA. First- and second-order levels of classification are shown. This scheme was used in a slightly modified form for the airphoto interpretations (Fig. 7) and the automated interpretation of the single date LANDSAT imagery (Tables 6, 7, 8, and 9). (After Anderson, Hardy, and Roach, 1972).

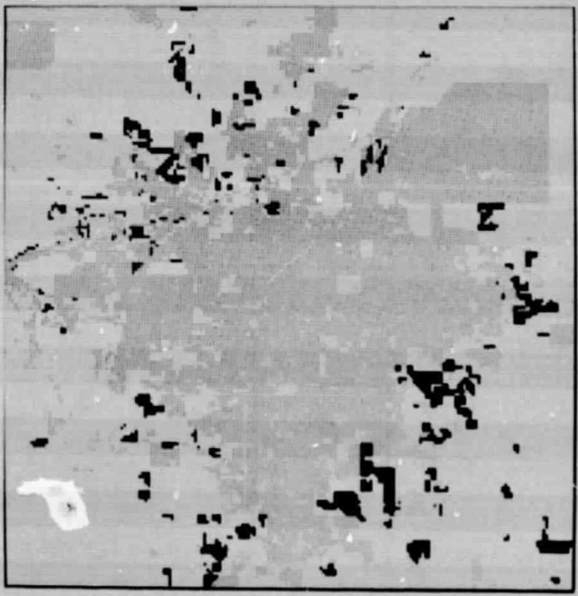
FIRST-ORDER LAND USE	Second-Order Land Use
AGRICULTURAL LANDS	
	Cropland, Nonirrigated
	Cropland, Irrigated
	Pasture
FORESTED LANDS	
	Coniferous, Intermittent Crown
	Coniferous, Solid Crown
	Deciduous, Intermittent Crown
RANGE LANDS	
	Chaparral
	Grassland
URBAN LANDS	
	Commercial and Services Area
	Extraction - Pit, Quarry, Strip Mine
	Recreational - Park, Golf Course, Drive-In Theater
	Cemetery
	Industrial
	Open Land - Vacant Land in Built-up Areas
	Public and Institutional - Schools, Federal Reservations
	Residential - High and Low Density
	Transportation Area - Airports, Railroad Yards, Interchanges
	Utility - Sewage Plant, Power Plant, Antenna Field
	Solid Waste Dump - Land Fill
BARREN LANDS	
	Hilly Slopes - Nonforested or Sparsely Timbered
	Exposed Rock - Sparse Vegetation
WATER AREAS	
	Streams and Canals
	Lakes
	Reservoirs



(a) 1963 Land Use

(b) 1963 Land Use

(c) 1970 Land Use



(d) 1970 Land Use

FIGURE 7. SAMPLE DATA PLANES FROM THE LAND USE SUBMODEL OF THE DENVER URBAN AREA. Scale 1:500,000. Land use maps were compiled for 22 land use categories by very detailed interpretation of low-altitude, back-and-white airphotos.

(a) and (c) Land use data planes emphasizing single- and multiple-unit residential areas in black.

(b) and (d) Land use data planes emphasizing strip and cluster residential areas in black.

(a) Loss in Open Space, 1963 to 1970

(b) Loss in Agricultural Land, 1963 to 1970

FIGURE 8. LOSSES IN SELECTED LAND USES FOR THE DENVER URBAN AREA. Scale 1:500,000. Computed from a comparison of the 1963 (Fig. 7a) and 1970 (Fig. 7c) land use maps.

(a) Open space of 1963 which was converted to other land uses by 1970 is in black.

(b) Agricultural land of 1963 which was converted to other land uses by 1970 is in black.

TABLE 3. NET CHANGES IN 1963 LAND USE RELATIVE TO 1970. The specific net transitions such as those illustrated in Figure 8 which occurred between various specific land use classes are detailed below. Computer comparison of the land use data planes illustrated in Figure 7 provides these simple statistics.

Land Use Type	1963 Acreage (in acres)	1970 Acreage (in acres)	1970 Acreage (net gain (+) or loss (-) in acres)
Single- & Multiple-Unit Residential Dwellings	64,210	70,500	+6,290
Commercial & Service Facilities	11,020	11,820	+800
Industrial Facilities	8,870	10,610	+1,740
Extractive Mining Operations	4,630	6,360	+1,730
Transportation, Communications, & Utilities	7,290	8,650	+1,360
Institutional Facilities	31,250	31,590	+340
Strip & Cluster Development	13,500	16,550	+3,050
Mixed Urban Land Uses	40	0	-40
Open & Other Urban Land Uses	37,410	35,620	-1,790
Cropland & Pasture Agricultural Land	160,090	146,240	-13,850
Orchards, Groves & Other Horticultural Areas	60	60	0
Livestock Feeding Operations	20	20	0
Other Agricultural Land	330	70	-260
Deciduous Forest Land	180	180	0
Streams & Waterways	960	1,010	+50
Lakes	5,930	6,410	+480
Reservoirs	1,580	1,750	+170
Other Water Uses	50	50	0
Vegetated Nonforested Wetland	1,710	1,710	0
Sand (Other Than Beaches)	640	520	-120
Other Barren Land	18,870	18,920	+50
Totals	368,640	368,640	±32,120

TABLE 4. DENVER LAND USE TRANSITION MATRIX, 1963 TO 1970. Entries in the matrix are the proportion of each 1963 land use which converted to another land use in 1970. A blank in the matrix means no conversion occurred between the respective land uses during the 1963 to 1970 time period. A 1.0 in the matrix means that the area of that land use was not changed or was increased by the conversion to it from some other land use between 1963 and 1970. Based on 10 acre cells.

1963 LAND USE		CONVERTING TO 1970 LAND USE																				
LAND USE TYPE	CODE→ ↓	11	12	13	14	15	16	17	18	19	21	22	23	24	41	51	52	53	55	61	73	75
Single & Multiple Unit Residential Dwellings	11	.99	<.01							<.01												
Commercial & Service Facilities	12	<.01	.99							<.01												
Industrial Facilities	13	<.01	<.01	.99			<.01															
Extractive Mining Operations	14	<.01		.01	.96						.01						.01					
Transportation, Communications, & Utilities	15					1.0																
Institutional Facilities	16	<.01	<.01				.99			<.01							<.01					
Strip & Cluster Development	17							1.0														
Mixed Urban Land Uses	18							1.0														
Open & Other Urban Land Uses	19	.06	.01	.01	<.01	.01	.01	.01		.85	.01						<.01					<.01
Cropland & Pasture Agricultural Land	21	.02	<.01	<.01	<.01	<.01	<.01	.02		.02	.91						<.01	<.01				
Orchards, Groves, & Other Horticultural Areas	22											1.0										
Livestock Feeding Operations	23												1.0									
Other Agricultural Land	24	.03			.24	.39				.06	.09			.15			.03					
Deciduous Forest Land	41														1.0							
Streams & Waterways	51	.01														.99						
Lakes	52										<.01						.99					
Reservoirs	53																	1.0				
Other Water Uses	55																		1.0			
Vegetated Nonforested Wetland	61																			1.0		
Sand (other than beaches)	73			.02	.14					.03											.81	
Other Barren Land	75						<.01				<.01											.99

The probability transition matrix is input to a Markov projection process which operates on the relative amounts of each of the 24 land uses present in the most current land use data plane (1970) and projects future trends in the land use (Fig. 9). These future trends can be projected as far into the future as desired; however, only the projections of first few years are realistic. After several future years have passed the assumption of homeostasis of the processes noted above does not hold. Only gross interpretation can be made of the long run behavior of the landscape from this data, as new, unanticipated demands will quickly impact upon future urban growth and attendant land use evolution.

Spatial Changes by Discriminant Analysis

A water yield model of the Denver urban area would provide improved prediction of the anticipated future changes in runoff if a sequence of maps of the future land use were available. The data planes of the current (1970) and earlier (1963) land use are overlaid in the landscape model with the 30 landscape variables which control and correlated with the recently observed changes. Those 2,039 of the 36,864 cells in the model which made a change between the two land use dates provide a basis for determining how the landscape variables correlated with changes in land use in a multivariate sense. The 2,039 cells which made a transition from one land use to another over the test period of seven years provide a group of observations. These observations are used to model how the changes in land use will proceed in the future based on the landscape variables such as slope, aspect, distance to freeways, etc. (Table 5).

A single, simplified test case may clarify this approach. Cropland and pasture agricultural land were converted to single- and multiple-unit dwellings for the seven year period. All 397 examples of this in the 36,864 cell model can be assembled together and correlated in a multivariate sense: with the 30 landscape variables for these cells. This provides a basis for examining any cell of cropland and pasture agricultural land in the entire landscape model and computing the probability that it will make this conversion to single- and multiple-unit dwelling in land use in the future.

The Denver urban area was mapped with 24 land use classes on the initial (1963) and subsequent (1970) date. Thus 24^2 possible changes in land use might occur. Only 38 of the possible 576 changes actually did occur as seen from the earlier probability transition matrix (Table 4). Many kinds of possible land use changes seldom or never occur, e. g., the backward conversion from some higher state of land use, such as industrialized land, back to a lower state, such as agricultural land. All test cells which have undergone a specific type of transition can be assembled together so that the 2,039 changes observed between the two dates are grouped into the 38 "change" classes. The statistical technique of discriminant analysis is applied to these 38 groups of observations to form a simulation model trained to recognize the multivariate range of each landscape variable associated with each of the 38 types of changes. This model

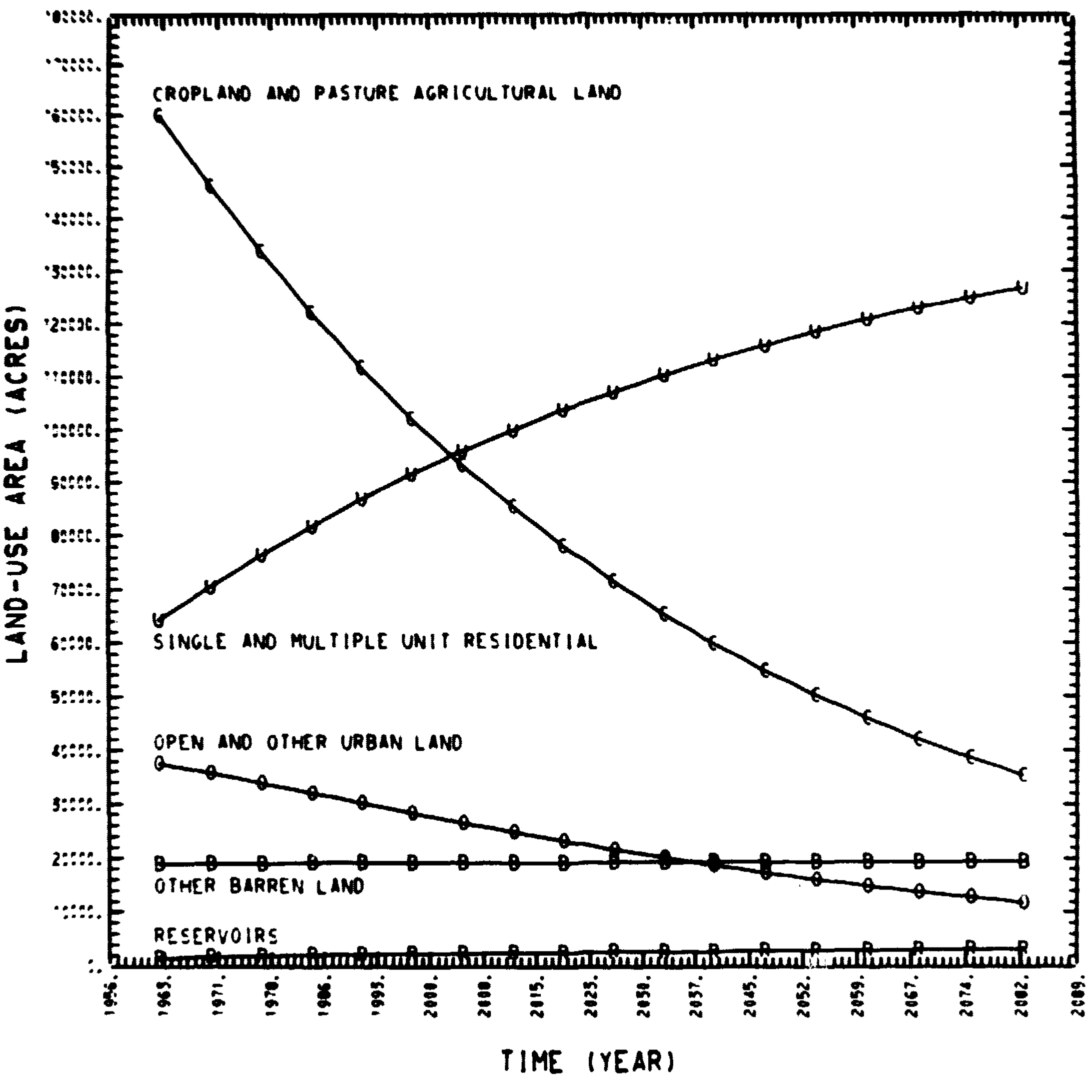


FIGURE 9. PREDICTION OF FUTURE TRENDS IN THE AMOUNT OF OPEN SPACE AND COMPETING LAND USE IN THE DENVER URBAN AREA. Simulated using a Markov process and the transition matrix (Table 4) provided by a 36,864 cell-to-cell comparison of the 1963 to 1970 land use data planes (Figs. 7 and 8).

TABLE 5. ACCURACY OF PREDICTION OF FUTURE CHANGES IN LAND USE ON A CELL-BY-CELL OR SPATIAL BASIS FOR THE DENVER URBAN AREA. Based on predicting the change in land use from 1963 to 1970 for the 2,039 cells in the landscape model which underwent a change during the period. The change is predicted by discriminant analysis from the landscape variables with reference to the initial or 1963 land use. Accuracy is based upon the number of cells whose future or 1970 land use is correctly predicted.

1963 Land Use Predicted to 1970 Land Use	Total Sample Cells	Total Cells Correct	Prediction Accuracy (percent)
Cropland & Pasture Agricultural Land			
Δ *to* Single & Multiple-Unit Residential	397	314	79.1
Commercial & Service Facilities	27	6	22.1
Industrial Facilities	123	42	34.2
Extractive Mining Operations	139	86	61.8
Transport., Communic., & Utilities	72	36	50.0
Institutional Facilities	23	2	8.7
Strip & Cluster Development	262	108	41.2
Open & Other Urban Land Uses	344	199	57.9
Other Agricultural Land	2	2	100.0
Streams & Waterways	4	3	75.0
Lakes	22	4	18.2
Reservoirs	17	17	100.0
Other Barren Land	5	3	60.0
Other Agricultural Land			
Δ *to* Single- & Multiple-Unit Residential	1	1	100.0
Extractive Mining Operations	8	5	62.5
Transport., Communic., & Utilities	13	9	23.1
Open & Other Urban Land Uses	2	2	100.0
Cropland & Pasture Agricultural Land	3	3	100.0
Lakes	1	0	0.0
Open & Other Urban Land Uses			
Δ *to* Single- & Multiple-Unit Residential	231	184	79.7
Commercial & Service Facilities	53	20	37.7
Industrial Facilities	45	24	53.3
Extractive Mining Operations	33	27	81.8
Transport., Communic., & Utilities	51	20	39.2
Institutional Facilities	26	7	26.9
Strip & Cluster Development	39	24	61.5
Cropland & Pasture Agricultural	43	13	30.2
Streams & Waterways	1	1	100.0
Lakes	5	4	80.0
Extractive Mining Operations			
Single- & Multiple-Unit Residential	3	2	66.7
Industrial Facilities	5	5	100.0

TABLE 5. (Continued)

1963 Land Use Predicted to 1970 Land Use	Total Sample Cells	Total Cells Correct	Prediction Accuracy (percent)
Extractive Mining Operations (Continued)			
Δ *to* Cropland & Pasture Agricultural	3	3	100.0
Lakes	5	4	80.0
Sand (Other Than Beaches)			
Industrial Facilities	1	1	100.0
Δ *to* Extractive Mining Operations	9	6	66.7
Open & Other Urban Land Uses	2	2	100.0
Institutional Facilities			
Δ *to* Lakes	15	15	100.0
Mixed Urban Land Uses			
Δ *to* Strip & Cluster Development	4	4	100.0
Totals	2,039	1,208	59.2

is then applied to all 2,039 test samples to determine how many of these training cells can be assigned to the correct change group (Table 5). Overall the model correctly identified the expected change in land use of 1,208 of these test cells based only upon their beginning land use and the 30 landscape variables. This means that the model could predict the proper new or future land use for the 1,208/2,039 training cells 59.2% of the time. Since a choice was made from 38 different land uses the accuracy of 1/38 groups times 100% = 2.6 % would have resulted from random placement of the 2,039 cells. The 59.2% prediction most certainly is not perfect, but clearly indicates that this model approach is feasible.

The discriminant model could be applied to all 36,864 cells in the landscape model to predict the next most probable change in land use for each and every cell based upon its current land use and associated landscape variables. The earlier Markov model provided the number of cells which will become some new land use in a given future time increment (Fig. 9). After the discriminant model predicts the next change in land use for each cell, the actual changes in a given future time period can be determined by assembling all changes of a given type from the 36,864 predictions, ordering them by their probability of occurrence, and selecting the correct number from the highest probabilities at the top of the list. The exact spatial location of each selected cell is preserved and the process can be repeated for each of the 38 types of changes. A predicted map of the future distribution of each land use for a particular date can be displayed. The total process can be iteratively performed to yield a succession of projected land use maps at selected time increments for input to the hydrologic model.

At present these spatial projections are still being prepared and cannot be illustrated.

Improvement in LANDSAT Image Classification

Deterministic hydrologic modeling and the spatial landscape projections outlined above require accurate mapping of current and past land use in a cellular format. These data planes could most easily be obtained by direct computer reduction of LANDSAT digital imagery. LANDSAT imagery has been available since 1972 and thus presents a sufficient time base for analysis of land use change. Accuracy of the computer analysis of LANDSAT data can be measurably improved by the input of landscape variables, such as the near-instantaneous solar insolation computed from landscape variables for the date and time of available imagery (Fig. 10). LANDSAT multispectral bands 4, 5, 6, and 7 and the six ratios of these bands were overlaid by all the landscape variables exclusive of the various maps of land use (Fig. 11). Stepwise discriminant analysis was used to test the computer recognition and mapping of each of the 24 land use categories (Table 2) using a total of 2,413 representative sample cells grouped into 24 training sets. The first test classification used only the four LANDSAT MSS spectral bands and no other information and correctly classified 65.2% of the training set samples into the correct land use (Table 6). A second classification using the four LANDSAT MSS spectral bands and six transformed images consisting of ratios of the four spectral images yielded an improvement of only 2.1 percentage points to 67.3%. This indicates that ratios of image spectral bands contributed little to this land use classification (Table 7). Next, the 30 landscape data planes, exclusive of any of the land use data planes, are included in the image classification and the accuracy of the correct computer identification of the training sets increases to 99.7% for the 24 classes (Table 8). This means that 99.7% of the 2,413 training set image cells could be correctly assigned to their land use category. The random assignment of these cells to the 24 land use classes would have yielded 1/24 classes times 100% = 4.1% accuracy. This is a significant increase in the accuracy of the land use mapping capability of automatically interpreted LANDSAT images.

The stepwise discriminant multispectral image classification algorithm automatically adds each variable in the order in which it will add the most to the land use classification accuracy achieved at that step. Clearly, the addition of many of the less sensitive landscape variables has not measurably increased the final accuracy achieved and has significantly increased the cost of the test classification (Fig. 12). Accuracy and cost figures were used as a basis for selecting three optimal LANDSAT MSS spectral bands and four landscape variables from the 40 initial variables for a final test. These seven variables were able to correctly assign all 24 land uses with an accuracy of 96.6% (Table 9). It should be carefully observed that these tests indicate only the training set accuracy for the use of LANDSAT and landscape or ancillary data

FIGURE 10. SOLAR INSOLATION DATA PLANE FROM THE PHYSIOGRAPHIC SUB-MODEL OF THE DENVER URBAN AREA. Scale 1:500,000. Near-instantaneous solar radiation at the ground surface. Computed from the slope (Fig. 4b) and aspect (Fig. 4c) data planes for the scan time of the August 15, 1973 LANDSAT image (Fig. 11). Areas of lowest solar insolation are emphasized in black.

(a) LANDSAT MSS Band 5

(b) LANDSAT MSS Band 7

FIGURE 11. SAMPLE DATA PLANES FROM THE SATELLITE IMAGERY SUBMODEL OF THE DENVER URBAN AREA. Scale 1:500,000. Graymaps of the August 15, 1973 LANDSAT image showing each center picture element of 1.11 acres taken from a three by three square array of picture elements totalling ten-acres. Before the sampling the LANDSAT image was geometrically rectified to overlay the landscape data planes with a square resolution cell of 1.11 acres (Fig. 2).

TABLE 6. ACCURACY OF AUTOMATED INTERPRETATION OF THE FOUR ORIGINAL MSS BANDS OF AN IMAGE OF THE DENVER URBAN AREA. Based on identifying 24 land uses (Table 2) with a training set sample of 2,413 picture elements. Variables were added in a stepwise fashion and classified using discriminant analysis.

Step Number	Variable Name	Training Set Accuracy (% correct)	Computer Time Expended (seconds)
1	LANDSAT MSS Band 7	50.1	8.7
2	LANDSAT MSS Band 5	62.9	9.7
3	LANDSAT MSS Band 4	65.7	10.5
4	LANDSAT MSS Band 6	65.2	24.8

TABLE 7. ACCURACY OF AUTOMATED INTERPRETATION OF THE FOUR ORIGINAL MSS BANDS AND SIX RATIOS FOR A SINGLE DATE LANDSAT IMAGE OF THE DENVER URBAN AREA. Based on identifying 24 land uses (Table 2) with a training set sample of 2,413 picture elements. Variables were added in a stepwise fashion and classified with discriminant analysis.

Step Number	Variable Name	Training Set Accuracy (% correct)	Computer Time Expended (seconds)
1	LANDSAT MSS Band 7	50.1	11.5
2	LANDSAT MSS Band 5/4 Ratio	61.3	12.1
3	LANDSAT MSS Band 7/6 Ratio	63.1	12.8
4	LANDSAT MSS Band 5	64.3	13.6
5	LANDSAT MSS Band 4	66.6	14.4
6	LANDSAT MSS Band 6/4 Ratio	67.2	15.3
7	LANDSAT MSS Band 7/4 Ratio	67.3	16.2
8	LANDSAT MSS Band 5/6 Ratio	66.9	16.9
9	LANDSAT MSS Band 6	67.3	17.5
10	LANDSAT MSS Band 7/5 Ratio	67.3	34.3

TABLE 8. IMPROVEMENT IN THE ACCURACY OF AUTOMATED INTERPRETATION OF A SINGLE DATE LANDSAT IMAGE OF THE DENVER URBAN AREA BY THE ADDITION OF 30 ANCILLARY LANDSCAPE VARIABLES. Based on identifying 24 land uses (Table 2) with a test sample of 2,413 picture elements. Ancillary landscape variables were added in a stepwise fashion and classified using discriminant analysis. (M.D.) = minimum distance.

	Step Number	Variable Name	Training Set Accuracy (% correct)	Computer Time Expended (seconds)
Forced LANDSAT Variables	1	MSS Band 7	50.1	24.2
	2	MSS Band 5/4 Ratio	61.3	25.0
	3	MSS Band 7/6 Ratio	63.1	25.8
	4	MSS Band 5	64.3	26.5
	5	MSS Band 4	66.6	27.3
	6	MSS Band 6/4 Ratio	67.2	28.0
	7	MSS Band 7/4 Ratio	67.3	29.0
	8	MSS Band 5/6 Ratio	66.9	29.8
	9	MSS Band 6	67.3	30.4
	10	MSS Band 7/5 Ratio	67.3	31.1
Free Landscape Variables	11	Census Tract Acreages	84.4	31.7
	12	Fully Developed City Streets (M.D.)	89.6	32.5
	13	Topographic Elevations	94.4	33.2
	14	Freeway Interchanges (M.D.)	97.1	34.0
	15	Freeways (M.D.)	97.5	34.7
	16	Median Housing Unit Rent	97.4	35.5
	17	Major Roads (M.D.)	97.5	36.3
	18	Median Housing Unit Value	98.3	37.0
	19	Total Vacant Housing Units	98.6	37.8
	20	Average Number of Cars per Family	98.5	38.6
	21	Housing Unit Density	98.9	39.3
	22	Population Density	98.7	39.9
	23	Total Population	98.8	40.6
	24	Mean Family Income	98.6	41.3
	25	Two-Car Families	98.8	42.1
	26	Three-Car Families	99.1	42.8
	27	Year-Round Housing Unit Density	99.3	43.5
	28	Total Housing Units Density	99.6	44.3
	29	Total Number of Families	99.4	45.0
	30	One-Car Families	99.3	45.9
	31	Family Density	99.3	46.8
	32	Solar Insolation	99.4	47.6
	33	Topographic Slope	99.7	48.1

TABLE 8. (Continued)

Step Number	Variable Name	Training Set Accuracy (% correct)	Computer Time Expended (seconds)
34	Surficial Geology	99.7	48.7
35	Minor Roads (M.D.)	99.7	49.6
36	MSS Band 5/ Solar Insolation	99.7	50.3
37	MSS Band 4/ Solar Insolation	99.7	51.0
38	MSS Band 7/ Solar Insolation	99.7	51.8
39	Topographic Aspect	99.7	52.5
40	MSS Band 6/ Solar Insolation	99.7	53.4

to map land use. Current tests are underway to determine how accurately these procedures project to map the entire study site. These verification tests are being performed by classifying all 36,864 cells for each variable added in a stepwise fashion. The accuracy of each successive map is them verified on a cell-by-cell basis by comparison with the known 24 class land uses stored in the landscape model. The results at this point are not complete but clearly indicate that more than seven variables will finally be required, as total map accuracy does not increase as rapidly as training set accuracy. All LANDSAT imagery employed to date has been for a single date; the subsequent overlay of several different seasonal dates of LANDSAT imagery will provide increased accuracy or better map accuracy with the overlay of fewer landscape data planes.

NORTHERN THAILAND FOREST SITE CASE STUDY

Background

A second application of landscape modeling and improvement in image interpretation procedures has been underway for five years (Wacharakitti and Miller, 1975). It is presented as an example of how the same procedures are being applied to an area typical of many natural watersheds. Accurate mapping of the forest and agricultural land cover of these watersheds and prediction of their future changes would significantly improve the application of deterministic hydrological modeling in such areas. At first glance it might be assumed that this project might be handicapped due to a shortage of maps or data planes. However, not only is there no shortage of data in this very remote test area but the forest and agricultural land uses appear to evolve in simpler patterns free of many complicated spatial constraints of urban areas, such as the zoning which regulates the urban land changes. While man-made changes occur, they appear more nearly coupled with the landscape. For example, the clearing of trees for shifting agriculture is a function of the land slope, soil type, and other

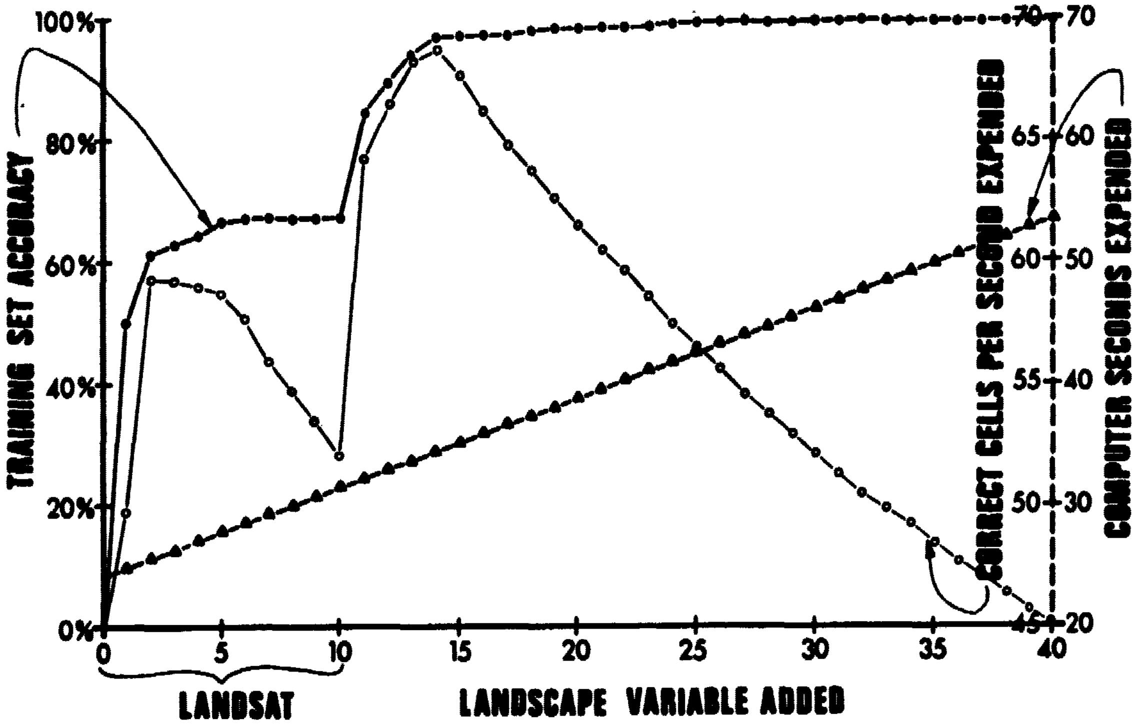


FIGURE 12. ACCURACY AND COSTS OF PROCESSING SINGLE DATE LANDSAT IMAGE OF THE DENVER URBAN AREA WITH 30 ANCILLARY LANDSCAPE VARIABLES. Based on identifying 24 land uses (Table 2) with a training set sample of 2,413 picture elements. LANDSAT variables were forced in a predetermined optimal order and the landscape variables were added in a free stepwise fashion. The variable numbers coincide with step numbers in Table 8.

TABLE 9. HIGH ACCURACY AND ECONOMY ACHIEVED BY AUTOMATED INTERPRETATION OF A SELECTION OF THREE MSS BANDS OF A SINGLE DATE LANDSAT IMAGE OF THE DENVER URBAN AREA WITH OVERLAYS OF FOUR LANDSCAPE VARIABLES. Based on identifying 24 land uses (Table 2) with a training set sample of 2,413 picture elements. Ancillary landscape variables were added in a stepwise fashion and classified by discriminant analysis. (M.D.) = minimum distance.

	Step Number	Variable Name	Training Set Accuracy (% correct)	Computer Time Expended (seconds)
Forced LANDSAT	1	MSS Band 7	50.1	10.0
	2	MSS Band 5	62.9	10.8
	3	MSS Band 4	65.7	11.6
Free Landscape	4	Census Tract Acreages	82.6	12.4
	5	Fully Developed City Streets (M.D.)	88.8	13.1
	6	Topographic Elevation	92.9	13.8
	7	Freeway Interchanges (M.D.)	96.6	14.7

landscape variables. This natural landscape model is just being completed and thus only preliminary results are available. It does show the extension of the procedure to another totally different landscape and suite of problems.

Site Description

The Northern Thailand forest site was selected to represent the northern region of Thailand. It is situated near the Golden Triangle at the corner intersection of China, Burma, Laos, and Thailand (Fig. 13). It represents mountainous area which was originally heavily forested but has been rapidly cleared for shifting cultivation of opium, dry-land rice, and other cash crops. It is typical of a large portion of the world's tropical forests where cut-and-burn agriculture is out of balance with regrowth and the watersheds are being rapidly denuded.

Construction of the Landscape Model

The site modeled is 360 square kilometers and has been cellularized with a resolution of one hectare (approximately 2.5 acres), yielding 36,000 cells (Fig. 14). Input of the data planes into the landscape model was completed entirely by the manual dot sample method described earlier. Area planes, such as topographic elevation and geology, are directly sampled cell-by-cell from 1:50,000 maps (Fig. 15a). Additional derived area planes are computed, such as topographic slope and aspect from elevation, as noted earlier (Figs. 15b and 15c). Point feature planes, such as the location of temporary huts or permanent dwellings for four different dates, were interpreted from low-altitude, black-and-white airphotos (Fig. 16a). These planes, in turn, are computed into minimum distance area planes (Figs. 16c and 16d). Linear features, such as roads and trails and drainage, were similarly interpreted from the airphotos for four dates and computed into minimum distance planes (Figs. 16d and 16b). Airphoto interpretation maps for four different dates were prepared covering nine forest and agricultural types (Table 10) and overlaid onto the model via the area dot sampling procedure. These land use maps were all interpreted by a single individual in a consistent fashion and clearly illustrate the evolution of the area from forest to shifting and permanent cultivation (Fig. 17).

Projection of Future Land Use Patterns

Visual Display and Tabulation of Tendencies

Intercomparison of the land use data planes for this site on a cell-by-cell basis yields visual graymaps which clearly display the current imbalance between forest depletion by shifting cultivation and forest regeneration upon agricultural abandonment (Figs. 18 and 19). A type of subsistence-level, dry land, permanent

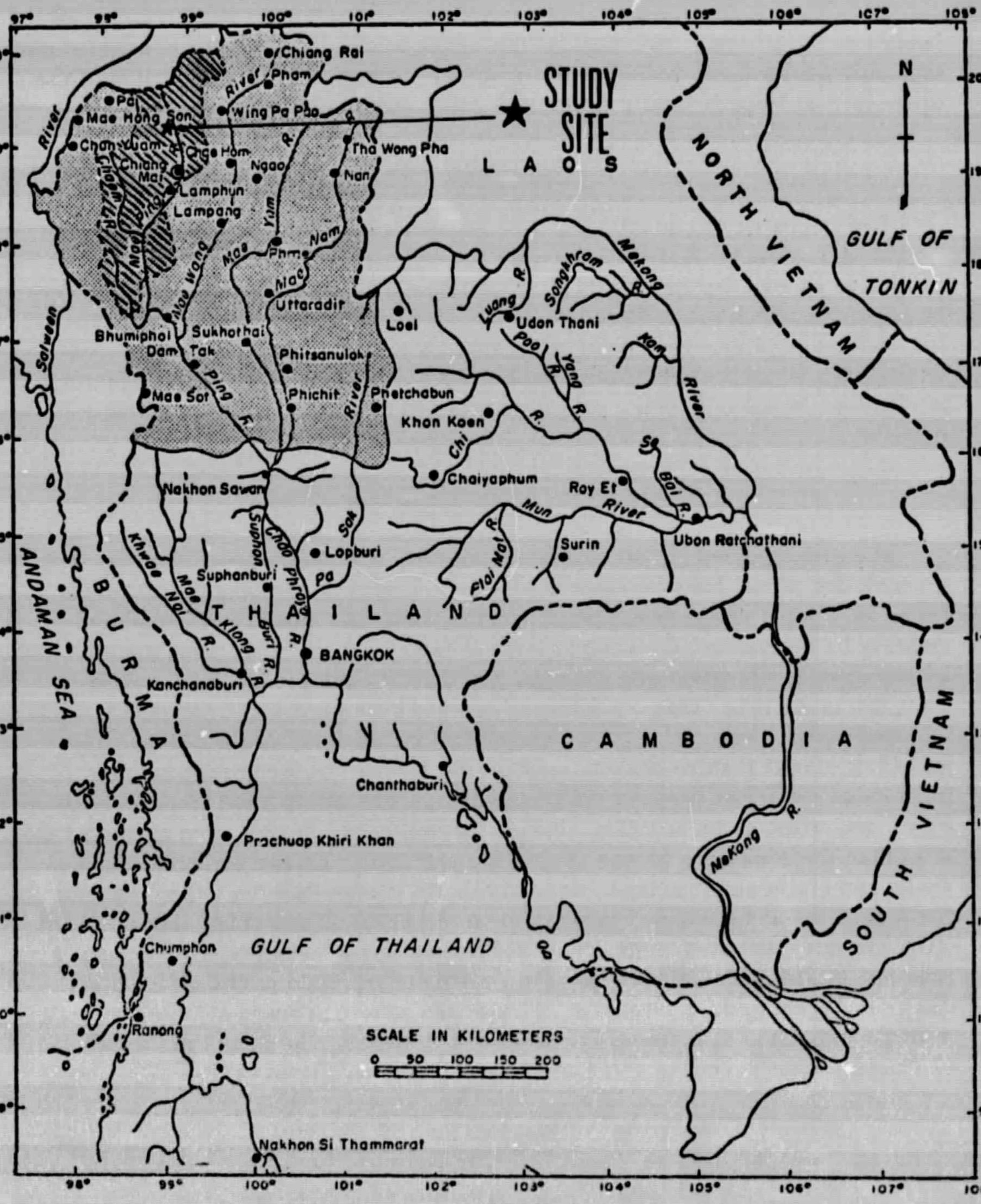
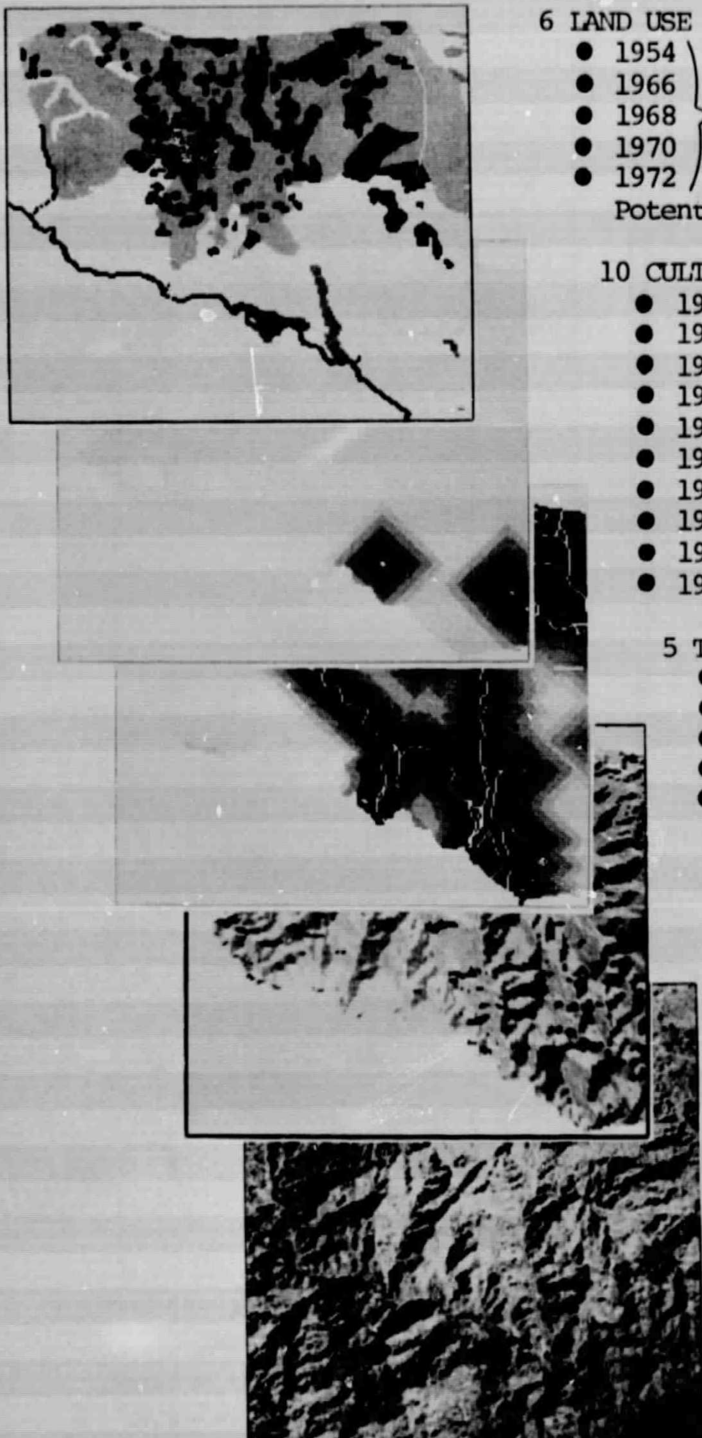


FIGURE 13. REFERENCE MAP FOR THE NORTHERN THAILAND FOREST SITE. The area modeled is approximately 360 square kilometers. The data planes for this site were digitized at a one-hectare cell size yielding approximately 36,000 cells.



6 LAND USE SUBMODEL VARIABLES:

- 1954
- 1966
- 1968
- 1970
- 1972

} Forest Types and Related Land Use

Potential Natural Vegetation

10 CULTURAL FEATURES SUBMODEL VARIABLES:

- 1954
- 1966
- 1968
- 1970
- 1972

} Minimum Distances to Temporary Structures

- 1954
- 1966
- 1968
- 1970
- 1972

} Minimum Distances to Permanent Structures

5 TRANSPORTATION SUBMODEL VARIABLES:

- 1954
- 1966
- 1968
- 1970
- 1972

} Minimum Distances to Roads and Trails

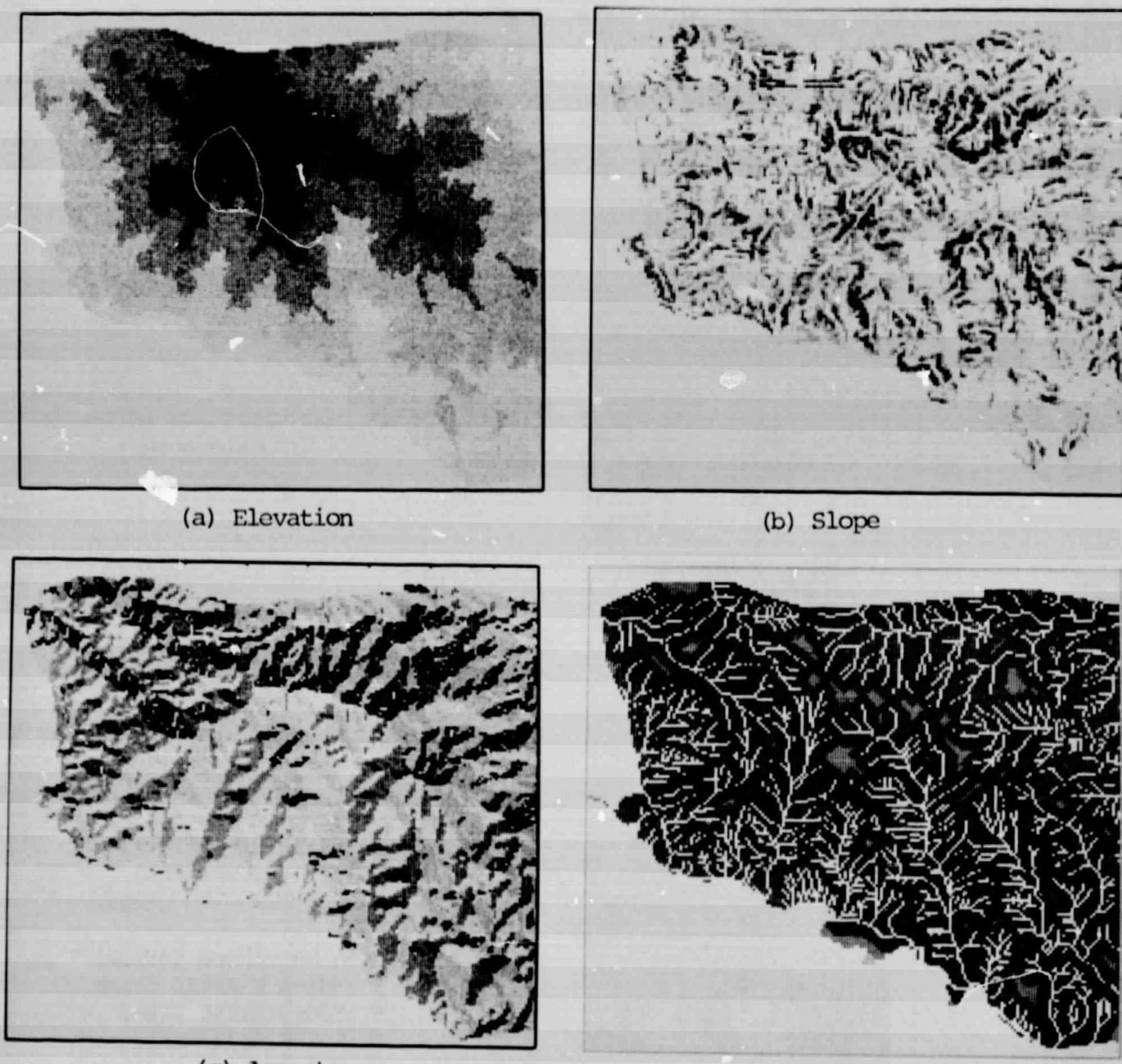
9 PHYSIOGRAPHIC SUBMODEL VARIABLES:

- Topographic Elevation
- Topographic Slope (2 versions)
- Topographic Aspect
- Drainage (2 versions)
- Geology (2 versions)
- LANDSAT Image Insolation

17 LANDSAT IMAGE VARIABLES:

- MSS-4 Visible Green
- MSS-5 Visible Red
- MSS-6 Solar Infrared
- MSS-7 Solar Infrared
- 6 MSS Channel Ratios
- 4 MSS Insolation Ratios
- Photo Interpretation MSS-5
- Photo Interpretation MSS-7
- Photo Interpretation MSS Color IR

FIGURE 14. CONCEPTUAL DIAGRAM OF THE FOUR LANDSCAPE SUBMODELS OVERLAYING THE LANDSAT IMAGERY FOR THE NORTHERN THAILAND FOREST SITE. The multivariate landscape modeling program will be used to model future spatial forest land use changes with the 30 landscape variables. Improved, automated LANDSAT image classification of forest land use can be achieved when the landscape variables are used as collateral or ancillary data planes.



(a) Elevation

(b) Slope

(c) Aspect

(d) Drainage

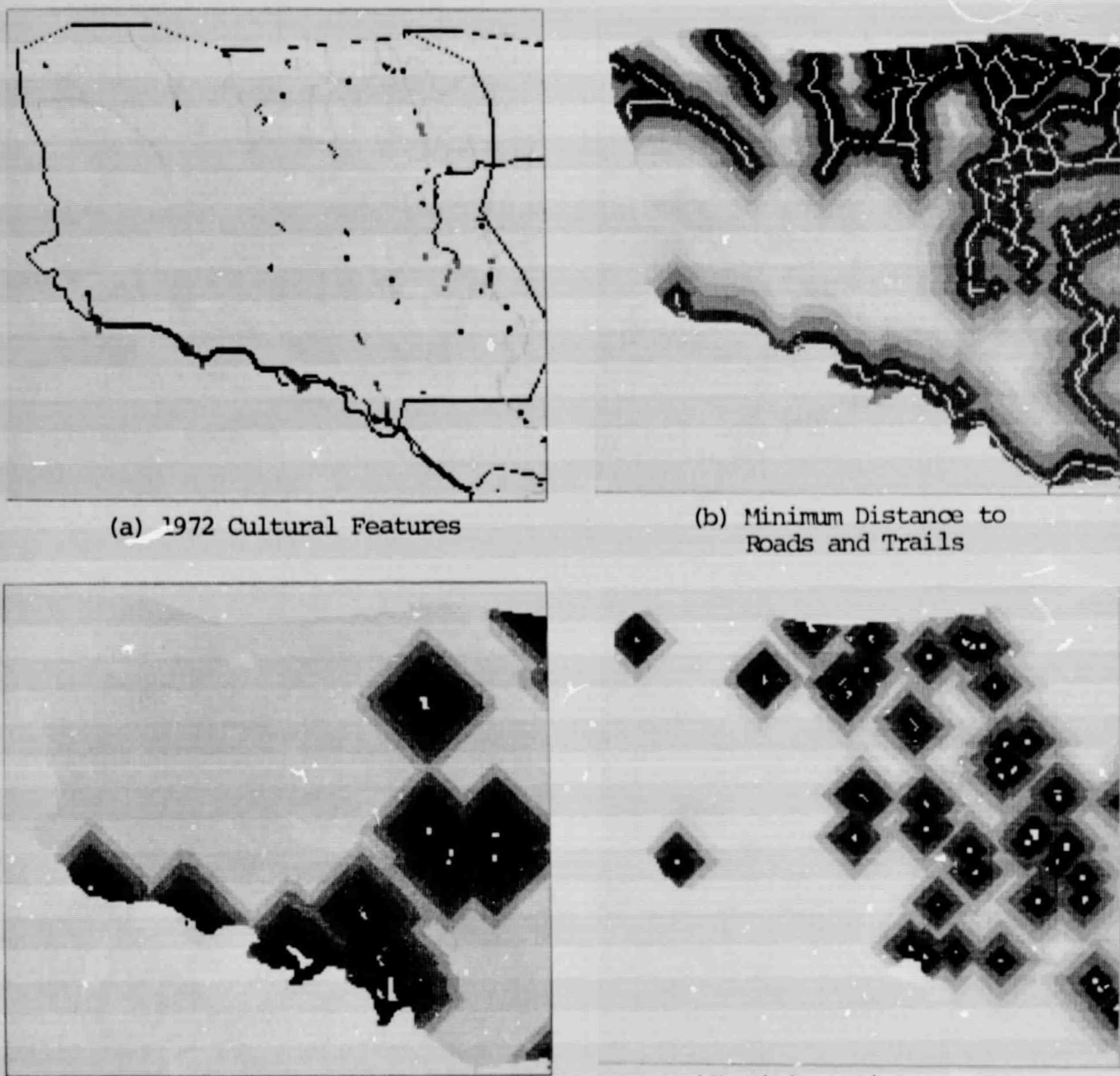
FIGURE 15. SAMPLE DATA PLANES FROM THE PHYSIOGRAPHIC SUBMODEL ON THE NORTHERN THAILAND FOREST SITE. Scale 1:250,000.

(a) Topographic elevation data plane emphasizing highest areas in black.

(b) Topographic slope data plane emphasizing steepest slopes in black. Computed from the elevation data plane (a).

(c) Topographic aspect data plane emphasizing northwest-facing areas in black. Computed from the elevation data plane (a).

(d) Minimum distance to the drainage data plane emphasizing smallest distances in black. The drainage was interpreted from low-altitude airphotos of 1972.



(a) 1972 Cultural Features

(b) Minimum Distance to Roads and Trails

(c) Minimum Distance to Permanent Structures

(d) Minimum Distance to Temporary Structures

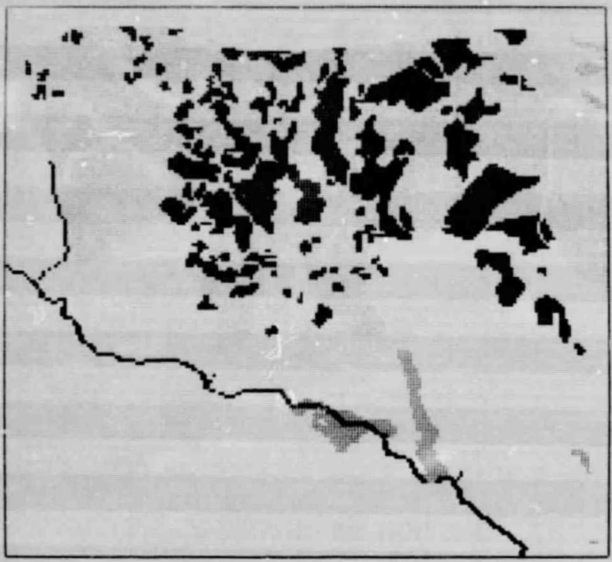
FIGURE 16. SAMPLE DATA PLANES FROM THE CULTURAL FEATURES SUB-MODEL ON THE NORTHERN THAILAND FOREST SITE. Scale 1:250,000.

(a) Cultural feature maps were compiled for three features as interpreted from low-altitude, black-and-white airphotos for 1972.

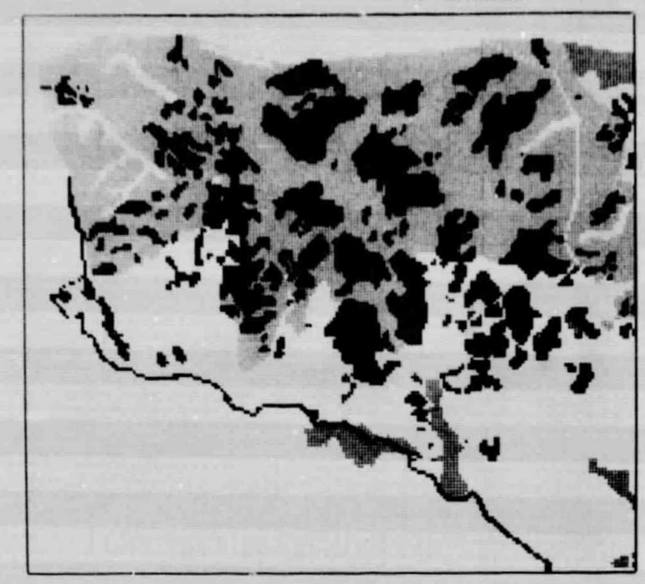
(b) Minimum distance to the road and trail network emphasizing smallest distances in black. Computed from (a).

(c) Minimum distance to permanent structures emphasizing smallest distances in black. Computed from (a).

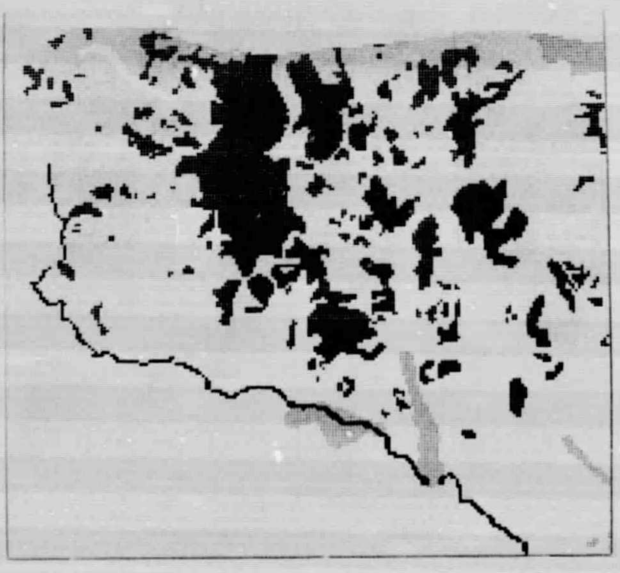
(d) Minimum distance to temporary structures emphasizing smallest distances in black. Computed from (a).



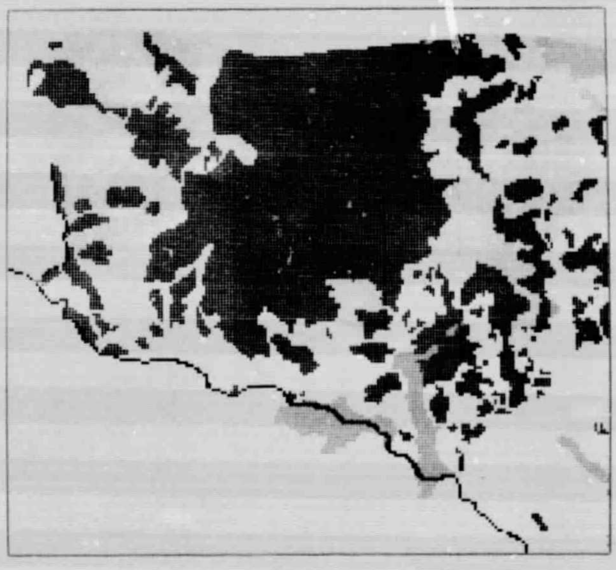
(a) 1954 Forest Types



(b) 1966 Forest Types



(c) 1968 Forest Types



(d) 1972 Forest Types

FIGURE 17. SAMPLE DATA PLANES FROM THE LAND USE SUBMODEL OF THE NORTHERN THAILAND FOREST SITE. Scale 1:250,000. All forest cover type maps were compiled for nine land use categories by very detailed interpretation of low-altitude, black-and-white airphotos. Each display emphasizes the areas of shifting cultivation in black.

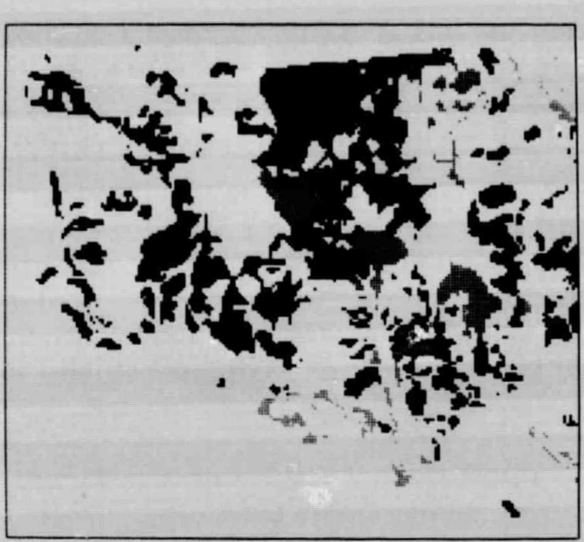
agriculture is setting into this area with attendant alteration of the hydrologic processes, such as a marked increase in sediment yield, increased water yields, and shorter duration hydrographs. The process is rapidly approaching the irreversible point where all significant forest regeneration will cease.

TABLE 10. HIERARCHIAL LAND USE CLASSIFICATION SCHEME USED FOR THE NORTHERN THAILAND FOREST SITE. First- and second-order levels of land use classification are shown. This scheme was used for the airphoto interpretations (Fig. 17) and the automated interpretation of the single data LANDSAT imagery (Table 11). (After Wacharakitti and Miller, 1975).

FIRST ORDER LAND USE Second Order Land Use
FORESTED LANDS
Dry Dipterocarp Forest
Dry Evergreen Forest
Hill Evergreen Forest
Mixed Deciduous Forest with Teak
Dry Dipterocarp Forest with Pine
AGRICULTURAL LANDS
Swidden Areas
Tea Plantations
Irrigated Rice Fields
Teak Plantations

Markov Trend Model

Cross-tabulation of the most recent pair of land use data planes (1968 and 1972) provides a probability transition matrix which is, in turn, applied to the distribution of land use recorded for the second or more recent data to project future trends (Fig. 20). A few years of validity may be assumed for these projections and the difficulties of longer-term interpretations have been previously mentioned. This model, based upon the most recent pair of land use planes, predicts that irrigated rice lands will continue to increase over the long term, as they have over the training period. This cannot be the case, as the amount of land suitable for irrigation is being rapidly exhausted even though it is not yet in short supply. This simple Markov model has used only changes in the recent land uses to project future trends. The discriminant spatial projection model developed for the Denver area is about to be tested on this application. It makes projections based upon landscape features, such as topography,



(a) Forest Depletion, 1968 to 1972

(b) Forest Regeneration, 1968 to 1972

FIGURE 18. LOSSES AND GAINS IN LAND USES FOR THE NORTHERN THAILAND FOREST SITE. Computed from a comparison of the 1968 (Fig. 17c) and 1972 (Fig. 17d) forest type maps.

(a) Forested areas lost to other land uses by 1972 emphasizing those converted to shifting cultivation in black.

(b) Forested areas gained from other land uses by 1972 emphasizing those converted from shifting cultivation in black.

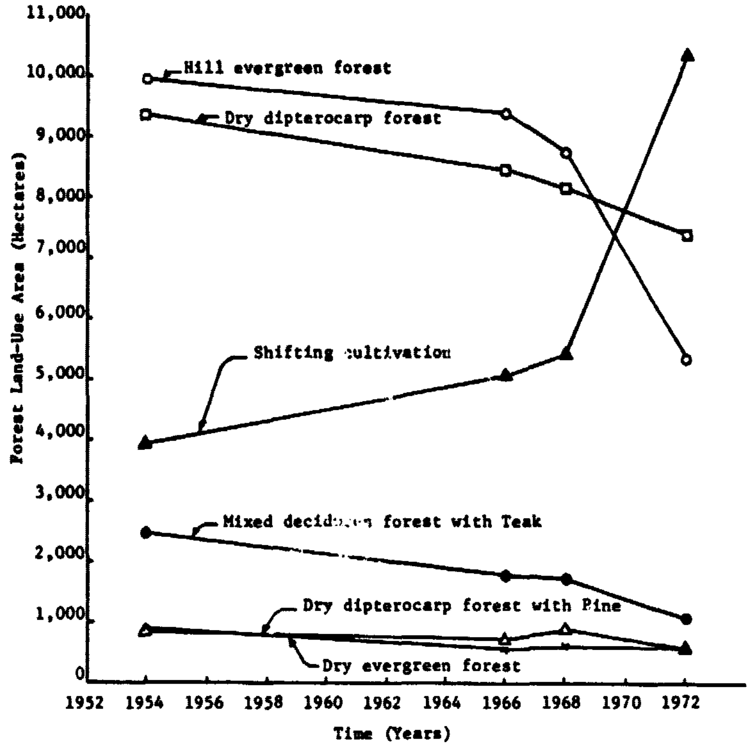


FIGURE 19. FOREST LAND USE DEPLETION AND THE CONCOMITANT INCREASE IN THE AREA OF SHIFTING CULTIVATION. Area of each forest type was obtained by simple computer tabulation of the forest type data planes (Fig. 17).

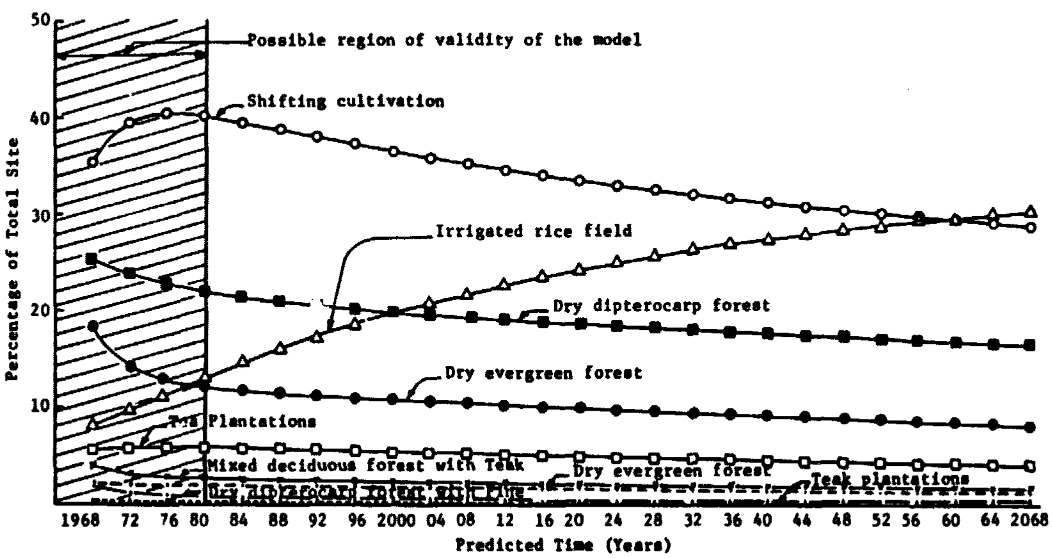


FIGURE 20. PREDICTION OF FUTURE TRENDS IN THE AMOUNT OF EACH FOREST TYPE AND COMPETING AGRICULTURAL LAND USE IN THE NORTHERN THAILAND FOREST SITE. Simulated using a Markov process and transition matrix provided by a 36,000 cell-to-cell comparison of the 1968 to 1972 land use data planes (Figs. 17c and 17d)

and therefore is sensitive to the future exhaustion of the lands of suitable slope and elevation for conversion to irrigated rice. Thus, the discriminant spatial projection of future land use is much more complex using many landscape features and is far more deterministic and sensitive to the actual landscape involved.

Improvement in LANDSAT Image Classification

The computer analysis of LANDSAT-type multispectral imagery is severely handicapped in mountainous terrain where the topography casts long shadows. Almost all of the easy applications of LANDSAT imagery have been tested for that one-half of the world's land area which is relatively flat. No detailed successful computer classification of land use, forest type, or agricultural cropping in mountainous tropical terrain has yet been shown. Inspection of LANDSAT imagery of the Thailand site clearly illustrates this tropographic shadow problem. The shaded relief appearance of the images is typical of all mountainous areas and is accentuated in lower sun angles associated with mountains located further from the equator. The slope and aspect data planes in the landscape model can be used to compute the near-instantaneous solar insolation to each cell for the date and time of any LANDSAT image (Fig. 21). The graymap display of this insolation plane looks very similar to the corresponding LANDSAT image graymap and leaves little doubt that topographic-induced lighting effects dominate the LANDSAT images of mountainous terrain (Fig. 22). Land use is a secondary variable hidden in the shaded relief portrayed by the images. It must be extracted by the proper combination of ancillary landscape variables, such as the computed near-instantaneous solar insolation.

A test classification of the nine forest and agricultural land uses further underlines the serious impact of mountainous topography on image classification. Only nine classes are sought and the four LANDSAT MSS spectral bands and six band ratios produce an accuracy on only 32.0%, versus a random classification of 1/9 classes times 100% = 11.1% (Table 11). Considerable room for improvement exists as the ancillary landscape planes are added to the image classification process. The computed solar insolation plane will also provide a direct basis for the improvement of the LANDSAT classification. Dividing each of the four LANDSAT MSS spectral bands on a cell-by-cell basis by near-instantaneous solar insolation for that cell should provide four new, normalized image data planes which are much more closely correlated with the existing land use cover. Clearly, all of the expected improvement by overlay of landscape variables into the image classification procedures is needed if land use maps of any value to hydrology or any other purpose are to be achieved in mountainous terrain.

CONCLUSIONS

Landscape modeling can provide nonempirical, deterministic inputs into hydrologic planning processes ranging from sophisticated hydrologic modeling to more simplistic engineering design problems. Little is yet known about

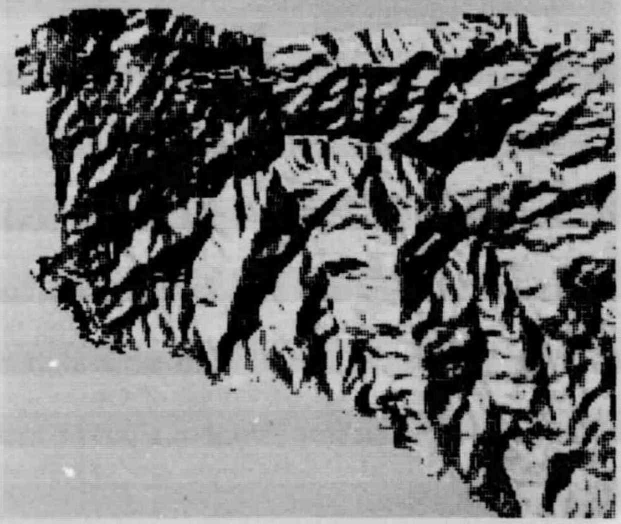


FIGURE 21. SOLAR INSOLATION DATA PLANE FROM THE PHYSIOGRAPHIC SUBMODEL OF THE NORTHERN THAILAND FOREST SITE. Scale 1:250,000. Near-instantaneous solar radiation at the ground surface. Computed from the slope (Fig. 15b) and aspect (Fig. 15c) data planes for the scan time of the January 27, 1973 LANDSAT image (Fig. 22).

(a) LANDSAT MSS Band 5

(b) LANDSAT MSS Band 7

FIGURE 22. SAMPLE DATA PLANES FROM THE SATELLITE IMAGERY SUBMODEL OF THE NORTHERN THAILAND FOREST SITE. Scale 1:250,000. Graymaps of LANDSAT imagery of January 27, 1973 which have been geometrically rectified, resampled to one hectare resolution, and overlaid upon the landscape data planes.

procedures used in this new interface of maps and remote sensing imagery to hydrologic analysis. The two case studies reviewed illustrate the general concept, some of the initial procedures which have been forged, and the results expected. Landscape modeling coupled with hydrologic modeling does provide the possibility that in the future the expected results of a land management activity may be deterministically portrayed before it is undertaken. Considerable effort must be expended if this technique is to be perfected and interfaced to hydrology. Hydrologists, remote sensing specialists, land managers, and related professionals must continue to work toward the goal of spatially modeling and displaying the future landscape. Projections of future spatial implications of alternative courses of action, such as siting of a power plant at various locations, can thus be presented to land use decision makers in an understandable, map-like format.

Step Number	Variable Name		Training Set Accuracy (% correct)
1	LANDSAT MSS Band 5		20.6
2	LANDSAT MSS Band 7/4	Ratio	27.7
3	LANDSAT MSS Band 7/5	Ratio	27.8
4	LANDSAT MSS Band 7		30.4
5	LANDSAT MSS Band 4		31.7
6	LANDSAT MSS Band 5/4	Ratio	32.3
7	LANDSAT MSS Band 6/5	Ratio	33.5
8	LANDSAT MSS Band 7/6	Ratio	32.4
9	LANDSAT MSS Band 6		31.9
10	LANDSAT MSS Band 6/4	Ratio	32.0

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