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HYDROLOGIC MODELING USING LANDSAT MSS DATA

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ABSTRACT

Facilities for processing Landsat satellite and airborne scanner data are becoming more common in Government, private and academic institutions. It is thus possible for a diverse range of resource managers to have access to digitized data already in a format which is inherently suitable for incorporation into spatial or physically based models. This paper discusses a particular application of Landsat satellite data which is used to derive a land use classification of the ungaged Sugar Creek watershed near Lafayette, Indiana, U.S.A., as input to a hydrologic model. The technique discussed herein requires a data bank to be constructed to store land use classification data and other variables which are used in the HEC-1 Flood Hydrograph Package computer program to generate hydrographs corresponding to proposed land use management alternatives.

The Hydrologic Engineering Center (US Army Corps of Engineers, Davis, California) pioneered this concept resulting in the technique being successfully used in a number of Corps of Engineers' field office studies. The presently discussed independently conducted "proof of concept" hydrologic analysis of Sugar Creek Watershed using spatial data management techniques is the first of its type to be carried out at Purdue University. Its documentation is intended to encourage greater use of remotely sense data in spatial models, in applications ranging from County to State level resource studies.

I. INTRODUCTION

Watershed simulation studies which combine concepts of hydrologic modelling, remotely sensed data input and geographic information systems herald a new era in simulation studies when compared to the rather limited mathematical techniques available prior to 1970. Studies which incorporate these techniques will play an important part in resolving water resources management issues over the next few decades as researchers seek to develop predictive models capable of evaluating alternative management strategies.

The practical applications of the modelling procedure are far reaching. With over two-thirds of the population of the United States occupying only about one-twentieth of the land surface and with unrelenting pressure for further urbanization, prime watersheds close to metropolitan areas are constantly under threat by urban expansion [If projections for the United States based on historic growth trends prove valid, the amount of urbanized land will double in the next 30 years (Task Committee Report, 1975, pp. 449 - 465]. Problems relating to the management of water resources, either quantity or quality, are usually identified when it is too late to implement an alternative strategy.

State and County planning authorities faced with the task of determing the consequences of changing land use in a watershed must plan to mitigate accelerated runoff before erosion and flooding cause irreversible damage. Hydrologic design parameters corresponding to proposed levels of development in the watershed are required for sizing drainage systems, detention basins and for delineating flood plains under fully developed conditions.

The overall objective of the hydrologic analysis procedure discussed herein is to simulate runoff from rainfall of a specified recurrence interval from the Sugar Creek Watershed in Indiana. Principal tasks involved in the analysis, namely the Landsat land use classification, the creation of the grid cell data bank and the hydrologic analysis are quite distinct studies in their own right. However, the interrelationship and implications leading from one task to another require that the analyst has a working knowledge of all three aspects of the operational procedure.

Land use input to the model defined from Landsat or airborne scanner digital data provides a convenient method for analyzing properties of watersheds where, because of size or data availability, conventional methods would be prohibitively time consuming and costly. Those with access only to aerial photography should not be deterred from using the modelling concept as, although it is time consuming, it is possible to carry out a manual land use classification and data entry to the model with greater accuracy than is available from satellite data which has a poorer resolution.

Establishment of a grid cell data bank provides a permanent record of the watershed characteristics and permits variations in coefficients and parameters to be evaluated quickly and efficiently. For example, the hydrologic evaluation of future land use changes can be readily carried out. The discharge-frequency hyrographs for 25, 50 and 100 year, 6 hour rainfall depths corresponding to existing land use, all forest and all agriculture scenarios are quickly established for the Sugar Creek Watershed (by the Soil Conservation Service (SCS) dimensionless unit hydrograph method) once the data bank is created.

This approach can be accommodated by the HEC-1 Flood Hydrograph package, which is the principal computer program used to model runoff from the watershed. The spatial data stored in the data bank is accessed by the computer program Hydrologic Parameters (HYDPAR), which services the HEC-1 computer program by supplying parameters such as weighted imperviousness (average curve number) and sub-basin lag. Future management options for land use in the watershed can be readily simulated from the existing data bank or by adding other variables to the data bank.

II. THE STUDY AREA

A factor which largely influenced the decision to select ungaged Sugar Creek Watershed for the hydrologic analysis is a proposal by the Indiana Senate in 1982 to create a State Park in a part of the watershed, complete with a recreational lake. This gently sloping agricultural watershed, approximately 10 miles northeast of Lafayette, Indiana, has an area of 30 square miles and drains in a westerly direction to the Wabash River. As the flow in Sugar Creek has never been measured, the necessary hydrologic design information required for sizing the recreational lake and spillway is not available. Therefore, the peak flow and the hydrographs are estimated by using the HEC-1 rainfall-runoff model. Further details of study area are found in (Alexander, 1984; Alexander and Rao, 1984).

III. DEFINITION OF LAND COVER CLASSES USING REMOTELY SENSED SATELLITE DIGITAL DATA

The application of satellite-derived reflectance measurements to classify land cover was first used in conjunction with the Soil Conservation Service (SCS) watershed model in 1973, for computing direct runoff by using runoff curve numbers (CN). Ragan and Jackson, (1976) and Franz and Lieu, (1981) found Landsat data to be cost-effective in estimating the curve numbers required for the SCS model. More recently, the trend has been towards integrating hydrologic models and Geographic Information Systems (GIS), with remotely sensed data forming one of many inputs to physically based continuous simulation models. Groves and Ragan (1983), Groves (1983), and Loveland and Johnson (1983, pp. 1183 - 1192), have worked with such models.

Landsat data can be used to estimate hydrologic parameters more readily and cost effectively for large areas than traditional data gathering methods (George et al., 1980). From an economic standpoint this would appear to be in the vicinity of 10 square miles although it has been shown to be feasible for watersheds of 2 to 3 square miles (Ragan and Jackson, 1975, pp. 1469 - 1475).

Landsat-derived remotely sensed data are appealing for modelling purposes as they offer the latest as well as a reasonably lengthy historical coverage (10 years) of the Earth's surface characteristics. It has sufficient accuracy, resolution and availability to be successfully interfaced with mathematical models.

Landsat I MSS data of 9 June 1973, of Sugar Creek Watershed was digitally analyzed at the Laboratory for Applications of Remote Sensing (LARS) at Purdue University. Special training classes were obtained using the hybrid approach which combines aspects of both the supervised and unsupervised classification (Tilton and Bartolucci, 1982, II/7 - II/9). A technique used to assist in identifying spectral classes is to obtain a plot of the calibrated spectral response curves (Figure 1) generated by the CALBRAZ processor available from the LARSYS suite of processors. The calibrated mean radiance in each channel for the 12 initial land use categories shows characteristic curves typical of vegetation, soil and water response.

A two-dimensional bi-spectral plot (Figure 2) of the 12 land use classes shown in Figure 1 shows the average of the class means of spectral response in the two visible channels plotted against the average of the class means in the two infrared channels. The distribution of the classes is typical of the roughly triangular shape (tassled cap) above a constant soil brightness line (line A-H) with the state of vegetation development (towards class F) perpendicular to line A-H. (Kauth and Thomas 1976, pp. 6/29 - 7/72). Divergence theory (Swain and Davis 1978) is applied as a measure of statistical separability of identified classes ideally to reduce the number of classes to around six to ten for hydrologic modelling purposes.

A critical part of the digital data analysis procedure is the acquisition of accurate "ground truth" information in the form of maps, photographs and field observations. The accuracy with which land cover classes are assigned to training areas reflects in the accuracy of the final classification. The importance of adequate "ground truth" information and its thorough interpretation cannot be over-emphasized.

The following reference information is used to assist in locating the study area in the digital data, and to correlate shapes, patterns and features:

1. USGS 7.5 minute quadrangle topographic map coverage of the entire watershed at a scale of 1:24,000 which forms a base for registration of other sets of data variables.
2. Ozlid blackprints of December 1980, aerial photography (1:4800).
3. Black and white aerial photography flown in 1971 (1:20,000).
4. Colour infra-red photography flown in October 1972 (1:100,000).

The land use classification for the Sugar Creek Watershed resulted in seven categories for input to the data bank; cultivated soils, open grasslands, woodlots - forest, water body, grass/vegetation, soil/vegetation, low density urban (Table 1). It should be noted that it is the expertise of the remote sensing analyst in accurately identifying land cover categories that will ultimately reflect in the accuracy of SCS curve number type hydrologic models.

IV. DEVELOPMENT OF A GRID CELL DATA BANK

Spatial data management techniques used in this study were developed in 1975 at the Hydrologic Engineering Centre (HEC) (U.S. Army Corps of Engineers, 1979, p. 3) and were extensively used in the Corps of Engineers' Expanded Flood Plain Information Studies (XFPI). Constructing a data bank is conceptually similar to overlaying data maps of the same scale one on top of another and recording all levels of map data (variables such as soil type, land cover) for all grid cells (Figure 3).

Both user requirements and the accuracy of the source material to be digitally represented affect the accuracy of the Geographical Information System (GIS). Positional accuracy in the GIS cannot exceed that of the original data source and may be regarded as a potentially serious problem if further overlaying of data sets is attempted. The degree of accuracy required for a particular data set should be carefully assessed to avoid expensive, tedious, and over-precise data input preparation. A high degree of accuracy is generally more expensive to attain and may have little effect on the end result.

Table 1. Land Use Categories as a Percentage of the Total Area of Sugar Creek Watershed

Land Use Category	Percentage of Area
1. Cultivated Soils - Agricultural Land	61.0
2. Grassland - Open Space	6.1
3. Woodlots - Medium Density Forest Strands	4.2
4. Water Bodies	0.2
5. Grass / Pasture / Sparse Vegetation	10.0
6. Cultivated Soils / Emerging Crops / Agricultural Land	17.1
7. Urban - Low Density Residential	0.5

Assisted by reasonably uniform land cover classes, the results of the watershed classification are believed to be extremely accurate, based on a visual examination of the classified image. A classification accuracy in the order of 75% is considered to be reasonable in this study for determining hydrologic input parameters, considering the imprecision of existing hydrologic models.

A general strategy and procedure for creating a data bank recommended by the U.S. Army Corps of Engineers (USACE 1983, pp. 6 - 14) applicable to Sugar Creek Watershed is summarized below:

Table 2. Summary of Analyses.

Procedure	Relevance to Sugar Creek Watershed
1. Select the runoff computation method	SCS Dimensionless Unit Hydrograph scheme
2. Select the data variables	Sub-basin boundaries Hydrologic soil group Land surface slope Existing land cover or land use
3. Adopt a base map	USGS 7.5 minute quadrangles
4. Select the grid cell size	10 acres (600 x 750 feet)
5. Gather data	Land use classification County soil and slope maps USGS 7.5 minute quadrangles
6. Encode data	Cell by cell or run length encoding
7. Create and update the data bank	BANK program developed in HEC
8. Verify and edit the data bank	Resource Information Analysis (RIA) program developed by HEC

V. HYDROLOGIC ANALYSIS

One of the capabilities of the HEC-1 Flood Hydrograph Package computer program (U.S. Army Corps of Engineers, 1981) developed in 1967 is stream network modelling to simulate the rainfall-runoff process in a river basin. This capability is the focus of virtually any application of HEC-1, allowing the calculation of flood hydrographs at desired locations in a river basin.

It is possible to optimize parameter estimation and to calibrate HEC-1 according to observed streamflow records. However, the absence of stream gauging information limits the present study to simulation of runoff from watersheds with different land uses.

The HEC-1 model simulates the rainfall-runoff process as it would occur in a watershed, using simple mathematical relationships to represent individual hydrologic and hydraulic processes. These processes may be categorized in terms of precipitation, interception/infiltration, transformation of precipitation excess to sub-basin outflow, addition of baseflow and flood hydrograph routing (U.S. Army Corps of Engineers, 1981).

The Hydrologic Parameters (HYDPAR) computer program (U.S. Army Corps of Engineers, 1978) is designed to access the grid cell data bank. HYDPAR uses only land use and soil type information in determining curve numbers (Table 3), each grid cell being assessed to determine these values. The curve number is used in computation of sub-basin or watershed hydrologic parameters that permit determination of precipitation loss-rate functions and surface runoff response. HYDPAR program develops parameters for any specified watershed status (existing, historical or future land use patterns) simply by specifying a different land use data variable in the data bank.

To develop the shape of the discharge hydrograph (discharge versus time), the SCS developed the simplified dimensionless unit hydrograph to transform excess rainfall to discharge as a function of time (U.S. Soil Conservation Service, 1972). The SCS method determines direct runoff from rainfall based on the physiographic characteristics of land use, antecedent moisture conditions and soil type. The hydrograph developed by the SCS method has its shape defined by a single parameter, basin lag (time response of runoff to rainfall). Basin lag is normally developed from either empirical equations, travel time studies or observed flood hydrographs. However, HYDPAR uses the following empirical equation:

$$\text{Lag (hours)} = \frac{(L)^{0.8} * (S+1)^{0.7}}{1900 * (y)^{0.5}}$$

where L is the length of travel, S is the ultimate storage in the watershed and y is the watershed slope.

VI. RESULTS

To demonstrate the application of the HEC-1 rainfall-runoff model in its simplest form, the following procedure is adopted to determine:

Table 3. SCS Curve Numbers Assigned to Existing Land Use Categories

Land Use Category	SCS Curve Number (Corresponding to Hydrologic Soil Group) A	B	C	D
1. Cultivated Soils - Agricultural Land	72	81	88	91
2. Grassland - Open Space	30	58	71	78
3. Woodlots - Medium Density Forest Stands	25	55	70	77
4. Water Bodies	100	100	100	100
5. Grass / Pasture / Sparse Vegetation	49	69	79	84
6. Cultivated Soils / Emerging Crops / Agricultural Land	62	71	78	81
7. Urban - Low Density Residential	69	75	82	86

Table 4. Peak Flows Computed by the HEC-1 Rainfall-Runoff Model

Land Use	Peak Discharge (cfs) and Time of Peak by Recurrence Interval (years) 25	50	100
Forest	1683 (8.75 hr)	1683 (8.75 hr)	1686 (8.75 hr)
Existing	4031 (8.25 hr)	4029 (8.25 hr)	4039 (8.25 hr)
Agricultural	4744 (8.00 hr)	4741 (8.00 hr)	4751 (8.00 hr)

1. The peak discharge for the existing land use conditions for the 25, 30 and 100 year recurrence interval-six hour rainfall.
2. The peak discharge for a hypothetical "forest" watershed which existed prior to cultivation, for the same rainfall condition as in (1) above.
3. The peak discharge for a hypothetical "agricultural" watershed which is almost the present situation, for the rainfall conditions outlined in (1) above.

The results of the above analysis are shown in Table 4.

The slightly lower values obtained for the 50 year compared to 25 year recurrence interval rainfall are related to the initial abstraction calculation used in the HEC-1 model. It should be appreciated that with a calibrated HEC-1 rainfall-runoff model and recorded rainfall data, the discharge would increase with increasing rainfall. However, for practical demonstration purposes, it is seen that by completely clearing the watershed of all forest stands in favour of agricultural development, the peak discharge is increased by 282 per cent. The hydrographs generated by the HEC-1 model for the 25 year recurrence interval - six hour rainfall events for the "forest", existing land use and "agricultural" land cover categories, are shown in Figure 4. It is evident that the peak discharge from the "forest" watershed is, on average 3000 cubic feet per second (cfs) less than the peak discharge from the "agricultural" watershed. The time to peak discharge for the "forest" condition is 0.75 hours later than the time to peak for the "agricultural" watershed. The time of the peak discharge is delayed by approximately 10 per cent from the commencement of rainfall for the "forest" versus "agricultural" conditions. The watershed runoff coefficient, that is the ratio of rainfall excess to total rainfall, together with the estimated volume of runoff for each of the three watershed land cover scenarios are shown in Table 5.

Table 5. Watershed Runoff Coefficients and Estimated Runoff

Land Use	Watershed Runoff Coefficient	Estimated Runoff Volume (acre feet)
Forest	0.20	1200
Existing	0.47	2700
Agricultural	0.57	3300

VII. COMPUTER PROCESSING REQUIREMENTS

The processing of the Landsat digital data was carried out at the Laboratory for Applications of Remote Sensing, Purdue University, on an IBM computer with VM/CMS 370 operating system. LARSYS programs are stored in on-line program libraries and executed on an interactive time sharing or batch execution basis.

Primary outputs include line printer maps and tables, photographic image products taken from a cathode ray tube colour monitor, and computer compatible tapes.

The HEC computer programs including the databank were developed on Purdue University's CDC 6000 system made up of two CDC 6500 computers and one CDC 6600 computer. Each computer has 128 K 60-bit words of central memory with combined access to one-half million words of Extended Core Storage (ECS). The 30 square mile Sugar Creek Watershed with four levels of data input required the storage of some 6400 cells of information in the databank, using a 10 acre cell size.

Manipulation of data in the databank by the HEC analysis programs required 325 K of central memory, that is almost all that is available in the CDC 6000 system.

VIII. CONCLUSION

It is concluded that land cover classification derived from satellite or airborne scanner digital data offers a convenient method for classifying land use characteristics, particularly over large areas and is compatible for direct input to a grid cell data bank. The data bank allows various land use changes to be assessed and the HYDPAR and HEC-1 programs are easily adjusted to accommodate parameter variations. The variation in peak discharge for three land cover scenarios corresponding to 25, 50 and 100 year recurrence interval six-hour rainfalls demonstrate the operational aspects of the model.

The technique could be relatively easily adopted by County planning agencies wishing to do their own predictive modelling of smaller watersheds without sophisticated equipment. However, as the databank consumes considerable computer central memory (in the order of 320 K for a 30 square mile study area with four levels of data), agencies contemplating such a study will require access to larger computing systems generally available through Universities and Government agencies.

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BIOGRAPHICAL SKETCH

David Alexander graduated from the School of Civil Engineering at the Gippsland Institute of Advanced Education, Victoria, Australia, in 1972 and completed his M.S. in Civil Engineering from Purdue University in 1984. Since 1972 he has been involved in a wide range of water resources engineering projects in his position of Executive Engineer with the Rural Water Commission of Victoria, Australia, recently specializing in remote sensing applications to water resources management. His main research interests relate to hyrologic modelling using remotely sensed data as input to geographic information systems.

A. Ramachandra Rao graduated from the University of Mysore, India with a B.E. degree in Civil Engineering in 1960, with an M.S.C.E. degree in Hydraulic Engineering from the University of Minnesota in 1964 and with a Ph.D. degree in Hydrology from the University of Illinois in 1968. He has been with the School of Civil Engineering at Purdue where he is presently a professor of Civil Engineering. His research interests are in the fields of mathematical modeling of Hydrologic Systems, and Computational Hydraulics.

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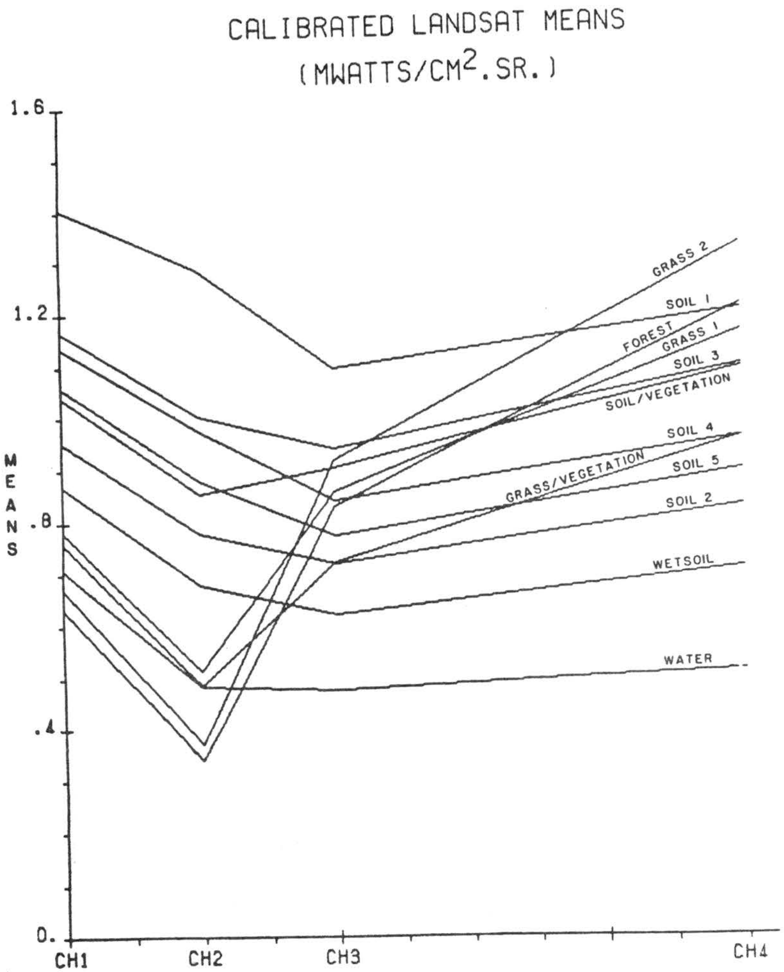
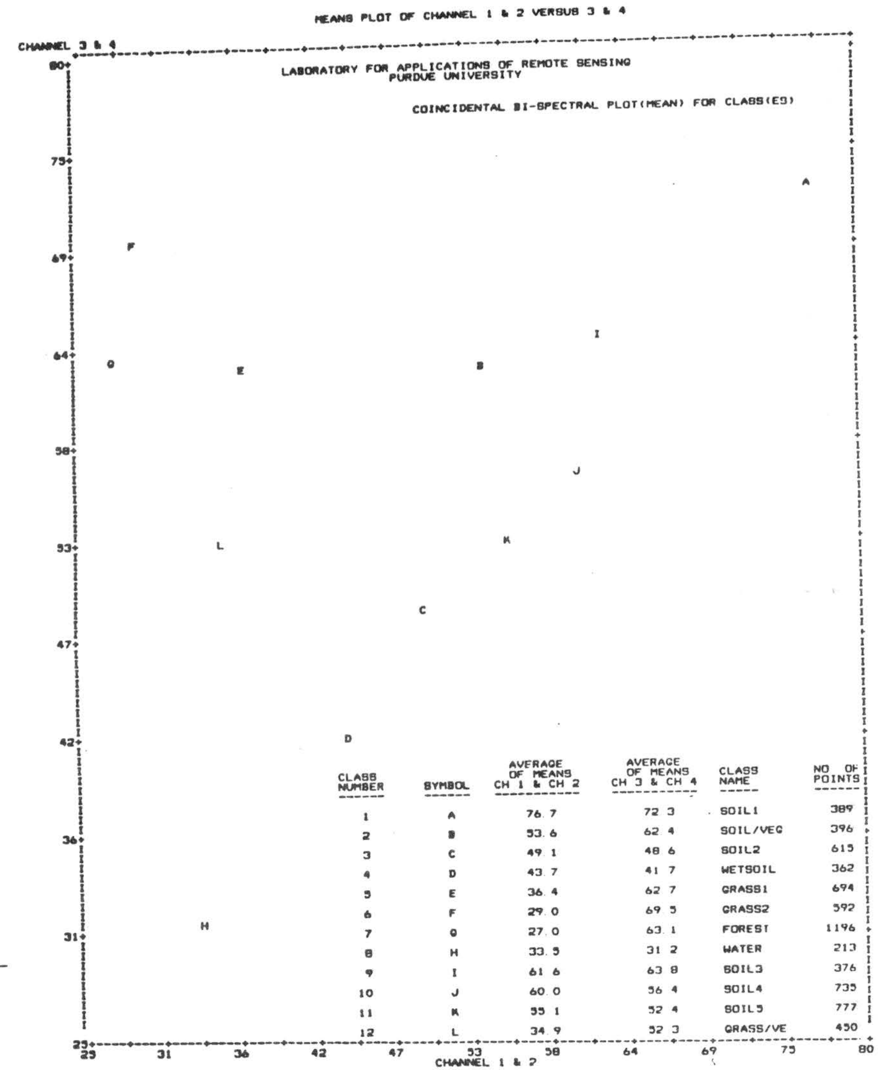
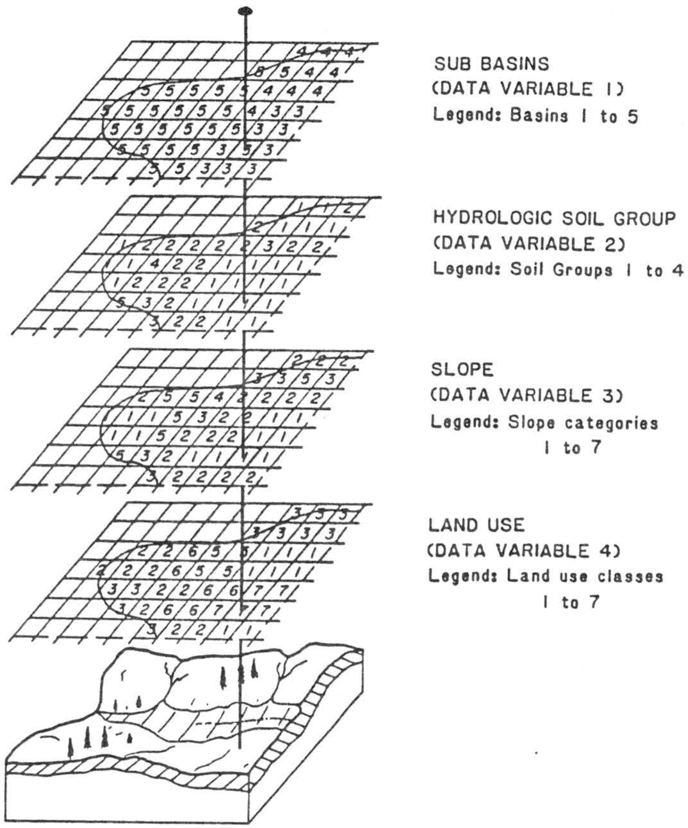


Fig. 1. Calibrated Curves - 12 Land Use Categories Identified in Sugar Creek Watershed



CLASS NUMBER	SYMBOL	AVERAGE OF MEANS CH 1 & CH 2	AVERAGE OF MEANS CH 3 & CH 4	CLASS NAME	NO OF POINTS
1	A	76. 7	72 3	SOIL1	389
2	B	53. 6	62 4	SOIL/VEG	396
3	C	49. 1	48 6	SOIL2	615
4	D	43. 7	41 7	WETSOIL	362
5	E	36. 4	62 7	GRASS1	694
6	F	29. 0	69 5	GRASS2	592
7	G	27. 0	63. 1	FOREST	1196
8	H	33. 5	31 2	WATER	213
9	I	61 6	63 8	SOIL3	376
10	J	60. 0	56 4	SOIL4	735
11	K	55 1	52 4	SOIL5	777
12	L	34 9	52 3	GRASS/VE	450

Fig. 2. Coincidental Bi-Spectral Plot



MULTIVARIABLE FILE STRUCTURE
(Grid Cell Value Assignments)

Grid Cell Location ROW	COLUMN	Data Var. 1	2	3	4
1	1	4	1	2	3
1	2	4	1	2	3
⋮	⋮	⋮	⋮	⋮	⋮
2	1	5	2	2	3
2	2	5	2	2	3
⋮	⋮	⋮	⋮	⋮	⋮

Fig. 3. Multivariable Data Bank Structure for Sugar Creek Watershed

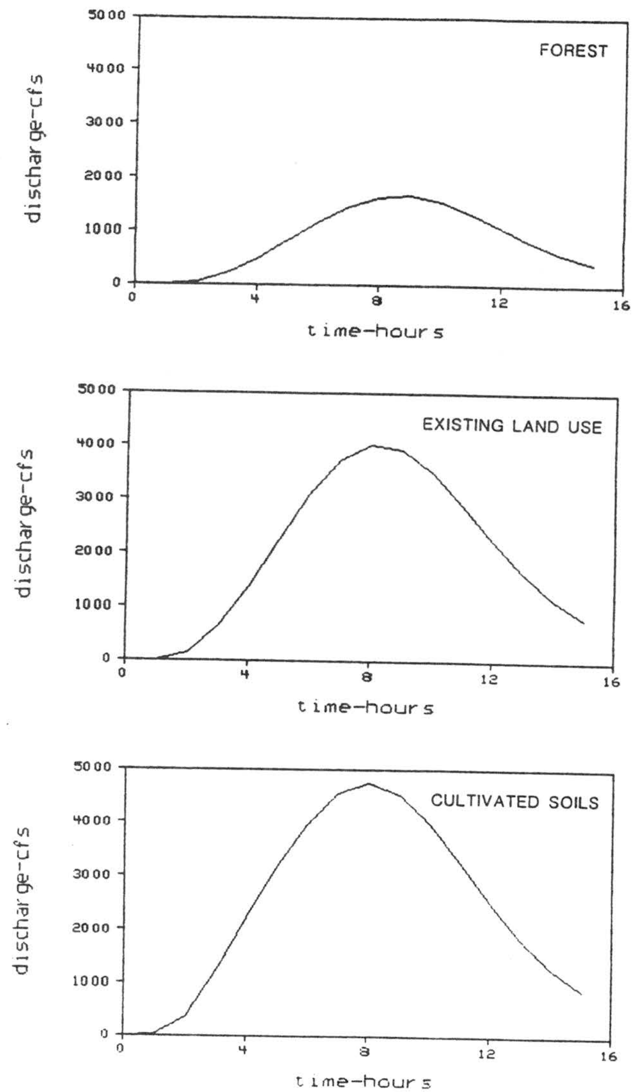


Fig. 4. 25 Year - 6 Hour Storm Runoff Hydrographs for Forest, Existing Land Use and Cultivated Soils