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THE APPLICATION OF REMOTE SENSING TO THE DEVELOPMENT
AND FORMULATION OF HYDROLOGIC PLANNING MODELS

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EXECUTIVE SUMMARY

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ECOSYSTEMS INTERNATIONAL, INC.

Post Office Box 225

Gambrills, Maryland 21054

JANUARY 7, 1975

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Structure of the Effort

The advent of a broad scale, low cost remote sensing capability initiated by the successful launch and operation of ERTS has given renewed promise and emphasis to the development of regional hydrologic planning models especially suited to ungaged watersheds.

This project was instituted to determine the effectiveness of a new hydrologic planning model specifically tailored to remote sensing inputs, and to determine which parameters impact most the minimization of errors associated with the prediction of peak flow events. The capability of accurately forecasting peak flow strongly influences the sizing and design of civil works and the process of general regional watershed planning. The objectives of the effort are summarized in Figure 1.

Peak runoff events in ungaged watersheds were chosen for investigation because:

- ° The prediction of peak runoff - throughout their watersheds - is of significant importance to users for the purpose of planning, sizing and designing waterworks.

FIGURE 1
OBJECTIVE OF EFFORT

**DEVELOP WATER RESOURCES
PLANNING MODEL:**

- **Built upon Remote Sensing capabilities**
- **Suitable for ungaged watersheds**
- **Based, for parameters not accessible to Remote Sensing, upon commonly available information.**

- The user community for ungaged hydrologic planning models is significant, including:
 - Federal Agencies involved in water resources.
 - Federal agencies involved in funding water resources research.
 - Developed and developing nations.
 - Foreign governmental and international agencies responsible for, or oriented towards water resources development.

From the start, this project espoused the four theses synthesized in Figure 2, and described in the following:

- Of the many phenomena and relationships underlying the behavior of hydrologic processes governing peak flow, only a few are dominant for planning models. Others can be neglected or, in the extreme, factored in as small, constant corrections.
- The inclusion of temporal and areal variations of watershed characteristics, which have generally been averaged or ignored in hydrologic modeling, should result in reduced errors of prediction.
- The crucial phenomena regulating peak events are, to a significant extent, surface-dependent and thus

FIGURE 2

THESIS

- **PEAK EVENTS (SUCH AS FLOODS) ARE CAUSED BY THE INTERRELATIONSHIP OF A RELATIVELY SMALL NUMBER OF WATERSHED PARAMETERS**
- **PEAK EVENT MODELS TO BE ACCURATE MUST INCORPORATE VARIABLE PARAMETERS**
- **REMOTE SENSING TECHNIQUES CAN BE BUILT INTO HYDROLOGIC FLOOD MODELS AB INITIO**
- **GOOD RESULTS CAN BE OBTAINED WITH RELATIVELY SMALL COMPUTER HARDWARE**

highly amenable to remote sensing. For the cases where subsurface phenomena play a significant role, peak events can still be predicted through a combination of remotely sensed observables and available subsurface parameters.

- o Exploitation of the sensitivities of the physical factors underlying hydrologic phenomena can lead to significant modeling simplifications from which economies in computing hardware will accrue.

To test the validity of these hypotheses, four investigations were undertaken:

1. A mathematical sensitivity analysis of the hydrologic processes cogent to peak watershed outflows was undertaken to ascertain which had the greatest influence. Further, physical characteristics of basins, such as soil type and vegetative cover, were examined to determine the sensitivity of peak flow to changes in their antecedent conditions.
2. The construction of a generalized hydrologic planning model was initiated along two courses. Analog computer circuits describing hydrologic processes were assembled and applied to examination of the sensitivities described above. Also, an analytic formulation for peak flow prediction was developed and tested against data from actual watersheds.

3. A data base of 158 watersheds was collected, containing physical parameters, rainfall and flow records. The application of this information was two-fold - to provide a measure of the validity of the models developed, and to permit the delineation of areas within the U.S. which are the most amenable to modeling from remotely sensed data. Their locations are shown in Figure 3.

4. The role of remote sensing in hydrologic modeling was identified and a procedure for its use demonstrated.

The interrelations of these sub-tasks are depicted in Figure 4.

TECHNICAL PROCEDURES

The Drivers

Examination of the rates and magnitudes of hydrologic processes, indicated that the following processes are important to peak flow prediction:

- 1) Precipitation
- 2) Infiltration
- 3) Overland Flow

Secondarily, according to the region under consideration, the statistical behavior of antecedent moisture condition

FIGURE 3 AGRICULTURAL RESEARCH BASINS

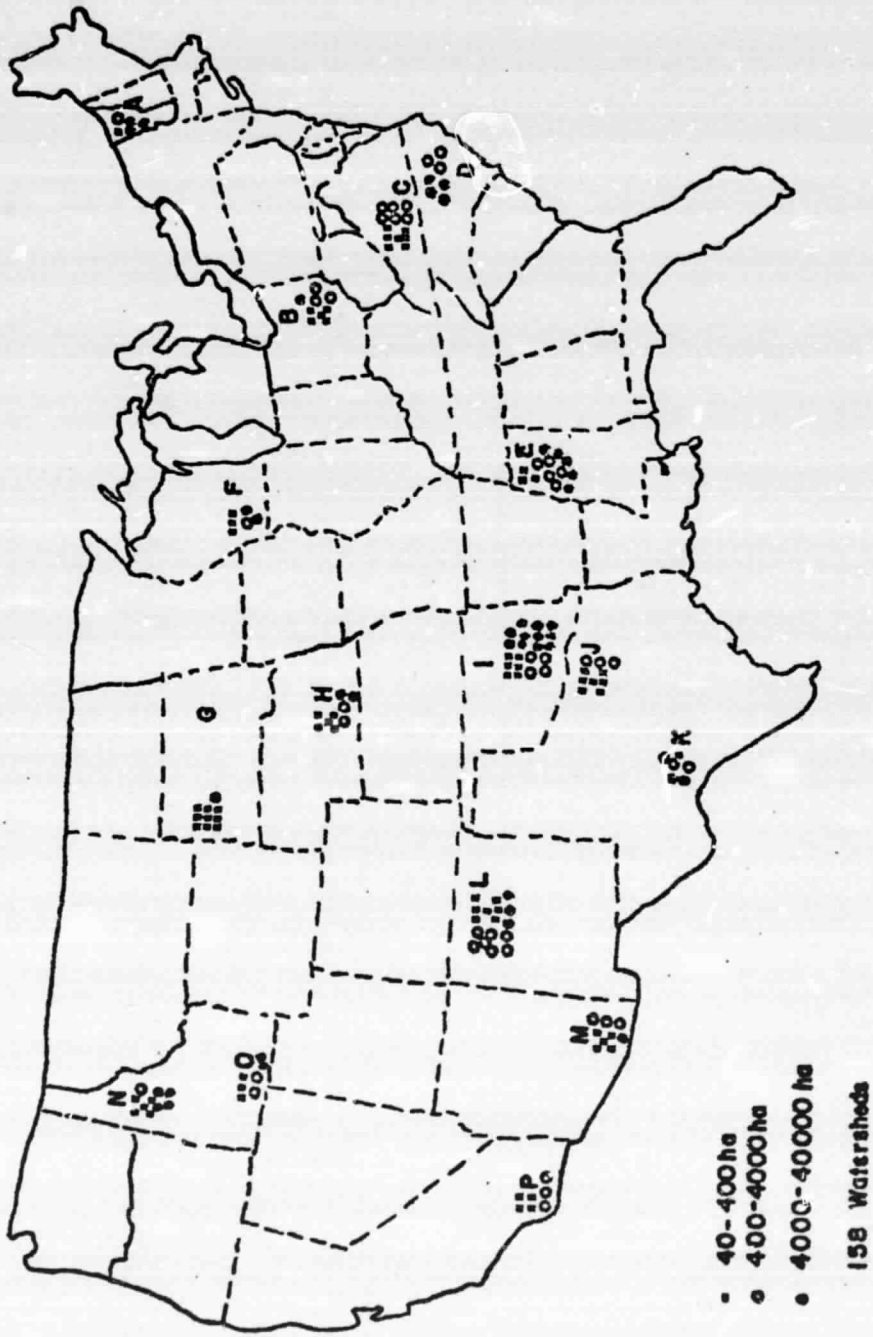
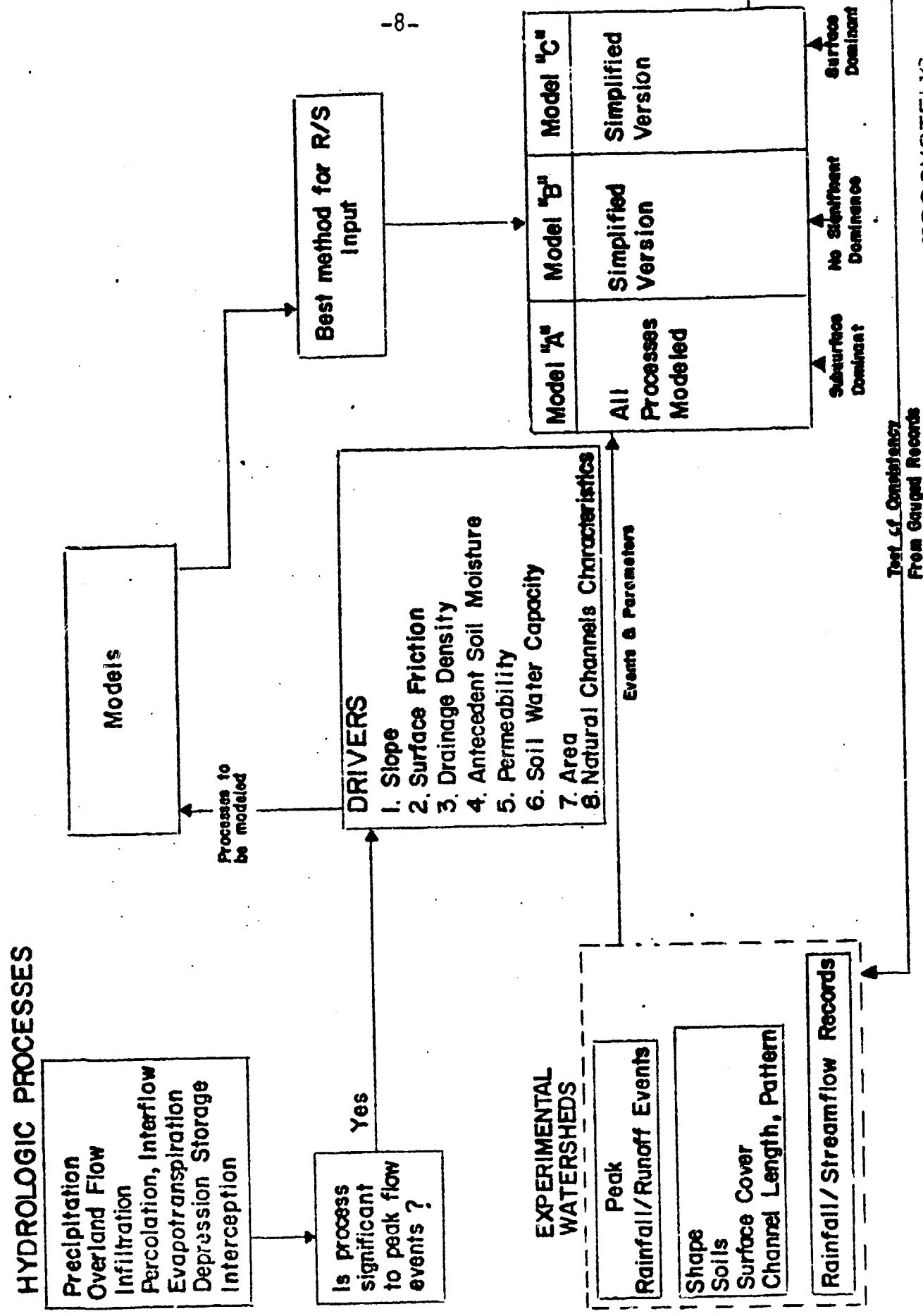


FIGURE 4 PROGRAM FLOW CHART, NAS8-30539



as it relates to peak rainfall events must be included.

Rainfall is the principal causative factor defining the magnitude of the peak flow. Its important characteristics are the recurrence statistics, determined by empirical correlation of regional rainfall records.

Infiltration governs the portion of the rainfall which contributes to the direct runoff peak. It can be evaluated from watershed soil records, abundantly available.

The overland flow process and channel flow determines the timing of the peak. The timing in turn determines the rainfall rate and mass for a given recurrence frequency, and hence determines the peak flow. The overland flow can be modeled from knowledge of the surface characteristics of the watershed, which are directly amenable to remote sensing.

The relative contribution of each of the above factors to the peak event varies with the antecedent conditions of a specific set of watershed parameters. Rainfall, infiltration, and overland flow are sensitive to these parameters, and their rates and magnitudes are "driven" by the particular mix of the parameters present. Thus, the rate, volume, and timing of the peak event are directly related to this set of drivers.

The phenomena which are the key drivers of peak flow, in addition to rainfall statistics, are:

1. Soil Permeability - high permeabilities mean high acceptance of water and smaller runoff mass.
2. Soil Water Capacity - a soil having a greater water capacity will retain more rainfall and produce less runoff.
3. Antecedent Soil Moisture - as soil moisture rises, the soil becomes more saturated, slowing infiltration rates, reducing total soil moisture capacity, and increasing the runoff volume.
4. Slope - flow velocity varies directly but non-linearly with slope.
5. Surface Friction - velocity varies inversely and non-linearly with surface friction.
6. Drainage Density and Pattern - defines the relative distances that water will flow overland and in the channel in combination with slope and surface friction, and defines concentration time.

Data acquired from the 158 test watersheds provided the basis for partitioning the United States into areas evidencing either surface-dominated or subsurface-dominated hydrologic regimes based on the relative magnitudes of

the drivers listed above. An initial partition of the United States into 3 categories of hydrologic regimes was made. The three regions are:

1. Heavily Surface Dominant - Where the percentage of rainfall to runoff significantly exceeds the percentage of rainfall to infiltration.
2. Surface Dominant - Where more rainfall runs off than infiltrates.
3. Subsurface Dominant - Where more rainfall infiltrates than runs off.

It should be noted that the regions which are surface dominated, and, therefore, most amenable to modeling from remotely sensed information are also those which have historically experienced the greatest flood damage. The initial partition is presented in Figure 5.

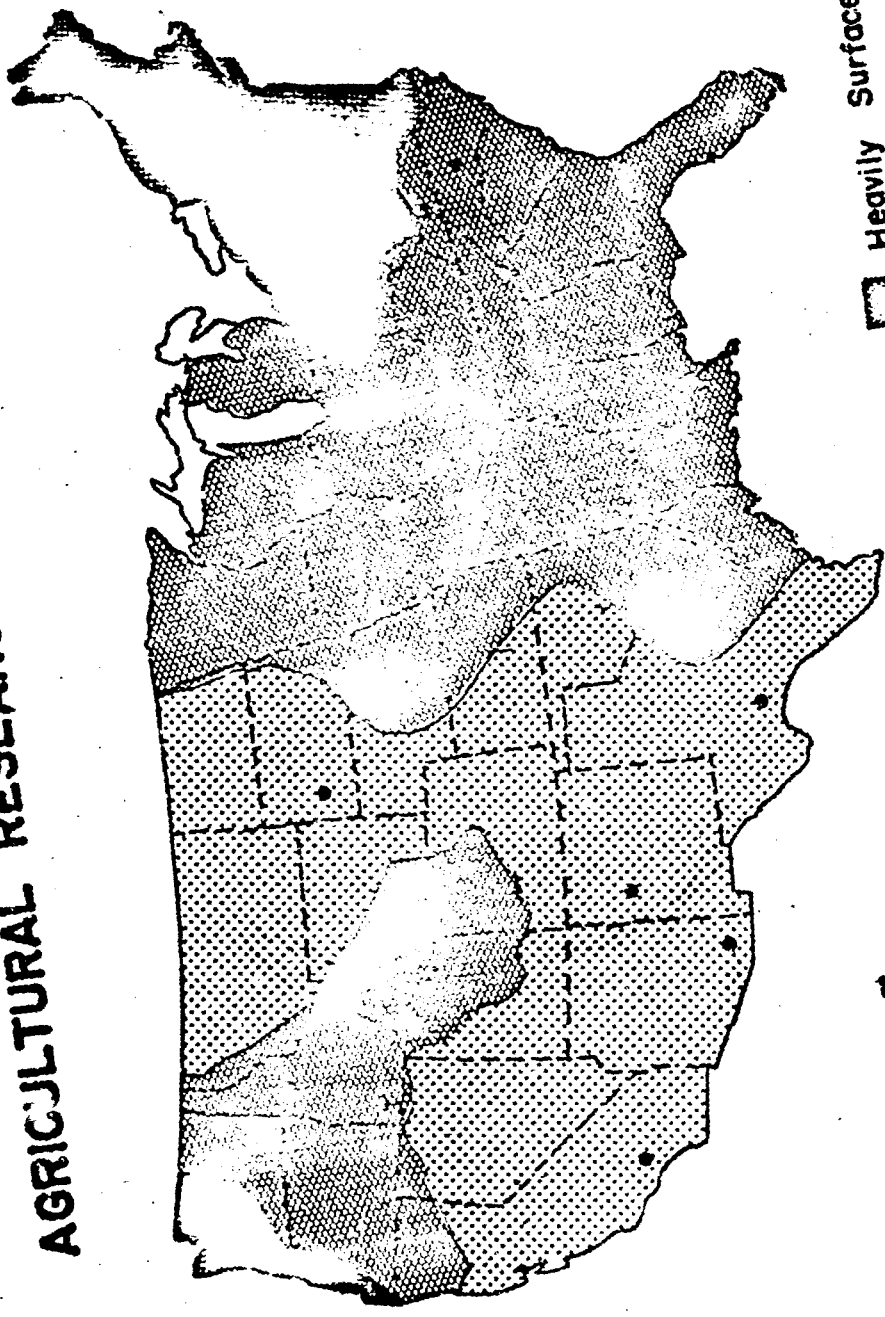
The Analytic Model

The analytic model was developed modularly. The modules are:

1. Rain recurrence - by examination of U.S. records, a general expression of the form:

$$I = \frac{\alpha_1 T^{\alpha_2}}{(t+d)^{\alpha_3}}$$

INTEGRATED
BASED ON
RESEARCH
AGRICULTURAL



- Heavily Surface Dominant
- Surface Dominant
- Subsurface Dominant

FIGURE 5

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INITIAL PARTITION
BASED UPON
AGRICULTURAL RESEARCH BASINS 100-100,000 ACRES

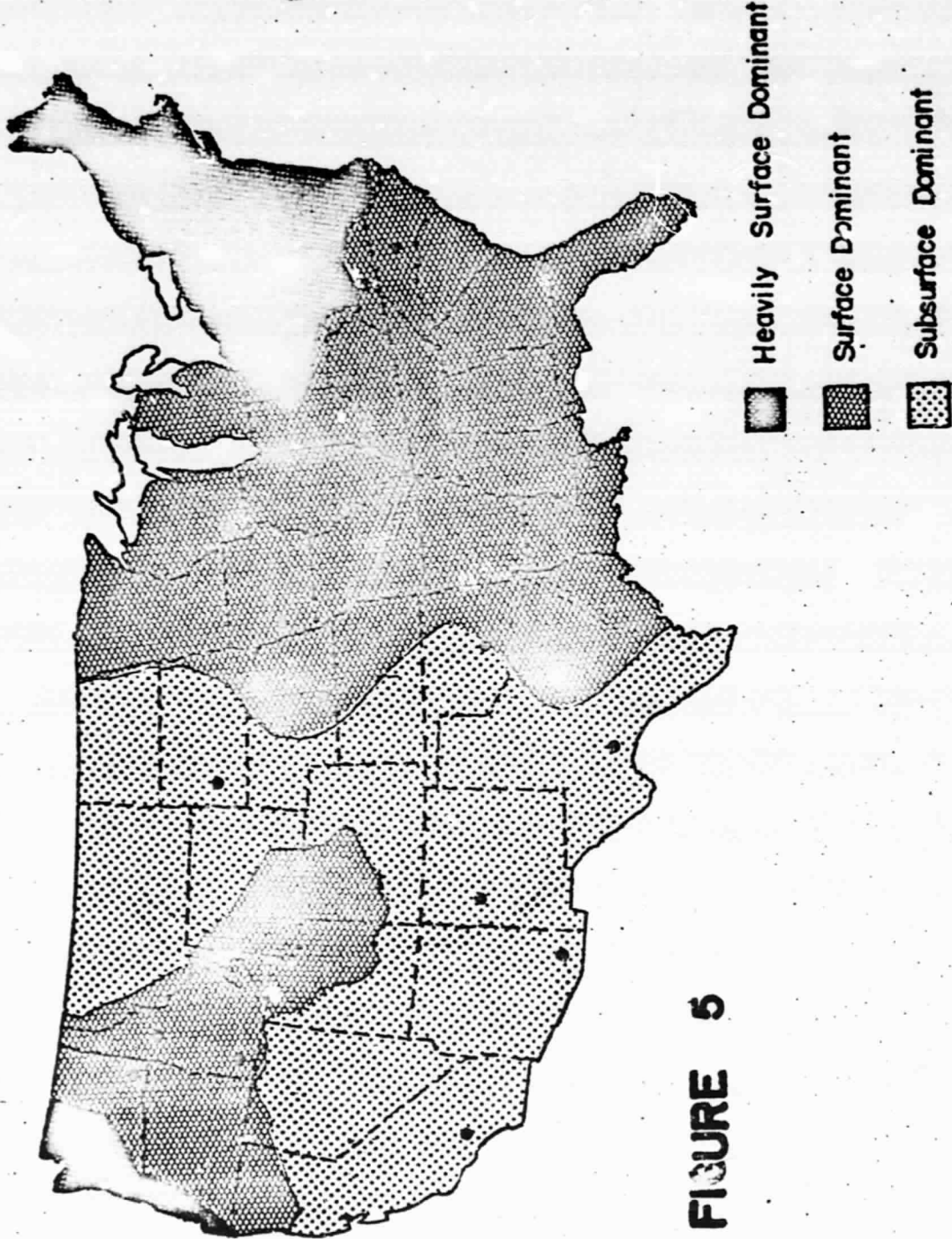


FIGURE 5

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Where:

i = rain rate m/sec.

T = recurrence period, years

t = duration, hours

$\alpha_1, \alpha_2, \alpha_3, d$ = constants, function of location

has been developed. The coefficients vary among regions, but can be determined for each. By this means, the intensity of a rainfall of any duration and recurrence, within any region, can be predicted.

2. Rainfall Spatial Correction - In the larger watersheds the use of point rainfall in a hydrologic model does introduce errors. For accuracy, a correction factor must be included of the type:

$$P_e = cP$$

Where:

P_e = effective rainfall rate, cm/hr

P = point rainfall rate, cm/hr

C = correction factor

3. Subsurface Abstractions - based upon analysis of various formulations, the Holtan equation for infiltration has been adopted for the time being to describe the subsurface precipitation losses.

$$\dot{i} = \bar{a} \cdot GI \cdot (\bar{S}a - I)^{1.4} + \dot{i}_f$$

Where:

\dot{i} = total infiltration rate (or subsurface abstraction rate)

\bar{a} = average vegetative cover factor

GI = maturity of cover

$\bar{S}a$ = average available water capacity = total available storage - initial moisture content

I = cumulative infiltration

\dot{i}_f = final infiltration rate

4. Overland Flow

A closed form solution for the unit peak flow from a simple unitary watershed (Figure 6) was formulated.

This formula is primarily dependent on variables which can be obtained by remote sensing techniques.

The equation takes the form:

$$Q_{\max} = 2L\bar{I}\xi \left[\frac{\phi(\bar{I}n)^{3/5}}{\xi^{2/5} S^{3/10} (3600)} \right]^{1/5 - \frac{1}{\alpha_3}}$$

5. Point-of-Flooding

In most practical applications, the user of a hydrologic planning model is interested not only in the accurate value of the peak flow, but in the coordinate where, along its length, the stream or channel will actually begin to flood. The stream begins to flood when the water level equals the height of the banks.

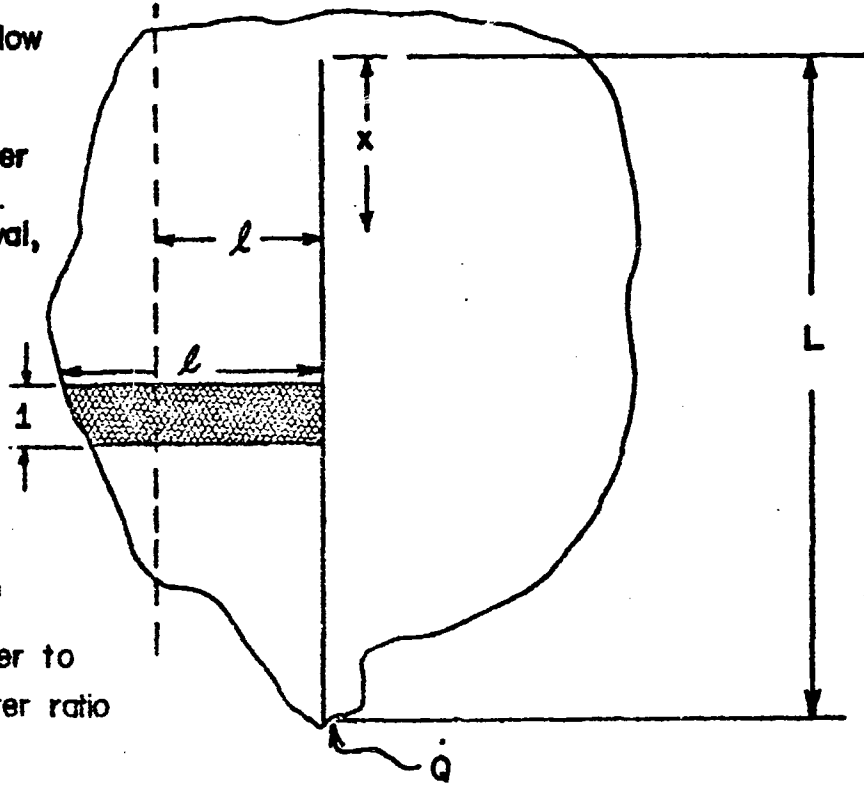
\bar{l} = Average overlandflow length, meters
 N = friction coeff.
 S = Slope, meters/meter
 t = Rain duration, hrs.
 T = Recurrence interval, years

$\alpha_1, \alpha_2, \alpha_3$ = Regional rainfall coefficients, derivable from rainfall records

$$\xi = K \alpha_1 T^{\alpha_2}$$

L = Channel length, m

ϕ = Channel parameter to overland parameter ratio



$$i_{max} = \frac{\alpha_1 T^{\alpha_2}}{(t + d)^{\alpha_3}}$$

$$Q_{max} = 2 L \bar{l} \xi \left[\frac{\phi (\bar{l} N)^{3/5}}{3600 S^{3/10} \xi^{2/3}} \right]^{\frac{1}{2/5 - \frac{1}{\alpha_3}}}$$

PEAK FLOW FOR SURFACE-DOMINATED WATERSHEDS-OVERLAND FLOW CONTRIBUTION

FIGURE 6

Flooding does not necessarily have to occur at the watershed's outlet; it is a function of channel shape, slope, and roughness. These factors are conveniently combined into a single formulation expressed in terms of the most easily observable parameter, namely channel width. Flooding begins to occur when channel width (w_c) at any point along the channel is less than:

$$w_c < \frac{L_c^{3/8} \xi^{3/8} Y_o^{5/8}}{\left(\frac{k^{3/2}}{1+2k}\right)^{1/4}}$$

Where:

L_c = channel length, m

ξ = roughness ratio surface/channel

k = channel geometric correction factor

Y_o = depth of overland flow, m

w_c = channel width at distance L_c from beginning of channel

Figure 7 supplies an example for typical values of the parameters.

A test of the model's validity was made on a randomly selected subset of nine of the ARS watersheds. These were selected to maximize geographic and physical diversity. A detailed analysis of each was performed to quantify those parameters required to operate the model. A summary of data collected for the Coshocton, Ohio watershed is presented in Figure 8 as an example.

THE EFFECT OF OVERLAND FLOW ON FLOOD CONDITIONS

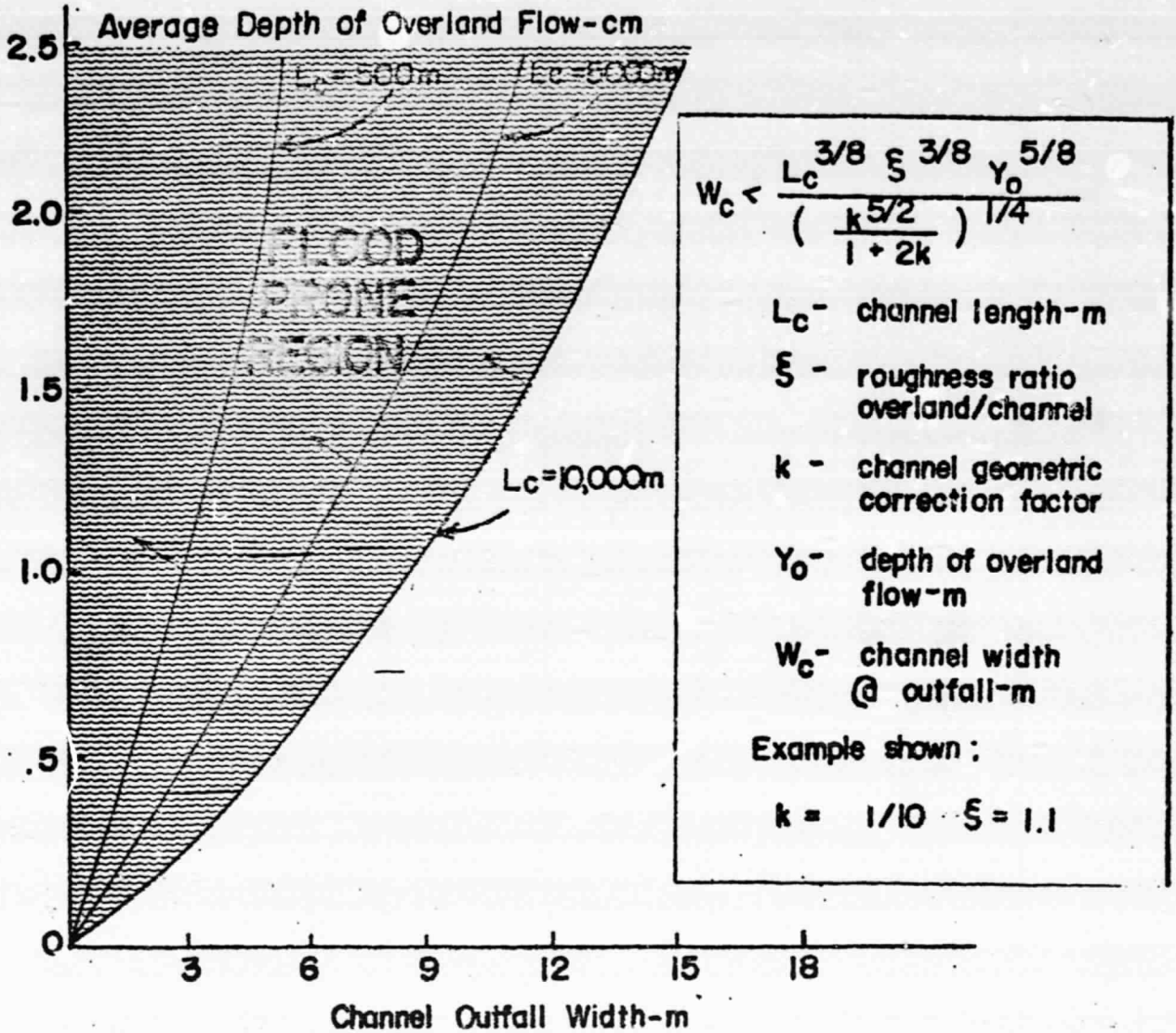


FIGURE 7

FIGURE 8

COSHOCTON OHIO ECO-2

Area = .76km²

Slope = .172 m/m

Shape = Square

Length of Channel - 1491 m

Drainage Density = 1/510 m/m²

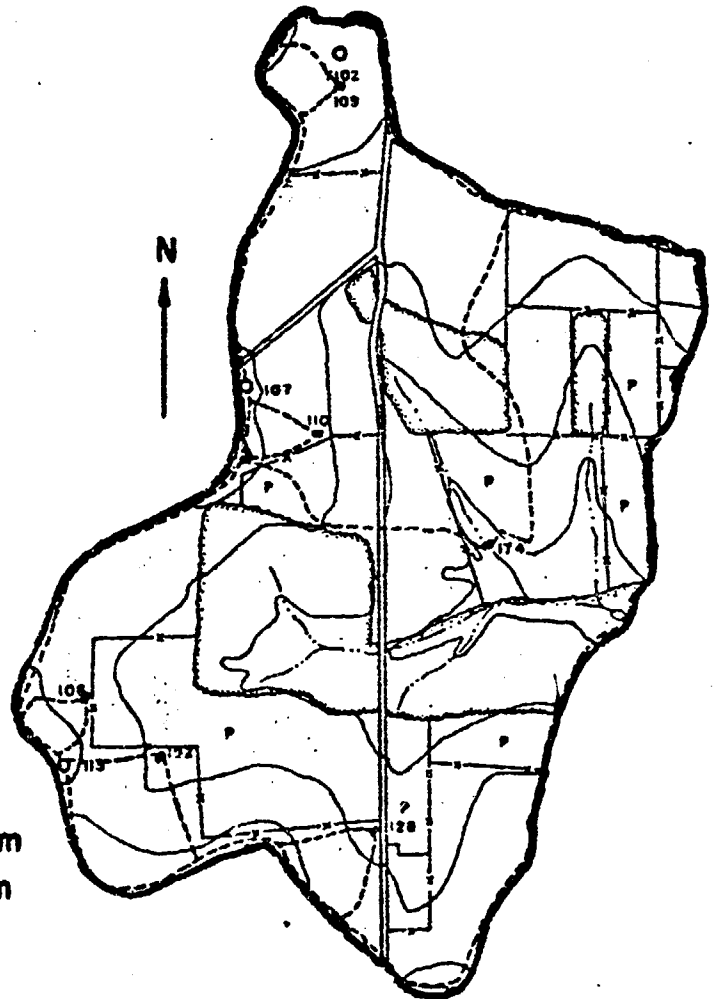
$$i_{m/m} = \frac{.039 T.15}{(t + .2) \cdot 83}$$

Cover

- 23% Hardwood Forest
- 58% Grassland
- 11% Cultivated
- 8% Miscellaneous

Soils

- 33% Muskingum silt loam
- 19% Keene shallow loam
- 17% Keene silt loam
- 17% Mixed silt loam
- 14% Muskingum stony loam



The analytic model was applied to each of the watersheds.

Verification of the Model

Equally applied were three other hydrologic planning models in wide current use - the Rational formula method, Cook's method, and the Soil Conservation Service method.

The 50-year peak flow statistically determined was used to compare the model's predictions with reality. Figures derived are reported in Figure 9.

The results of the tests, albeit on this limited sample, showed that a remote sensing oriented planning model has the potential for reducing prediction errors that occur in conventional models for relatively small unitary ungaged watersheds. The balance of the effort centered on identifying the applicability of current and near-future remote sensing techniques for developing the information required by the model.

A task was initiated to derive the information required to operate planning models from satellite imagery. To this end, a 4x enlargement of an ERTS photograph (Figure 10) of the Chickasha, Oklahoma test watershed was examined. It was determined that basin area and drainage density could be quantified directly from the picture, and that surface cover could be identified. The assessment of

FIGURE 9 COMPARISON OF RESULTS FOR PEAK OF THE FIFTY YEAR EVENT

| | $Q_{50} - m^3/sec/km^2$ | | | | |
|--------------------|-------------------------|-------|----------|------|------|
| | Records | ECO | Rational | SCS | Cook |
| 1. Danville Vt. | 0.95 | 0.91 | 4.8 | 2.14 | 5.49 |
| 2. Coshocton, Ohio | 10.6 | 25.5 | 17.6 | 4.4 | 12.6 |
| 3. Blacksburg, Va | 1.33 | 1.01 | 12.7 | 7.5 | 11.1 |
| 4. Oxford Miss. | 11.9 | 10.8 | 7.3 | 3.1 | 8.4 |
| 5. Fennimore Wisc. | 11.8 | 12.5 | 18.8 | 3.5 | 13.1 |
| 6. Chickasha, Okla | 0.88 | 0.08 | 3.3 | 2.9 | 6.44 |
| 7. Waco, Texas | 13.6 | 11.5 | 15.4 | 22.8 | 5.7 |
| 8. Safford, Ariz. | 6.25 | 5.3 | 14.4 | 15.2 | 5.0 |
| 9. Reynolds, Ohio | 0.87 | 0.001 | 1.7 | 13.7 | 3.9 |

**4x ERTS IMAGE, CHICKASHA, OKLA.
FIGURE 10 WATERSHED**



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**4x ERTS IMAGE, CHICKASHA, OKLA.
FIGURE 10 WATERSHED**



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subsurface conditions would require inference from cover data, but this is beyond the scope of this effort. It appears that current experimental techniques for extracting information from imagery and computer-compatible tapes, when fully operational, could play a significant role in obtaining this information.

Results and Conclusions

1. An improved model for the prediction of peak flow events has been structured, which is specifically designed to take maximum advantage of the data and information stream available from remote sensing.
2. The development of the model has been carried to the point where the overall framework has been constructed and five modules simulating the behavior of significant hydrologic processes have been developed.
3. The improved model is considerably more sophisticated than conventional hydrologic planning models. In particular, its modules are not simply interconnected, but require feedback. In spite of this greater complexity, however, the model is readily adaptable to analog computation

with modest amounts of hardware. Preliminary sizing shows that the technique can also be programmed onto one of the smaller types of digital minicomputers.

4. The model was exercised -- not in its fully interconnected form, but rather in a simplified version -- to predict the peak runoff from nine experimental Agricultural Research Service watersheds, selected at random from among a set of 158 instrumented and well-described watersheds.
5. The predictions of the new model in its simplified version were tested against:
 - a. The predictions from three of the most employed contemporary planning models -- i.e., the rational formula method, Cook's method, and the Soil Conservation Service method.
 - b. The streamgage records of the nine test watersheds.
6. The results indicate that, within the range of applicability of its simplified version, the new model appears to be considerably more accurate than conventional hydrologic planning

models. Specifically, in six out of nine of the watersheds tested, the new model supplied predictions of peak flow for the 50-year event falling within error bounds of $\pm 15\%$. For these same six watersheds, conventional models yielded discrepancies with respect to the records ranging from a minimum of 1.2 to 1 to a maximum of 15 to 1. For the three remaining watersheds, the new model yielded predictions of lesser accuracy, the worst being 2 to 1. Reasonable explanations for the discrepancy are:

- a. The fact of having oversimplified the model by not operating it in its fully interconnected form.
 - b. The three watersheds are considerably more complex than the other six, and they need to be split into subwatersheds, predicting the output from these, then routing all outputs through the watershed channels. This technique, which appears to be well in hand, is proposed for future phases of this effort.
7. The appropriate techniques whereby to extract the inputs and parameters required by the new model from remotely sensed information -- whether imagery or digital tapes -- were explicitly de-

find. Their feasibility was identified from specific past and ongoing ERTS investigator efforts.