2-(m/x)

NASA CR-139031

A STUDY OF REMOTE SENSING AS APPLIED TO REGIONAL AND SMALL WATERSHEDS

IBM No. 74W-00175

FINAL REPORT

VOLUME I - SUMMARY REPORT

HUNTSVILLE

(NASA-CR-139031) A STUDY OF REMOTE SENSING AS APPLIED TO REGIONAL AND SMALL WATERSHEDS. VOLUME 1: SUMMARY REPORT Final Report (International Business Machines Corp.) 46 p HC $5.50 CSCL 08H

N74-27813

Unclas
G3/13 42837

IBM

46

A STUDY OF REMOTE SENSING AS APPLIED TO REGIONAL AND SMALL WATERSHEDS

IBM No. 74W-00175

FINAL REPORT

VOLUME I - SUMMARY REPORT

HUNTSVILLE

June 1974

Prepared for
Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland

Contract No. NAS5-21942

i

IBM

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

PREFACE

This volume is a summary technical report on the study "Application of Remote Sensing As Applied to Regional and Small Watersheds," recently completed for NASA's Goddard Space Flight Center under Contract NAS5-21942. Section 1 of the report summarizes the highlights of the entire study and its results and conclusions. Sections 2, 3 and 4 provide some elaboration on study methodology, results and conclusions, respectively. References are listed in an Appendix. Supporting technical details are provided in Volume II.

The authors are grateful to many individuals for support of and contributions to the study. Dr. Vincent Salomonson of GSFC sponsored the study and gave excellent technical guidance. Dr. Al Rango of GSFC also provided support and technical advice. Dr. Peter Castruccio, president of Ecosystems International, advised the study team in interpretation and presentation of results. Dr. L. Douglas James, of the Georgia Institute of Technology Environmental Resources Center, reviewed results of the sensitivity analysis task.

Information on the small snowshed modeled in the study and on snowmelt simulation were provided by Dr. W. David Striffler and Dr. Gearold R. Johnson of Colorado State University. In the National Weather Service's Hydrologic Research Laboratory, Mr. Eric A. Anderson and Mr. John C. Monro supplied computer programs and data related to routing in a major river system and snowmelt modeling. Mr. Charles E. Schauss of the NWS Hydrology Office provided data pertaining to the Pearl River basin.

These acknowledgements of assistance do not imply any endorsement or approval by those whose help we appreciate so much. The conduct of the study, the results achieved and the content of this report are the responsibility of the authors. Any errors of fact, methodology or logic, or ineptness of expression should be attributed solely to us.

R. Ambaruch
Reuben Ambaruch
Principal Investigator

John W. Simmons
John W. Simmons
Study Manager

SECTION 1

SUMMARY

1.1 OBJECTIVE

The objective of the study was to determine how accurate remotely sensed measurements must be to provide inputs to hydrologic models of watersheds, within the tolerances needed for acceptably accurate synthesis of streamflow by the models.

The study objective was achieved by performing a series of sensitivity analyses, using continuous simulation models of three watersheds, to determine:

- the optimal values and permissible tolerances of inputs to the model needed to achieve an acceptably accurate simulation of streamflow from the watersheds;
- which model inputs can be quantified from remote sensing, directly, indirectly or by inference; and
- how accurate remotely sensed measurements (from spacecraft or aircraft) must be to provide a basis for quantifying model inputs within permissible tolerances.

1.2 SUMMARY OF RESULTS

The sensitivity analysis showed quantitatively how variations in each of 46 model inputs and parameters affect simulation accuracy with respect to five different performance indices. Of these inputs, 21 were found to have no meaningful effect on simulation accuracy in the basins modeled. The remaining 26 were further analyzed to quantify their permissible tolerances as a basis for estimating remote sensing resolution requirements. Finally, each input was assessed as to the degree of applicability of earth observation data, from low-flying aircraft to high earth orbit, with the following results.

- It is feasible at present to measure eight of the model inputs from Skylab and Earth Resources Technology Satellite (ERTS) bulk-processed images.
- Ongoing research and developments in sensor technology and image data analysis indicate a strong near-future potential for quantifying seven additional model inputs from image data comparable to that of Skylab and ERTS. When these potentials are realized, the results of the sensitivity analysis will be available to provide quantitative resolution requirements.

- The remaining inputs analyzed have sufficient influence on simulation accuracy to be of interest, although they are only practicably measurable by ground survey or low-flying aircraft or by calibration based on historical observations. All of them are potential candidate measurements for future data collection systems using satellite relay, and permissible tolerances have been estimated as a basis for accuracy requirements on such future systems.

Table 1-1 lists five of the parameters studied, with associated watershed characteristics, permissible tolerances, how derived from remotely-sensed data, required image resolutions, and potential remote-sensing system sources.

Table 1-1. Partial Tabulation of Study Results

INPUT OR PARAMETER	PERMISSIBLE TOLERANCE	RELATIONSHIP TO WATERSHED GEOMORPHOLOGY	DERIVATION FROM REMOTE-SENSED DATA	REQUIRED IMAGE RESOLUTION*
IMPERVIOUS AREA (FIMP)	14% OF FIMP 1.4% OF BASIN AREA	ROCK OUTCROPPING; STREETS, HIGHWAYS, CITIES	IMAGE ANALYSIS: LAND USE CLASSIFICATION	100 M (ERTS, SKYLAB)
WATER SURFACE AREA (FWTR)	15% OF FWTR 1.5% OF BASIN AREA	LAKES; PONDS; RIVERS	IMAGE ANALYSIS: LAND USE CLASSIFICATION	120 M (ERTS, SKYLAB)
VEGETATIVE INTERCEPTION (VINTMR)	+95% -60%	TYPE & DENSITY OF VEGETATIVE COVER	IMAGE DATA CLASSIFICATION & INTERPRETATION	200 M (ERTS, SKYLAB)
MEAN OVERLAND SLOPE (OFSS)	+200% -67%	TOPOGRAPHY: DISTANCES & RELATIVE ELEVATIONS	IMAGE ANALYSIS & MEASUREMENT	100 M HORIZONTAL; 20 M VERTICAL (AIRCRAFT)
MAXIMUM INFILTRATION RATE (BMIR)	+35% -28%	SOIL ASSOCIATION/TYPE	INFER FROM VEGETATIVE COVER; LOCATION & CLIMATE	200 M (POTENTIAL EOS APPLICATION)

*GENERALLY DEPENDS ON AREA OF WATERSHED OR SMALLEST SUBWATERSHED.

IBM USE OR DISCLOSURE OF THIS DATA IS SUBJECT TO THE RESTRICTION ON THE TITLE PAGE OF THIS DOCUMENT

1.3 CONCLUSIONS

The general conclusions of the study are summarized as follows.

- At present, remote sensing from space is directly applicable to determination of model parameters related to prominent surface features such as land use vegetation, overland distances, snow coverage, water and impervious surfaces. Permissible tolerances in the parameters associated with these features are large enough not to impose stringent resolution requirements. Eight of the parameters can be quantified from Skylab and ERTS image data.

- The sensitivity analysis has quantified permissible tolerances for several other inputs and parameters, and their corresponding image resolutions. This information will be applicable in the future to systems and techniques that are presently under study. For example, use of a spaceborne laser altimeter in conjunction with photographic or multispectral scanner images would provide data from which topographic information could be determined and thereby allow additional model parameters to be quantified through remote sensing.

- Sensitivity analysis is a valid tool for determining specifically and quantitatively how remotely sensed data (and supporting data from other sources) can be used to derive inputs for a model of the sort used in the study. Because of the popularity and widespread use of the model and others of the same pedigree, as well as having three physiographic regions represented, the study results should be of significant interest to a variety of investigators and potential users.

- Proven watershed simulation models have been designed and implemented to accept inputs known to be available from ground based instrumentation systems, topographic maps, field surveys and empirical relationships. It would be useful to have available a model designed to accept inputs more directly related to the data outputs of remote earth observation systems. The model used in the study could, for example, be improved in accuracy by accepting a daily soil moisture reading as an input rather than calculating soil moisture internally. Soil moisture determination through remote sensing is the subject of other research projects.

There are several closely related topics which deserve continued and intensive further study. Some investigators are presently exploring some of these topics; such investigations should be closely monitored and supplemented as needed. Those of particular interest are as follows.

- Determination of soil associations and classifications as well as subsurface characteristics by inference from, or statistical correlation with, remotely observable characteristics such as land use and vegetative cover;

- Remote measurement of temporal phenomena; precipitation, air temperature, relative humidity, evaporation rate;

- Determination by remote observation of snowpack depth at sufficient points to calculate total snowpack volume and water equivalent;

- Remote measurement of soil moisture on a daily basis;

- Determination of surface topography from orbital altitudes;

- Development of a multiple application watershed simulation model capable of accepting inputs and parameters directly or closely related to the data outputs of remote sensing systems.

- Extension of the sensitivity analysis to include parameter/input perturbations in logical combinations rather than singly, as a step toward greater realism. It is likely that the parameter tolerances resulting from such an analysis will be closer than those those produced by this study.

1.4 METHODOLOGY

1.4.1 TECHNICAL BACKGROUND

The basis for the study lies in the relationships shown in Figure 1-1. Prediction of streamflow within and from a watershed requires use of a simulation model, which may be physical, statistically-based or continuous (sometimes termed "parametric" or "deterministic"). Statistically-based models are widely used in operational (short term) streamflow forecasting but are currently being replaced by continuous models, which have been made more practicable by the availability of high-speed large-capacity digital computers. Continuous models are also suitable for long-term (multi-year) synthesis of streamflow for urban/industrial planning, water resources management and research into the hydrological effects of changes in land use. Continuous models were used in this study principally because of the variety of applications they serve.

A watershed simulation model requires two classes of inputs. The temporal inputs are the independent climatological variables -- precipitation, temperature, evaporation -- which change continuously. The watershed model parameters are the coefficients in the set of empirical equations implemented in the model. Some of the parameters can readily be assigned values derived directly, indirectly or by inference from observable and measurable characteristics of the watershed. The remaining parameters are not so readily evaluated; at present, they are quantified by a trial-and-adjustment process (usually with computer assistance) known as calibration. A "best set" of model parameters has been found when the model's synthesized streamflow matches actual streamflow (for the same climatological inputs) to a degree acceptable to the model's user.

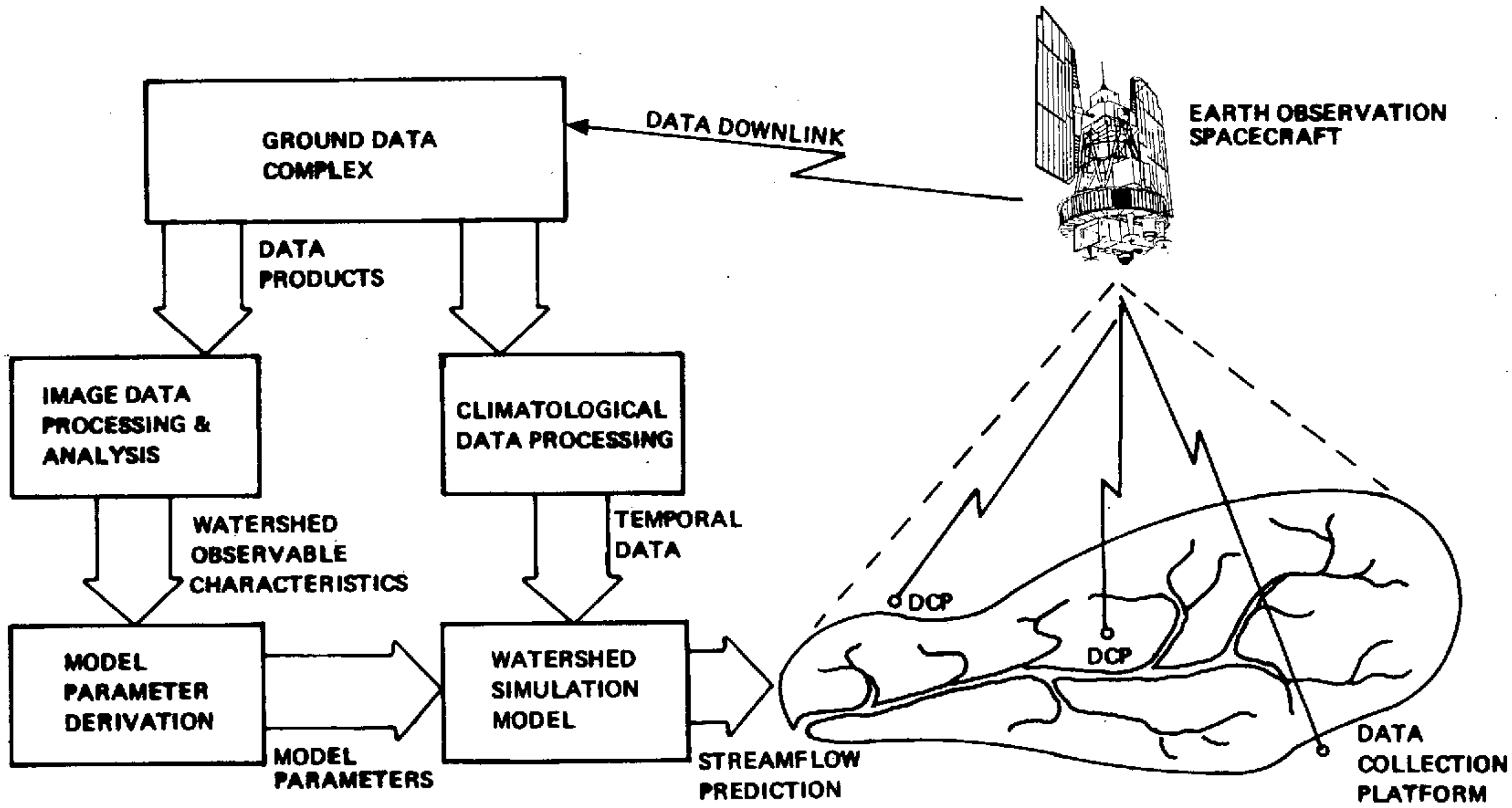


Figure 1-1. Remote Sensing Application Concept

The remote sensing application as represented in Figure 1-1 envisions acquisition of temporal data as well as observable physiographic data by a spacecraft. The physiographic observations need not be made frequently, because physical characteristics in general (except snowpack size) change slowly. Quarterly observations -- perhaps once per season -- should be more than adequate. Temporal data observations should be daily, and at least one precipitation reading should be an hourly (or bi-hourly or six-hourly) record acquired daily. After reception, the remotely sensed data are transformed into model inputs through the appropriate processes and analyses. Inputs not obtainable through remote sensing must be obtained through other means, such as from data collection platforms, ground truth surveys, aerial photography, and/or the climatological data systems operated by the National Weather Service and other agencies.

1.4.2 STUDY TASKS

The study consisted of five technical tasks, in addition to the final report. A literature search was conducted and continued throughout the study to take advantage of the results of other projects and to avoid duplicating the results of other investigations. The technical tasks were as follows.

1.4.2.1 Watershed Selection

Watersheds were chosen, with the concurrence of the NASA Technical Officer, as test sites for modeling and analysis. Two small watersheds (area less than 1,000 square kilometers) and one regional watershed (area greater than or equal to 1,000 square kilometers) were selected to include some geographic and climatic variety among the test sites. This task also included collection of physiographic and historical (climatological and streamflow) data pertaining to each watershed. The watersheds chosen are as follows.

- Town Creek near Geraldine, Alabama - a rural basin located in the Tennessee River Valley; land use is almost entirely light forest and agriculture;

- Alamosa Creek above Terrace Reservoir (near Monte Vista), Colorado - a mountainous basin in the Rio Grande drainage area of southern Colorado; precipitation is predominant winter snow;

- Pearl River at Pearl River, Louisiana - a regional-sized watershed lying almost completely in southern Mississippi, with a small portion in Louisiana; the watershed is divided into 12 subwatersheds for modeling and simulation purposes; subwatersheds vary in degrees of urbanization.

Some of the characteristics of the selected watersheds are listed in Table 1-2. Ample historical and physiographic data were collected to determine optimal values for all model parameters and provide good input data for the sensitivity analysis.

Table 1-2. Characteristics of Selected Watersheds

WATERSHED CHARACTERISTIC	UNIT	WATERSHED		
		TOWN CREEK	ALAMOSA CREEK	PEARL RIVER
LOCATION		ALABAMA (NE)	COLORADO (S)	MISSISSIPPI (S)
AREA	km^2	365	277	22,248
NUMBER OF SUBWATERSHEDS		1	1	12
MAXIMUM ELEVATION*	m	594	4152	197
MINIMUM ELEVATION*	m	305	2628	0
MEAN SURFACE SLOPE	m/m	0.062	0.340	0.019
DAILY PRECIPITATION STATIONS		5	0	25
HOURLY PRECIPITATION STATIONS		2	2§	12
EVAPORATION STATIONS		1	1§	1
TEMPERATURE STATIONS		N/A	2§	N/A
MEAN ANNUAL PRECIPITATION	cm	132	31	147
MEAN ANNUAL STREAMFLOW	m^3/s	8.0	3.3	280
SENSITIVITY ANALYSIS WATER YEAR		1964	1958	1968
NUMBER OF SENSITIVITY ANALYSIS RUNS		166	137	139

*ABOVE MEAN SEA LEVEL # EQUIVALENT RAINFALL; SNOW PREDOMINATES

§MEAN BASIN DATA OBTAINED FROM COLORADO STATE UNIVERSITY

1.4.2.2 Simulation Model Set-Up

The model used in the study is a highly automated derivative of the well-known and widely-used Stanford Watershed Model IV. Basically a multi-year model applicable to small watersheds, it required several modifications to adapt it to this study. Modifications included simplification to a one-year (rather than multi-year) simulation, introduction and verification of a snowmelt routine, and adaptation to regional watershed simulation by incorporation of a subwatershed streamflow routing routine.

In operation, the model implements a moisture-accounting flow, distributing input (precipitation and snowmelt) among storages (vegetative interception, soil moisture, ground water, snowpack, channel flow, overland flow), losses (evapotranspiration) and output (streamflow from the basin mouth where the stream gage is located). The model produces tabulations and plots of simulated and observed (or reference) streamflow, as shown in Figure 1-2 for example, as well as statistical analyses and summaries.

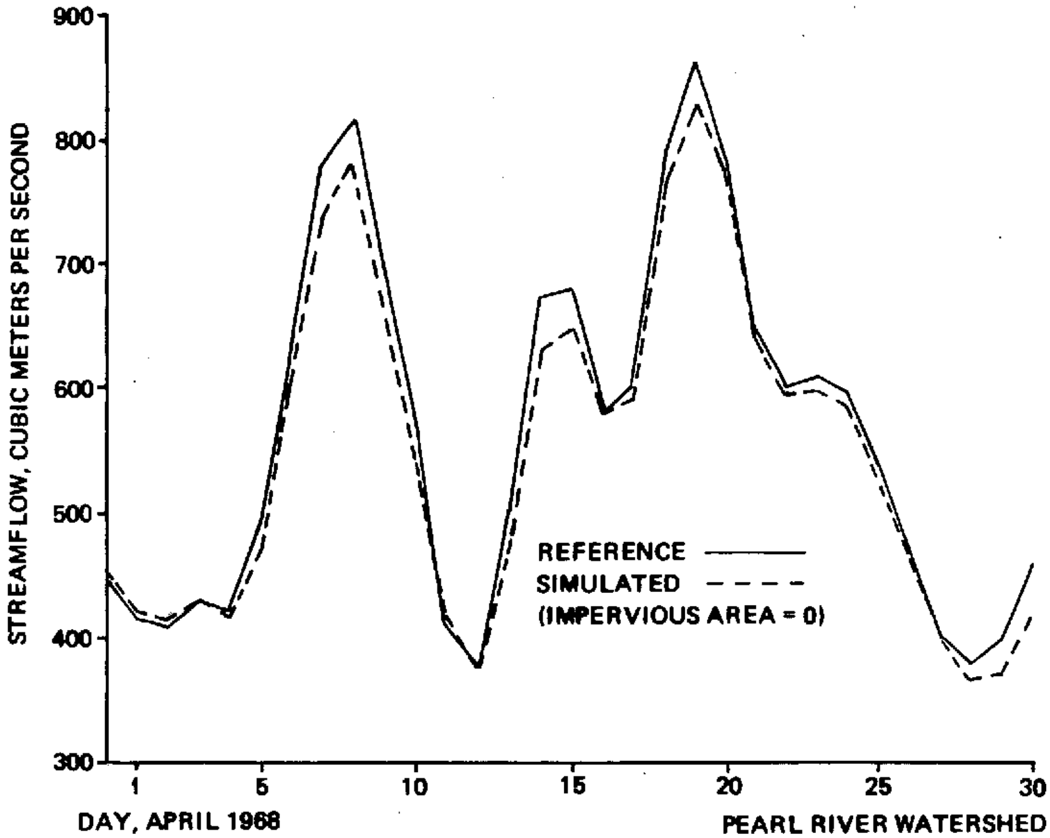


Figure 1-2. Example of Reference and Simulated Hydrographs

1.4.2.3 Sensitivity Analysis

This was the central task of the study. It consisted of a series of perturbation experiments. After a reference configuration (corresponding to the set of parameters yielding the most accurate simulation) was established, parameter values were changed one at a time and the effects on simulation accuracy noted. After this was done for all parameters (at least four perturbations per parameter), for a total of 442 simulation runs, the data were analyzed to determine the allowable parameter tolerances. The empirical equations implemented in the simulation model, to represent the hydrologic phenomena taking place in the watershed, are too many and too complexly interrelated for a theoretical sensitivity analysis by evaluating partial derivatives.

The sensitivity analysis task sought to answer the question, "By what percentage may a given parameter or input be varied without degrading simulation accuracy by more than an allowable amount?" The answer was found to depend upon the performance index selected for observation from among the several available, such as mean daily streamflow, mean monthly streamflow, total annual flow, and selected storm-event parameters (peak flow, time of peak, total runoff). The sensitivity analysis task produced a prodigious amount of data which was analyzed to yield a large number of sensitivity plots such as those of Figure 1-3, showing the effect, on runoff from three simulated storms and annual flow, of significant variations in the parameter representing that portion of the watershed covered by impervious surfaces. From the plots, it is estimated that the parameter can vary as much as 14% from its reference value without changing simulation accuracy by more than 10%. In the example given, this would imply an areal resolution requirement of 1.4% of the regional watershed area, or 31.2 square kilometers. But the 1.4% tolerance should apply to the smallest subwatershed (440 square kilometers in area) also, yielding an areal resolution of six square kilometers. If the impervious areas are largely urban development, quantification of the parameter from ERTS or Skylab imagery is readily done. Table 1-3 lists a few examples of permissible tolerances.

1.4.2.4 Sensor/Parameter Dependencies

The model parameters were individually reviewed to determine which ones could be quantified from remotely sensed data and by what methods, whether directly, indirectly or inferentially. For those parameters not quantifiable from remotely sensed data, alternative means were identified, and possible future developments in data interpretation and analysis were reviewed.

1.4.2.5 Sensor Performance Requirements

The permissible tolerances on model inputs and parameters were translated, where possible, into performance requirements on remote sensing systems. These requirements mostly take the form of image spatial resolution. Several examples were listed previously in Table 1-1.

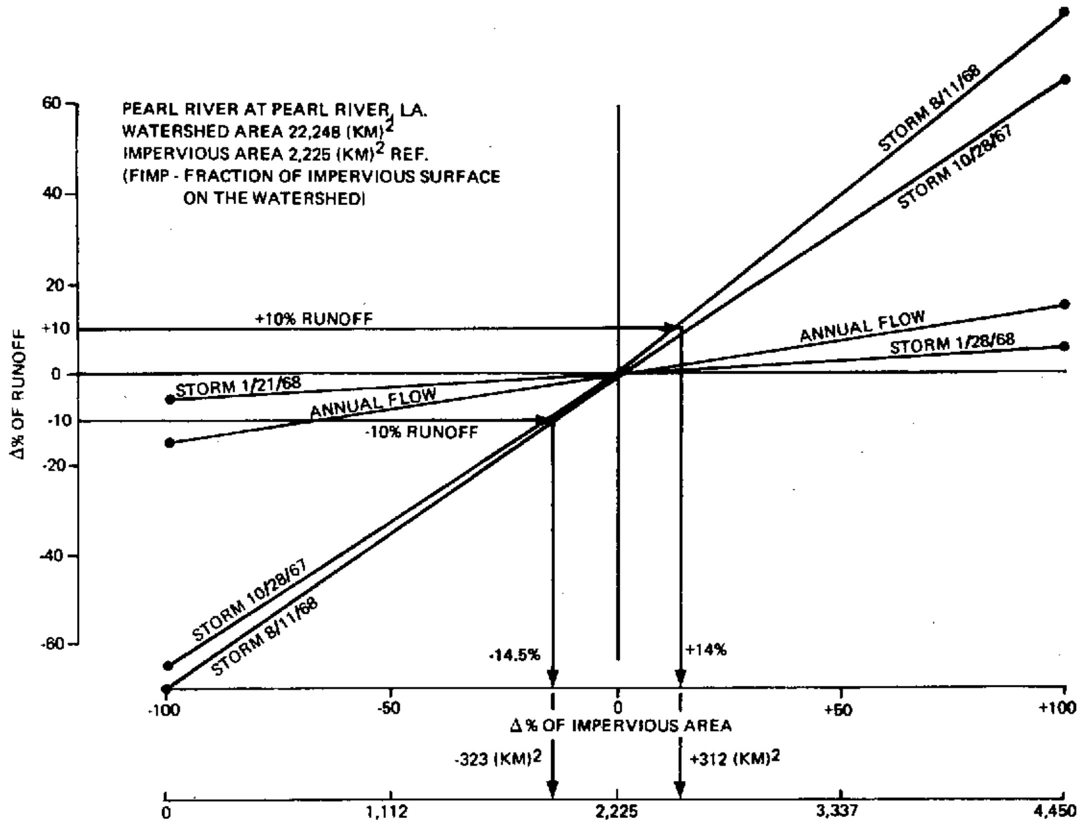


Figure 1-3. Sensitivity Analysis, Impervious Area, Regional Watershed

Table 1-3. Examples of Permissible Tolerances

MODEL INPUT	PERMISSIBLE TOLERANCE
IMPERVIOUS AREA	±1.4% OF WATERSHED AREA
WATERSHED SURFACE AREA	±1.5% OF WATERSHED AREA
FORESTED AREA	NEGLIGIBLE EFFECT
OVERLAND FLOW SURFACE LENGTH	±200 METERS (SMALL EFFECT)
OVERLAND FLOW SURFACE SLOPE	±6% OF SLOPE
PRECIPITATION	±3% IN RAINFALL RATE
ANNUAL POTENTIAL EVAPOTRANSPIRATION	±4"/YEAR OR ±10%
BASIC SOIL STORAGE CAPACITY	±14% WITHOUT SNOW ±7% WITH SNOW
SOIL PERMEABILITY (MAXIMUM INFILTRATION RATE)	±28%

SECTION 2

STUDY METHODOLOGY

The study consisted of five technical tasks which were completed sequentially (although there were parallel activities at times during the study) as indicated in Figure 2-1. The feedback from Task 4 to Task 3 was simply an identification of which sensitivity analysis results were most meaningful from a remote sensing application standpoint and what additional analysis was needed. The performance of each task took advantage of experience and/or knowledge acquired previously by the study team.

A previously-ongoing literature search was intensified at the beginning of the study for assurance that other research efforts were not duplicated and that advantage was taken of pertinent results achieved by other investigators. The IBM Huntsville collection of documents pertaining to environmental resources and remote sensing was purged, and the index of such documents was updated. Collection and review of pertinent documents and their listing in the comprehensive index continues. Pertinent data, key words and abstracts are stored for each document; an example from the index appears in Figure 2-2. Listings by key word are available.

Study tasks were performed as described in the following paragraphs.

2.1 WATERSHED SELECTION

The contract requires that sensitivity analyses be performed on models of watersheds of two sizes: small (area less than 1,000 square kilometers) and regional (area equal to or greater than 1,000 square kilometers but less than 10^6 square kilometers). It is also desirable that the watersheds selected be broadly representative of areas that are presently objects of remote sensing from space (i.e., the United States), with respect to geomorphology and climate. It was not deemed essential to use real watersheds; hypothetical watersheds would suffice if they were "realistic," that is, their models would represent the hydrologic processes found in a real watershed.

Achievement of realism within study budgetary and schedule constraints limited the choice of watersheds to those for which adequate historical and physiographic data were available. It was preferable, also, that each watershed selected have been the subject of previous investigations using the same or a similar simulation model, to minimize the labor of acquiring input data and calibrating the model.

It was decided, with the Technical Officer's concurrence, to model two small watersheds of widely different geographic locations, geomorphology and climate, one whose precipitation is predominantly snow and one in which snowfall is negligible.

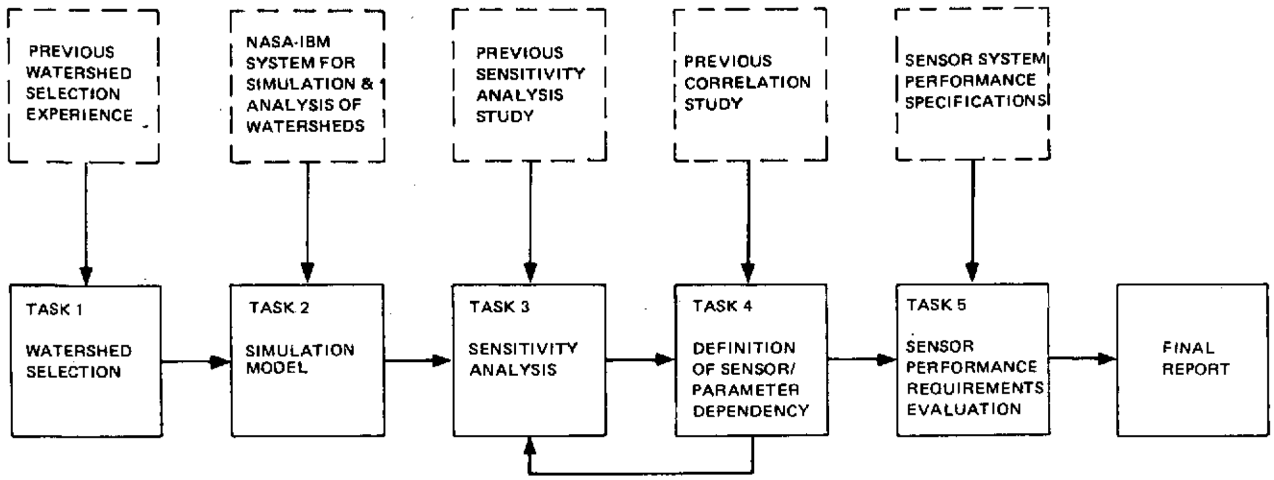


Figure 2-1. Study Methodology

```
73W-00-5012

    AIAA-69-1085.  THE ROLE OF SATELLITES IN EARTH ECOLOGY.
    AIAA 6TH ANNUAL MEETING AND TECHNICAL DISPLAY.  ANAHEIM,
    CALIF.  OCTOBER 1969.
    CASTRUCCIO, P
    IBM GAITHERSBURG, FSD
    AIAA-69-1085
    MOST OF THE APPLICATIONS OF EARTH OBSERVATION SATELLITES
    ARE AIMED AT IMPROVED EXPLOITATION OF SPECIFIC NATURAL
    RESOURCES.  IN PRACTICE, THE SPHERE OF INFLUENCE OF
    TECHNOLOGICAL EXPLOITATION HAS ALREADY REACHED SUCH A
    SIZE THAT MANY HUMAN ACTIVITIES, ALBEIT IN DIVERSE FIELDS OF
    ENDEAVOR, ARE BEGINNING TO COUPLE.
    ECOLOGY# ARTIFICIAL SATELLITES
```

Figure 2-2. Example of Document Listing

2.1.1 SMALL WATERSHED, WITHOUT SNOW

The watershed designated "Town Creek near Geraldine, Alabama,"* was one of a number studied by IBM under a previous NASA contract. Six years of usable historical data had previously been collected, using two hourly and five daily precipitation stations, and model calibration had been completed. The basin is representative of temperate-climate rural areas of moderate topography.

The basin is located in northeast Alabama, at the edge of the Tennessee River Valley, in the Cumberland Plateau physiographic region. Its area (see Figure 2-3) is 365 square kilometers (141 square miles), approximately 65% moderately forested and 35% cultivated. Impervious surfaces and water surfaces represent approximately 0.2% and 0.1%, respectively, of the entire watershed area. Surface soil is predominately sandy loam; the watershed is, in fact, located on top of what is known as "Sand Mountain." The stream channels are generally deep and steep-sided, without well-defined flood plains; overflows have not occurred, even after the heaviest of recent precipitation events (e.g., March 1973).

Most accurate simulation was achieved using climatological data for water year 1964 (October 1963 through September 1964). A comparison of some single-year and long-term statistics is included in Figure 2-3. Although October was one of the driest months ever recorded, total precipitation was approximately 8% over the long-term average. Some heavy rains occurred in March 1964 (approximately 10 inches on March 25) but did not cause damage.

2.1.2 SMALL WATERSHED, WITH SNOW

The basin designated "Alamosa Creek above Terrace Reservoir," is in the south central part of the state in the Rocky Mountains. The dominant precipitation is winter snow. Moisture accumulates in the snow pack during winter, when streamflow is small but unreadable because the stage height - discharge relationship is affected by icing. Greatest runoff occurs in the spring during snowmelt.

The Alamosa Creek watershed (Figure 2-4) was selected as a basis for modeling and sensitivity analysis in the study because it is representative of small mountainous snowsheds yet low enough in altitude so that seasonal effects on its hydrological behavior are pronounced. Additionally, it had previously been the subject of modeling and study by Colorado State University, using the same basic simulation model as was used in the IBM study. Basin descriptive data, model parameters, streamflow and mean basin climatological data for the water year 1958 were provided by CSU.

---

*A watershed designation refers to the name of the stream gage which measures stream stage (height) at the point of outflow from the basin. The gage location, with basin topography, uniquely defines the basin boundary.

STATISTICAL DATA		
STATISTIC	LONG TERM	1964*
Average Discharge, m^3/s	8.04	9.20
Peak Discharge, m^3/s	500.9	243.2
Least Discharge,	0	0
Annual Precipitation, cm	137	148

*Reference values used in sensitivity analysis

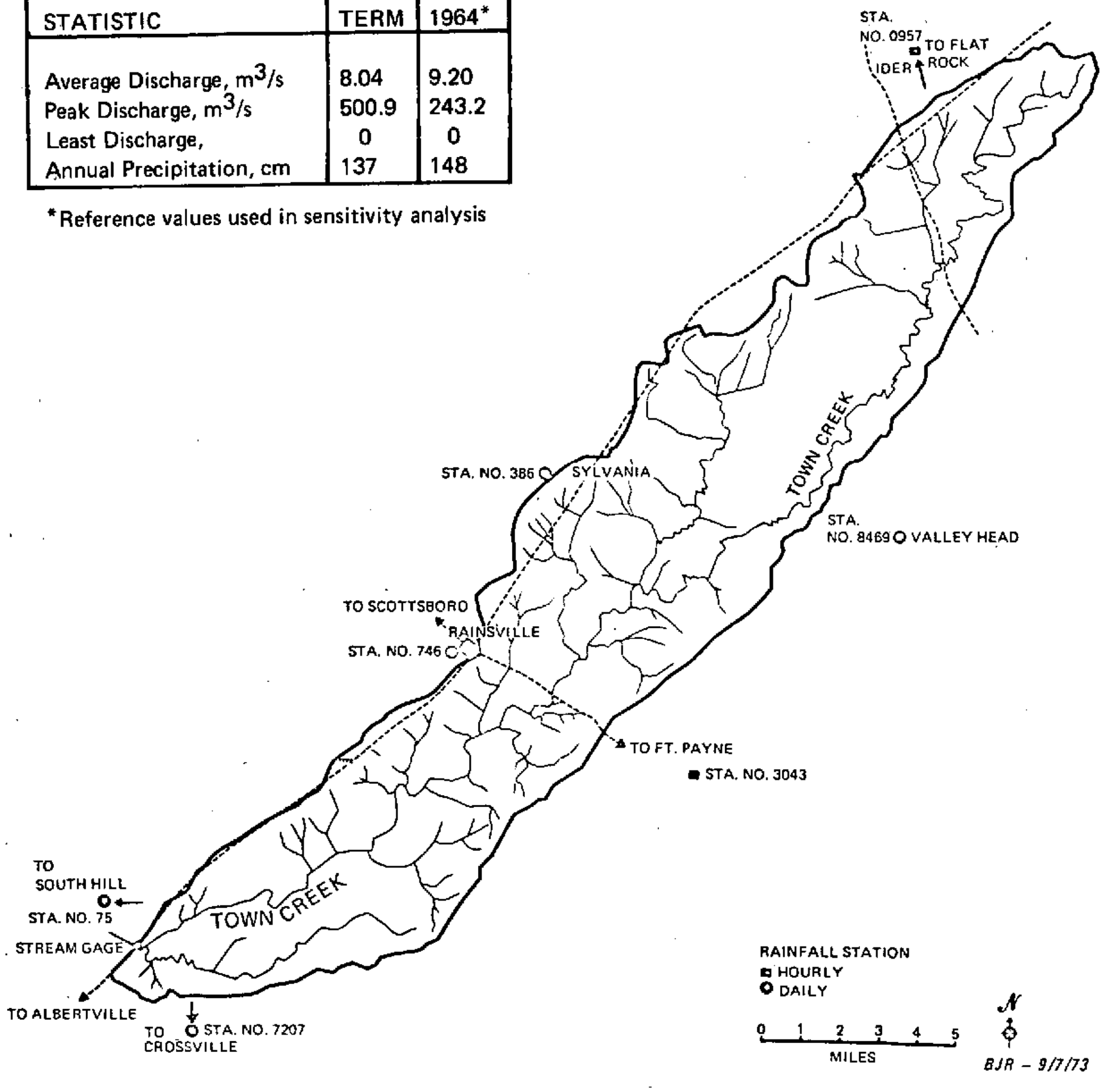


Figure 2-3. Town Creek Watershed

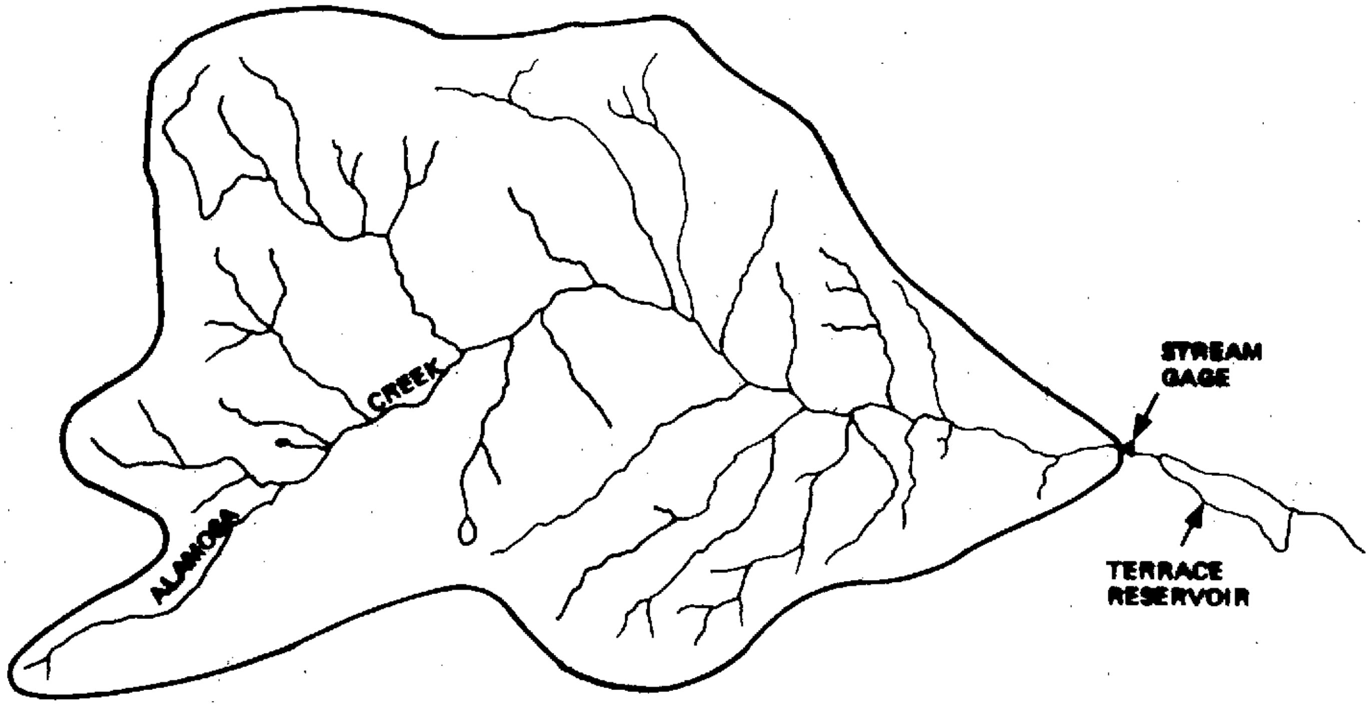


Figure 2-4. Alamosa Creek Watershed

For the water year 1958, the reference average and peak discharges were 2.24 and 24.8 cubic meters per second respectively. The published 17-year average was 3.25 m^3/s, and the highest recorded discharge was 147.2 m^3/s. The least actual discharge cannot be determined. The total annual mean basin precipitation for the reference year is 85 cm, compared with an annual average estimated at 120 cm. (Note: In a mountainous region, average annual precipitation varies widely for points only a few miles apart; calculation of mean basin precipitation on a long-term or a short-term basis in such a region is hazardous at best).

2.1.3 REGIONAL WATERSHED

The choice of regional watershed was influenced principally by the fact that it had been modeled and calibrated for river forecasting purposes by the National Weather Service Lower Mississippi River Forecast Center, Slidell, Louisiana, using a model of the same basic type as that used by IBM in this study. It is designated "Pearl River at Pearl River, Louisiana," and is located in the Gulf Plain Physiographic Region, lying mostly in south central Mississippi and a small part of Louisiana.

The regional watershed (Figure 2-5) has a total area of 22,248 square kilometers (8,590 square miles) and is composed of 12 subwatersheds, each with its own stream gage. The water year 1968 was the one for which most accurate overall simulation was achieved. A total of 12 hourly and 25 daily precipitation stations were used to calculate mean basin precipitation for each subwatershed. Table 2-1 lists some of the characteristics of interest pertaining to the subwatersheds and their associated precipitation and streamflow data. Approximately half the population of the basin is concentrated in and around the city of Jackson, Mississippi. The topography varies from nearly flat land near the Gulf Coast to gentle hills near the northern end.

2.2 <u>WATERSHED SIMULATION MODELS</u>

2.2.1 WATERSHED MODEL SELECTION

2.2.1.1 <u>Streamflow Forecasting</u>

That aspect of hydrology known as streamflow forecasting undertakes to predict the outflow from a river basin, in terms of flow rate as a function of time, in response to a given precipitation event under given initial conditions. This capability is vital to effective planning for urban/industrial development, flood control, hydroelectric power, navigation, and water resources management.

Figure 2-6 depicts the cross section of a somewhat idealized rural catchment and identifies the principal phenomena at work in the rainfall-runoff relationship. The input (precipitation) is partially intercepted by vegetation and water retention areas. Moisture reaching pervious surfaces divides between overland flow, infiltration, and evaporation. Through subsurface processes, interflow, and groundwater flow contribute ultimately to streamflow, with some losses due to transpiration through plant life. In

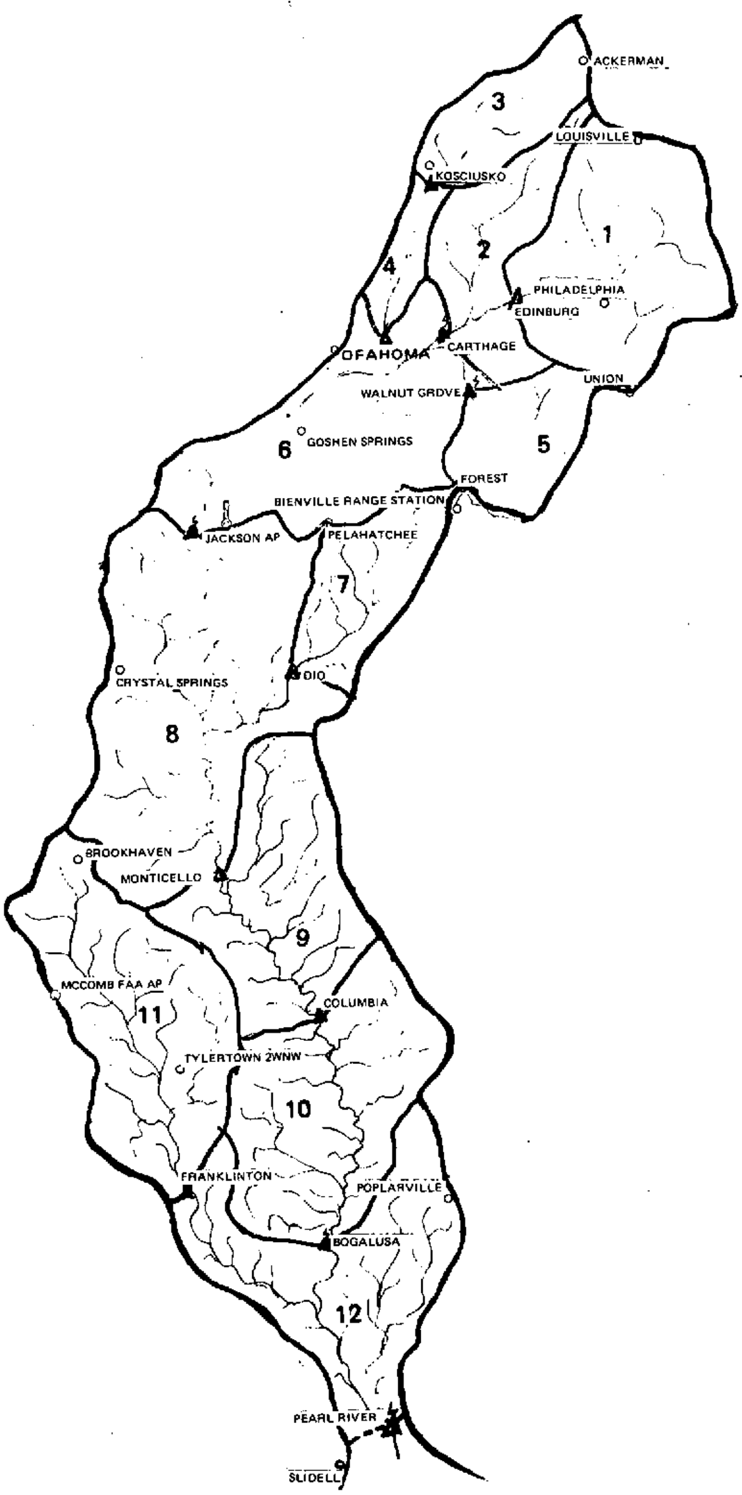


Figure 2-5. Pearl River Regional Watershed

Table 2-1. Pearl River Subwatershed Characteristics Summary

SWS NO.	SUBWATERSHED NAME	STREAM GAGE EL, m	SWS AREA, km^2	AVERAGE DISCHARGE		LOW DISCHARGE		PEAK DISCHARGE		ANNUAL RAINFALL	
				LONG TERM	REF. YEAR	LONG TERM	REF. YEAR	LONG TERM	REF. YEAR	LONG TERM	REF. YEAR
1	PEARL RIVER AT EDINBURG, MS	104	2326	29.4	36.7	.048	.76	889	306	137	151
2	PEARL RIVER AT CARTHAGE, MS	96	1163	37.1	55.5	.88	1.22	515	442	132	145
3	YOCKANOOKANY RIVER NEAR KOSCIUSKO	114	813	10.8	17.1	.07	.34	546	246	132	166
4	YOCKANOOKANY RIVER NEAR OFAHOMA, MS	95	440	17.4	24.5	.14	1.13	586	286	135	160
5	TOSCOLAMETA CREEK AT WALNUT GROVE	101	1064	13.2	19.1	.07	.11	979	166	142	125
6	PEARL RIVER AT JACKSON, MS	72	2222	106	125	1.27	3.08	2406	848	130	112
7	STRONG RIVER AT DIO, MS	79	1111	15.3	16.3	.34	.48	702	133	132	129
8	PEARL RIVER NEAR MONTICELLO, MS	448	3913	170	186	7.61	7.8	1797	969	1421	123
9	PEARL RIVER NEAR COLUMBIA, MS	*	1684	*	204	*	2.07	*	1006	147	122
10	PEARL RIVER NEAR BOGALUSA, LA	16.8	2435	246	227	28.9	14.6	2496	1030	150	104
11	BOGUE CHITTO RIVER AT FRANKLINTON	*	2551	*	26.3	*	.35	*	270	157	91
12	PEARL RIVER AT PEARL RIVER, LA	0.1	2525	280	275	44.7	1.05	3246	1095	163	106

NOTES: Discharges are in cubic meters per second.
Rainfall is in centimeters.
Long term annual rainfall is an approximation from weather data.
Reference year is water year 1968, reference simulation run.
*Data not obtained.

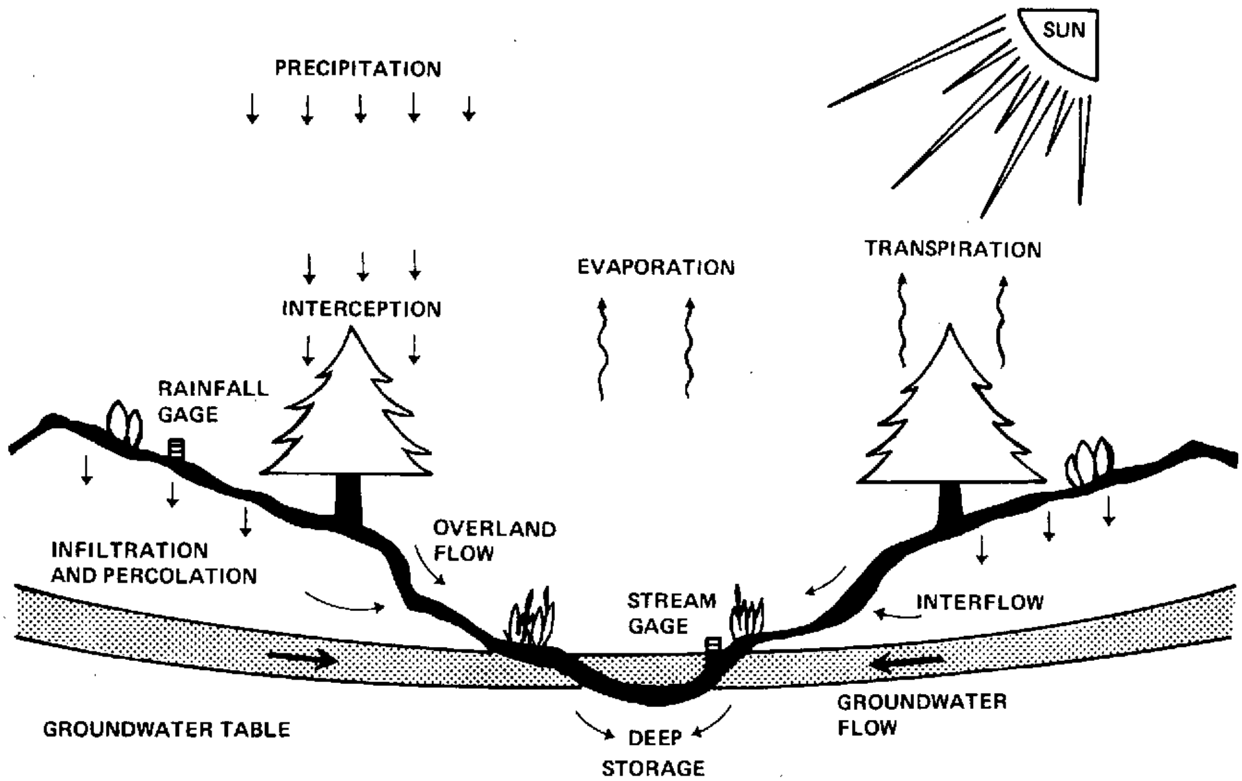


Figure 2-6. Cross Section of Idealized Rural Catchment

certain regions, in winter, moisture is stored in the form of snow in portions of the basin, and melts to produce additional moisture movement in spring.

All the phenomena involved in this portion of the hydrologic cycle are widely and well understood qualitatively, and several empirical relationships have been developed from a combination of theory and experiment. The relationships are numerous, many of them are nonlinear, and they are interrelated. Manual solutions for streamflow by manipulation of such a set of equations are inefficient and so time consuming as to be of little value in an operational situation. Individuals and organizations responsible for streamflow forecasting have turned to watershed models as effective tools for their work.

2.2.1.2 Model Selection Criteria

The model used in the study was required to (1) describe the various hydrologic processes directly involved with or related to runoff and the water balance of a representative watershed, and (2) be of a type that has a capability for providing an assessment of how well remotely sensed measurements from spacecraft or aircraft can be used to study or specify the hydrologic processes occurring within the watershed. The first criterion immediately excludes the entire class of stochastic models, which obscure the cause and effect relationships among the conditions and hydrologic processes in the watershed. The model used in the study is a parametric model, so called because its operation depends upon quantification of several parameters which represent coefficients and exponents in the equations implemented in the model.

The parametric model used in the study also (3) is one which is likely to be used by operational users of remote sensing in the future; (4) supports a variety of user objectives; and (5) is so implemented for a comprehensive sensitivity anslysis could be completed and evaluated for a minimum manpower expenditure.

2.2.1.3 The Kentucky Watershed Model

The Stanford Watershed Model[1] is probably the best known of the parametric hydrological models and, in all its modifications, is probably the most widely used. Since it was originally published in 1962, several reports have appeared in the literature describing modified versions and applications (References 2 through 7, and others). As a proven tool it was attractive to IBM for studies of applications of remote sensing to hydrology. A derivative of the Stanford model, known as the Kentucky Watershed Model (KWM), and a companion calibration program known as OPSET were first used yb IBM early in 1972, because of their availability and utility and the availability of reports describing them. [8, 9, 10] Since then IBM has incorporated KWM and OPSET into a system of programs and methods for simulation and analysis of watershed behavior. Improvements in programming have been introduced without disturbing the basic hydrological processes implemented in the model. The improved man-machine interactions and operator efficiency realized thereby enabled a small study staff to complete 442 simulation runs.

Figure 2-7 depicts the accounting of moisture entering the watershed until it leaves by streamflow, evapotranspiration, or subsurface outflow. A series of relations each based on empirical observation or theotetical description of a specific hydrologic process, is used to estimate rates and volumes of moisture movement from one storage category to another, in accordance with current storage states and the calibrated watershed parameters. The model routes channel inflow from the point where it

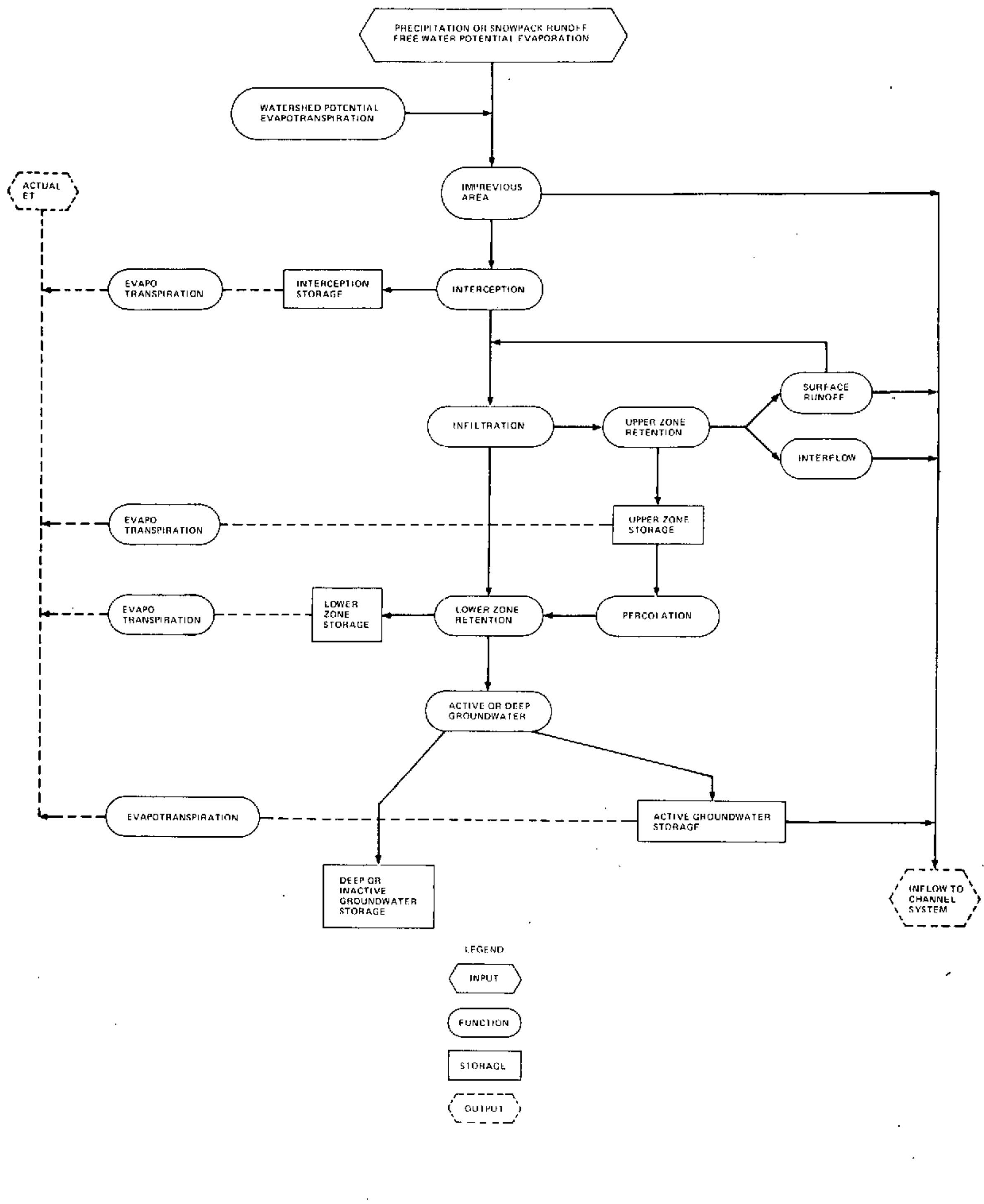


Figure 2-7. Moisture Accounting in the Stanford Watershed Model

enters a tributary channel to the downstream point for which a hydrograph* is required. A more detailed discussion of model operation is given in Volume II, Section 5.

2.2.2 SMALL WATERSHED MODEL, WITHOUT SNOW

The Kentucky Watershed Model was originally designed to simulate the hydrologic behavior of small watersheds, using three classes of inputs:

- recorded climatological data, precipitation, evaporation and (for snowmelt situations) temperature;

- measurable watershed characteristics (parameters) such as drainage area and fraction of the watershed in impervious surfaces which are determined from knowledge of basin geomorphology, such as might be obtained through interpretation and analysis of aerial photographs or images acquired from space; and

- parameters used in the computation process which are known to vary in magnitude among watersheds but have not been quantitatively tied to specific measurable watershed properties. For example, one parameter indexes the capacity of the soil of the watershed as a whole to retain water.

The third class of inputs normally requires a trial and error series of calibration runs to quantify a set of model parameters which will synthesize flows with acceptable accuracy for each of three separate water years. In the study, this much calibration was not necessary. The following sequence of action was used instead.

1. Either the result of a previous calibration was used, or enough calibration was performed to tailor the model to a real watershed so that it would simulate streamflow with acceptable accuracy for one water year.

2. The model was run with the "best set" of parameter values and temporal inputs for the selected water year.

3. The hourly streamflow synthesized by this run then replaces the "observed" streamflow and is termed "reference" streamflow.

---

*A hydrograph is simply a plot of streamflow in volume per unit time or river height as a function of time. See Reference 11, Chapter 9.

This straightforward process converts the "best" set of parameters, which characterize a model which roughly represents a real watershed, to a "perfect" set of parameters, which charcterize a model which exactly represents a hypothetical but realistic watershed.

Output routines associated with the simulation model program prepare and present tabular and plot outputs of simulation results, including the following.

- tables of reference and simulated mean daily streamflows,
- yearly statistical summaries (example, Figure 2-8),
- summaries of monthly and annual totals (example, Figure 2-9),
- selected storm analysis summaries, comparing reference and simulated results with respect to peak flow, time of peak and total runoff,
- plots comparing simulated and observed hydrographs (as previosuly illustrated in Figure 1-1), with the option of plotting precipitation unscaled on the same coordinates.

2.2.3 SMALL SNOWSHED MODEL

In the model of the Town Creek watershed, the snow subroutine is inoperative. When snow accumulation and snowmelt become significant in the total moisture accounting, the snow subroutine is necessary. In addition to the same basic inputs and parameters as for the Town Creek model, the Alamosa Creek model requires evaluation of several additional parameters and acquisition of additional climatological data. The snowmelt parameters include factors for calculating rates at which snow will melt and runoff, the capacity of the forest for intercepting snow, and an index for adjusting snow albedo. Temporal inputs relate to incident solar radiation over the calendar year, potential snow evaporation data over the calendar year and daily maximum and minimum temperatures.

Snowshed simulation outputs, in addition to the basic ones listed under Section 2.2.2 above, include tabulation of five indices related to snowpack size and condition: average snow depth, snow total mositure density, snow albedo index, total accumulated negative snowmelt (snow-chilling), and snow pack liquid water content. An informative report on a version of the Kentucky Watershed Model, including snowmelt, has been published by Colorado State University[12].

YEARLY STATISTICAL SUMMARY				
	MONTHLY		DAILY	
	REFERENCE	SIMULATED	REFERENCE	SIMULATED
MEAN	9914.90	10085.50	325.06	330.65
MAXIMUM	32757.35	34005.84	5430.90	6017.22
VARIANCE	110596272.00	117735280.00	429042.81	601067.06
STANDARD DEVIATION	10516.48	10850.59	655.01	775.29
SUM OF (REFERENCE - SIMULATED)	-2047.31		-2047.32	
ROOT SUM SQUARE	2630.77		3268.44	
SUM SQUARED	0.39		54.14	
SUM SQUARED (IBM METHOD)	0.31		48.38	
CORRELATION COEFFICIENT	0.9979		0.9855	

Figure 2-8. Example of Yearly Statistical Summary

SUMMARY OF MONTHLY AND ANNUAL TOTALS

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEPT	ANNUAL	
PRECIPITATION	0.100	4.580	3.790	6.320	3.570	11.240	9.140	3.670	3.810	7.010	3.090	1.910	58.230	IN
EVP/TRAN-NET	0.317	1.106	0.412	0.451	1.034	1.584	2.583	3.646	3.082	4.368	3.320	1.810	23.714	IN
-POTENTIAL	2.296	1.155	0.412	0.451	1.034	1.584	2.772	4.753	3.836	5.024	4.545	2.891	30.753	IN
SURFACE RUNOFF	0.000	0.347	0.123	3.431	0.834	5.921	3.314	1.405	0.549	1.337	0.232	0.015	17.510	IN
INTERFLOW	0.0	0.0	0.010	0.306	0.268	0.917	1.017	0.214	0.000	0.043	0.0	0.0	2.774	IN
BASE FLOW	0.000	0.212	0.652	1.490	1.230	2.133	2.346	1.315	0.564	1.063	0.530	0.131	11.666	IN
STREAM EVAP.	0.000	0.001	0.000	0.000	0.001	0.002	0.003	0.005	0.004	0.005	0.005	0.003	0.028	IN
TOTAL RUNOFF(SIM)	0.000	0.558	0.785	5.227	2.331	8.969	6.674	2.929	1.109	2.438	0.758	0.144	31.922	IN
TOTAL RUNOFF(REF)	0.0	0.370	0.791	4.798	2.434	8.640	6.683	3.248	1.100	2.269	0.861	0.188	31.382	IN
REFERENCE TOTALS	0.0	1401.6	3000.0	18189.9	9228.8	32757.4	25336.6	12314.6	4170.2	8604.3	3264.1	711.6	118978.8	CFS
SIMULATED TOTALS	0.0	2114.8	2978.0	19815.4	8837.7	34005.8	25302.3	11104.3	4206.3	9244.3	2873.1	544.3	121026.1	CFS

BALANCE -0.0117 INCHES

MONTHLY FLOW CORRELATION COEFFICIENT 0.9979
MEAN DAILY FLOW CORRELATION COEFFICIENT 0.9855

Figure 2-9. Example of Monthly and Annual Totals

2.2.4 REGIONAL WATERSHED MODEL

A regional watershed is much larger in size than the KWM was designed to simulate. The Pearl River watershed model is implemented by applying the KWM (without snow) to each of the 12 subwatersheds individually and integrating the watersheds through a routing routine, into a river system. This means that each subwatershed has its own set of parameters and climatological data inputs.

The way the model operates is indicated by the following: (1) subwatersheds (SWS) 1, 3 and 5 are modeled as headwatersheds to synthesize a record of hourly streamflow from each, (2) SWS2 and SWS4 are first simulated individually to produce hourly synthesized streamflow for each, (3) the streamflows from SWS1 and SWS3 are added, respectively, to those from SWS2 and SWS4 after appropriate time delays and channel attenuations have been applied, (4) SWS6 is simulated to produce an hourly synthesized streamflow at its outlet near Jackson, (5) the simulated streamflows from SWS2, 4 and 5 are delayed and attenuated and combined with that of SWS6. This process continues until the discharge from SWS represents the entire regional watersheds outflow. The routing technique is virtually identical to that implemented by the National Weather Service Hydrology Research Laboratory.[13]

2.3 SENSITIVITY ANALYSIS

The inputs to the Sensitivity Analysis Task are a set of watershed parameters, climatological data, and a "reference" streamflow record from the modeling task. Sensitivity Analysis consists of (1) changing a model parameter or input, (2) running the simulation model and printing out the performance indices which indicate the deviations between the reference record and the simulation output, (3) evaluating the results and then repeating the steps after selecting another input perturbation.

The total number of simulation runs was 442: 166 for Town Creek, 137 for Alamosa Creek, and 139 for Pearl River, In the case of the regional watershed model, a printout was produced for every one of the 12 subwatersheds. The study team analyzed a total of 1971 printouts and an uncounted number of plots. Each one of 46 different inputs and parameters was tested at from two to ten different perturbed values. Not all were tested on all watersheds; the snowmelt parameters, for example, do not apply to the Town Creek and Pearl River models.

2.3.1 PERFORMANCE INDICES

The performance of a watershed simulation model may be judged differently by different potential users, each with a particular application in mind. One may be interested in the effect of a parameter variation on low flow, another on total annual flow, a third on magnitude and timing of hydrograph peaks and total runoff resulting from storm events in a particular season. Varying a particular parameter may have a pronounced effect on some of these indices and not on others. It was therefore deemed advisable in the sensitivity analysis task to provide in the tabular summary outputs for indicators of the following:

- Storm runoff and percent variation from reference runoff for a selected storm event in each season, for each headwater SWS of the regional watershed and the two small watersheds.
- Monthly runoff for October, January, April and August and percent variation from reference for each of those months for the regional watershed.
- Variation from reference low flow.
- Variation from reference annual flow.

2.3.2 UNIT SENSITIVITY

The definition of Unit Sensitivity as used in this study is (percent change in performance index) ÷ (percent change in parameter). It was adopted to provide a basis for comparison of the sensitivities of the models to variations in the several different parameters. It corresponds roughly to the "relative sensitivity" concept suggested by McCuen in a theoretical paper.[14] The correspondence is rough because many of the perturbations used in the Sensitivity Analysis are large (expressed as percentage), and the sensitivity curves are often nonlinear. Nevertheless, the unit sensitivity concept served its purpose well.

2.3.3 TASK PRODUCTS

The Sensitivity Analysis runs were assigned code numbers and indexed. Results were extracted from printouts and tabulated by parameter and by Watershed model. Sensitivity plots were also constructed for selected parameters and inputs. Examples are shown in Section 3 of this volume, and a complete listing is included in Section 6, Volume II.

2.4 SENSOR/PARAMETER DEPENDENCY

Each model parameter or input of interest was examined to determine the feasibility or practicality of quanitfying it from remotely sensed data from space, now or in the future. Alternative sources of data from which each parameter could be derived were also considered. Examples of the latter are aerial photography, data collection, platforms with satellite relay, and ground-truth patrols. Particular attention was given to those parameters with the highest potential for determination from remote sensing.

2.5 REMOTE SENSING PERFORMANCE REQUIREMENTS

For each parameter or input which can or potentially could be derived from remote sensing the permissible tolerance on that parameter was translated into an accuracy requirement (spatial resolution, with little attention to spectral resolution) on the remote sensing system. For example, suppose a particular parameter should be determined from a remotely acquired image with a tolerance of $\pm 1.6\%$ of the basin area, and the basin has an area of 1000 square kilometers. Then the system should be able to produce an areal resolution of 16 KM^2 or a linear resolution of 4 KM, for modeling that basin.

SECTION 3

RESULTS

3.1 SENSITIVITY ANALYSIS DATA INTERPRETATION

The Sensitivity Analysis produced copious data from which certain qualified results can be drawn. This is not surprising when one considers that some parameters were varied as many as ten times and the effects on six performance indices evaluated for each perturbation in as many as eight basins (Town Creek, Alamosa Creek, Pearl River and five headwatersheds within the Pearl River basin). Table 3-1 is an example of a tabulation of sensitivity analysis results. There is a complete set of such tables in Volume II, Section 6.

The numerical results in terms of unit sensitivities, showed considerable variation from one performance index to another within a given basin as well as from one basin to another for a given performance index; the former are largely seasonal effects. A better assessment of results was achieved by constructing sensitivity plots like those appearing in Figure 3-1. In each of them, the abscissa scale is the percentage variation in the input parameter, and the ordinate scale is the percentage variation in performance indices (runoff).

3.2 PERMISSIBLE TOLERANCES AND RESOLUTIONS

Of all the parameters and inputs tested and analyzed in the study, 26 are listed in Table 3-2, which shows the permissible tolerances found for each parameter, the effect of its variation on runoff, its relation to watershed geomorphology, how it can be determined from remote-sensed data or other data source, and the image resolution corresponding to the permissible tolerance, if applicable.

The parameters and inputs tested but not listed in Table 3-2 were found not to produce a meaningful result when varied or to be of negligible effect. An example of the first is the area of the watershed itself. Changing the area by a given factor simply changed the runoff by the same factor for all basins in all seasons. An example of the second (no effect) is the overland flow roughness coefficient (Manning's "n") for impervious surfaces, designated OFMNIS. The range of values it is normally assigned is from 0.013 to 0.017, and varying it from 0.001 (-93%) to 0.5 (+3233%) in the regional watershed model produced negligible change in simulated runoff. This is logical, because in every watershed modeled, the portion of basin area covered by impervious surfaces is less than 10% (as it would be expected of nearly any basin except small, highly urbanized ones). This small value of impervious area prevented varying OFMNIS from having any effect.

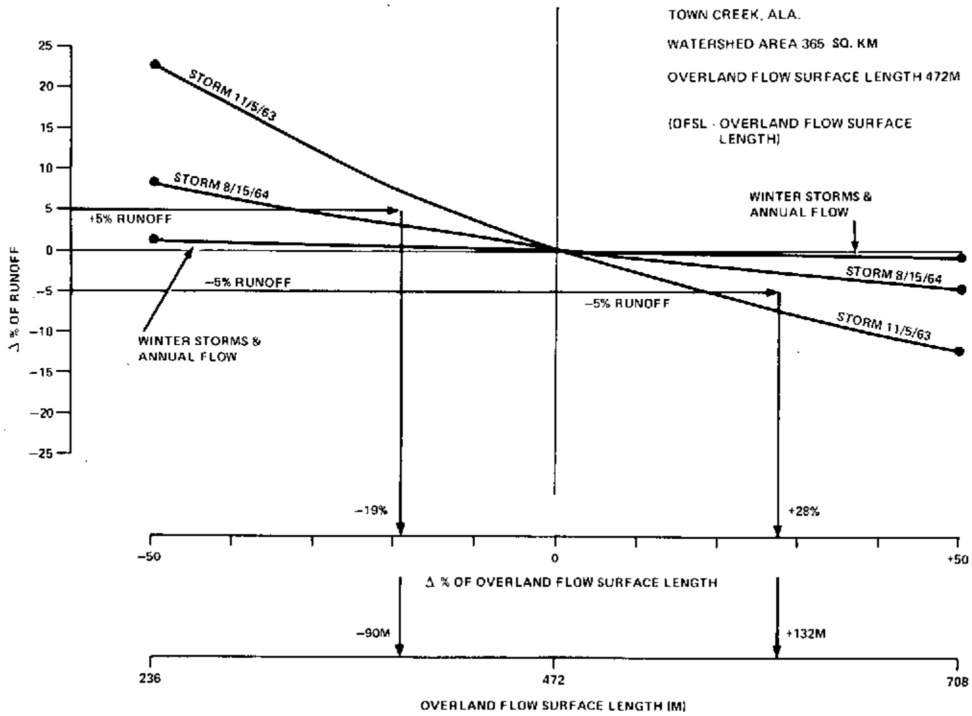
Table 3-1. Example of Sensitivity Analysis Tabulation

SENSITIVITY ANALYSIS OF FIMP -100% PERTURBATION (0.10 REFERENCE)

SMALL, SNOW & REGIONAL WATERSHEDS

WATERSHED	AREA (SQ. KM)	EPAET (IN)	OUTPUT	SIGNIFICANT STORMS FALL	WINTER	SPRING	SUMMER	LOW FLOW	ANNUAL FLOW
RUN ID S000			Δ% OF R/O	-60.9	-4.2	-4.4	-39.5	+3.95	-7.15
			STORM R/F	11/4/63 3.13	1/23/64 3.19	5/1/64 2.87	8/14/64 2.16	9/27/64	STORM U/S
SMALL	365	45	REF. R/O	0.46	2.41	2.03	0.43	REF = 7.6	F +0.609
			PERT. R/O	0.18	2.31	1.94	0.26	SIM = 7.9	W +0.042
			REF (R/F/R/O)	6.80	1.32	1.41	5.02		SP +0.044 SU +0.395
RUN ID 01			Δ% OF R/O	-63.9	-35.7	-19.1	-72.3	0.0	-13.9
			STORM R/F	10/18/57 2.99	4/21/58 0.0	5/10/58 1.78	8/13/58 1.09	9/7/58	STORM U/S
SNOW	277	32	REF. R/O	0.077	0.068	1.106	0.124	REF = 3.0	F +0.636
			PERT. R/O	0.028	0.037	0.895	0.034	SIM = 3.0	W +0.357
			REF (R/F/R/O)	38.83	—	1.61	8.79		SP +0.191 SU +0.723
RUN ID RW06			Δ% OF R/O	-64.7	-4.9	-13.0	-70.0	-53.8	-16.0
			Δ% OF MONTHLY R/O	OCT -44.1	JAN -5.7	APR -7.8	AUG -67.2	9/15/68	STORM U/S
REGIONAL	22,248	41	REF. R/O	0.17	1.02	0.54	0.10	REF = 1340	F +0.647
			PERT. R/O	0.06	0.97	0.47	0.03	SIM = 619	W +0.049
			REF. MONTHLY R/O	0.247	3.785	2.743	0.479		SP +0.130 SU +0.700
RUN ID RW06			Δ% OF R/O	-83.3	-8.0	-20.4	-79.2	+3.0	-15.0
			STORM R/F	10/15/67 2.16	1/8/68 1.91	4/26/68 3.49	8/18/68 2.79	9/25/68	STORM U/S
SUB-WATERSHED NO. 1	2,326	50	REF. R/O	0.24	1.74	0.93	0.24	REF = 33	F +0.833
			PERT. R/O	0.04	1.60	0.74	0.05	SIM = 34	W +0.080
			REF (R/F/R/O)	9.0	1.10	3.75	11.6		SP +0.204 SU +0.792
RUN ID RW06			Δ% OF R/O	-85.7	-4.4	-18.0	-75.9	+4.6	-12.5
			STORM R/F	10/15/67 2.51	1/9/68 3.11	4/25/68 1.70	7/31/68 2.21	9/2/68	STORM U/S
SUB-WATERSHED NO. 3	813	50	REF. R/O	0.28	2.25	0.61	0.29	REF = 22	F +0.857
			PERT. R/O	0.04	2.15	0.50	0.07	SIM = 23	W +0.044
			REF (R/F/R/O)	8.96	1.38	2.79	7.62		SP +0.180 SU +0.759
RUN ID RW06			Δ% OF R/O	-90.0	-2.6	-12.0	-90.5	+25	-9.9
			STORM R/F	10/15/67 1.08	1/9/68 2.04	4/25/68 1.82	8/13/68 2.22	9/29/68	STORM U/S
SUB-WATERSHED NO. 5	1,064	37	REF. R/O	0.10	1.94	1.00	0.21	REF = 4	F +0.900
			PERT. R/O	0.01	1.89	0.88	0.02	SIM = 5	W +0.026
			REF (R/F/R/O)	10.8	1.05	1.82	10.57		SP +0.120 SU +0.905
RUN ID RW06			Δ% OF R/O	-82.4	-8.8	-16.4	-72.7	+2.6	-13.8
			STORM R/F	10/15/67 1.58	1/8/68 2.76	4/26/68 1.42	8/14/68 2.95	9/30/68	STORM U/S
SUB-WATERSHED NO. 7	1,111	40	REF. R/O	0.17	1.70	0.73	0.44	REF = 39	F +0.824
			PERT. R/O	0.03	1.55	0.61	0.12	SIM = 40	W +0.088
			REF (R/F/R/O)	9.29	1.62	2.63	6.70		SP +0.164 SU +0.727
RUN ID RW06			Δ% OF R/O	-61.1	-8.9	-20.6	-75.0	0.0	-17.1
			STORM R/F	10/28/67 1.35	1/8/68 1.37	5/8/68 1.91	8/20/68 0.50	9/14/68	STORM U/S
SUB-WATERSHED NO. 11	2,551	30	REF. R/O	0.18	0.79	0.63	0.04	REF = 9	F +0.611
			PERT. R/O	0.07	0.72	0.50	0.01	SIM = 9	W +0.089
			REF (R/F/R/O)	7.50	1.73	3.03	12.50		SP +0.206 SU +0.750

OVERLAND FLOW SURFACE LENGTH STUDY SMALL WATERSHED



FORESTED AREA STUDY SMALL WATERSHED

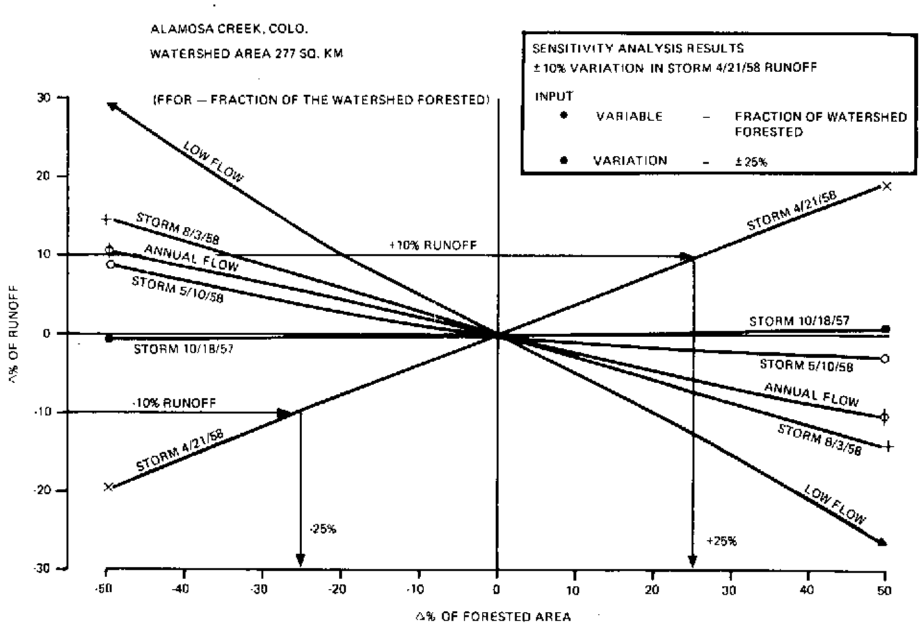


Figure 3-1. Examples of Sensitivity Plots

Table 3-2. Permissible Tolerances and Resolutions

INPUT OR PARAMETER	PERMISSIBLE TOLERANCES %	EFFECT ON SIMULATED RUNOFF,%	RELATIONSHIP TO WATERSHED GEO-MORPHOLOGY	DERIVATION FROM REMOTE-SENSED DATA OR OTHER SOURCE	REQUIRED IMAGE RESOLUTION,M
IMPERVIOUS PORTION OF BASIN AREA	±1.4 OF BASIN AREA	±10 (FALL)	ROCK OUTCROP-PINGS, STREETS, HIGHWAYS, URBAN AREAS	IMAGE ANALYSIS; LAND USE CLASSIFICATION	100
WATER SURFACE PORTION OF BASIN AREA	+1.5, −1.6 OF BASIN AREA	±10 (FALL)	LAKES, PONDS, RIVERS	IMAGE ANALYSIS; LAND USE CLASSIFICATION	120
VEGETATIVE INTERCEPTION MAXIMUM RATE (VINTMR)	+95 −60	−5 +5 (SUMMER)	TYPE & DENSITY OF VEGETATIVE COVER, TREES, MEADOWS, ETC.	IMAGE DATA CLASSI-FICATION AND INTERPRETATION	200
UPPER ZONE STORAGE CAPACITY (BUZC)	+50 −50	−2.5 +2.5 (SUMMER)	SOIL PERMEABILITY, OVERLAND SLOPES, FOREST COVER	INFERENCE FROM LAND USE CLASSIFICATION	500
SEASONAL FACTOR UPPER ZONE CAPACITY (SUZC)	+70 −30	−20 +20 (SUMMER)	SOIL PERMEABILITY, VEGETATIVE COVER	INFERENCE FROM LAND USE CLASSIFICATION	100
LOWER ZONE STORAGE CAPACITY (LZC)	+14 −15	−10 +10 (WINTER)	SOIL ASSOCIATION, VEGETATIVE TYPES AND COVERAGE DENSITY	INFERENCE FROM LAND USE CLASSIFICATION	100
EVAPOTRANS-PIRATION LOSS FACTOR (ETLF)	+15 −15	−10 +10 (SUMMER)	VEGETATIVE COVER, TYPE & DENSITY: ESPECIALLY FOREST	IMAGE ANALYSIS; LAND USE CLASSIFICATION	100
SEASONAL INFIL-TRATION ADJUST-MENT FACTOR (SIAC)	+20 −22	−1 +1 (SUMMER)	VEGETATIVE COVER, SOIL ASSOCIATION	INFERENCE FROM LAND USE CLASSI-FICATION (DOUBTFUL; CALIBRATION NEEDED	300
BASIC MAXIMUM INFILTRATION RATE (BMIR)	+35 −28	−5 +5 (WINTER)	SOIL PERMEABILITY, VEGETATIVE TYPE AND DENSITY	INFERENCE FROM LAND USE CLASSI-FICATION	150
MEAN OVERLAND SURFACE SLOPE (OFSS)	+200 −67	+0.5 −0.6 (WINTER)	TOPOGRAPHY	DIRECT MEASURE-MENT IF RELATIVE ELEVATION IS AVAILABLE	100 HORI-ZONTAL, 20 VERTICAL
MEAN OVERLAND SURFACE LENGTH (OFSL)	+40 −35	−0.3 +0.3 (WINTER)	AVERAGE DISTANCE FROM RANDOMLY SELECTED POINTS TO NEAREST STREAMS	DIRECT MEASURE-MENT IF STREAM-LINES ARE DISCERNABLE	500
OVERLAND FLOW ROUGHNESS COEFFICIENT (OFMN)	+80 −50	−0.5 +0.5 (WINTER)	SURFACE TYPE; FOREST AND VEGE-TATIVE COVER	IMAGE ANALYSIS; LAND USE CLASSIFICATION	500
PRECIPITATION MULTIPLIER (RGPMB)	+3 −3	+10 −10 (FALL)	ADJUSTS FOR BIAS IN PRECIPITATION GAGE DATA; NOMINAL VALUE IS 1.0	ADJUST FIELD INSTRUMENT READINGS FOR BETTER SIMULATION	+3% IN PRECIP. MEASURE (BIAS)

Table 3-2. Permissible Tolerances and Resolutions (Continued)

INPUT OR PARAMETER	PERMISSIBLE TOLERANCES %	EFFECT ON SIMULATED RUNOFF, %	RELATIONSHIP TO WATERSHED GEO-MORPHOLOGY	DERIVATION FROM REMOTE-SENSED DATA OR OTHER	REQUIRED IMAGE RESOLUTION,M
EVAPORATION DATA (EPAET)	+ 5 −4.5	−10 +10 (SUMMER)	POTENTIAL AVERAGE ANNUAL LAKE EVAPORATION	FIELD INSTRUMENTS AND/OR CALCULA-TION FROM CLIMATE DATA	±4.5%
MEAN NUMBER OF RAINY DAYS (MNRD)	+11.5 − 10	−5 + 5	CLIMATOLOGICAL STATISTICS	CLIMATOLOGICAL STATISTICS	±10%
(THE REMAINING ENTRIES IN THIS CHART PERTAIN TO THE SNOWSHED MODEL ONLY.)					
PRECIPITATION (PERTURBED ONLY DURING STORMS)	+ 11 −11	+ 5 −5	ERRORS IN PRECIPITATION INPUT	FIELD INSTRUMENTS	±11% IN PRECIP. MEASURE (RANDOM)
EVAPORATION (PERTURBED ONLY DURING STORMS)	+ 20 −20	−5 +5	ERRORS IN EVAPORA-TION DATA	FIELD INSTRUMENTS AND/OR CALCULA-TION FROM CLIMATE DATA	±20%
TEMPERATURE (PERTURBED ONLY DURING STORMS)	+ 2.3 −4.0	+ 20 −20	ERRORS IN TEMPERATURE DATA	FIELD INSTRUMENTS OR FUTURE REMOTE RADIOMETRY	N/A
FRACTION OF INCOMING RADIATION REFLECTED BY SNOW (FIRR)	+ 15 −12	−20 +20	SNOW SURFACE ALBEDO; INDE-PENDENT OF GEOMOPHOLOGY	CALCULATION IN THE MODEL FROM SNOW SURFACE AGE; RADIOMETRY IN FUTURE	N/A
BASIC DEGREE DAY FACTOR FOR SNOWMELT (BDDFSM)	+ 3.6 −1.6	+ 20 −20	MATHEMATICAL CONSTRUCT; NO RELATION TO WATERSHED GEOMORPHOLOGY	SIMULATION MODEL CALIBRA-TION; NO REMOTE SENSING APPLICATION	N/A
SNOWPACK BASIC MAXI-MUM FRACTION IN LIQUID WATER (SPBFLW)	+ 16 −13.5	−10 +10	SNOW PHYSICS; NO RELATION TO WATERSHED GEOMORPHOLOGY	SIMULATION MODEL CALIBRA-TION; NO REMOTE SENSING APPLICATION	N/A
SNOWPACK MINIMUM TOTAL WATER CONTENT (SPTWCC)	+ 0 −32.5	−1 +1	SNOW PHYSICS; NO RELATION TO WATERSHED GEOMORPHOLOGY	SIMULATION MODEL CALIBRATION; SOME FUTURE REMOTE SENSING APPLICATION	N/A
ELEVATION DIFFERENCE BETWEEN BASE THEROMETER AND MEAN BASIN ELEVATION (ELDIF)	+ 20 −12.5	−28 +28	BASIN TOPO-GRAPHY	DIRECT MEASUREMENT IF RELATIVE ELEVA-TIONS ARE AVAIL-ABLE	30 VERTICAL
FRACTION OF SNOW INTER-CEPTED (FFSI)	+ 25 −25	+ 10 −10	TYPE AND DENSITY OF FOREST	IMAGE DATA CLASSI-FICATION AND INTERPRETATION	500
FRACTION OF SNOW INTER-CEPTED (FFSI)	+ 25 −21	+ 2 −2	TYPE AND DENSITY OF FOREST	IMAGE DATA CLASSI-FICATION AND INTERPRETATION	200
PRECIP. INDEX FOR CHANGING SNOW ALBEDO (PXCSA)	+ 50 −11	+ 2.9 −10	SNOW PHYSICS; NO RELATION TO WATERSHED GEOMORPHOLOGY	SIMULATION MODEL CALIBRATION; RADIOMETRY IN FUTURE	N/A

3.3 COMMENTS ON AND QUALIFICATIONS OF RESULTS

Several remarks on the information contained in Table 3-2 are in order, and they appear in the following paragraphs.

The permissible tolerances shown in the second column were generally estimated from plots such as the one shown in Figure 3-1. Some judgments and compromises were necessary because of nonlinearities in many of the response curves. The same is true to a greater extent with respect to the effect on simulated runoff appearing in the second column. The image resolutions estimated in the sixth column are believed somewhat conservative, more stringent than actually may be required, pending further study. Most of them depend upon the basin size; if one is interested in observing and simulating watersheds of areas not less than 50 square kilometers, the image resolutions can be relaxed considerably. Another consideration which enters into the estimation of required image resolution is the likelihood that parameters of interest (such as the impervious fraction of basin area) may consist of scattered small areas rather than be concentrated into a single larger one, the latter condition requiring less stringent resolutions.

The comments in the fifth column on the derivation of parameters from remote sensing should generally be regarded as optimistic. Although many of the derivations indicated are feasible, considerable maturing of several image analyses and interpretation techniques will be needed to make the applications operational. The applications are presently practical for quasi-permanent features such as land use and vegetation, but optimistic with respect to inferences about soil characteristics and subsurface conditions.

In the early days of the sensitivity analysis, some problems were encountered with respect to the impervious portion of basin area (FIMP) and water surface portion of basin area (FWTR). In all the basins used in the study these parameters were of such small value that very large percentage variations in them caused very small variations in simulation model outputs. Because they are both excellent parameters for determination from remote-sensed data, special reference simulation runs were made with each of them separately set to .10 (that is 10% of the total basin area). Sensitivity analysis runs were then made based on departures in FIMP and FWTR from these special reference values, in order to get a more meaningful assessment of their effects on simulation model operation.

In the operation of a simulation model, it is necessary to assume that the measured precipitation inputs accurately represent the actual precipitation over the basin, even though the operator is morally certain that this is not the case. In order to test the effects of errors in precipitation input, several runs were made in which the effect of changing precipitation was achieved by assigning values other 1.0 to the recording gage precipitation multiplier (RGPMB). The unit sensitivities resulting from the simulation runs were much greater than unity. It was concluded that varying RGPMB is equivalent to introducing biases in the precipitation inputs throughout the year, rather than introducing random errors as would normally be expected in the rain gage network. The effect is one of accumulating errors in soil moisture throughout the water year simulated, causing the errors in simulation output to be greater in percentage than the perturbations in RGPMB. It would be interesting, in a refinement of the study, to test the effect of introducing errors in the precipitation inputs in accordance with some probability density function. A very small step in this direction was taken in the sensitivity analysis involving the Alamosa Creek basin, for which precipitation input was perturbed only during storm events, and left at the reference value for the rest of the year. The results of this experiment appeared to be more reasonable.

3.4 APPLICABILITY OF REMOTE SENSING

It is presently feasible, given existing image data processing and analysis techniques, to quantify eight of the parameters involved in the simulation models from either Earth Resources Technology Satellite (ERTS) or Skylab bulk - processed images. These parameters are: impervious fraction of basin area (FIMP), water surface fraction of basin area (FWTR), vegetative interception maximum rate (VINTMR), evapotranspiration loss factor (ETLF), mean overland surface length (OFSL), overland flow roughness coefficient (OFMN), fraction of watershed in forest (FFOR), and fraction of snow intercepted (FFSI)

Given successful development of image interpretation and analysis techniques presently in research and development, it will become feasible to quantify four additional parameters from remote-sensed image data of the same quality as that available from ERTS or Skylab. These parameters are: upper zone storage capacity (BUZC), upper zone capacity seasonal adjustment factor (SUZC), lower zone storage capacity (LZC), and basic maximum infiltration rate (BMIR).

In order to calculate basin area, it is necessary to determine the boundary of the watershed, which in turn is determined from basin topography and the location of the stream gage at the basin mouth. Knowledge of basin topography is also necessary to derivation of mean overland surface slope (OFSS) and the elevation difference between base thermometer and mean basin elevation (ELDIF). Such parameters are readily measured from stereo image pairs, something obtained from aerial photography but not at present from space. An attractive alternative technique would be to obtain topographic data from the output of a spaceborne laser altimeter, in several passes across the watershed. This would provide the information from which contour lines could be superimposed on the remotely sensed images. The vertical resolutions required for determination of these parameters is several times coarser than that which would be provided by a laser altimeter.

There are a large number of research and development activities in sensor technology and interpretation and analysis techniques which hold considerable promise for future applications and hydrologic modeling. New developments in radiometric sensing will eventually allow remote measurement of atmospheric temperature at earth or snowpack surface, snow surface albedo and thereby the fraction of incoming radiation reflected by snow (FIRR), snowpack water content and related snow parameters, and soil moisture. All these inputs should be measured and quantified on at least a daily basis. Other intermediate to far future potential applications include determination of subsurface phenomena and conditions, such as seasonal infiltration adjustment factor (SIAC). A potential alternative approach to this latter class of parameters is by statistical correlation with observable features, a question previously investigated by IBM[15].

For the foreseeable future, direct measurements of precipitation, evaporation and such statistics as the mean number of rainy days (MNRD) will be done by instruments located in the field, perhaps reporting their readings through satellite relay.

There are two parameters in Table 3-2 which have no recognizable relationship to watershed geomorophology and which are not susceptible to any present or future remote sensing application. They are the basic degree day factor for snowmelt (BDDSM) and a snowpack basic maximum fraction in liquid water (SPBSLW). There are other parameters involved in watershed simulation modeling to which the same comment applies. Such parameters will always have to be estimated by the hydrologist or operator of the simulation model, either through empirical relationships, experience or model calibration, unless developments in watershed simulation models lead to ways in which such parameters can be dispensed with, a much more desirable approach.

SECTION 4

CONCLUSIONS

4.1 UTILITY OF REMOTE SENSING AND HYDROLOGIC MODELING

At present, remote sensing from space is directly applicable to determination of model parameters related to prominent surface features such as land use, vegetation, overland distances, snow coverage, water and impervious surfaces. Permissible tolerances and parameters associated with these features are large enough not to impose stringent resolution requirements. For eight of the parameters used in the study, the image quality afforded by ERTS and Skylab are adequate.

Presently active research and development projects in sensor technology and in image data processing and analysis will make quantification of additional parameters through remote sensing available to hydrologic modeling. These parameters generally have to do with topographic features, land use classification, and soil associations. Many of these investigations are being carried on using ERTS and Skylab image data.

Radiometric instrument developments now in progress hold some promise for the future for remote measurements of snowpack depth, water content and albedo; atmospheric temperature at earth and snowpack surfaces; and soil moisture. These are temporal measurements and need to be made at least daily and in some cases more often, depending upon the model application.

4.2 NEEDS IN REMOTE SENSING

The results of the study indicate most strongly that the needs of hydrologic modeling for data from remote sensing systems can best be met by improved techniques of interpretation and analysis of that data, rather than improved resolution. With respect to sensor development, hydrologic models designed to take advantage of remote sensing can best benefit from direct measurements of snow parameters, atmospheric temperature and soil moisture.

4.3 NEEDS IN HYDROLOGIC MODELING

Proven watershed simulation models have been designed and implemented to accept inputs known to be available from ground based instrumentation systems, topographic maps, field surveys and empirical relationships. To take advantage of the potential benefits to be expected from remote sensing, a hydrologic simulation model should be designed or redesigned to accept inputs more directly related to the data outputs of remoter observation systems. The model used in the study could, for example, be improved in accuracy by accepting a daily soil moisture reading as an input rather than calculating soil moisture internally.

The model used in the study was particularly disappointing from a remote sensing application standpoint with respect to its management of moisture in the form of snow. Many of the parameters used internally and as inputs depend upon empirical relationships and the acquisition of statistics over a long period of time and careful calibration and adjustment generally based upon the knowledge and experience of a hydrologist. Only three of the snow parameters used in the study can be determined from remotely sense data, either now or in the near future. Modifications will be required to enable the model to accept inputs from newly developed remote sensing systems and techniques when they become available.

4.4 VALIDITY OF SENSITIVITY ANALYSIS

Sensitivity analysis is a valid tool for determining specifically and quantitatively how remotely sensed data (and supporting data from other sources) can be used to derive inputs for a model of the sort used in the study. Because of the popularity and wide spread use of the model and others of the same pedigree, as well as having three physiographic regions represented, the study results should be of significant interest to a variety of investigators and potential users. One of the weaknesses in the analysis is the fact that all parameters were perturbed singly, while holding all others at their reference values. It is desirable to undertake a refinement of the analysis in which parameters could be varied in logical combinations (such as BUZC, SUZC, BIMR, LZC, and SIAC) which are likely to be affected simultaneously by errors in deriving information from remote sensing.

4.5 RECOMMENDED ADDITIONAL WORK

There are several closely related topics which deserve continued and intensive further study. Some investigators are presently exploring some of these topics; such investigations should be closely monitored and supplemented as needed. Those of particular interest are as follows:

- Determination of soil association and classification as well as subsurface characteristics by inference from remotely observable characteristics such as land use and vegetative cover;
- Remote measurement of temporal phenomena: precipitation, air temperature, relative humidity, evaporation rate;
- Determination by remote observation of snowpack depth at sufficient points to calculate total snowpack volume and water equivalent;
- Remote measurement of soil moisture on a daily basis within the watersheds;
- Determination of surface topography from orbital attitudes by a laser altimeter or stereographic images.
- Development of a multiple application watershed simulation model capable of accepting inputs and parameters directly or closely related to the data outputs of remote sensing systems.

- Extension of the sensitivity analysis to include parameter/input perturbations in logical combination rather than singly, as a step toward greater realism. It is likely that the parameter tolerances resulting from such an analysis will be closer than those produced by this study.

- Thorough, rigorous investigation of multivariate statistical relationships which can be used in the future to estimate model parameters not derivable from remote sensing from remotely observable basin characteristics. This is an alternative to the development of more subtle and complex image interpretation techniques for achieving the same objective.

APPENDIX

REFERENCES

1. Crawford, N.H., and Linsley, R.K., Digital Simulation in Hydrology: Stanford Watershed Model IV, Stanford, California: Stanford University, Department of Civil Engineering, Technical Report No. 39, July, 1966.

2. Hydrocomp International, "HSP Operations Manual," Palo Alto, California, 1969.

3. Anderson, E.A., and Crawford, N.H., The Synthesis of Continuous Snowmelt Hydrographs on a Digital Computer, Stanford, California: Stanford University, Department of Civil Engineering, Technical Report No. 36, 1964.

4. Hydrocomp International, "Simulation of Continuous Discharge and Stage Hydrographs in the North Branch of the Chicago River," Palo Alto, California, 1970.

5. James, L.D., Economic Analysis of Alternative Flood Control Measures, Lexington: University of Kentucky Water Resources Institute, Research Report No. 16, 1968.

6. Ligon, J.T., Law, A.G., and Higgins, D.H., Evaluation and Application of a Digital Hydrologic Simulation Model, Clemson, South Carolina: Clemson University, Water Resources Research Institute, Report No. 12, November 1969.

7. Lumb, A.M., Hydrologic Effects of Rainfall Augmentation, Stanford, California: Stanford University, Department of Civil Engineering, Technical Report No. 116, November, 1969.

8. James, L.D., An Evaluation of Relationships Between Streamflow Patterns and Watershed Characteristics through the Use of OPSET: A Self-Calibrating Version of the Stanford Watershed Model, Lexington: University of Kentucky, Water Resources Institute. Research Report No. 36, 1970.

9. Liou, E.Y., OPSET: Program for Computerized Selection of Watershed Parameter Values for the Stanford Watershed Model, Lexington: University of Kentucky, Water Resources Institute, Research Report No. 34, 1970.

10. Ross, G.A., The Stanford Watershed Model: The Correlation of Parameter Values Selected by a Computerized Procedure with Measurable Physical Characteristics of the Watershed, Lexington: University of Kentucky Water Resources Institute, Research Report No. 35, 1970.

11. Linsley, Ray K., Kohler, Max A., and Paulhus, Joseph L. H., Hydrology for Engineers. New York: McGraw-Hill Book Company, 1958.

12. Striffler, W.D., "Users Manual for the Colorado State University Version of the Kentucky Watershed Model," Colorado State University, published under NASA Contract NAS9-13142, September 1973.

13. Hydrology Research Laboratory, National Oceanic and Atmospheric Administration, National Weather Service, U.S. Department of Commerce, "National Weather Service River Forecast System Forecast Procedures." NOAA TM NWS-HYDRO-14, Washington, D.C., December 1972.

APPENDIX

REFERENCES

14. McCuen, R.H., "The Role of Sensitivity Analysis in Hydrologic Modeling," Journal of Hydrology, 18 (1973) 37-53.

15. Ambaruch, R., and Simmons, J.W., "Application of Remote Sensing to Hydrology," Final Technical Report, IBM No. 73W-00387, September 1973, for NASA George C. Marshall Space Flight Center.