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IMPACT OF REMOTE SENSING UPON THE PLANNING, MANAGEMENT, AND DEVELOPMENT OF WATER RESOURCES

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16. Abstract Principal water resources users were surveyed to determine the impact of remote data streams on hydrologic computer models. Analysis of responses demonstrated that: <ol style="list-style-type: none"> 1. Most water resources effort suitable to remote sensing inputs is conducted by 11 major Federal agencies or through Federally stimulated research, 2. Most hydrologic models suitable to remote sensing data are Federally developed, 3. Federal computer power is extensive. <p>An analysis of current computer usage by major water resources users was made to determine the trends of usage and costs for the principal hydrologic users/models. The laws and empirical relationships governing the growth of the data processing loads were described and applied to project the future data loads. Data loads for ERTS CCT image processing were computed and projected through the 1985 era. The analysis shows significant impact due to the utilization and processing of ERTS CCT data. This impact and the mechanisms required to optimally utilize new remote sensing data were assessed.</p>			
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1.0 PREFACE

In the three years since ERTS (now LANDSAT) has been launched, many interesting and provocative results of immediate and future benefit to water resource users have been identified.

Hydrologists and water resource planners are presented with the opportunity of repeatedly observing surface and surface-inferred subsurface parameters which, when incorporated into the technology, could significantly contribute to man's understanding and proper use of his water resources.

Remote sensing technology is rapidly approaching a phase of maturation, wherein several important, specific applications can be translated into operational user procedures. Principal among these are:

1. Determination of runoff from ungaged and gaged watersheds;
2. Delineation of the extent of flood plains;
3. Improved assessment of irrigation water demand;
4. More precise determination of the runoff from snowmelt;
5. Determination of peak flow events for optimal design of waterworks.

There are, however, two problems implicit in the rapid and cost-effective adaptation of these new remotely sensed data streams into current water resource practices.

The first is the theoretical development of relationships having hydrologic importance and which are sensitive to remotely

sensed parameters, i.e. relating surface characteristics to required hydrologic variables.

The second is the identification and alleviation of bottlenecks which may be caused by the large mass of data which will become available from remote sensing satellites.

The purpose of this effort is twofold: 1) to assess and quantify the impact of remotely sensed data upon the various categories of the water resource users; and 2) to recommend policies and procedures aimed toward optimizing the utilization of remotely sensed data, especially for those users and applications wherein the impact should prove to be most severe.

2.0 OBJECTIVES

The objectives of this effort are:

1. To identify the U.S. hydrologic users, their applications, magnitude of effort, data processing equipment and models.
2. To establish the already experienced and potential contributions of remotely sensed data to the user's objectives.
3. To determine the expected computer data load induced by the remotely sensed data.
4. To analyze and project the cost trends of acquiring, processing and classifying remotely sensed data.
5. To ascertain the critical impact caused by the introduction of remotely sensed data on the user's conventional and expected computer processing facilities.
6. To formulate recommendations and guidelines for optimizing the phasing of remotely sensed data into the hydrologic user's activities.

3.0 SUMMARY & CONCLUSIONS

1. In the United States, Agencies and Organizations concerned with Water Resources number in excess of 6,000.
2. The principal contributor to research, development and implementation of water-related activities is the Federal Government, with over 80% of the budget. Most of this effort is carried on by 11 Federal Agencies.
3. In descending order of activity are State Agencies (several hundreds), State Water Resources Institutes (50), Universities (70 principal), Local Governments (in excess of 3,000), Private Contractors (approximately 3,000).
4. State Water Resource Institutes and Universities are primarily funded by the Federal Government. Private Contractors primarily support Local Governments.
5. Activities amenable to Remote Sensing, ordered in descending order of funds expended by all agencies are: Hydrologic Watershed Modeling; Flood Plain Mapping; Snowmelt/Runoff Modeling; Sedimentation/Erosion Assessment; Water Resources Inventory. Water Quality is also an important activity, not addressed in this effort.
6. Computers in use for Water Resources range from the largest machines, mostly used by the Federal Agencies, to hand calculators, employed in some of the Local Governments. The Federal Agencies have the largest share, approximately 85%,

of the computer power devoted to Water Resources (expressed in mega-instructions-per-second, or MIPS). Principal computer usage in the area of Water Resources is in Hydrologic Modeling:

7. The cost of processing hydrologic models will remain essentially constant with time, as a result of the contrasting trends of decreasing data processing costs and increasing model complexity.
8. The cost of processing remotely sensed data in the form of CCT's will also remain essentially constant with time, because the historical decrease in processing costs will be offset by the increasing sophistication of the remotely sensed data.
9. The costs of procuring CCT's under current policy of selling one entire ERTS frame are high with respect to the costs of processing the hydrologic models. This is because the watershed areas of interest to a large population of users are only a fraction of the area encompassed by one ERTS frame.
10. The costs of processing are higher for the small machines than for the larger ones. As a consequence of the relatively high costs of processing and procuring CCT's, the small and intermediate users will be potentially impacted in their effective use of remotely sensed imagery.

11. The potential consequences are threefold: 1) the small and intermediate users will significantly lag the larger user in taking advantage of the remotely sensed data stream; or 2) they will resort to the more economical method of direct analysis from imagery, suffering the consequent disadvantage of only partial utilization of the full gamut of information contained in the radiometric data; or 3) they will have to be served by some form of centralized facility, able to convert the CCT's into information usable by the users.

12. Reduction of the impact on user's processing facilities is achievable in several ways:
 - a - Reduce acquisition costs by "stripping out" portions of the ERTS frame covering the user's watersheds of interest, and selling them as "minitapes."
 - b - Process CCT's on a centralized facility, using large machines and preprocessors, and supply the hydrologic user only "digested" products in the format he desires and is accustomed to (e.g. maps of surface cover, of impervious areas, etc.).

13. An alternate option is to induce the users to compare the costs incurred in preparing watershed information by conventional methods with those achievable from analysis of remotely sensed imagery. Indications from ERTS investigation are that space-derived remotely sensed information will turn out to be less expensive than information gathered with conventional methods, even though the user's DP costs will turn out to be higher. The tradeoff between increased DP costs and decreased overall costs will have to be made by each user.

in light of his institutional constraints (availability of personnel, obsolescence of existing facilities, etc.).

The key is to develop the techniques and the method of presentation to the users, which will enable them to perform their tradeoff judgments based upon hard facts.

14. Several important ancillary factors which impact the rapid diffusion of remote sensing techniques have emerged from the study. Recommendations for the alleviation of the impact are:
 - a - The user must achieve a minimum level of training prior to utilizing remotely sensed data. Particularly severe is the gap in understanding the true meaning and value of radiometric versus geometric information.
 - b - Special software specifically designed for hydrologic use should be made available to users.
 - c - Special arrangements are needed for interchange of software and training materials with foreign users.
 - d - The delay between order and receipt of ERTS products poses somewhat of a barrier to the user's use of remotely sensed information. For hydrologic users, this barrier is essentially psychological. Efforts should be made to expedite the delivery time.

4.0 SURVEY OF PRINCIPAL WATER RESOURCE USERS

4.1 Objective

The objective of this task was to obtain a comprehensive data base specifying the significant agencies and organizations active in the water resources field. The principal items of information sought were: scope of activities; research or operational nature of the effort; hydrologic models used; and characteristics and utilization of data processing equipment.

4.2 Procedure

The first step was to develop an overall count of how many such agencies and organizations exist in the United States. From analysis of budgets and charters, direct discussions, telephone conversations and literature survey, an overall picture of the principal agencies and organizations involved in one or more aspects of the water resources field emerged:

o Federal Agencies	11
o State Agencies	200
o State Water Resource Research Institutes	50
o Universities (Major)	70
o Local Governments	>3000
o Private Contractors	>3000

Since the magnitude of the number of potential users did not allow for a 100% survey, it was decided to concentrate upon a selected subset of users, representative of the entire field. The initial data-gathering effort provided appropriate guidance for the selec-

tion of such a subset. A purposive sampling strategy was followed which focused principal attention on the users most active in the type of water resources activities which would potentially be most affected by remote sensing technology and data processing. Agencies in this category were carefully evaluated, using the following criteria of significance:

- o Water resources budgets.
- o Significant water resources research effort.
- o Portion of budget devoted to research, thus indicating model development orientation, rather than operational responsibilities.
- o Scope of activity. Specifically, selecting those activities which "a priori" appeared to relate to remote sensing, in contrast to those, such as the engineering of hydraulic works, in which the application of remote sensing techniques was primarily indirectly related.

Based upon the above criteria, it was decided to include in the subsequent sampling the following agencies and organizations:

1. Federal Agencies. 11 Federal Agencies were included which account for the overwhelming share of the budget, research efforts, and data processing facilities devoted to water resources activities.
2. State Agencies. Since the water resources activities of States tend to overlap among State Agencies, and since often several agencies are involved in the same aspect of water resources planning, development, and implementation, it was decided to sample all fifty States, but only those agencies within each State which appeared to be most heavily involved with aspects of water resources related to remote sensing and use of data processing equipment.
3. State Water Resources Research Institutes. All 50 were sampled.
4. Universities. 67 institutions, which appeared from the initial survey and from information available to project personnel to be the most active in the water resources field, were included.
5. Local Governments (Counties and Municipalities). In general, local activities were found to be highly fraction-

ized and of small scope relative to those of Federal and State Agencies. Although some counties (for example, Santa Clara County, California) are quite active in water resources, their activities are mostly oriented towards public works projects, such as sewage and water treatment plants and water supply. Therefore, it was decided to devote the available budgetary resources to the detailed survey of those counties within the local area which are more progressive in the water resources field.

6. Private Contractors. The initial survey indicated that private contractors devote most of their efforts to satisfying the needs of Local Governments. To a large extent, then, they mirror the activities of the counties and municipalities. For these reasons, it was decided to confine the survey to a select number of major local private contractors.

The methods used in preparing the detailed sample consisted of the following:

1. Federal Agencies: Detailed study of their activities from published information and personal discussions.
2. States: Sampling by questionnaire, with telephone follow-up where appropriate.
3. State Water Resources Research Institutes: Same method as for States,
4. Universities: Questionnaire plus telephone follow-up plus personal visits within local area.
5. Local Governments: Study of published information plus personal visits.
6. Private Contractors: Telephone interviews.

4.3 Responses

A list of the 187 agencies and organizations which were surveyed is presented in Appendix A.

Table 1 summarizes the survey, giving number of agencies surveyed and number of responses received. In all, 75 agencies out of a total of 187 queried provided information and data. These organ-

TABLE I

SUMMARY OF RESPONSES TO WATER RESOURCES SURVEY

	Agencies Surveyed	Agencies Responding	Number of Computers Used	Number of Different Models Used	No. of origi- nal Models with Remote Sensing Potential
Federal Agencies	11	11	75	47	33
State Agencies	50	31	49	106	28
State Water Resource Inst.	50	12	24	37	15
Universities	67	12	14	22	12
Local Governments	3	3	1	1	1
Private Contractors	6	6	9	11	2
TOTALS	187	75	172	224	91

izations process a total of 224 hydrologic and water resources models on 172 computers, applied to a variety of water resources users. While water research activity is substantial at all levels, further examination confirmed that commitment to water resource projects of the type which could directly benefit from remote sensing inputs is centered mainly in direct Federal or Federally-funded activities.

The 75 replies were first analyzed to assess the adequacy of the sample. Where noticeable information gaps became apparent, follow-up calls were made to fill them.

The analysis indicated that the sample is adequate for the following reasons:

1. The Federal Agencies were sampled 100%. These alone represent 80% of the water resources effort in terms of budgets expended.
2. The State Agencies yielded a 60% response; however, included among the responses were such major water resources-oriented states as California and Texas. A special telephone follow-up was made to several Texas and California organizations in order to augment some of the information.
3. The State Water Resources Research Institutes yielded a 24% response. Again, included therein were several major States. In addition, the activities of these Institutes is well documented from other sources, such as the Office of Water Resources and Technology, Department of the Interior. These sources were used to round out the picture.
4. The response from Universities was 21%. Some of these Universities also act as State Water Resources Research Institutes. Of particular importance is Colorado State, which was contacted by telephone as well as by questionnaire.
5. 100% of Local Governments and private contractors sampled responded. Although the sample number was small relative to the total population of these users, the sample is believed to be reasonably representative, as discussed

previously.

Following is an overview of the principal characteristics of the non-Federal users. The Federal users, which represent the bulk of the water resources effort of interest to this study, are discussed in Section 4.10.

4.4 State Users

Each of the 50 States has one or more agencies which deal with water resources problems. Information relating to the activities, hydrologic models, and computer complement of these agencies is presented in Appendices B through D. State Agencies operate 28% (by number) of the computers and 47% of the hydrologic models identified in the sample.

This level of activity, although significant, requires further qualification. First, the range of the functions of State Water Resources Agencies varies greatly with the resources of the State and the magnitude of its water resource problems. California and Texas alone, for example, operate 36% of the models used by all the States and 27% of the computers.

Second, an analysis of the models used by the States shows that they are generally adapted from models created by Federal Agencies or through Federal Agency support.

Third, almost half of the computer models developed by the States address those elements of hydrology in which remote sensing data as currently understood has little or no direct impact (for example, statistical support programs, stage-discharge computational pro-

grams, and backwater curves requiring detailed channel cross section information). Table 1 shows that only about one-fourth of all models used by the States were originated by that sector and are of the type amenable to remote sensing.

Fourth, the water resources research budgets of State Agencies are typically orders of magnitude less than the budgets of the Federal Agencies involved in similar research.

Table 2 presents a profile of the water resources activities of State Agencies which have significant data processing content. Figure 1 is an overview of the distribution of hydrologic models used by State Agencies, indicating major scope of applications and origin of the models (Federal, University, or privately developed, or developed in-house by the agencies themselves). Figure 1 also indicates that approximately 40% of the hydrologic models used by State Agencies are not amenable to remote sensing, at least within the capabilities of current technology.

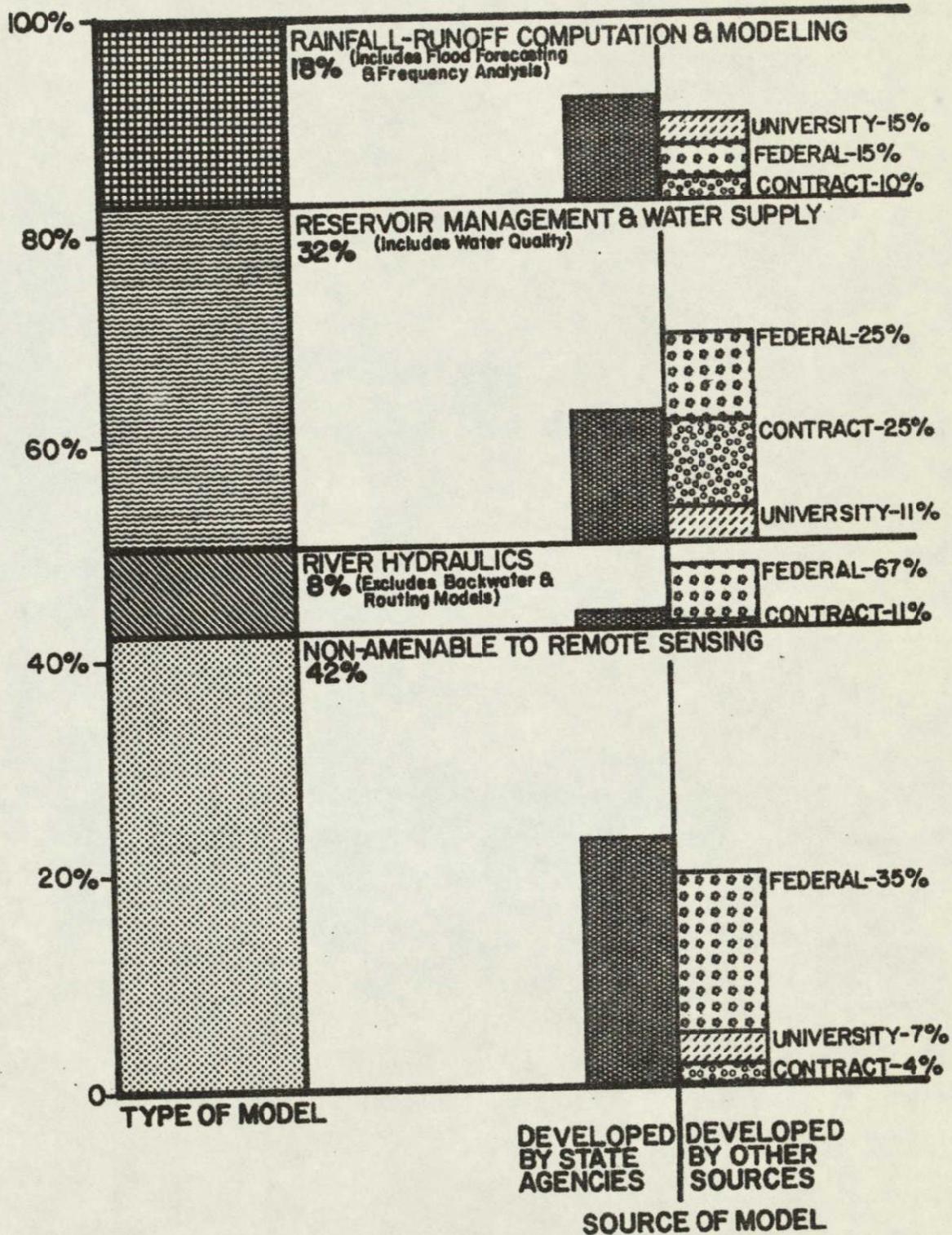
4.5 State Water Resource Research Institute Users

The activities of State Water Resource Research Institutes, shown in Appendix E, represent an extension of Federal involvement in water resources since they are funded as a result of the 1964 Water Resources Research Act. As can be seen in Appendix F, most of the models used by the Water Resources Research Institutes have their source in the Federal Government. The use of large computers by these agencies is small; the percentage of this use devoted to water resources is, in all but one case where figures

TABLE 2

PROFILE OF HYDROLOGIC COMPUTER USE BY STATE AGENCIES	
RANK/CATEGORY	% OF STATE AGENCIES HAVING SIGNIFICANT COMPUTER ACTIVITIES
1. RESERVOIR/WATER SUPPLY MANAGEMENT	85%
2. WATER RESOURCES/MANAGEMENT - DATA COLLECTION/PROCESSING/CORRELATION	81%
3. WATER QUALITY ASSESSMENT	70%
4. FLOOD: ESTIMATION/MAPPING/FORECAST	67%
5. RAINFALL - RUNOFF COMPUTATION/MODELING	56%
6. ECONOMIC ANALYSIS & PLANNING	48%
7. CONSERVATION	41%
8. SANITARY ENGINEERING DESIGN	37%
9. PUBLIC WORKE DESIGN (Generally contracted)	33%
10. GROUNDWATER	19%
11. SNOWMELT/RUNOFF	15%

TYPES AND SOURCES OF HYDROLOGIC MODELS USED BY STATE AGENCIES



are given, 5% or less (see Appendix G).

Table 3 shows the profile of the State Water Resources Institutes in terms of data processing activities and Figure 2 presents an overview of the distribution of hydrologic models used by these Institutes.

4.6 Local Water Resources Agency Users

The response of the local water resources agencies contacted, combined with budget information from the large counties and metropolitan Governments, permit the following conclusions:

1. County and local budgets for the hydrologic aspects of water resources are small by comparison to the Federal Government.
2. The greatest share of Local Government appropriations are channeled into the construction of civil works, an area which would indirectly benefit from remotely sensed data as improved design inputs; but are not immediately impacted by new remote sensing data streams.

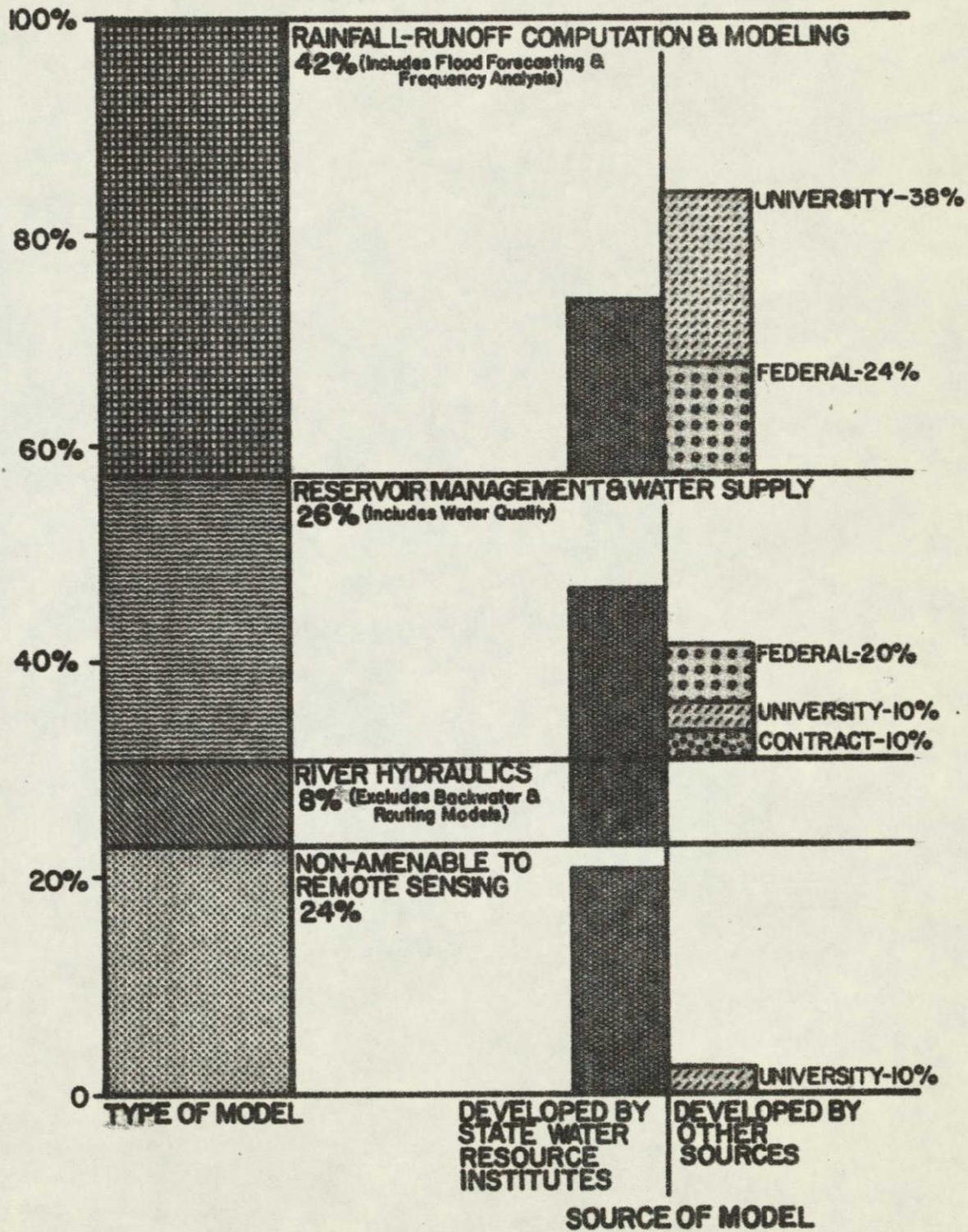
4.7 Universities

Universities operate significantly in the field of basic hydrologic research and are producers of original water resource models. Their work, however, is mainly dependent upon Federal stimulation. Figure 3 shows the magnitude of research support from the Federal Agencies, of which a significant percentage is contracted to Universities. For example, the Office of Water Resources Research grants 87% of its allocation of \$12,400,000 to Universities and other non-profit organizations. Likewise, the Bureau of Reclamation contracts 69% of its allocation of \$5,119,000 to Universities. The University sector may be viewed as an extension of Federal in-

PROFILE OF HYDROLOGIC COMPUTER USE BY STATE WATER RESOURCE INSTITUTES	
<u>RANK/CATEGORY</u>	<u>% OF INSTITUTES HAVING SIGNIFICANT COMPUTER ACTIVITY</u>
1. ECONOMIC ANALYSIS & PLANNING	83%
2. WATER QUALITY ASSESSMENT	83%
3. FLOOD: ESTIMATION/MAPPING/FORECAST	58%
4. RESERVOIR/WATER SUPPLY MANAGEMENT	58%
5. SANITARY ENGINEERING DESIGN	58%
6. WATER RESOURCES/MANAGEMENT - DATA COLLECTION/PROCESSING/CORRELATION	58%
7. RAINFALL - RUNOFF COMPUTATION/MODELING	58%
8. PUBLIC WORKS DESIGN	42%
9. SNOWMELT/RUNOFF	33%
10. GROUNDWATER	17%
11. CONSERVATION	8%

FIGURE 2

TYPES AND SOURCES OF HYDROLOGIC MODELS USED BY STATE WATER RESOURCE INSTITUTES



FEDERAL SUPPORT OF WATER
RESOURCES RESEARCH

FY 73

Dept.	Agency	Funding Budget in 1973 Dollars
DOI	USGS	\$ 550,000
	BUREAU OF RECLAMATION	5,119,000
	FISH AND WILDLIFE SERVICE	381,000
	BPA	---
	OWRR	12,400,000
DOA	FOREST SERVICE	---
	ARS	---
	SCS	2,472,000
DOC	NOAA	986,000
DOD	COE	4,315,000
EPA		15,957,000 NOTE: Mostly Water Quality
TVA		5,000
TOTAL		42,185,000

volvement. The responses received from the Universities are presented in Appendix H. A typical data processing profile and an overview of hydrologic models employed are shown in Table 4 and Figure 4 respectively.

4.8 Private Contractors

Private contractors depend mostly upon funds from the Local Governments. Furthermore, the orientation of the private organizations sampled was toward public works design. Their responses are included as Appendix I. Figure 5 shows an overview of the hydrologic models employed.

Several of the private contractors, e.g. Hydrocomp, Inc. and Water Resources Engineers, do provide significant input to hydrologic modeling with impact on remote sensing. The project support for development, however, is generally from the Federal sector. Once developed, these companies provide services throughout all sectors.

4.9 Summary

Analysis of the total water resource effort of all sectors gives rise to the following conclusions:

1. The Federal Government, directly and through its University, State Water Resources Research Institutes, & support contractors, is the principal developer of hydrologic models and generally is the sector wherein the models are first reduced to practice. Therefore, the sensitivity of water resources to remote sensing data input can most profitably and adequately be tested by analysis of this sector.
2. Water resource activity of other Government sectors, and of private, State and University organizations of the type directly sensitive to remote sensing data input is

TABLE 4

PROFILE OF HYDROLOGIC COMPUTER USE BY UNIVERSITIES	
RANK/CATEGORY	% OF UNIVERSITIES HAVING SIGNIFICANT COMPUTER ACTIVITIES
1. RAINFALL - RUNOFF COMPUTATION/MODELING	60%
2. WATER QUALITY ASSESSMENT	50%
3. WATER RESOURCES/MANAGEMENT - DATA COLLECTION/PROCESSING/CORRELATION	50%
4. ECONOMIC ANALYSIS & PLANNING	30%
5. GROUNDWATER	30%
6. FLOOD: ESTIMATION/MAPPING/FORECAST	20%
7. RESERVOIR/WATER SUPPLY MANAGEMENT	20%
8. SNOWMELT/RUNOFF	10%
9. CONSERVATION	*
10. PUBLIC WORKS DESIGN	NA
11. SANITARY ENGINEERING DESIGN	NA

FIGURE 4

TYPES AND SOURCES OF HYDROLOGIC MODELS USED BY UNIVERSITIES

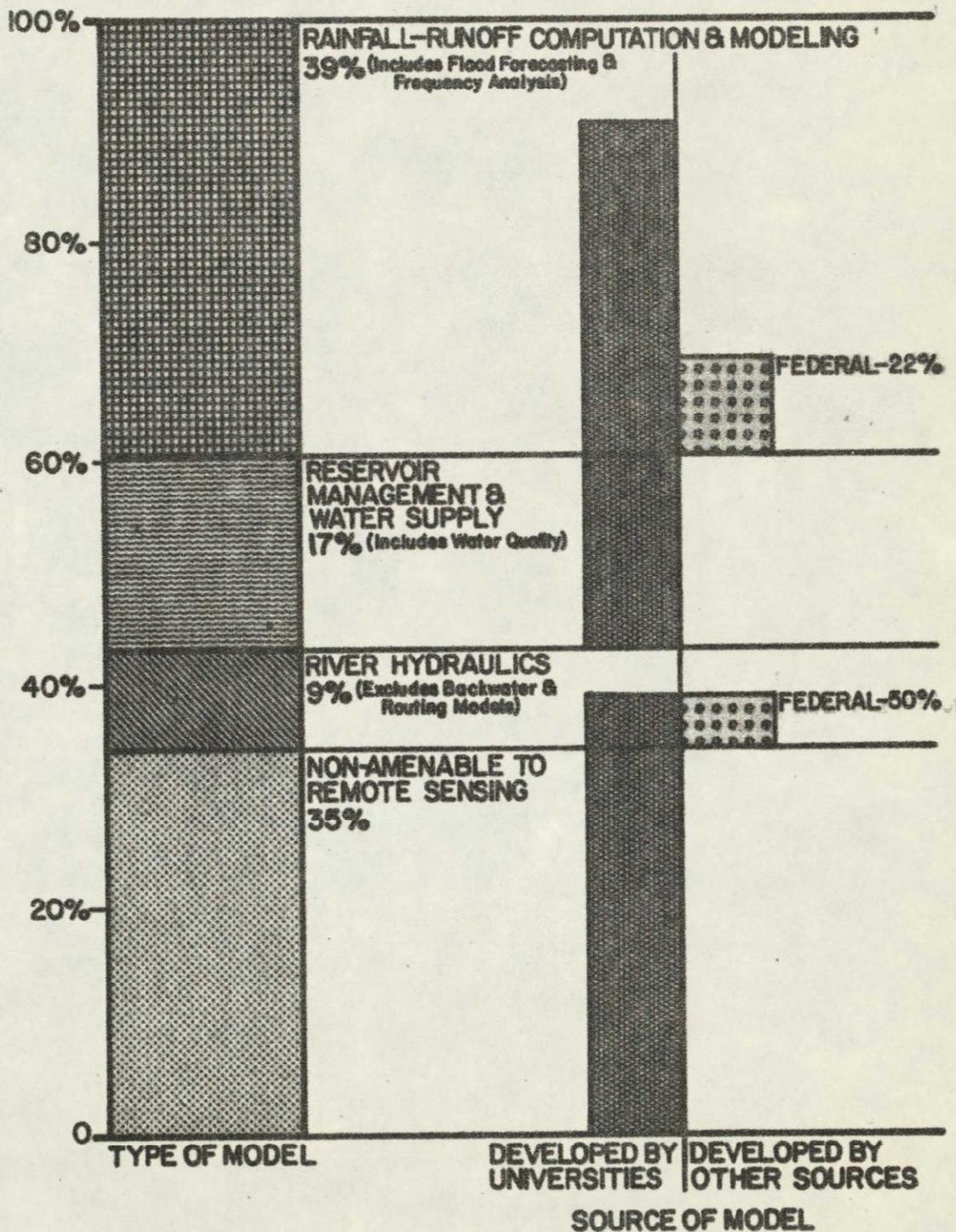
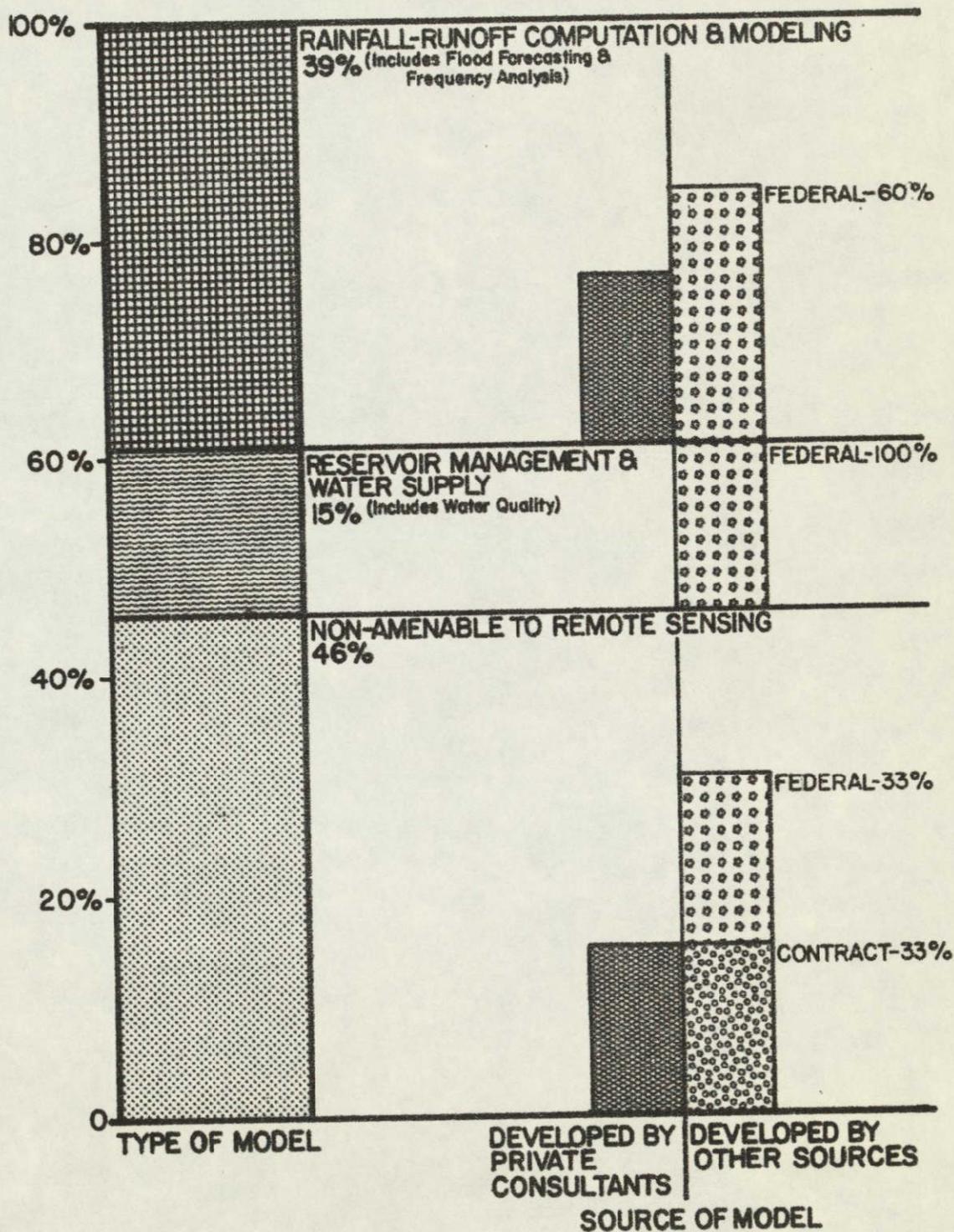


FIGURE 5

TYPES AND SOURCES OF HYDROLOGIC MODELS USED BY PRIVATE CONSULTANTS



primarily Federally stimulated. The large bulk of the money and activities of these sectors is centered on construction and fiscal operation of civil works. Benefits induced by the impact of remote sensing on the Federal sector will have an important but time-delayed impact in these sectors.

4.10 Principal Federal Water Resources Research

The eleven organizations listed below, distributed among six Federal Agencies, spend 93%, or approximately 470 million dollars, of the total Federal water resources research budget of approximately 509 million dollars (FY 1973).

1. Department of Commerce - National Oceanographic & Atmospheric Administration
2. Department of Agriculture
 - a. Agricultural Research Service
 - b. Soil Conservation Service
 - c. Forest Service
3. Department of the Interior
 - a. Geological Survey
 - b. Bureau of Reclamation
 - c. Fish and Wildlife Service
 - d. Bonneville Power Administration
4. Environmental Protection Agency
5. Department of Defense - Army Corps of Engineers
6. Tennessee Valley Authority

A summary of the activities and detailed budget of each agency is given in Appendix J.

Figure 6 presents a breakdown of Water Resources research and total budgets of the eleven agencies surveyed. Figure 7 depicts an overview of the application of hydrologic models by Federal Agencies.

FIGURE 6

FEDERAL WATER RESOURCES AGENCY BUDGETS-FISCAL YEAR 1973

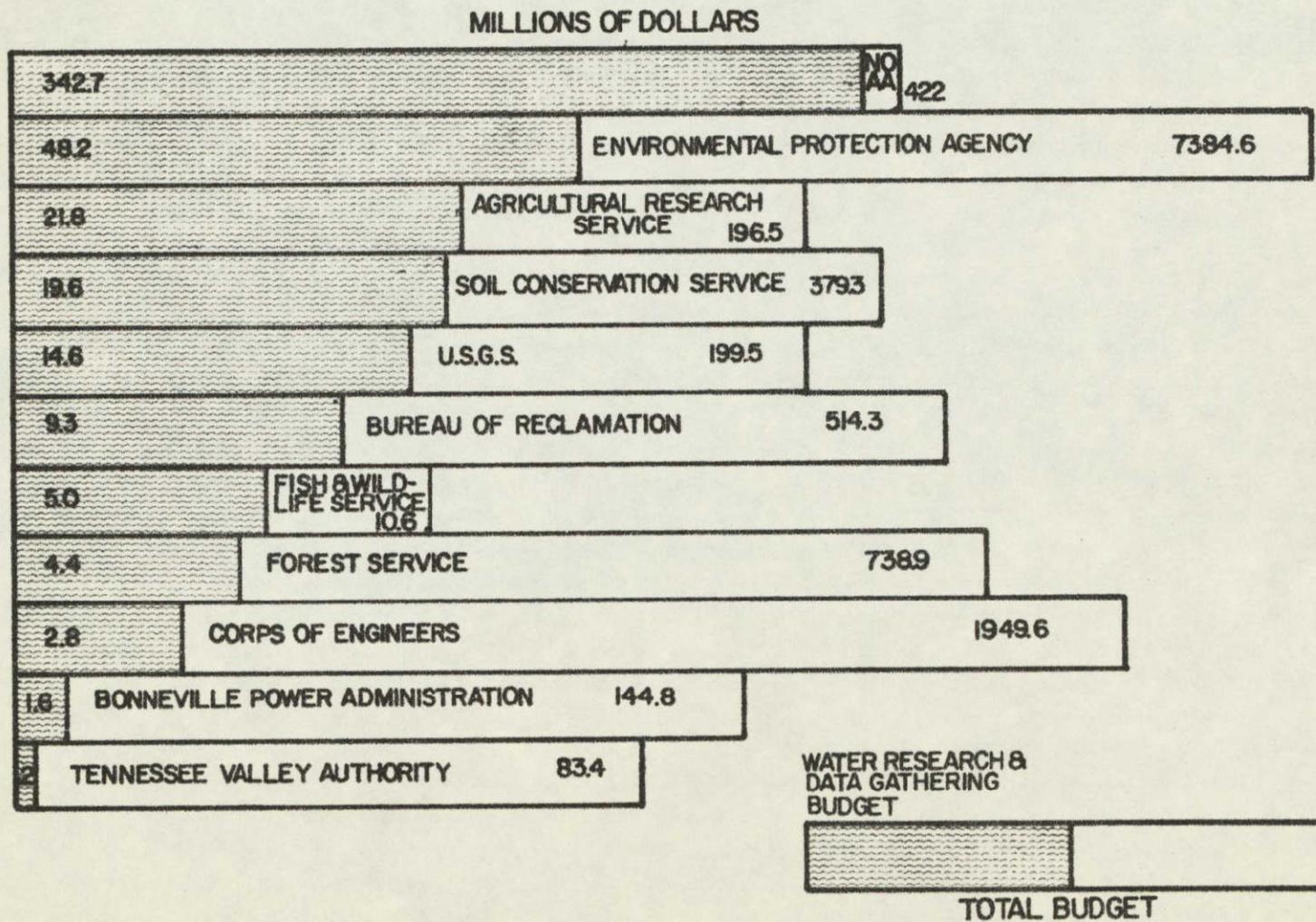
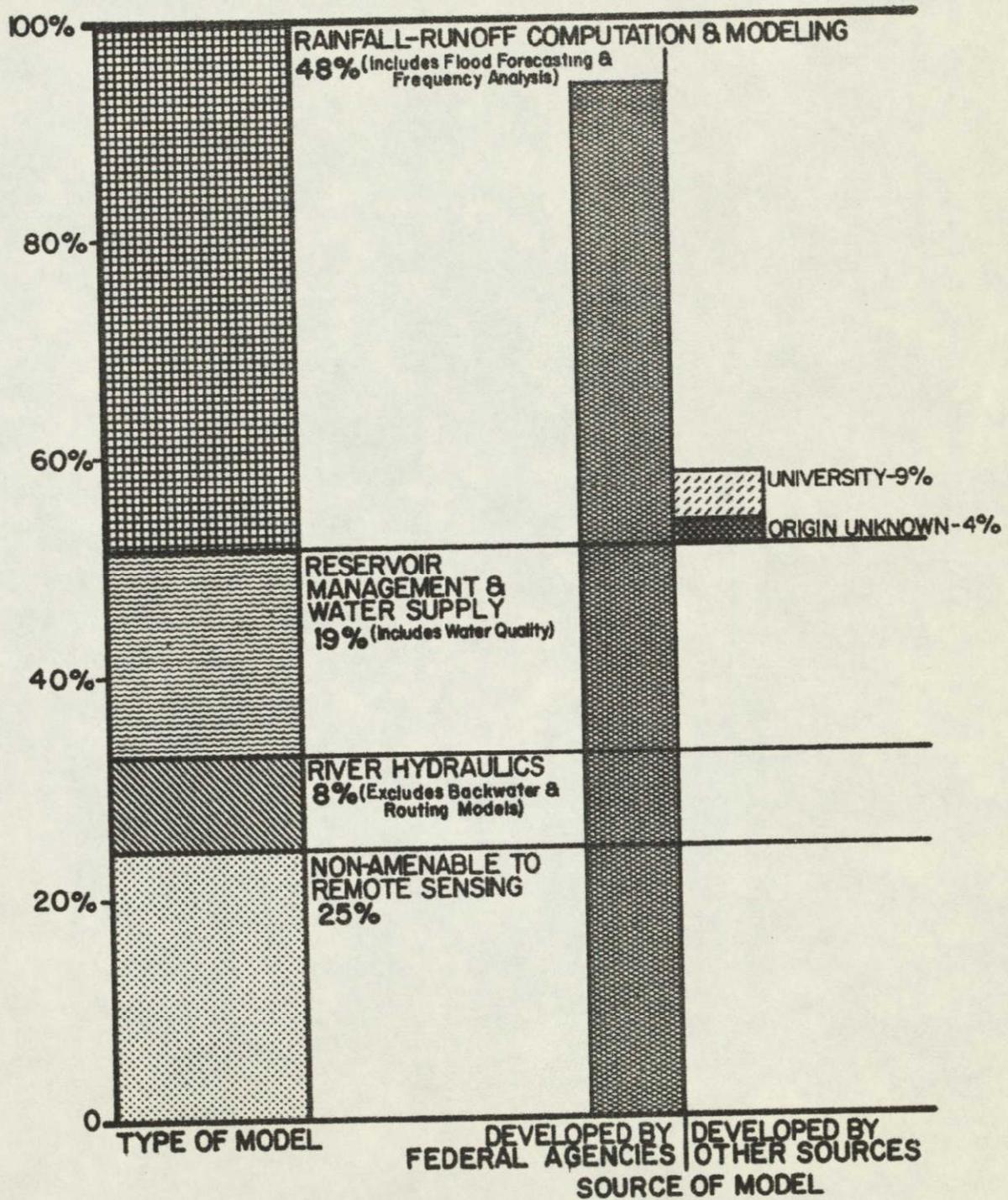


FIGURE 7

TYPES AND SOURCES OF HYDROLOGIC MODELS USED BY FEDERAL AGENCIES



4.11 Focus of Principal Federal Agencies Relative to Remote Sensing

In order to assess the potential impact of remote sensing technology on the planning, management, and development of water resources, it is important to determine whether the Federal Water Agencies concentrate their efforts in activities potentially affected by input of remote sensing data.

An inventory, which appears in Appendix J, was taken of the primary functions of the eleven water resource agencies listed in the previous section. Of these activities, the following were determined to be not directly amenable to remote sensing:

1. Activities which are not directly affected by remote sensing, such as subsurface flow studies.
2. Purely economic activities, such as the marketing of surplus electric power.
3. Construction projects, such as the building of dams.
4. Legal activities, such as the determination of water rights.
5. Administrative functions.

The residual water resources activities that could not be definitely ruled out were considered to be potentially amenable to remote sensing and were grouped into sixteen areas, listed and summarized in Table 5.

Consideration of Figure 8, which compares agencies with functions, leads to the following conclusions:

1. All of the Federal water organizations surveyed are engaged in activities that are potentially amenable to remote sensing data.
2. The Corps of Engineers, NOAA, the Geological Survey, TVA,

TABLE 5

THE RELATIONSHIP OF REMOTE SENSING TO IMPORTANT WATER RESOURCES FUNCTIONS	
Hydrologic Modeling	Study and modeling of basic physical hydrologic processes.
Urban Hydrology	Assessment of urban storm drainage and effects of urbanization upon runoff.
Flood Plain Mapping	Physical and cartographic delineation of land areas inundated by peak flows.
Influence of Land Use	The application of land management practices as they relate to stream, lake or estuarine resources.
Water Resources Inventory	Location and classification of water, and identification of areas of critical concern (ex., aquifer recharge areas, coastal zones, etc.).
Lake and Estuarine Hydrology	Basic hydrology of lakes and estuaries, including water movement, wave action, interlake flow, and limnology.
River Hydraulic Modeling	Study of tidal hydraulics, wave phenomena, and shore processes.
Flood Control	Reservoir sizing and non-construction alternatives of flood control.
Rainfall/Runoff Modeling	Streamflow determination, hydrograph analysis, and watershed transfer function development.
Reservoir & Water Supply Management	Operation of reservoirs and determination of supply and demand.
Meteorological and Hydrological Data Analysis	Compilation, synthesis and summarization of weather and water data.
Sedimentation & Erosion	Study of sedimentation, siltation, and erosion and development of methods of problem amelioration.
Flood Forecasting	Determination of peak flows and river stage forecasting.
Snowmelt/Yield	Snow surveys, snowmelt models, and relation of snowmelt to water supply and runoff.
Thermal Pollution	Study of effects of temperature alterations on water bodies.
Water Quality	Location, classification and abatement of pollution.

FIGURE 8

FUNCTIONS OF FEDERAL AGENCIES POTENTIALLY AMENABLE TO REMOTELY SENSED DATA

AGENCY	FUNCTION	FLOOD PLAIN MAPPING	INFLUENCE OF LAND USE	WATER RES. INVENTORY	HYDROLOGIC MODELING	URBAN HYDROLOGY	LAKE/ESTUARY HYDROLOGY	RIVER HYDRAULIC MODELING	FLOOD CONTROL	RAINFALL-RUNOFF MODELING	RESERVOIR/WATER SUPPLY MGMT	METEOROLOGICAL/HYDROLOGICAL DATA ANALYSIS	SEDIMENTATION/EROSION	FLOOD FORECASTING	SNOWMELT/YIELD	THERMAL POLLUTION	WATER QUALITY	TOTAL
N.O.A.A.																		7
AGRICULTURE RESEARCH SERVICE																		4
SOIL CONSERVATION SERVICE																		6
FOREST SERVICE																		3
GEOLOGICAL SURVEY																		7
BUREAU OF RECLAMATION																		3
FISH & WILDLIFE SERVICE																		3
BONNEVILLE POWER ADMINISTRATION																		2
ENVIRONMENTAL PROTECTION AGENCY																		3
CORPS OF ENGINEERS																		9
TENNESSEE VALLEY AUTHORITY																		7
TOTAL		2	4	1	4	3	3	1	4	5	5	5	4	2	5	3	3	54

MAJOR FUNCTION



OTHER FUNCTIONS



and SCS are the agencies involved in the largest variety of areas potentially amenable to remote sensing technology. Therefore, these agencies constitute the most likely set of Earth Resources Satellite data users.

3. Though the range of agency activities is fairly diverse, some concentration can be observed in rainfall/runoff modeling, reservoir/water supply management, meteorological/hydrological data and snowmelt yield. The introduction of remote sensing to water resources, then, would be facilitated by stressing applications in these areas.
4. Those agencies that perform the most diverse functions also concentrate their effort in areas with the largest common involvement.

Table 6 compares the profiles of the principal agencies surveyed by ranking the computer usage by application and type of agency: Federal, State, State Water Resources Institutes, and University.

Table 7 ranks the data processing usage of hydrologic models, for the U.S. water resources agencies, by application.

TABLE 6

COMPARISON OF WATER RESOURCES PROFILES BY USER CATEGORY				
CATEGORY	RANK			
	<u>Federal</u>	<u>State</u>	<u>Water Resource Institutes</u>	<u>University</u>
WATER RESOURCES/MANAGEMENT DATA COLLECTION/PROCESSING/ CORRELATION	1	2	6	3
RAINFALL-RUNOFF COMPUTATION/ MODELING	2	5	7	1
WATER QUALITY ASSESSMENT	3	3	2	2
ECONOMIC ANALYSIS & PLANNING	4	6	1	4
CONSERVATION	5	7	11	9
FLOOD: ESTIMATION/MAPPING/ FORECAST	6	4	3	6
PUBLIC WORKS DESIGN	7	9	8	10
SNOWMELT/RUNOFF	8	11	9	8
RESERVOIR/WATER SUPPLY MANAGEMENT	9	1	4	7
GROUNDWATER	10	10	10	5
SANITARY ENGINEERING DESIGN	11	8	5	11

TABLE 1

**RANKING OF HYDROLOGIC COMPUTER USE IN THE WATER RESOURCES
FIELD**

1. WATER QUALITY ASSESSMENT
2. WATER RESOURCES/MANAGEMENT - DATA
COLLECTION/PROCESSING/CORRELATION
3. RAINFALL - RUNOFF COMPUTATION/MODELING
4. ECONOMIC ANALYSIS & PLANNING
5. FLOOD: ESTIMATION/MAPPING/FORECAST
6. RESERVOIR/WATER SUPPLY MANAGEMENT
7. CONSERVATION
8. PUBLIC WORKS DESIGN
9. GROUNDWATER
10. SANITARY ENGINEERING DESIGN
11. SNOWMELT/RUNOFF

5.0 RELATIONSHIP OF REMOTE SENSING DATA INPUTS TO THE PRINCIPAL HYDROLOGIC MODELS

The computer models used to describe hydrologic processes and events are the cogent indicators of the impact of new data inputs on water resources activity. The potential impact of remotely sensed information hinges upon the specific data requirements of the principal models in use.

A survey of models used by the Federal Water Resource Agencies, included as Appendix K, indicates that:

1. All the organizations surveyed are active in modeling, with the exception of the Fish and Wildlife Service.
2. Most of the models utilized were developed in-house or directly under contract.

Table 8 summarizes the inputs to hydrologic models which would be potentially impacted by remotely sensed data streams and describes the mechanism by which such data would be used. In Figure 9, these inputs are related to specific models which were singled out for analysis because they generally combine a representative set of water resources users with potentially high remote sensing impact. Figure 10 illustrates the distribution of the models by user. Two immediate conclusions can be drawn from Figure 9.

1. The remote sensing inputs having the most universal applicability to the models are: drainage area, used by 100% of the models considered; vegetative cover, used by 67% of the models; drainage density, used by 42%. Note also the importance of snow cover, used by 58% of the models in areas where snow contributes significantly to the runoff. In addition, temperature is used in 67% of the models to compute evaporation and evapotranspiration. This measurement, however, is not available in the present version of LANDSAT and must be performed from meteorological satellites. Its operational application for day-to-day hydrologic purposes must await

TABLE 8

POTENTIAL REMOTE SENSING INPUT TO HYDROLOGIC MODELS

Vegetative Cover	Cover is an indicator of potential evapotranspiration, interception, surface roughness, and permits some inference of subsurface characteristics.
Snow Cover	Areal extent or water content of snow is applied to calculation of yield
Land Use/Change	Land use and change can be input to allow for seasonal cover fluctuations or urbanization effects.
Drainage Area	The geographic dimensions of watersheds and subsurface terrain variations are indicative of magnitude of runoff mass and flow rate.
Drainage Density	Average distances of overland flow to streams are used to deduce the time distribution of runoff. Drainage density is applicable as an input parameter to rational formulas.
Surface Water	Surface water contributes to total impermeable area. Standing water comprises, in part, surface detention capacity.
Soil Association	Soil type is an inferential determinant of infiltration rate and moisture capacity.
Soil Moisture	Antecedent moisture in the surficial soil level sets residual water capacity and indicates the propensity of the soil to produce surface flow.
Impermeable Areas	The areal extent and distribution of surfaces which prohibit infiltration influence runoff mass and flow rate.
Cloud Cover	Cloud cover acts to limit temperature available for evapotranspiration.
Temperature	Temperature indices will determine the form of precipitation (rain or snow), and influence evapotranspiration rate.

FIGURE 9

REMOTE SENSING VARIABLES OF HYDROLOGIC MODELS

MODELS	VARIABLES										
	VEGETATIVE COVER	SNOW COVER	LAND USE/ LAND USE CHANGE	DRAINAGE AREA	DRAINAGE DENSITY	SURFACE WATER	SOIL ASSOCIATION	SOIL MOISTURE	IMPERMEABLE AREAS	CLOUD COVER	TEMPERATURE
USDAHL 70/74	■	■	■	■			■	■			■
USGS				■			■	■	■		■
STANFORD MODEL	■	■		■	■	■	■	■			■
TEXAS MODEL	■	■		■	■	■	■	■			■
HYDRO 14	■			■	■	■	■	■	■	■	■
HYDRO 17		■		■						■	■
API	■		■	■							
SSARR		■	■	■		■		■			■
COSSARR			■	■		■		■			■
TR-20	■			■	■		■				
USGS RAINFALL-RUNOFF	■			■							

FIGURE 10

RELATIONSHIP OF HYDROLOGIC MODELS TO USER CATEGORY

MODEL NAME	USER CATEGORY				
	FEDERAL AGENCIES	STATE AGENCIES	WATER RESOURCE INSTITUTES	UNIVERSITIES	PRIVATE CONSULTANTS
STANFORD WATERSHED	Shaded	Shaded	Shaded	Shaded	Shaded
TR-20	Shaded	Shaded			Shaded
SSARR	Shaded			Shaded	
USDAHL 70/74	Shaded			Shaded	
API	Shaded				Shaded
USGS RAINFALL-RUNOFF	Shaded				Shaded
COSSARR	Shaded				
TEXAS WATERSHED (MODIFIED STANFORD)		Shaded			
HYDRO 14	Shaded				
HYDRO 17	Shaded				

the advent of more sophisticated techniques, such as possibly a Thematic Mapper devoted to water resources and hydrology.

2. The models which are potentially impacted by the highest number of remote sensing inputs are: the Hydro 14 model, with 9 of 11 inputs; the Texas model, with 8 inputs; the Stanford Watershed model with 7 inputs; and the USDAHL-70, 74 model with 7 inputs.

Table 9 demonstrates the procedure by which the information shown in Figure 9 was developed, using the USDAHL-70, 74 model as an example. An analysis was made of the role of each of the remote sensing inputs, and seven areas where remote sensing data would be contributive are identified. The importance of vegetative cover, land use and change, and drainage area, inputs which can presently be assessed by remote sensing, to the USDAHL-70, 74 model is apparent. Measurement of the distribution, seasonal and growth state of agricultural crops and the areal extent of the basin would also be required. Appendix K shows the input/output analysis of the USDAHL-70, 74, including important processes, remote sensing and non-remote sensing inputs, physical and non-physical model parameters, outputs and principal uses. Similar details for the other models are also presented in Appendix K.

Table 10 synthesizes the remotely sensed data utilization requirements of the principal hydrologic models. The table correlates the major components of the models with : 1) the required geometric and/or radiometric resolution (whether currently achievable from LANDSAT or not); 2) the intensity of processing, i.e. whether pixel by pixel or less intense - for example, in the opposite cases of determining vegetative cover versus only drainage density; 3) the time frame when the remote sensing capability is expected to

TABLE 9

POTENTIAL REMOTE SENSING INPUT FOR USDAHL-70/74

Vegetative Cover	Vegetative cover is used in the model in several areas. A crop growth index, equal to the % of crop maturity, is used as a seasonal correction factor in the infiltration equation. The index is calculated indirectly from temperature data. Remotely sensed input could permit direct measurement of crop growth and allow changes due to harvest, disease, etc. Vegetative cover is also used to calculate snowmelt and as a surface friction factor.
Snow Cover	Water equivalent of snow mass is used as a precipitation input in HL-70. In HL-74, snowmelt is calculated from temperature, infiltration and rainfall. Remote sensing information could permit more direct measurement of snowmelt.
Soil Moisture	Maximum soil moisture capacity is used in Holtan infiltration equation and soil moisture is employed to figure ET.
Soil Association	Soil type and depth are determinants of water storage capacity and infiltration rates, both of which are used in the model. Also, the watershed is divided into soil zones for ET and overland flow computation.
Land Use/Change	Land use is used as a constant in the infiltration equation based on SCS figures, parameters amenable to direct measurement by remote sensing.
Temperature	Temperature is input weekly to calculate crop growth and ET.
Drainage Area	Watershed area and area of soil zones are input, as is overland flow length.

TABLE 10: REMOTE SENSING REQUIREMENTS OF THE PRINCIPAL HYDROLOGIC MODELS

	% UTILIZATION	TIME FRAME	PRIMARY SENSING MODE		GEOMETRIC ACCURACY REQ'D (EQUIV. MAP SCALE)	RADIOMETRIC ACCURACY REQ'D (NO. OF GREY LEVELS)	COMPUTER IMPACT
			GEOMETRIC	RADIOMETRIC			
Vegetative Cover	66	75-80		X	1:62,500	128	Pixel x pixel
Snow Cover	58	75-80	X		1:125,000	4	Boundary pixels
Land Use/Change	58	75-80		X	1: 62,500	128	Pixel x pixel (submeso-scale)
Drainage Area	100	75-80	X		1: 62,500	32	Boundary Pixel
Drainage Density	42	75-80	X		1: 25,000	4 (HI-RES GEOM) 128 (Pixel Split)	Contour pixel & Pixel Split
Surface Water Area	50	75-80	X		1: 62,500	16	Boundary Pixel
Soil Association	58	80+		X	1:250,000	128	Pixel x pixel (submeso-scale)
Soil Moisture	58	85+		X	1:250,000	64	Pixel Sampling
Impermeable Area	25	80+		X	1: 62,500	128	Pixel x pixel (microscale)
Cloud Cover	16	80+	X		1:250,000	4	Boundary Pixel
Temperature	66	80+		X	1:1,000,000	128	Pixel x pixel (mesoscale)

-40-

be available.

The essential conclusion from Table 10 is that the remotely sensed data stream input to sophisticated hydrologic models requires total pixel-by-pixel processing over the entire area of the watershed.

6.0 SUMMARY OF COMPUTERS & COMPUTER GROWTH TRENDS FOR HYDROLOGIC MODELS

6.1 Logic of Approach

Having identified the principal major computer models in use, let us now focus upon the characteristics, application, and utilization of the computers which support these models.

Historically, the sophisticated hydrologic models are initially developed by the Federal Government or under Federal sponsorship; their primary application is initially in Federal projects. Subsequently, the technology filters to the States with delays of up to 5 to 10 years. Local agencies by and large do not utilize the sophisticated models; they employ simpler models or highly simplified derivatives of the complex models.

Therefore, a useful and logical approach for analysis is to first assess the impact of the potential remotely sensed data upon the larger models affecting primarily the Federal, and secondarily the State Agencies, and next, to overview the impact upon the smaller "local" models. The analysis will proceed within the perspective of the temporal delay characteristic of the technological transfer process from the advanced research sponsored by the Federal establishment to the results-oriented application of the local users.

The analysis is developed according to the following structure:

1. A brief overview on the principles of sizing the speed of digital computers.
2. Presentation of the trends which drive the growth of computer processing power,
3. The trends in the costs of data processing.

4. Quantitative estimation of the data processing load for processing hydrologic models and analysis of its growth trends.

6.2 Principles of Sizing Digital Computer Speed

Computing power is commonly defined in two ways: (1) Internal Performance, which is the computing speed of the Central Processing Unit (CPU), a definition which tacitly assumes that the Input-Output (I/O) is of infinite capacity; (2) Throughput, which is the speed of the system, including CPU and I/O peripherals. Throughput never exceeds Internal Performance.

The analysis for this effort will concentrate on the comparison of machines by internal performance. There are two justifications for this reasoning. First, analysis on the basis of throughput requires specification of the I/O configuration used, and of the problem being run. Secondly, information regarding throughput is difficult and costly to obtain, and not really needed for the "plus or minus three decibel" type of overall technological assessment that will be made here.

There is no general agreement in the trade, or at any international level, on the units of measurement of internal performance. The most used units and their corresponding methods of measurement are:

1. Benchmark timings, i.e. the time required to process specific, defined problems. This is by far the most accurate method, used frequently to select machines competitively, but is not practical for general comparisons. The reason is that data on benchmark timings are scarce because these measurements are quite expensive.
2. Instructions per second (IPS, and multiple KIPS and MIPS). One constructs a set of programs, "representative" of

typical spectra of scientific problems, and measures the "average" speed with which the CPU processes them. Strictly speaking, the method is exact only when comparing machines whose characteristics are roughly similar. Otherwise, one may find that Machine B which is slower than Machine A on the "representative" program may actually perform faster on actual problems. Nevertheless, KIPS and MIPS are becoming the yardstick of performance most used in the industry.

3. Operations per second. Similar to (2) above in concept. In general, depending upon the type of instructions and upon the architecture of the machine, in scientific applications one operation requires more time than one instruction.* For purposes of across-the-board comparison, a reasonable average figure is: 2 Instructions per second = 1 Operation per second; 1.5 Additions per second = 1 Operation per second.

It should be noted that this method of comparison is too coarse for precisely judging the relative performance of two machines for purposes of deciding which one to acquire. However, when applied to the charting of secular technological trends, experience has shown that the method works quite well, provided that a sufficient variety of machine models is included in the comparison. The reason is that errors in assessing individual machine performance tend to cancel out statistically over the large population of machine models.

*That this is so can be seen from a simple consideration. Take for example the operation of addition. What the instructions must do is to cause the machine to fetch both addends from memory, then add them together, and finally to return the result to memory. In a single-address machine, for example, this requires typically a LOAD instruction, then an ADD, then a STORE. Three instructions per operation. In double and triple-address machines, one instruction suffices. (For example, ADD A to B and store in C are all performed from a single three-address instruction). However, the time it takes to perform an operation of addition, or multiplication, or worse yet, division, is generally longer than the time required to perform a logical operation such as STORE or MOVE. Again, the time required depends on whether the operation must be done with single or double precision. Double generally takes longer, depending upon the design of the machine.

The ways in which the speed of a machine is measured or estimated are:

1. To actually measure the time required to run a specific program. This is known as benchmark timing.
2. To test the machine against typical mixes of programs. Widely used is the Gibson Mix, whose composition is shown in Table 11.
3. To break the program in to its individual instructions in BAL (Basic Assembly Language); calculate the mix of instructions; go back to the machine specification sheet and determine the speed of each instruction; and finally determine the total speed. This is a rather laborious procedure if there are many different programs to be considered.
4. To take an average, based on the general characteristics of the program. For avionics and aerospace programs of guidance and fire control, a widely employed measure of speed is to take the average between 4 additions and one multiplication time and divide the total time by 5. The result is taken to be the time required per operation. This yields the speed of the machine, not in kips, but in a somewhat different measure, known as kops (operations per second rather than instructions per second).

The above definitions of internal performance are applicable for programs in which there is a lot of internal number manipulation, with little input/output load. If the I/O load is significant, the correct measure is that of throughput, which is always smaller than internal performance. The degradation between internal performance and throughput depends upon whether the input rate or the output rate exceeds the machine's internal performance. In most cases, the bottleneck arises from output rate.

An idea of why this happens can be had as follows. Assume first that the program requires a lot of printing. Assume then a typical high-speed printer of 1,500 lines/minute (25 lines/second). This means that every time the machine is required to print a line

<u>TABLE II</u>	
TYPICAL PROGRAM MIX FOR MEASURING/ COMPARING COMPUTER POWER (GIBSON MIX)	
<u>FUNCTION</u>	<u>WEIGHTING</u>
Fixed Point	
Add/Subtract	0.330
Multiply	0.006
Divide	0.002
Branch	0.065
Compare	0.040
Transfer 8 Characters	0.175
Shift	0.046
Logical	0.017
Modification	0.190
Floating Point	
Multiply	0.040
Add	0.073
Divide	0.016

(regardless of how full the line is), it consumes 1/25th of a second. For a hundred kip machine, this is equivalent to consuming a time lapse of 100,000 divided by 25 or 4,000 instructions.

It is clear that if the machine must continuously print, no matter how fast it is internally, the throughput cannot exceed the number of instructions required to generate one line.

The throughput in this case is calculable from knowledge of the printout format.

Likewise for the input: conventional magnetic tape can feed approximately 125,000 bytes/second. If each byte calls for n instructions, the machine is required to perform 125,000 times n ips. If the internal performance is slower than this, the machine will slow down.

For programs written in Fortran, a widely used assumption is that one Fortran statement is equivalent to between four and 10 BAL (Basic Assembly Language) instructions. This assumption suffers from the same inaccuracies discussed above. For example, DO loops may require tens and up to hundreds of instructions. To achieve greater precision, one should count the number of Fortran statements in the program and the corresponding numbers of BAL instructions pertaining to each statement.

6.3 Growth Trends in Computing Power

The principal criteria of merit of data-processing systems are:

1. Computing power. The speed at which the system performs computations.

2. Reliability or "up-time". The productivity ratio of the system; i.e., hours worked divided by total hours available.
3. Memory size. The maximum available memory.
4. Price/performance. The price of the data processing installation, divided by its computing power. This has been shown to have a definite relationship to machine power and year of entry into the market (Grosche's Law).
5. Software complement. Number and quality of programs supplied with the machine.
6. Compatibility. The ease with which the software can be applied to other models of the same manufacturer's line, or generally available on the market.
7. Growth. What next larger model is or will be available.
8. Technology. The type of circuits employed. This is an indicator of "modernity."

When attempting to forecast evolution, the most comprehensive indicator is computing power. The reason is simple. A high-power computer is only practical if: 1) its size is not unreasonably large, implying the existence of a technology of "reasonable" compactness (i.e. a 360/75 could never be built out of vacuum tubes) 2) its reliability is tolerable (implying a technology of sufficiently high circuit reliability so that ensembles of 50,000 to 100,000 circuits, typical of large machines, are still reasonably proficient); 3) memory size is at least minimally adequate for the problems the computer is designed to solve (too small a memory would reduce the computing power of the machine, thus rendering its development somewhat pointless); 4) the price is reasonable.

In conclusion, the indicator "computing power" contains much implicit information regarding the other indicators: technology, reliability, memory size, and price.

Figure 11 plots the internal performance, in operations per second, of the U.S. top-of-the-line general-purpose scientific machine as a function of the year of first installation.

The top-of-the-line is the set of the most powerful machines. It is indicative of the "best" hardware that it is practical to produce in any one era. In the U.S., under the stimulus of demand and of improving technology, the growth of the top-of-the-line, independent of manufacturer, has followed over the last 20 years the empirical relationship:

$$P = P_1 \times 2^{0.5} \times (t-t_1)$$

or

$$P/P_1 = (\sqrt{2})^{(t-t_1)}$$

where:

P = computing power in year t

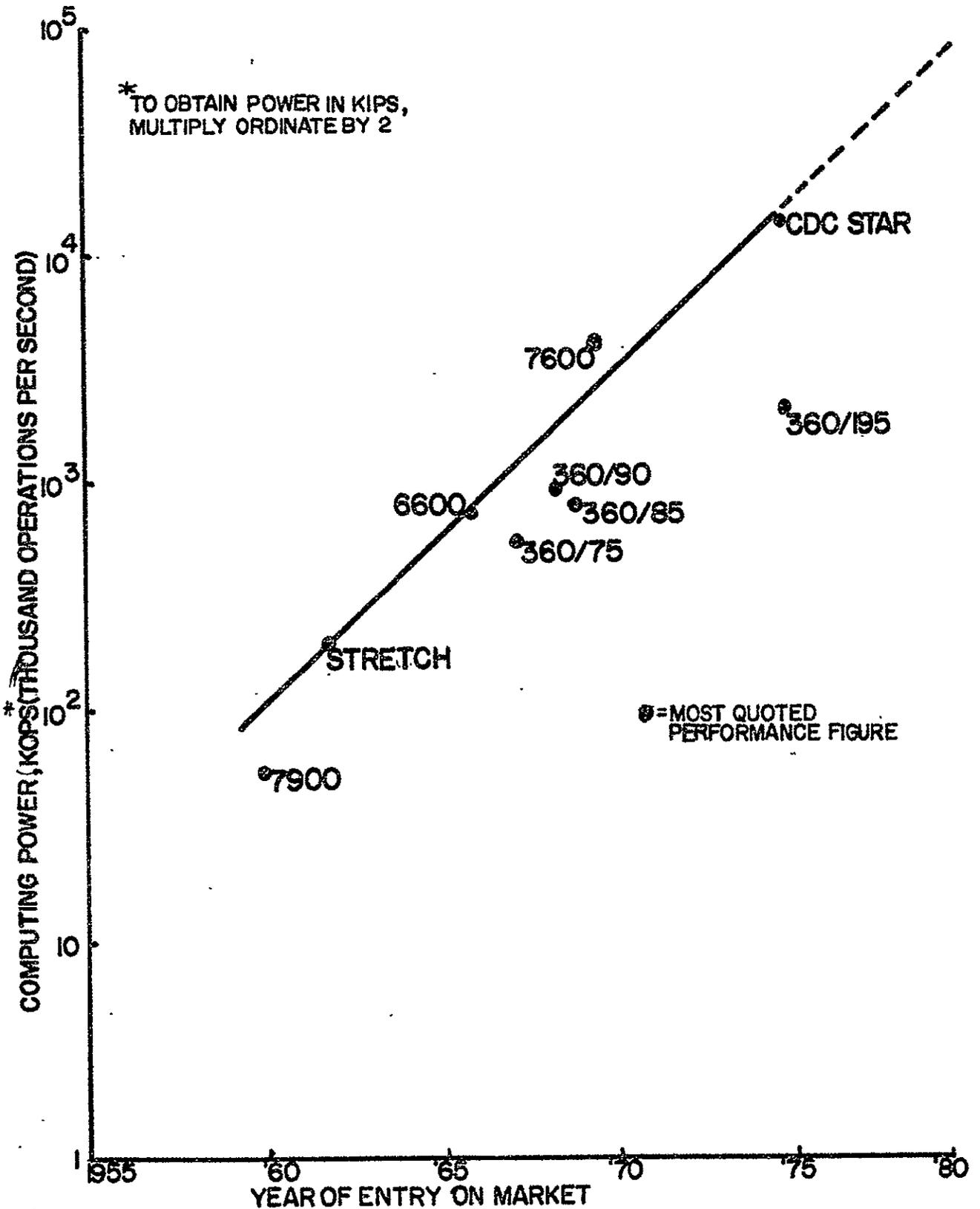
P_1 = computing power in year t_1

This says in essence that technological progress has grown at such a pace that the power of the fastest computers has doubled every two years.

It should be noted that this is a secular trend; it does not predict exactly when a specific growth machine will see the light, nor does it pinpoint the exact computing power of the most powerful machines within a given time frame.

FIGURE II

EVOLUTION OF U.S. SCIENTIFIC TOP-OF-THE-LINE COMPUTERS



As an interesting comparison, the trend for the USSR (the next major producer of big machines after the U.S.) is plotted in Figure 12. Note that the slopes (i.e. the growth exponents) are approximately the same for both nations.

As shall be seen in the next section, the cost of processing is least when the top-of-the-line (hereinafter referred to as TOL) is employed. Thus the computing power of the TOL is also an excellent indicator of data processing costs.

Of course, manufacturers do not confine themselves to producing the TOL class of machines. The region below the TOL is populated at any one time by several machines of lesser power, which span the gap between the TOL and the minicomputer class.

The U.S. machine population is well known. Representative elements most commonly used in hydrologic modeling are shown in Table 12. For comparison, Figure 13 depicts the USSR population of machines below the USSR-TOL level.

6.4 Data Processing Cost Trends

A universally used measure of the economic effectiveness of data processing equipment is price-performance, defined as the cost per instruction executed or the number of instructions executed per dollar.

The principal trends of interest in the evolution of computer economics are:

TABLE 12

REPRESENTATIVE US COMPUTERS MOST COMMONLY USED IN HYDROLOGIC MODELING				
NO.	COMPUTER	DATE OF ENTRY	MILLION \$/MIP	¢/MEGA-INSTRUCTION
1	CDC 6600	9/64	3/27	12.7
2	CDC 7600	1/69	1.15	4.5
3	IBM 360/65J	3/66	4.53	17.6
4	IBM 360/75J	11/65	3.36	13.1
5	IBM 360/91K	66	2.38	9.3
6	IBM 360/85L	9/69	3.08	12.0
7	IBM 360/85K	9/69	2.12	8.2
8	IBM 360/195L	2/71	1.58	6.1
9	IBM 370/165KJ	8/71	1.56	6.1
10	IBM 1130	66	10.02	39.0
11	IBM 360/30	65	5.14	20.0

FIGURE 12

EVOLUTION OF U.S.S.R. SCIENTIFIC TOP-OF-THE-LINE COMPUTERS

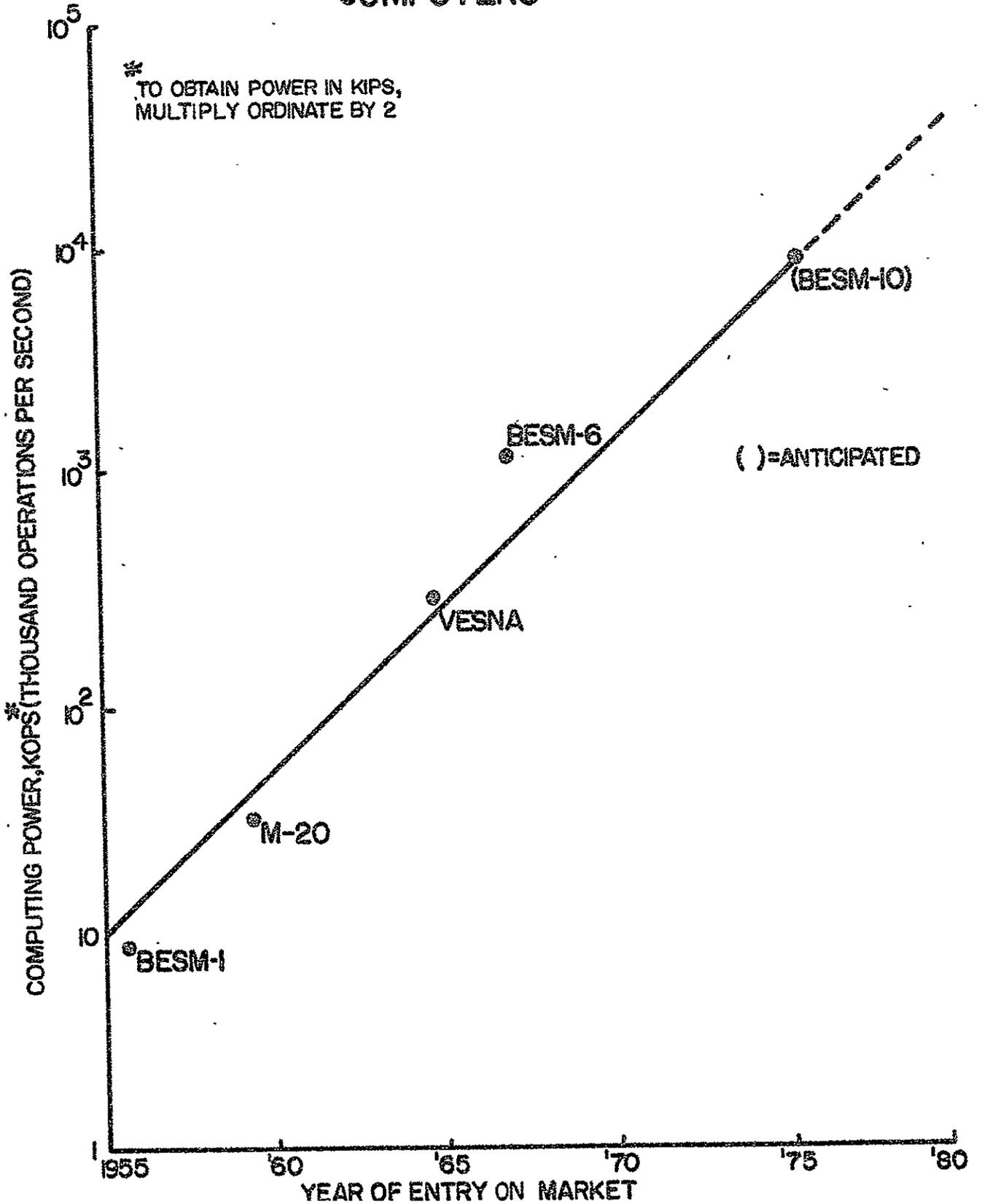
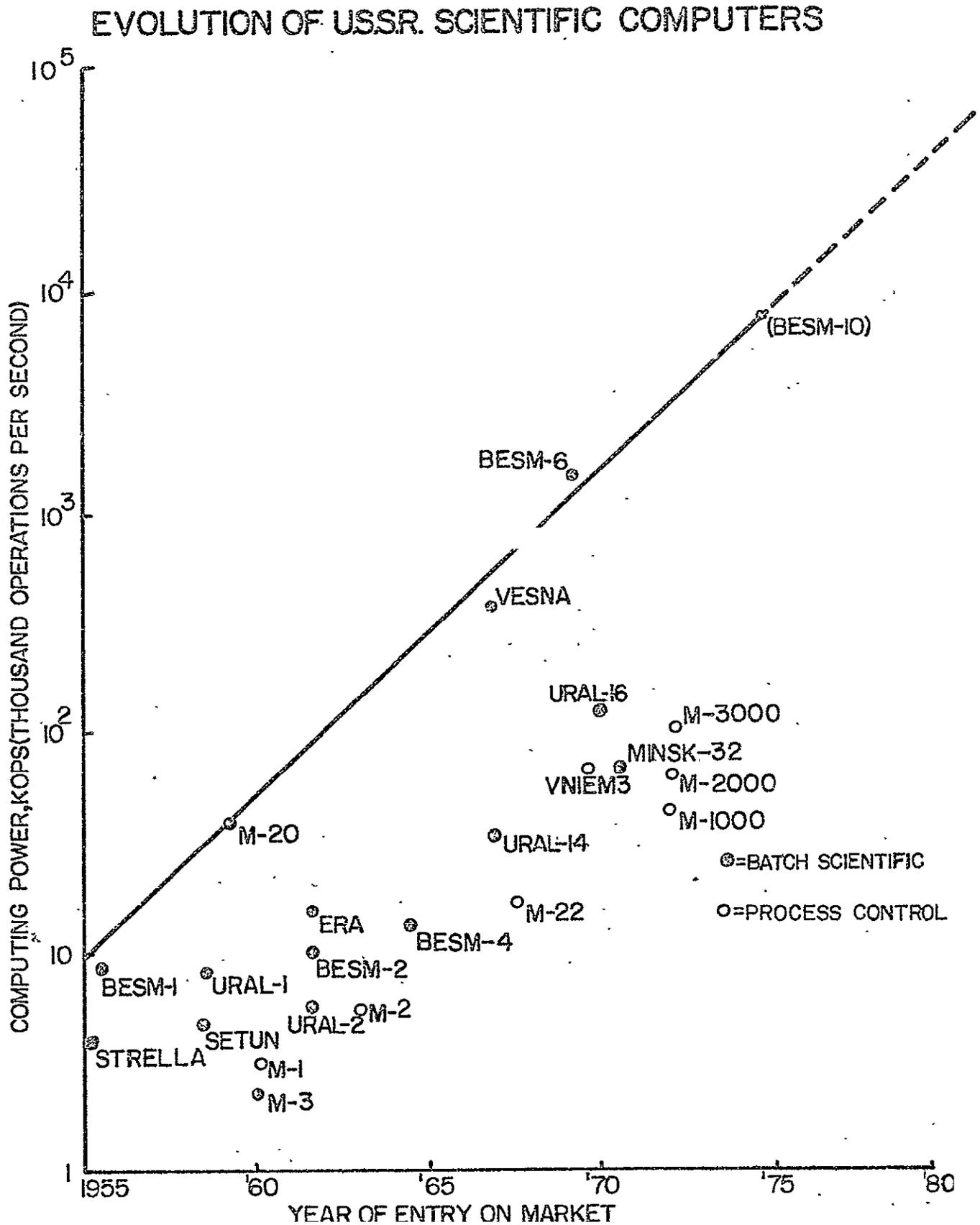


FIGURE 13



1. Grosche's law, which should be more properly referred to as Grosche's empirical relationship. It holds that, on the average and at any moment in time, the price of a computing machine is proportional to the square root of its computing power. This means that a high-priced machine performs more instructions per dollar than a smaller, lower-priced machine. As a typical example, the 360/195 complete system cost typically and approximately \$10 million at its point of entry into the market in 1970. Its average speed is 6 MIPS. In the same year the 360/65 system cost \$3 million. Its average speed is 0.65 MIPS. It can be seen that the ratio of speeds, $6/0.65 = 9$ is approximately the square of the prices: $10/3 = 3.3$. This relationship has proven valid in an approximate sense since the early 1950's. This means that the price-performance is better (more instructions per dollar, or less dollars per instruction) for large than for small machines. The obvious question is: why doesn't everybody use large machines? The answer is equally obvious: because they cannot afford the investment. As a matter of fact, some of the large users employ large machines for hydrologic processing, sharing this application with many others. The small user does not have that many other applications to warrant acquisition of large computers.
2. The law of the TOL, which again is not a law, but a historical trend which has held since the early 1950's. It states that the TOL (i.e. the largest machine which enters the market) increases in power by $\sqrt{2}$ every year. In other words, computer power doubles every second year.
3. The combination of these two relationships indicates that the cost of the TOL remains constant. In fact, since the early 1950's, the cost of the most powerful machine purchasable at any one time has remained at the approximate level of \$10 million.
4. The historical cost decrease. On the average, the price for equal computing power (MIPS) decreases by a factor of 0.8 every year.

$$P = P_0 (0.8)^{(t-t_0)}$$

where:

P_0 = price in year t_0

P = price in year t

Combining Grosche's law (1) with the historical cost decrease (4) shows that the price-performance with time of any machine can approximately be expressed as:

$$C = C_0 \sqrt{\frac{P_0}{P}} (0.8)^{(t-t_0)}$$

where:

C = price of machine of power P at future time t

C₀ = price of the TOL machine at time t₀

P₀ = power of TOL machine at time t₀

Note that the above are simply historical trends, which have been observed in retrospect over the last 25 years. Nothing guarantees that they will hold in the future; recent trends indicate some departure from these "laws" in the growth of the TOL. For example, extrapolation of the TOL trend to 1975 indicates that this year there should appear a commercial machine capable of approximately 120 MIPS. No such computer is available. To be sure, IBM was planning a 100-MIP machine for this time frame but this was discontinued. ARPA was at one time planning a 200-MIP plus version of the ILLIAC IV, approximately due in 1976 or 1977. The effort, however, has been slowed down.

The reason why the TOL trend is slowing down is that TOL machines, since the days of ENIAC, have been motivated by the Government market, fulfilling such requirements as weather forecasting, nuclear effects, and ballistic missile defense. Commercial requirements are primarily in seismic exploration. Under present conditions, the market is small and aleatory. Thus, commercial manufacturers prefer to invest their resources in the smaller and more saleable machines. It is difficult to foretell whether the TOL trend will change in the next several years. However, the growth of the second-and-third echelon machines below the TOL still appears to follow the "doubling-every-two-years" trend. It should further be noted that these trends hold only when averaged over the entire U.S. market. They do not imply that any one manufacturer will automatically enter the market, year after year, with machines exactly obeying the general trend. In fact, individual manufacturers tend to produce "generations" of machines, which remain constant over several years. Competition between manufacturers causes the various generations to interleave in time. Various other economic trends have been observed, more general and softer than those previously reported.

5. The migration trend, which can also be stated as an aspect of Parkinson's "law:" work expands to fill the computer, or, stated more pessimistically, "computers never save money." What this means is that, even though a computer is often purchased for the specific objective of saving labor in a defined operation, such as payroll or modeling, its availability unavoidably causes the user to try things never tried before. Thus, the original intended use expands into ever more sophisticated uses not contemplated at the time of purchase. The ever-expanding requirements, coupled with the historical reduction of price motivate the user to periodically acquire a more powerful machine. Thus, the user's computing power tends to "migrate" upwards. At the same time, the complexity of the application also migrates upwards.

The consequences of this trend for hydrologic modeling and possibly for image data processing, are that models and processing algorithms tend to grow apace with the expanding power of the machines. This trend is charted in the next section.

6. The size of fast available memory, for a given price level, grows with computing power. No hard and fast rules exactly quantify this growth, particularly since many users do not employ the maximum available memory for a given machine. A gross relationship is that the largest available memory grows as the cube root of computer power.
7. Hardware-software mix: In the early fifties, hardware costs represented the major share of data processing costs. Since then, the combination of decreasing hardware costs and increasing programming sophistication and programmer wages have shifted the hardware-software mix towards the fifty-fifty point. Forecasts for the future vary. For large, complex systems, by 1980 the software is expected to constitute 80% of the data processing costs. More significant for hydrologic applications is the forecast for all systems shown in Figure 14, which indicates a renewed climb of the hardware costs, mostly due to the expansion of peripheral equipment.
8. The trend towards increased peripherals is depicted in Figure 15. It is induced by increasing emphasis upon interactive systems, increased use of computers as communications switching and input-output devices, use of large buffer memories, and expanding employment of time-shared systems.

TABLE 13

PROFILE OF USERS OF COMPUTERS FOR HYDROLOGIC PURPOSES							
DESCRIPTION	SCOPE	PERSONNEL COMPLEMENT	COMPUTER COMPLEMENT	PROGRAM SIZE (NUMBER OF FORTRAN STMTS)	POTENTIAL DIRECT R/S INPUT	POTENTIAL DIRECT DCP DATA INPUT	COMMENTS
1 - SMALL GENERALIST <ul style="list-style-type: none"> CIVIL ENG. CONSULTANTS EX: W. T. BALLARD 	<ul style="list-style-type: none"> SMALL SCALE HYDRAULIC STRUCTURES DESIGN SOIL SURVEYS DRAINAGE DESIGN 	<ul style="list-style-type: none"> ENGINEER WITH LIMITED PROGRAMMING CAPABILITY 	<ul style="list-style-type: none"> TERMINAL TO TIME SHARED SMALL - MED. COMPUTERS MINICOMPUTERS (PDP 12) 	$10^2 - 10^3$	---	---	DATA COLLECTED FROM LARGER CATEGORIES WILL EVENTUALLY FILTRATE THIS LEVEL.
2 - SMALL SPECIALIST LG. CIVIL ENGINEERS EX: MATHIAS REUSCHERT, PASCOE BRUNSWICK, UNIVERSITIES	<ul style="list-style-type: none"> HIGHWAY PROJECTS URBAN/REGIONAL PUBLIC WORKS USE WATERSHED MODELS DEVELOPED BY OTHER AGENCIES 	<ul style="list-style-type: none"> ENGINEERS WITH LIMITED PROGRAMMING CAPABILITY PROGRAMMING SPECIALISTS IN LARGER ORGANIZATIONS HYDROLOGY SECTIONS 	<ul style="list-style-type: none"> TERMINALS TO MED. TIME SHARE MINI - MED. COMPUTERS (IBM 1130) 	$10^2 - 10^3$	<ul style="list-style-type: none"> ANALYSIS OF PARTIAL DATA FRAMES PICTORIAL FOR HYDROLOGIC LAND USE INFORMATION 	---	WILL POTENTIALLY BE A MARKET FOR UP-TO-DATE INFORMATION ON SMALL HYDROLOGIC AREAL UNITS.
3 - LARGE LOCAL SPECIALIST <ul style="list-style-type: none"> POWER COS. HYDROCOMP WRG WATER RES. INST. STATES 	<ul style="list-style-type: none"> REGIONAL/SUB REGIONAL MODELING ENVIRONMENTAL IMPACT RESPONSE PARAMETRIC MODELING OF WATERSHED RESPONSE 	<ul style="list-style-type: none"> PROGRAMMING SPECIALISTS HYDROLOGIC DATA/MODELING SPECIALISTS 	<ul style="list-style-type: none"> TIME SHARING OF MED - LG. COMPUTERS (IBM 350-20, 50) 24-HOUR COMPUTERS OPERATED MULTI-MED ANALOG DIGITAL DATA COLLECTION NET 	$10^2 - 10^4$	<ul style="list-style-type: none"> NEW DATA STREAMS FOR PLANNING PARAMETRIC MODELS (EXISTING) INPUTS FOR NEW PLANNING PARAMETRIC MODELS WATERSHED DATA UPDATES FOR HYDROLOGIC LAND-USE DATA 	---	LARGEST IMPACT ON PLANNING AND MANAGEMENT OPS
4 - LARGE REGIONAL SPECIALISTS <ul style="list-style-type: none"> MID ATLANTIC REG., COE TVA USGS REG. OFFICE STATE WATER RES. AGENCIES REG. POWER ADMIN. 	<ul style="list-style-type: none"> LARGE PUBLIC WORK DESIGN/CONSTRUCTIONS COMPILATION OF REGIONAL HYDROLOGIC STATISTICS REAL TIME DATA COLLECTION REAL TIME OPERATIONS 	<ul style="list-style-type: none"> SAVE AS ABOVE 	<ul style="list-style-type: none"> LINKED TO LG. SCALE COMPUTER NETS 24-HOUR COMPUTERS-MED ANALOG DIGITAL DATA COLLECTION (IBM 360, 370) 	$10^2 - 10^4$	"SAME AS FOR ITEM 3"	"SAME AS ITEM 3"	LARGEST IMPACT OF MODEL DEVELOPMENT
5 - FEDERAL AGENCIES <ul style="list-style-type: none"> REC. OPE INDRSCS 	<ul style="list-style-type: none"> HYDROLOGIC MODEL DEVELOPMENT TRAINING CENTER OPS MULTI-BASIN DEVELOPMENT 	<ul style="list-style-type: none"> PROGRAMMERS STAFF HYDROLOGIC DATA/MODELING SPECIALISTS OPERATION/TRAINING CENTER 	<ul style="list-style-type: none"> MULTIPLE MED. SCALE COMPUTERS (IBM 360, 70) OPERATE COMPUTER NETS 	$10^3 - 10^4$	"SAME AS ITEM 3"	LOW IMPACT GENERALLY HANDLED AT REGIONAL LEVEL.	LARGEST IMPACT OF MODEL DEVELOPMENT

ORIGINAL PAGE IS OF POOR QUALITY

FIGURE 14

HARDWARE/SOFTWARE COST TRENDS FOR COMMERCIAL COMPUTERS

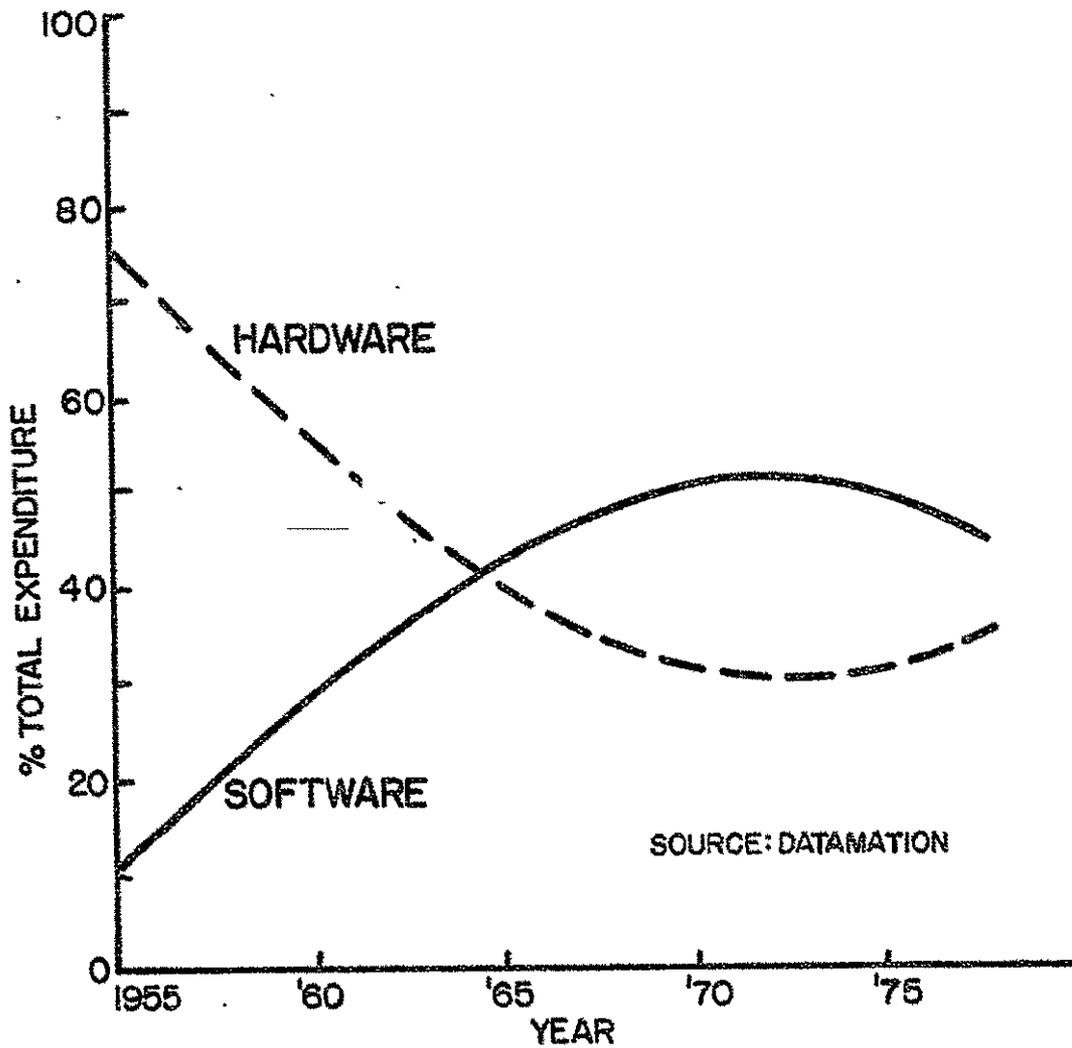
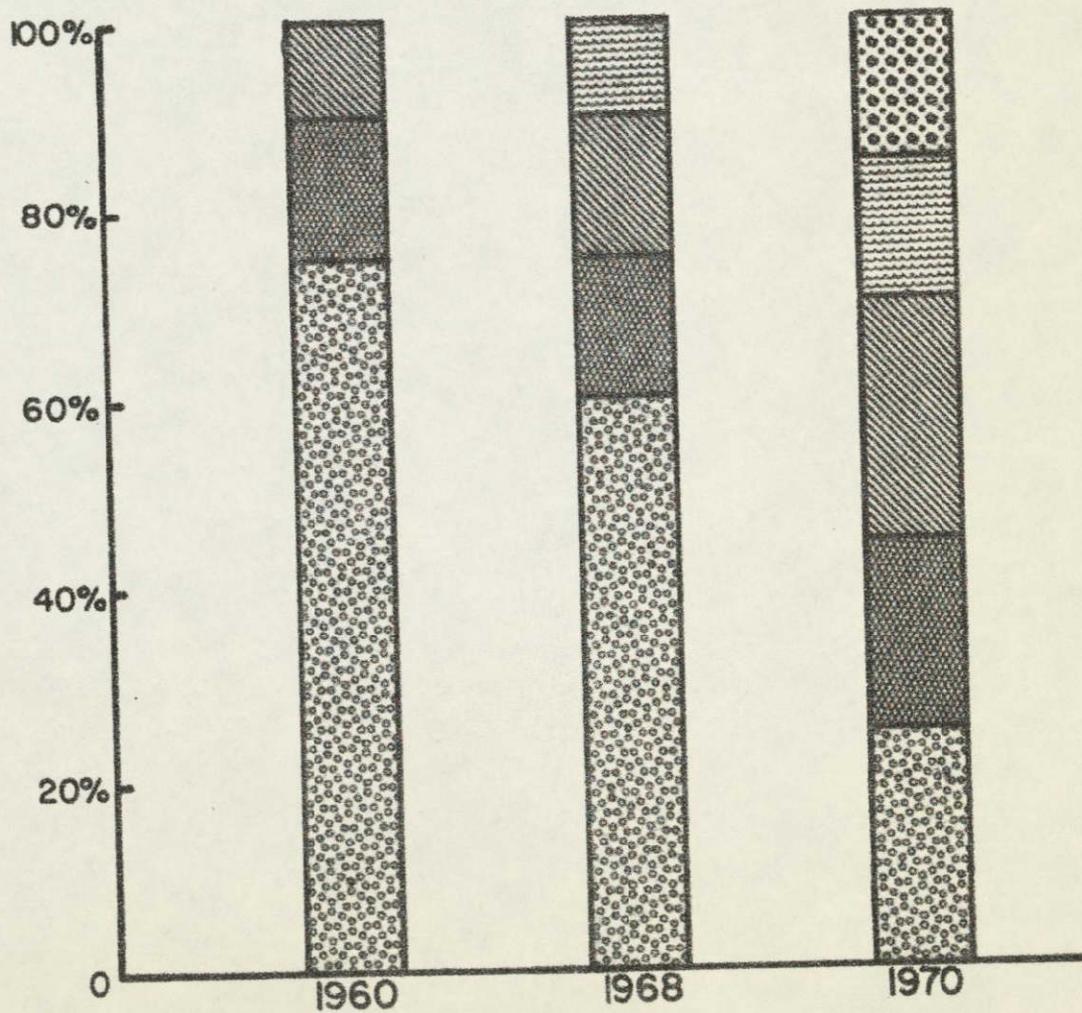


FIGURE 15

COMPUTER COST COMPOSITION

SOURCE: OECD

-  = CPU
-  = ALPHA-NUMERIC FILE MEMORY
-  = I-O
-  = DATA TRANSMISSION
-  = VIDEO FILE STORAGE/PROCESSING



9. The decreasing hardware costs have prompted the increase of minicomputers, wherein the term mini is strictly relative to the larger machines. The power of many current minis is equal to or larger than that of the top-of-the-line of the mid-fifties. The growth trend for minis is shown in Figure 16.

Note the large increase forecasted for data logging, switching and acquisition functions, and for process control (real-time) functions. The increase forecasted for scientific applications such as hydrologic modeling is, however, modest.

Figure 17 synthesizes the historical trend of computing costs. The parallel straight-line boundaries in the figure indicate the range of computing power, which has been employed for the more sophisticated hydrologic models (mostly processed on a shared basis). Items 11 and 12 in Figure 17 are small computers, which have been used in simpler hydrologic models. In particular, the IBM 1130 has found relatively wide application for river forecasting in the NOAA (formerly ESSA) organization.

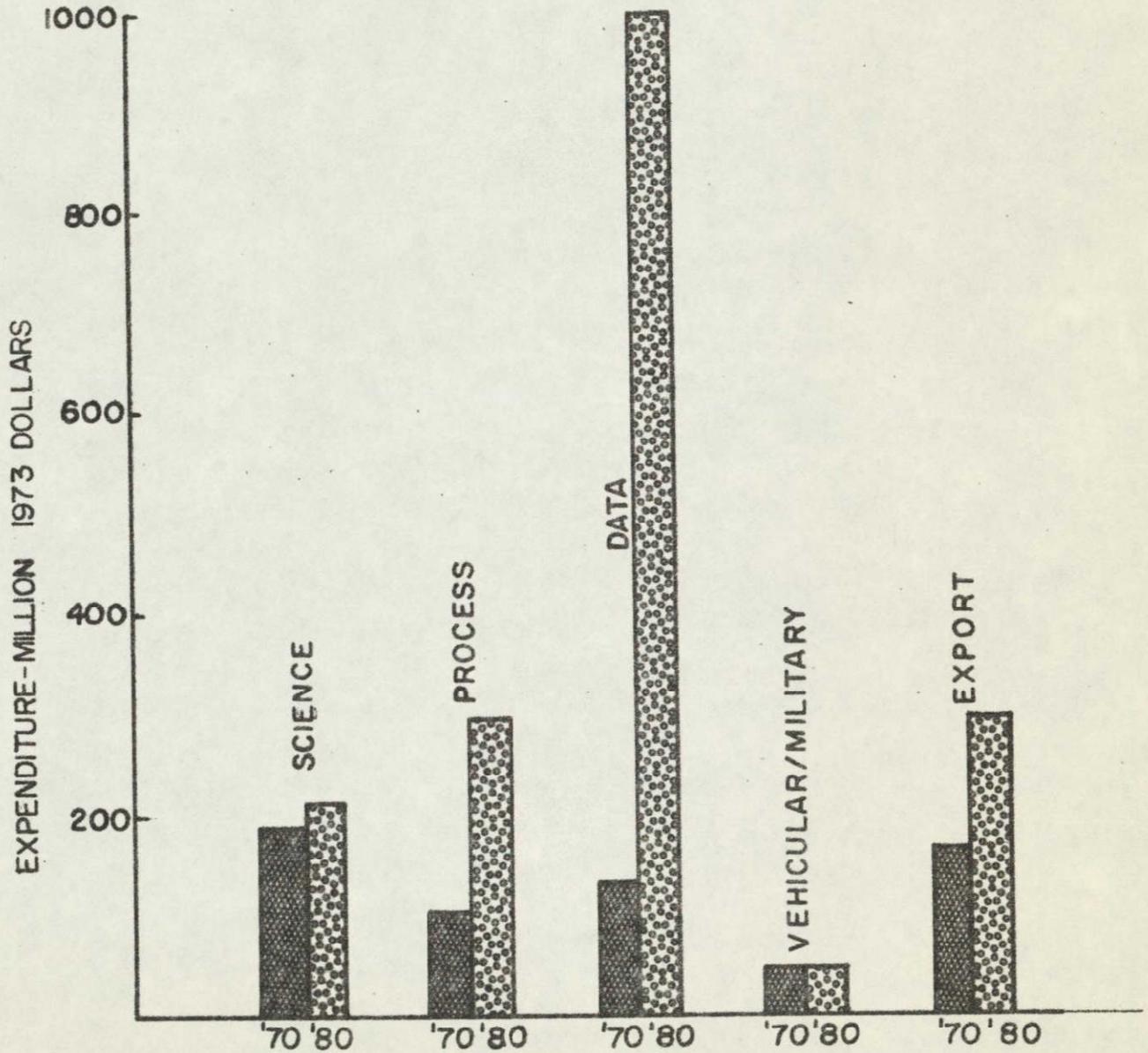
We can conclude that by 1980, if the historical trend experienced over the last two and a half decades continues, barring inflationary distortions, the cost of processing should come down to between one and five cents per million instructions.

As a final note, it must be remembered that Figure 17 reflects the processing costs only. To these must be added the costs of readying the data for computer usage, plus the costs of developing the software.

The cost of readying the data involves the standard functions of aerial photo interpretation, digitization of rain and stream-flow records, measurement of streamlengths and other parameters

FIGURE 16

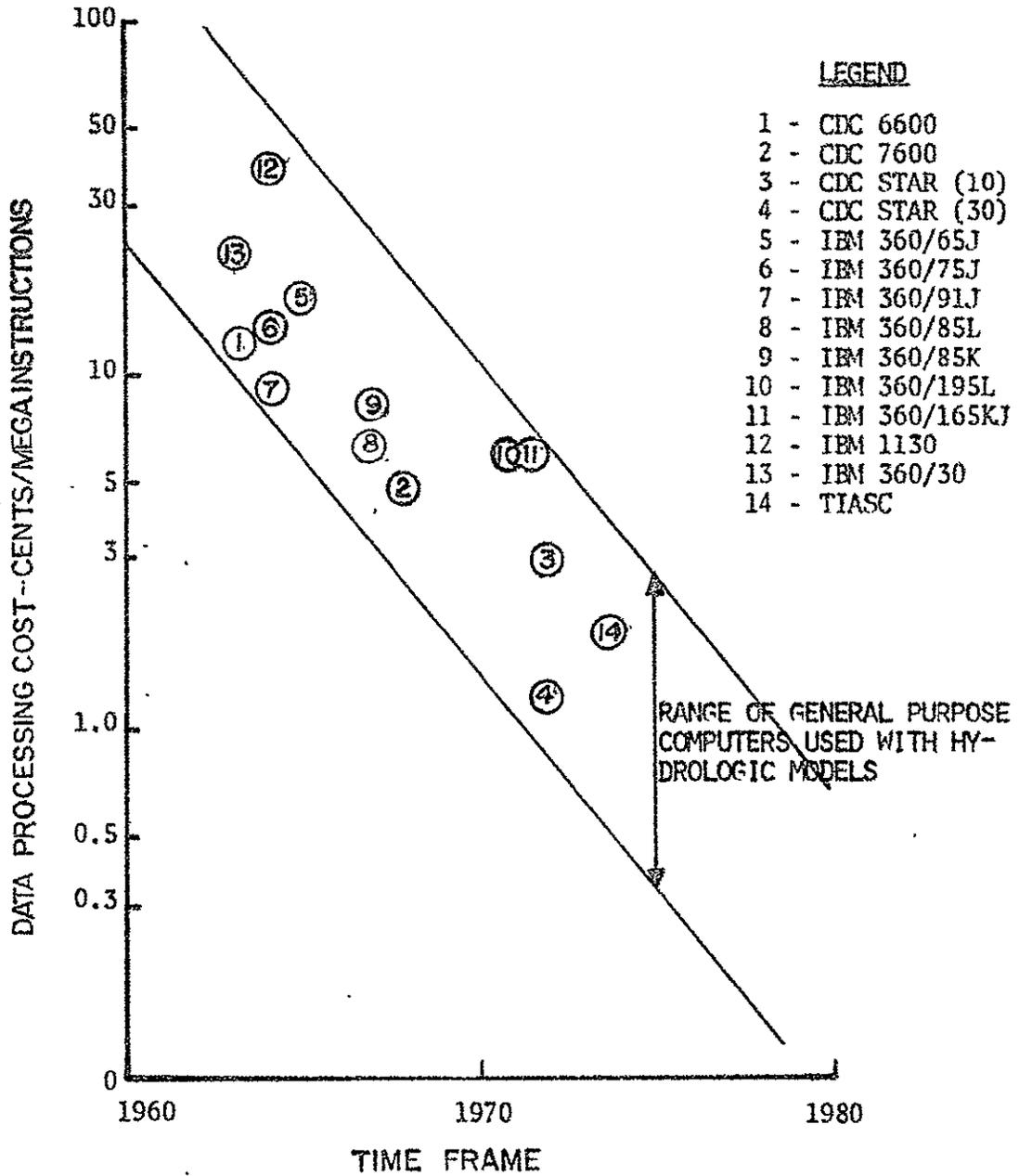
PREDICTED GROWTH OF MINICOMPUTERS 1970/1980



SOURCE: DATAMATION

FIGURE 17

COMPUTER OPERATION COST TREND



of interest from maps, aerial photos or ERTS imagery.

The costs of data preparation by manual means is not estimated here. The cost of automated data interpretation from ERTS-derived computer-compatible tapes is presented in a subsequent section.

The cost of developing the software is generally high. For this reason, by and large only Federal Agencies and some of the larger and wealthier States have performed this function and will in all probability continue to do so. The intermediate and small users will continue to employ standard, already developed software. Since hydrologic models are mostly developed on U.S. Government funds, they are public property and, therefore, their cost to users is essentially nil.

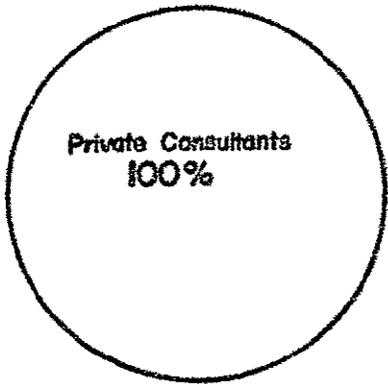
In summary, the cost of processing the hydrologic models, shown in this section, plus the costs of automated interpretation of ERTS imagery presented in a subsequent section, are good indicators of the impact of remote sensing upon hydrology users.

6.5 Data Processing Load and Growth Trends for Processing Hydro-logic Models

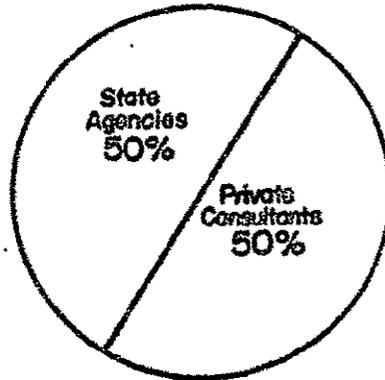
The information gathered from the survey is synthesized in Table 13 into profiles by distinct classes of users of hydrologic models. Figure 18 schematizes the relation between the type of user (e.g. Federal, State, etc.) and the user's functions. Note the ascension of the computing power available to the users: the power of the available machines increases with the size of the user. Similarly,

FIGURE 18

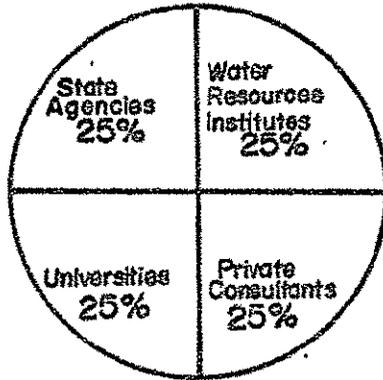
PROFILE OF USERS OF COMPUTERS FOR HYDROLOGIC PURPOSES



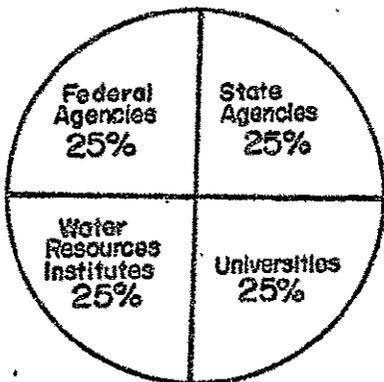
Small Generalists



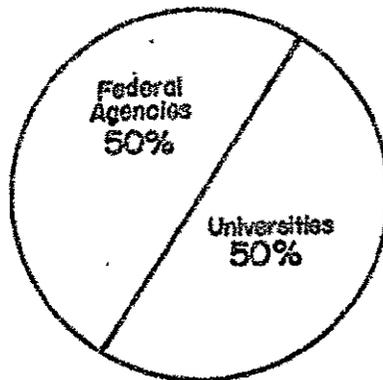
Small Specialists/Large Civil Engineers



Large Local Specialists



Large Regional Specialists



Multi-Regional

the magnitude of the hydrologic program grows with the size of the user. Note that the program sizes are given in terms of Fortran statements; this number must be multiplied by a factor of four and up to ten to obtain the program size in terms of BAL instructions.

In practice, to obtain the hydrologic behavior of a watershed, each program is run not just once, but several times, to allow for calibration, setting of constants, statistical checks, and so forth. Thus, a good overall measure of the program's length is the total number of BAL instructions required to perform a complete set. This number equals the number of BAL program instructions times the number of runs, plus the overhead required to set up and calibrate. The information gathered during the previous reporting period was collated to assess the trend of growth of hydrologic models. The results are depicted in Figures 19 and 20. Note that program load grows versus time. This is not surprising since it simply confirms the trend of expanding use (a form of Parkinson's law) indicated in the previous section. The last point on the curve of the figures is an estimation of the program load required by evolution of current hydrological programs towards the direction of microhydrology.

The above evolutionary trend applies to rainfall-runoff models. The additional load imposed by advanced applications, such as soil moisture accounting, will also be interesting to evaluate. The commonality across the users of the principal models derived

FIGURE 19

EVOLUTION OF COMPUTER REQUIREMENTS FOR HYDROLOGIC MODELS

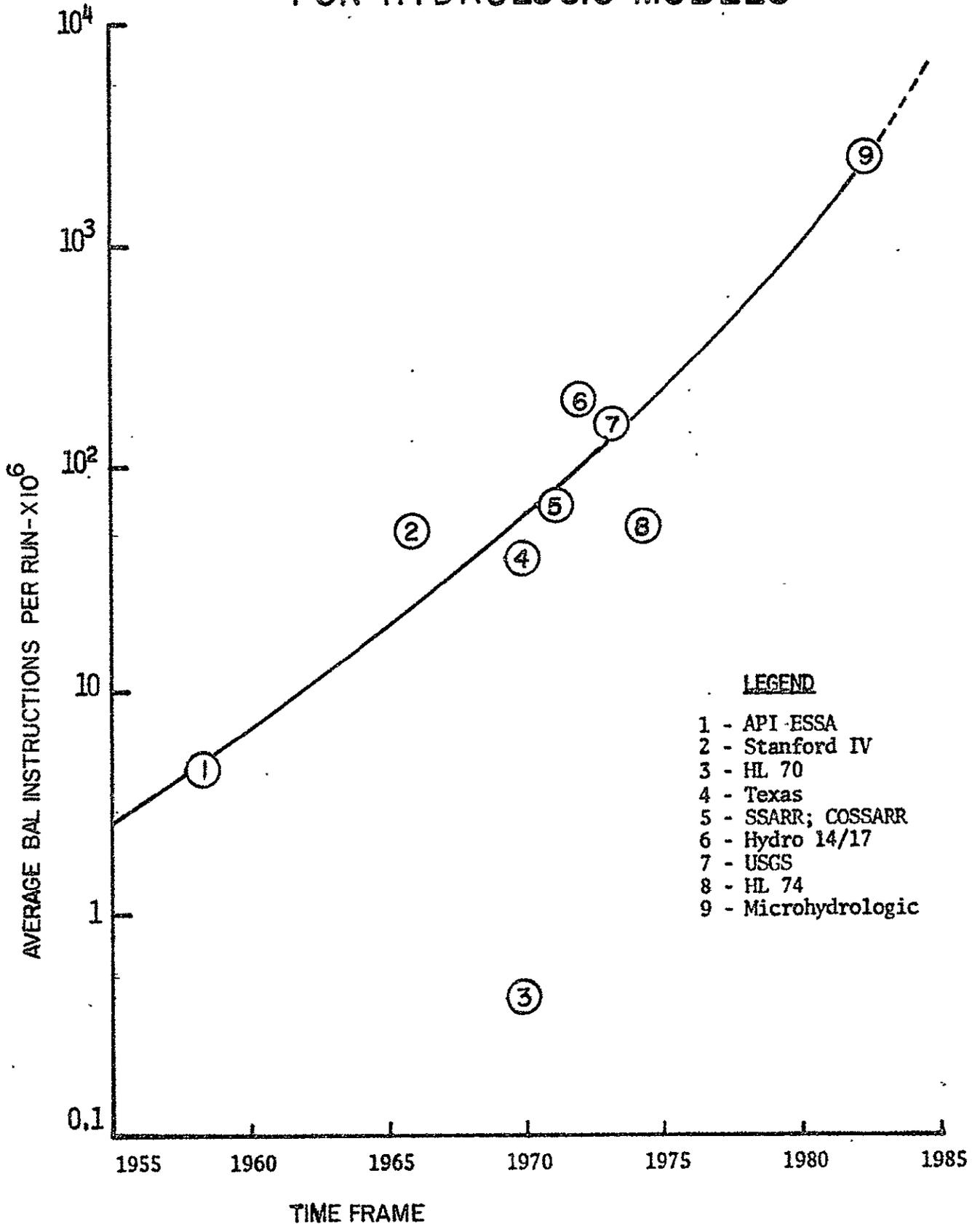
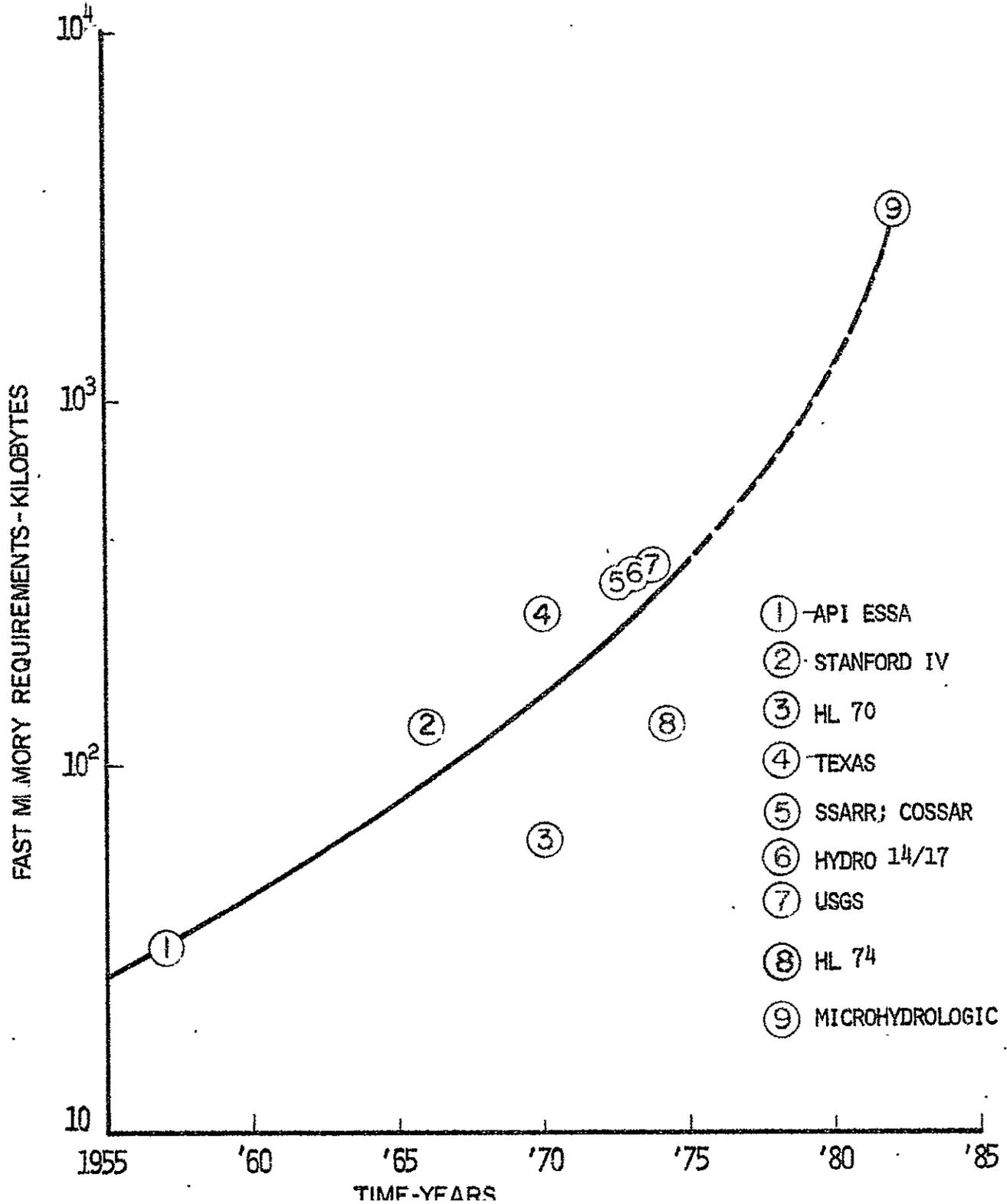


FIGURE 20

EVOLUTION OF COMPUTER REQUIREMENTS FOR HYDROLOGIC MODELS



from the sample responses is indicated in Figure 10, presented previously.

The computer requirements and characteristics of the major models are given in Table 14. Total Federal water resources data processing capacity in 1974 was approximately 30 million instructions per second. Analysis of the agencies making up the user community sample, shown in Appendix L, leads to three conclusions:

1. Federal computer hardware represents the largest share of DP equipment devoted to water resources.
2. These computers typically are not dedicated exclusively to water resources but are shared with other agency functions.
3. All but one of the agencies considered depend completely upon their own computer resources and do not contract out data processing work.

TABLE 17

COMPUTER CHARACTERISTICS OF HYDROLOGIC MODELS					
MODEL NAME	BASIN SIZE	COMPUTER	ASSUMPTIONS	CORE STORAGE REQUIREMENTS	COMPUTER TIME USED
USDA HL-70/74	<100 mi. ²	IBM 360/30	For agricultural watersheds. Divide basin into uplands, hillsides and bottom land zones. One year simulation. Includes rain, temperature, soils, and crop data.	98K	19 sec. (compile) CPU
		IBM 360/65			1.5 min. compile time; 1 min. CPU/year simulation
U.S.G.S. Rainfall-Run-off Model	< 50 mi. ²	IBM 360/65	Uses 5 yr. records of rainfall, ET, and discharge. Stage determined from 10 parameters which are calibrated through 10 iterations per parameter.	420K	35 sec. (compile) CPU; 180 sec.--execution time
Stanford Watershed Model (& modifications)		IBM 360/75	One year simulation from precipitation input. 16 parameters are calibrated through iterative process.	150K	35 sec. CPU
Hydro 14		CDC 6600	Models 14 days data including 10 snow-pack or soil moisture accounting areas with 10 streamflow nodes, 5 upstream inflow points, 3 pe. stations	29K	10 sec. CPU
SSARR		IBM 360/50	Thirty and sixty day, daily simulation of flows on a 100 node basin.	150K	480 sec. execution time (30 days)
COSSARR	> 11 mi. ² usually very large basins	IBM 1130		80K	900 sec. execution (60 days)
SCS-TR20		IBM 360-370		210K	1080-1200 sec. run time

TABLE 14 (Cont)

COMPUTER CHARACTERISTICS OF HYDROLOGIC MODELS					
MODEL NAME	BASIN SIZE	COMPUTER	ASSUMPTIONS	CORE STORAGE REQUIREMENTS	COMPUTER TIME USED
U.S.A. Corps of Engineers					
HEC-1		Large Dig.		32K	
HEC-2		Large Dig.		60K	
HEC-3		Medium to Large Dig.		60K	
HEC-4		Medium to Large Dig.		60K	
HEC-5		Medium to Large Dig.		60K	
Chicago (N.E.R.O.)	Small Urban watersheds	IBM 1130	25 Drainage areas modeled	8K	600 sec.
			1000 Drainage areas modeled		7200 sec.-include print-out time
MIT		IBM 360/65	Uses probability distributions of distribution, depth, duration and time between storms		10 sec. CPU 1500 sec. - (1 yr. execution time)

7.0 DATA PROCESSING LOAD FOR PROCESSING ERTS IMAGERY

With present state-of-the-art algorithms, the number of instructions required to assign each pixel to a class is approximately 1,000 per band. Complete pixel-by-pixel processing of one ERTS frame (3.5 million hectares), in four bands, requires approximately $4 \times 9 \times 10^6 \times 1,000 = 36 \times 10^9$, or 36 billion instructions (since one ERTS frame contains approximately 9 million pixels). In addition, some overhead must be added for training of the computer, and for the operating system. Further overhead is required for special processing functions such as border recognition. A reasonable rule-of-thumb for the overhead required for these functions (sophisticated processing) is a factor of two.

To give a feel for these numbers, consider the time required to process an ERTS frame in four bands on a large machine, the IBM 360/75: 10 hours without overhead, 20 hours with sophisticated processing.

To completely pixel-by-pixel process an area of 1,000 hectares, simple computations show that the number of instructions required is:

Without overhead: 9 million instructions

With overhead: 18 million instructions

The equivalent 360/75 processing times required are:

Without overhead: 8 to 10 seconds

With overhead: 16 to 20 seconds

The processing time for 1,000 hectares can serve as the basis for judging the processing time for watersheds. An approximate area

distribution of watersheds of importance to State and local users is shown in Figure 21. It indicates that the median watershed area is 10,000 hectares, ranking up to a maximum size of order 50,000 hectares. Watersheds of interest to Federal users range much higher.

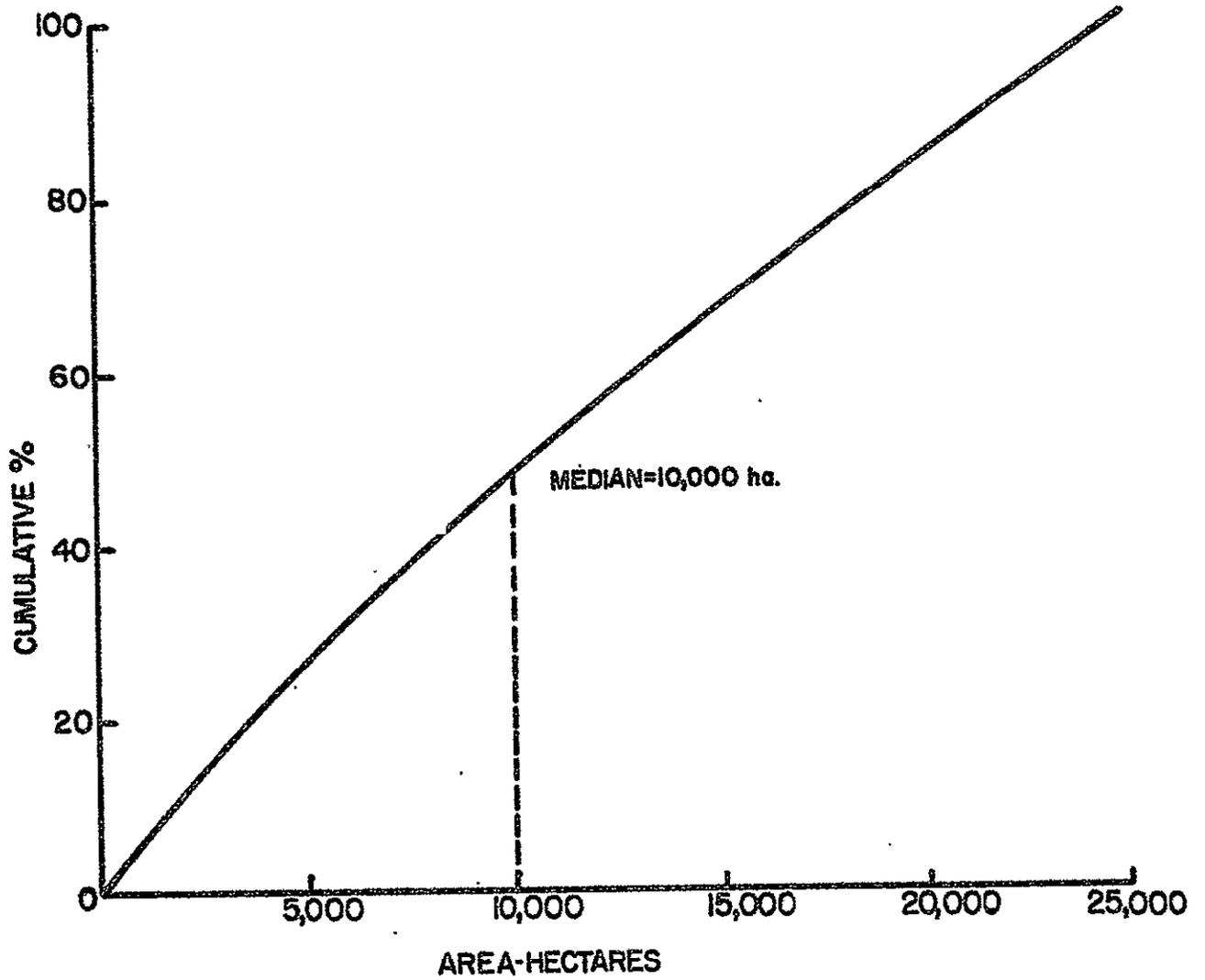
Since pixel processing is a highly repetitive procedure, it lends itself to so-called vector processing, or preprocessing. A pre-processor is a hard-wired (or microprogrammed) machine, which can be configured to perform sequences of the same operation at high speeds.

To illustrate, an add operation requires anywhere from three to five sequential elementary operations, known as stages. The exact number of stages depends upon the designer's option and the desired cost/performance. Each stage can be performed in a time commensurate with the switching time of the switching circuits. This time is approximately 10 nanoseconds for true and tried low-cost technology, and 3.5 nanoseconds for operational but costlier technology. Circuits can now be purchased, albeit at higher cost, with stage times as low as 2 nanoseconds. This means that a five-stage add can be performed currently in 50 nanoseconds with low-cost, 17.5 with medium-cost, and as low as 10 nanoseconds with high cost technology.

If, however, the program contains a string of adds, the second add can enter the multi-stage adder as soon as the first add has completed and cleared the first stage. This technique, known as pipelining, can cut the processing time down to the switching time of

FIGURE 21

APPROXIMATE AREA DISTRIBUTION OF WATERSHEDS OF IMPORTANCE TO STATE AND LOCAL USERS



one stage.

Thus, for add operations a preprocessor can achieve speeds of 100 MIPS for low, 300 MIPS for medium, and 500 MIPS for high-cost technology. A multiply requires from five to ten stages, a divide up to 30. Either can use the pipelining technique. It is clear that the average speed of a preprocessor will be a function of the "information entropy" of the program; the greater the number of elementary operations that can be arranged in sequence and pipelined, the higher the effective speed. The preprocessor output is buffered and fed as a summary to the general processor, which only performs the "synthesis operations." By this means, image analysis by a general-purpose computer can be speeded up.

It is obvious that the preprocessor is most effective when used in conjunction with the slower machines. For example, a 100-MIP preprocessor would do little good on a 100-MIP machine. Typically, on a 1-MIP machine such as the 360/75, a state-of-the-art preprocessor can cut the image processing time by a factor of approximately 40, thus reducing the time to process one ERTS frame from 10 hours to 15 minutes for simple processing, 30 minutes for sophisticated processing.

For very small machines, the preprocessor is also of limited velocity, because it has to "wait" for the machine to catch up after each batch of preprocessed instructions is fed to it.

The cost of preprocessing is expected to drop with time but not in step with the historical drop in data processing costs illustrated previously. The reason is that preprocessors are special-

ized devices, with far more limited market than general-purpose computers.

Figure 22 depicts the cost of processing ERTS computer-compatible tapes for hydrologic purposes on general-purpose computers for 1,000 hectares of watershed, under the following alternate conditions: 1) pixel by pixel classification; and 2) sophisticated processing.

An important consideration, whose impact will be considered in the last section, is the acquisition cost of computer compatible tapes (CCT). This cost is currently approximately \$225 per complete ERTS scene in four bands; it is expected to drop to \$100 by mid-1975, and to an estimated \$50 by 1980. Note that at present CCT's are sold only on a per-scene basis.

The cost trends shown in Figure 22 apply to "current" machines, i.e. computers of the latest models, whether large or small. Shown for comparison is also the cost situation for the smaller users, who utilize older machines. Note that the processing costs for the older machines are considerably higher, because their processing speeds are slow and the rental prices do not decrease in proportion to age. For example, the 360/30, which is now approaching 10 years of age since first entry to market, is still used rather widely for hydrologic modeling by small users.

Figure 23 depicts the processing costs achievable by addition of a typical preprocessor. The assumption made is that current commercially-available preprocessors have speeds of 100 MIPS equivalent; those of 1980, 280 MIPS; those of 1985, 500 MIPS. Although

FIGURE 22

**ERTS CCT-IMAGE PROCESSING COST
(WITHOUT PREPROCESSOR)**

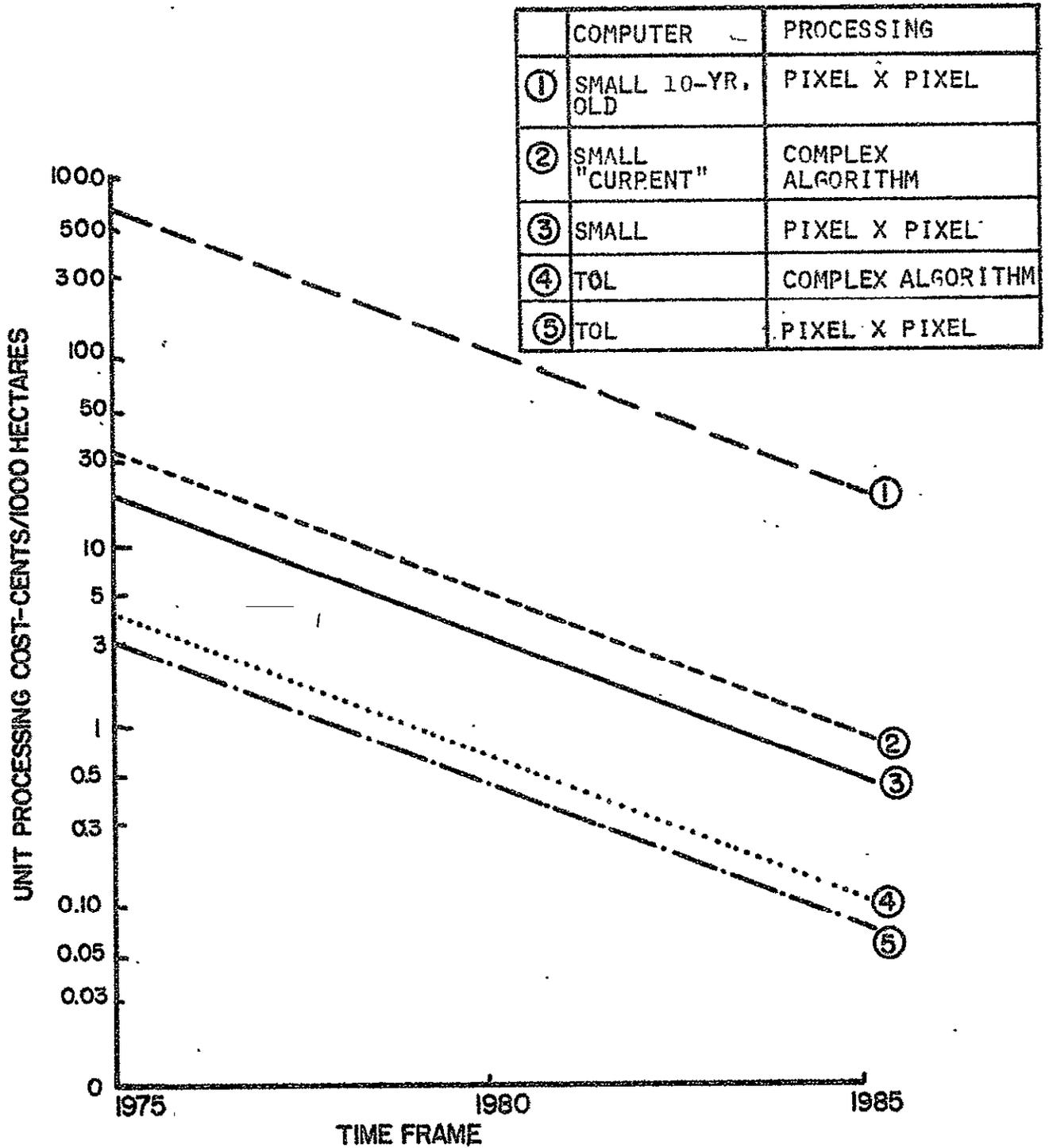
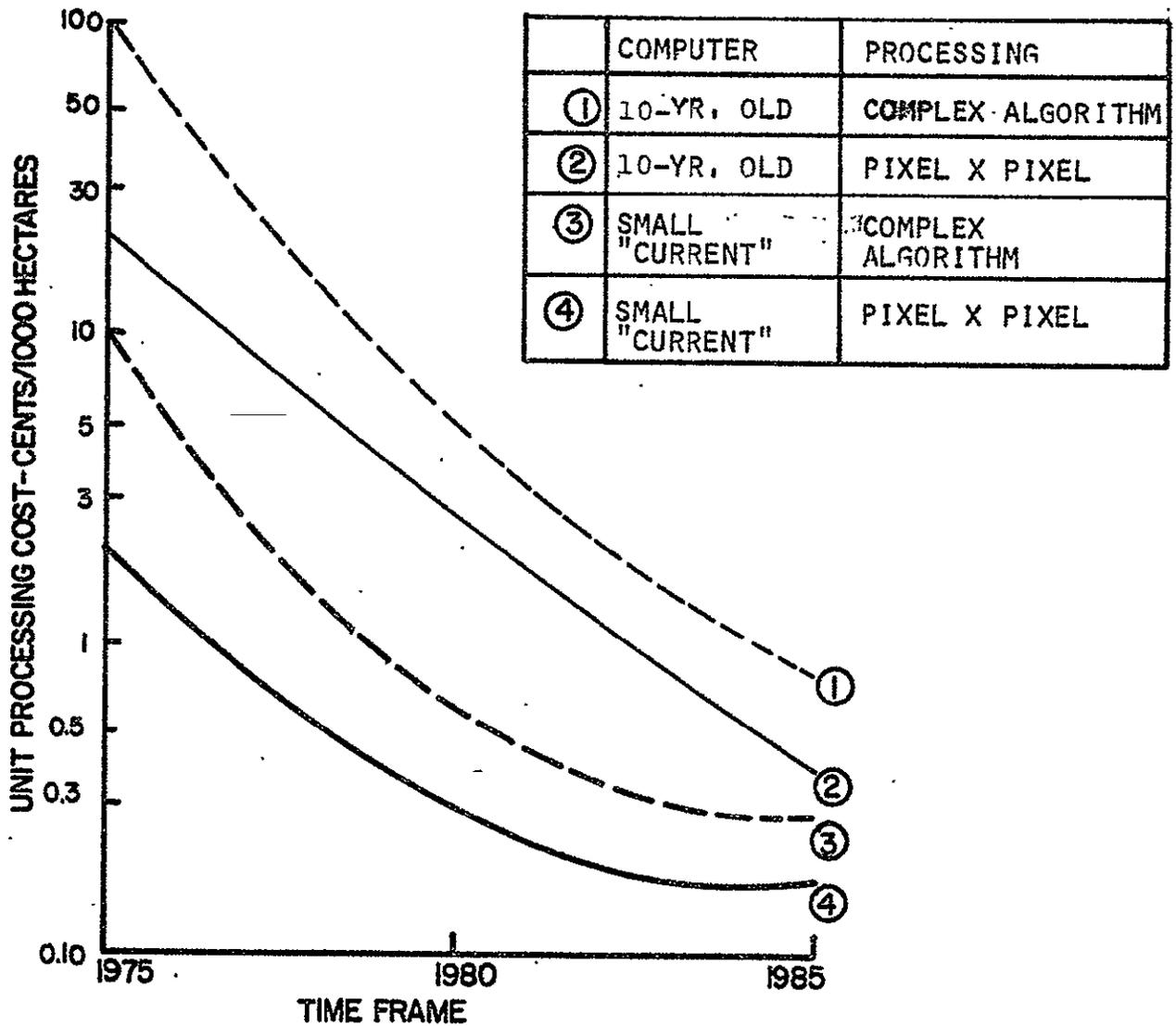


FIGURE 23

ERTS CCT-IMAGE PROCESSING COST (WITH PREPROCESSOR)

PREPROCESSOR SPEEDS, MIPS

1975: 100
1980: 280
1985: 500



faster preprocessors could be custom-made, the corresponding investment would only be warranted by a very large, continuous applications load.

The costs shown in Figure 23 apply to current small machines, which follow the trend depicted in Figure 22, and 10-year old machines. The costs of adding preprocessors to TOL machines is not shown since no significant speed improvements and, therefore, cost savings result.

Figures 22 and 23 apply to the data stream from ERTS. It is very likely that the post-ERTS remote sensing data will obey the historical law of expanding use (or, in more popular parlance, Parkinson's law).

The concern here is the growth in the complexity and consequent processing costs of remotely sensed imagery. Microwave radiometry, synthetic aperture radar and other more advanced applications are not treated in this effort.

To a first approximation, the number of instructions required to classify a pixel is directly proportional to the number of grey levels, inversely proportional to the square of the geometric resolution, directly proportional to the square dimension of the total area scanned, and directly proportional to the number of spectral bands.

$$i = \frac{kn\ell^2f}{d^2} \quad (1)$$

where:

- i = number of instructions
- l = linear dimension of area scanned
- f = number of spectral bands
- n = number of grey levels
- d = linear dimension of pixel
- k = proportionality constant

There exists, however, a fundamental relationship between the number of grey levels and linear pixel dimension, with all other system parameters remaining constant:

$$\frac{d^4}{n} = \text{const.} \quad (2)$$

Combining the above two relationships:

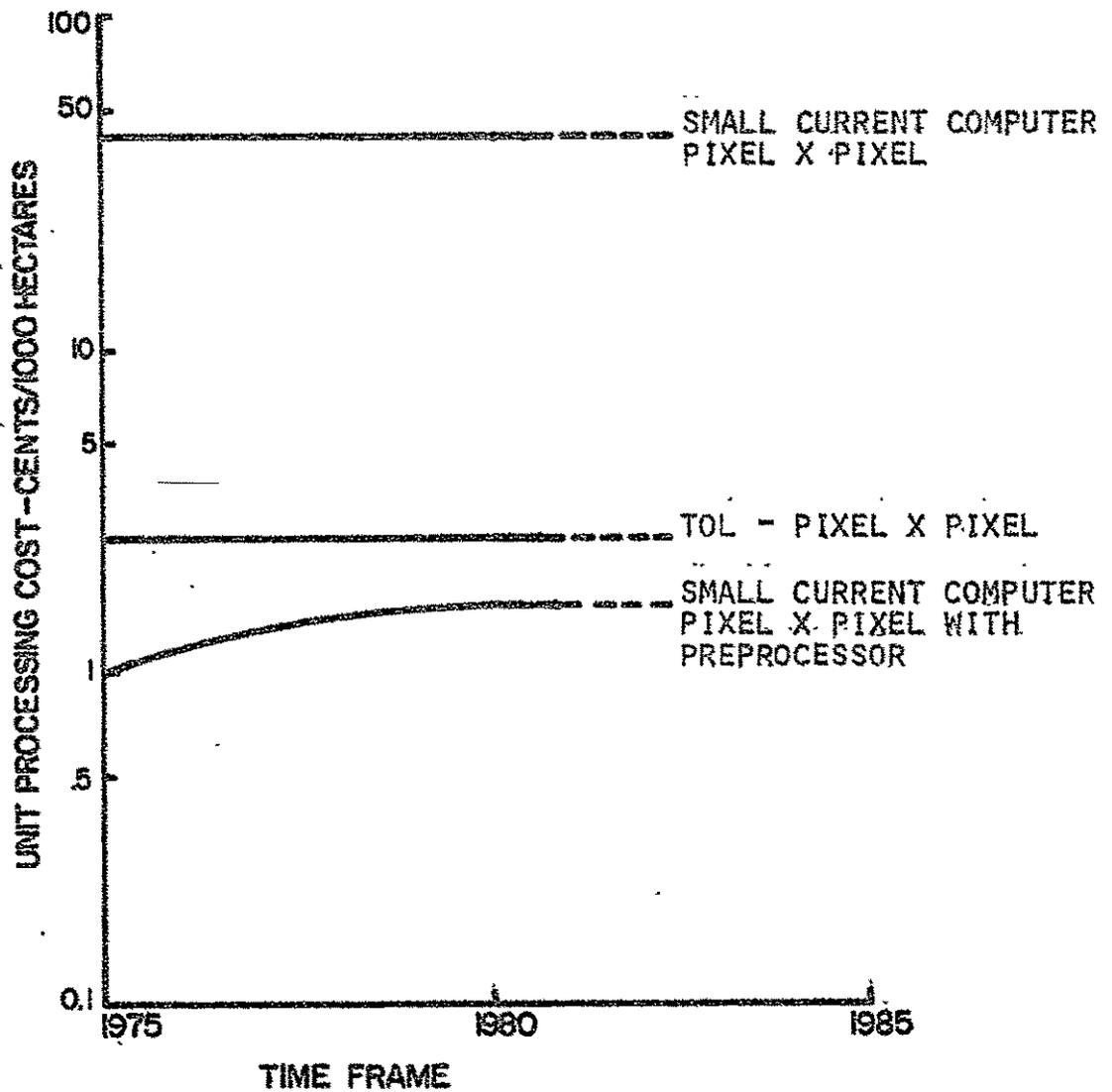
$$\underline{i} = kl^2f \quad (3)$$

Note that equation (3) holds only for system parameters equal to those of ERTS: aperture size, orbital velocity and altitude, detector sensitivity, single sensor package.

Thus, a first step in the growth of data load will be caused by the addition of spectral bands from the present 4 to the future 6: factor of 1.5. Increases in detector sensitivity and aperture size combined of approximately 12 db from the present MSS system can be reasonably anticipated by 1980. This is a further factor of 4. Thus, by approximately 1980, a total increase in data processing load of up to a factor of 6 for earth-orbiting remote sensors can be reasonably anticipated. Figure 24 depicts

FIGURE 24

GROWTH OF POST-ERTS CCT IMAGE PROCESSING COSTS



this trend.

Note that the CCT processing costs remain essentially constant. It is further interesting to note that the addition of a preprocessor to the smaller computers tends to increase the cost. The reason lies in the assumed growth pace of preprocessors, slower than the growth of general-purpose computing power.

The difficulty in estimating the impact upon the user's DP facilities of future remote sensing systems derives from the uncertainty in their specifications and in the estimation of their era of deployment.

A typical example is the EOS Thematic Mapper, currently in the phase of system definition. We have seen that hydrologic models require essentially pixel by pixel processing over the watershed area. Thus, the ratio of induced data load between EOS and LANDSAT can be established by means of the following rationale.

EOS geometric resolution is 30 meters, or approximately twice that of LANDSAT. This factor implies a 4-1 ratio in the number of required instructions.

EOS radiometric resolution is 128 levels, or double that of LANDSAT. This would result in a twofold increase in processing load.

Number of EOS bands is 7 as against LANDSAT's 4, implying an approximate factor of 2.

Thus the total DP load induced by the EOS data stream can be estimated at approximately 16 times that induced by LANDSAT, for the

same watershed area.

Assuming a deployment time of 1982, the data processing costs with respect to 1975 can be expected to decrease by approximately 5 times. Only in 1989 would the extra load imposed by EOS be matched by an equivalent reduction in processing costs. No theoretical limitations exist which constrain, by 1988, another increase in satellite remote sensing data stream volume by a factor of at least 10. Thus, apart from the budgetary and socioeconomic question of whether such advanced satellites will be implemented, it is safe to say that for the 1975-1990 era the technologically possible growth in remote sensing capabilities outstrips the historical rate of reduction of data processing costs.

Thus the conclusion reached previously, and depicted in Figure 24, that the data processing costs of satellite remote sensed data streams will remain essentially constant, should be regarded as a lower bound. The costs, and thus the impact on the user's DP facilities could increase by a factor of two and perhaps three during the next two decades.

8.0 ASSESSMENT OF THE SEVERITY OF THE IMPACT AND GUIDELINES FOR ITS ALLEVIATION

From Figure 25, the cost of performing one complete run on a complex hydrologic model is expected to remain essentially constant over time, at least during the next decade. This is due to the compensating trends of descending processing costs and ascending complexity of hydrologic models. The cost per run will range from approximately \$0.50 for the large TOL machines to approximately \$3 to \$4 for the smaller machines.

The cost per run should, within reasonably wide limits, be rather insensitive to the size of the watershed. This is so because current models generally average the properties of watersheds and a large fraction of the processing load is induced by the handling of rainfall and runoff data. A reasonable approximation is that the cost per run increases as the square root of the area.

The cost of processing remotely sensed imagery has two facets:

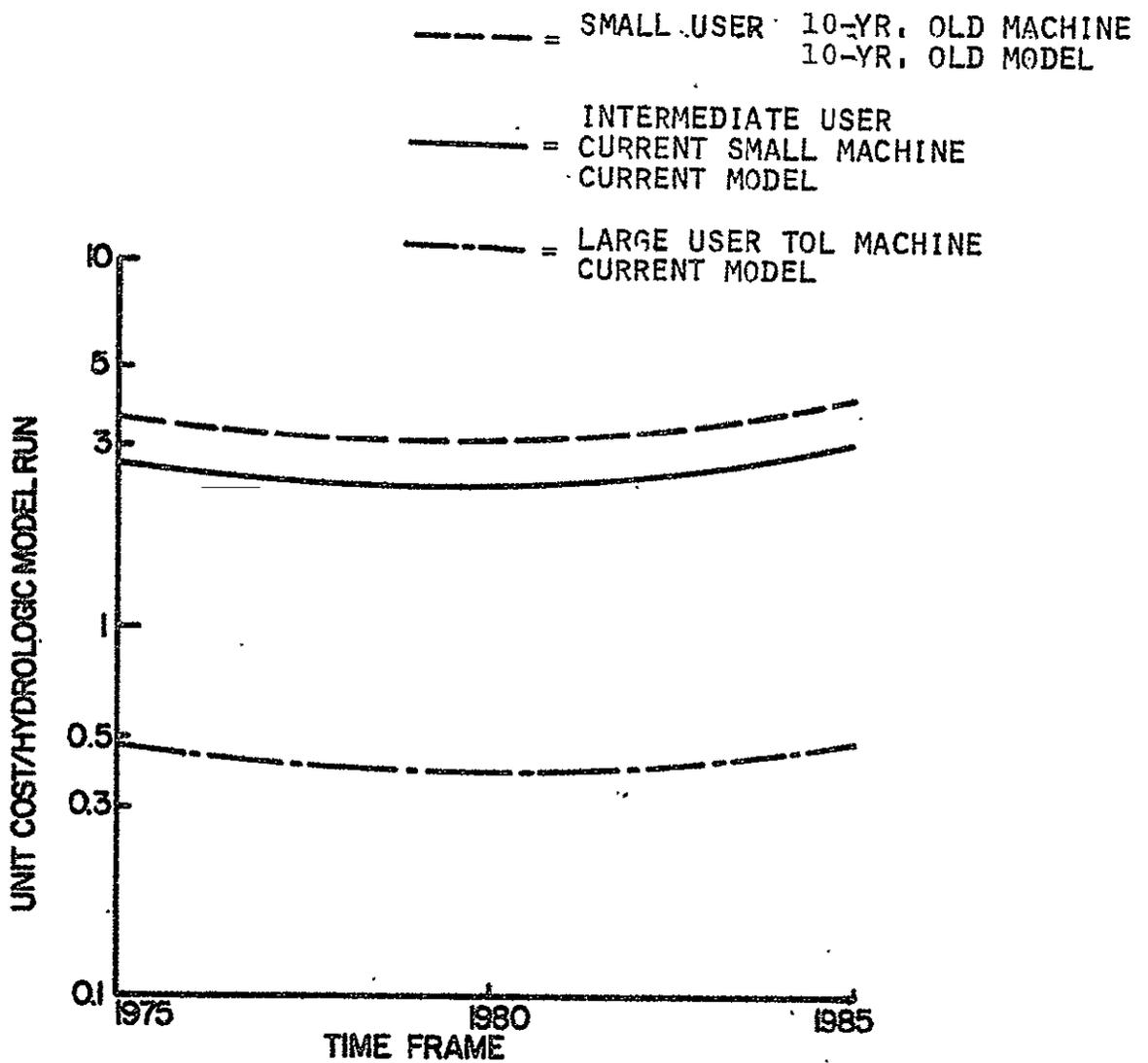
1. The cost of processing the CCT's;
2. The cost of acquisition of the CCT's and of the imagery required for ancillary visual or visual-aided analysis.

Figure 25 indicates that the costs of CCT processing will remain essentially constant with time because of the compensating trends of descending processing costs and increased processing complexity induced by the anticipated increase in sophistication of remote sensing systems.

These costs will range from approximately \$0.02 for the large TOL machines to \$0.50 for the smaller machines, per 1,000 hectares

FIGURE 25

DATA PROCESSING COST TREND FOR HYDROLOGIC MODEL RUNS



of watershed area.

Note that for watersheds of even relatively small area, such as the "median" small-user watershed depicted in Figure 26, the CCT processing costs are of the same order of magnitude as the costs of running the model.

The impact of the processing costs is a function of how many model runs are performed between updates of the watershed. It is clear that the larger the number of model runs that are performed between updates, the lower the apportioned cost of processing relative to the cost of running the model. During the survey phase of this effort, an attempt was made to determine the mean number of model computer runs per watershed update for various users and models. It was found that in many cases the respondents did not possess sufficient information to properly answer this question; in other cases, the information supplied was judged to be of low reliability. The most reliable information obtained is presented in Table 15.

Notice the significant variation between respondents, which makes it difficult to generalize. Nevertheless, two trends appear:

1. The smaller models, used by the smaller users, by and large tend to have fewer runs per update than the larger and more sophisticated models. The less sophisticated models are used by the largest number of users, even though this large number of users possesses less resources than the few users employing the more sophisticated models.
2. The smaller models, with few updates per run, are employed in the smaller watersheds; thus, their application is far more widespread than that of the sophisticated models, in terms of number of watersheds served (but not necessarily in terms of total area served).

FIGURE 26

RELATIVE COST OF ACQUISITION AND PROCESSING OF CCT VERSUS RUN

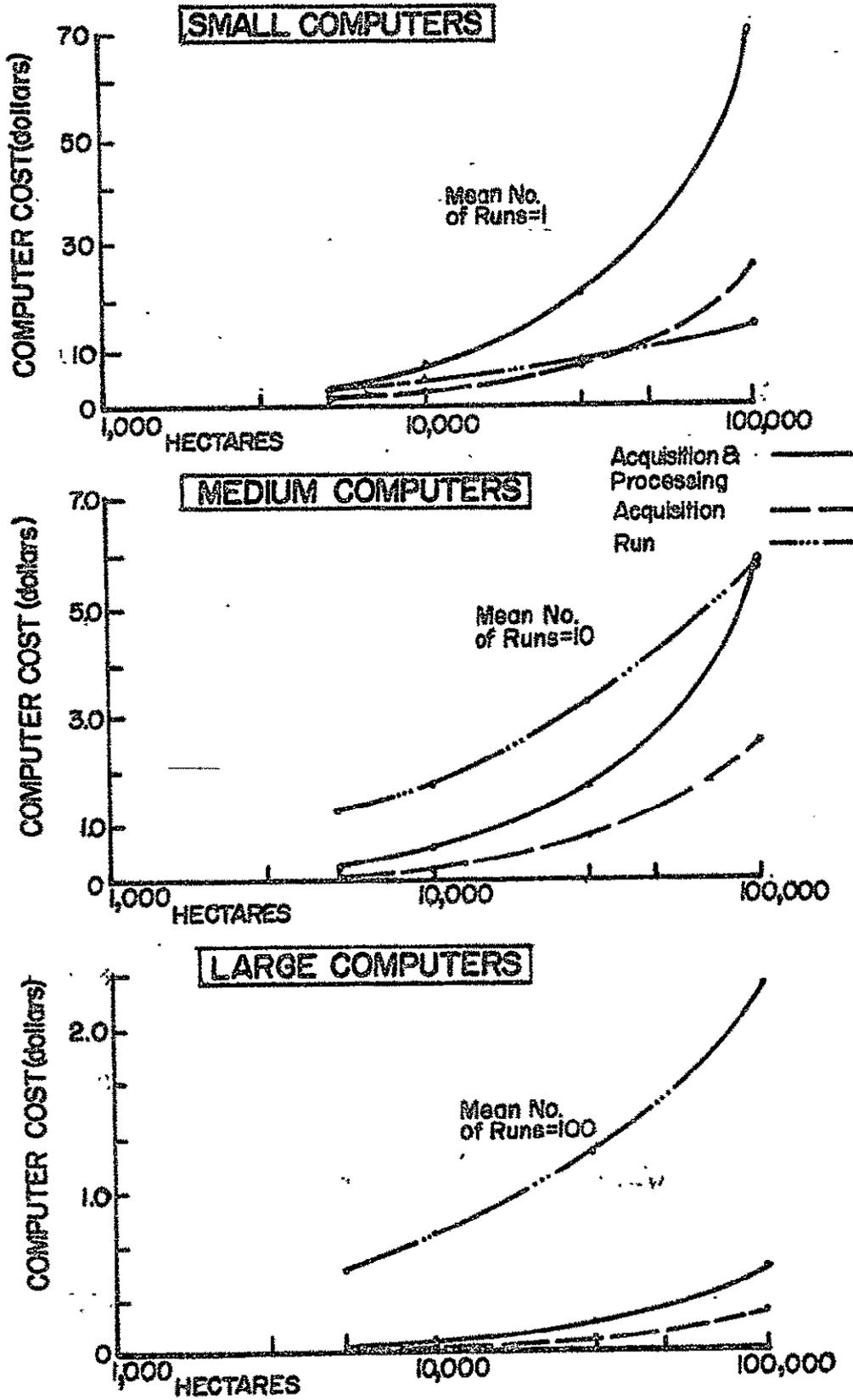


TABLE 15

ESTIMATE OF COMPUTER RUNS PER CALIBRATION			
MODEL <small>Information Source</small>	TIME BETWEEN CALIBRATIONS	RUNS PER CALIBRATION (typical)	CHARACTER OF CALIBRATIONS
HYDRO-14 (National Weather Service, D.C.) ^Δ	-5 years	1500-2000	Input data only - rain and runoff records updated
M.I.T. (Parsons, Brinkerhoff, and Quade, Fairfax, Virginia) ^Δ	Irregular-as required by hydrologic structures changes - frequent ~1 year in high gradient areas	1	Physical parameters which change - flow lengths, land use
HEC-1 (Corps of Engineers, Davis, Calif.) ^Δ	Irregular ~1 year	200-300	Changing hydrologic parameters - time of concentration
USDAHL-74 (Agricultural Research Service, Beltsville, Md.) ^Δ	Seasonally or annually	1-50	Changes in crop cover; initial crop growth index altered
TR-20 (Soil Conservation Service, D.C.) ^Δ	Irregular - as required by hydrologic structures changes - frequent ~2-3 years	1	Changes in flow lengths, routing parameters
USGS RAINFALL-RUNOFF (USGS, Reston, Virginia) ^Δ	Very infrequently, greater than yearly	300-500	Changes due to land use, time of concentration
SSARR (Corps of Engineers, Portland, Oregon) ^Δ	Very infrequently 5 years	300-500	Internal timing of model due to significant land use and physical changes in basins
TEXAS (STANFORD) (U. of Texas, Austin) ^Δ	Seasonally or annually with amenability to more frequent update if data were available	200-300	Variations in surface cover, land use, depression and interception storage

Obviously then, the apportioned cost of ERTS CCT processing is given by the formulation:

$$c = \frac{100K}{m}$$

where:

c = apportioned cost of processing the CCT, cents per 1,000 hectares

K = cost of processing the CCT, dollars per 1,000 hectares

m = number of model runs between updates

The impact of the acquisition cost of the CCT's and associated imagery, currently approximately \$0.07 per 1,000 hectares, is a function of 1) how much watershed area of interest to the user is contained within the ERTS frame; 2) how many different temporal passes of the same scene are required to achieve the reliability of information required; 3) the length of the update interval; and 4) the number of model runs per update.

The acquisition cost can be expressed as:

$$K = \left(\frac{n}{T}\right) \left(\frac{C}{35\eta}\right)$$

where:

K = acquisition cost, cents per 1,000 ha

C = cost of the CCT, dollars

n = number of temporal repetitive passes required

T = update interval, years

η = utilization coefficient

m = number of runs between updates

Typically, at least two ERTS frames (one in the dormant, one in the non-dormant season) are required for maximum utility; for watersheds undergoing rapid development, an update every 5 years is appropriate. The total area of watersheds of interest contained within the frame is best expressed in terms of a "utilization factor," which varies from user to user.

With the above reasonable parameters, the acquisition cost formula becomes:

$$K = \frac{0.011C}{\eta m} \text{ cents/1,000 ha}$$

Section 7 discusses the estimated trend in CCT acquisition costs. Note that, in spite of the estimated reduction of ERTS CCT costs, the impact of the more sophisticated EOS tape format and content will in all likelihood bring back the CCT cost for EOS to a level commensurate with current ERTS CCT costs. Thus we can assume, as a secular trend, that CCT costs will remain essentially unchanged, at the current price of approximately \$225 per scene.

The above formula thus becomes;

$$K = \frac{2.5}{\eta m} \text{ cents/1,000 ha}$$

A reasonable value for η is 0.1. Thus $K = \$\frac{0.25}{m}/1,000 \text{ ha}$.

Figure 26 combines the trends derived in prior sections to illustrate the relative cost of acquisition and processing of CCT tapes, and of running the hydrologic model. It is clear from Figure 26 that the cost of acquisition and processing of remotely sensed data is relatively small for the large user employing sophisticated

models; they are comparable to the costs of running the models for the small watersheds. The logical conclusion is that policies aimed at reducing these costs would be conducive to spreading the acceptance of the remote sensing technique to the smaller, and quite numerous, users.

What are the most likely policies in this respect? First, the acquisition cost was predicated upon the current Department of Interior's EROS policy of the users having to purchase the entire ERTS frame. A possibly significant reduction in cost might be achievable by instituting a service whereby the interested users could purchase only the portion of the CCT scenery pertaining to their watershed of interest. Technically, this could be accomplished by "stripping out" from the 185 x 185 kilometer frame selected rectangular portions encompassing the watersheds of interest. These could be sold as "minitapes" at reduced price. Clearly, the price reduction would not be proportional to the reduction in area, because of the residual overhead and handling costs; nevertheless, from personal communications with EROS personnel, the possibility exists of possibly achieving a "cost floor" of the order of \$50.00 per "minitape." This would immediately cut the acquisition cost by a factor of roughly four. It is recommended that the costs and marketing implications of this possibility be explored.

The second area of cost reduction lies in the CCT processing cost. This area can be addressed as follows. The user is not primarily interested in the raw remotely sensed products, but rather in the analyzed products; specifically, maps indicating

the location and characteristics of the features of hydrologic significance (cover, stream pattern, contour, etc.). This observation applies most especially to the small and intermediate users. This requires processing the ERTS frame, or selected portions thereof, in such a fashion as to extract the significant information.

The cost figures shown in Figure 26 indicate that the processing cost decreases significantly by employing the larger computers. Further, the cost could be reduced significantly by the use of special pre-processors. These are now technologically feasible; their rate of cost decrease does not, however, follow the rate of decrease of the general DP market because of their limited market. In other words, they are expensive and only justified if employed in applications having a high utilization factor.

The utilization of the larger types of machines and of appropriate pre-processors should be seriously considered in future planning of user-oriented processing facilities. This policy favors the centralized approach, in which one or a few processing facilities provide the data processing services, thus taking advantage of the inherent economies of scale, in preference to a larger number of regional or local facilities.

Another alternative is possible, and is in fact being attempted by various private concerns. This is to provide local "Service Centers," such as the General Electric Center in Beltsville, Maryland, or the Bendix Center in Rosslyn, Virginia. These centers in effect provide localized service to users on a fee basis.

The fundamental reasoning underlying the service is that the user, to accomplish a proper survey of his watershed by normal means, must resort to aerial photography, supplemented by field information, with the added expenses of mosaicking, photointerpreting, map compilation, manual or semi-manual extraction of hydrologic parameters.

The cost of compiling a good watershed data set can range as high as \$1 per hectare for the smaller watersheds. Thus the cost is significantly higher than that inherent in ERTS-derived information, even though the remotely sensed information yields at present somewhat less accurate results.

By contrast, the service supplied by the private facilities is much less costly; as a typical example, \$250 would process a 10,000 hectare watershed. The price increases significantly if more than one CCT is involved in the analysis, as is the case for temporal comparison, or if the watershed of interest overlaps more than one CCT.

One of the problems of the private centers is overcoming the "market resistance" of the user. As presently structured, the user generally has to travel to the center, and must be able to identify a sufficient number of ground truth elements in order to allow proper classification. The user must be educated to rely upon an unfamiliar technology, rather than upon his own usual tried and true system. Unless the user is convinced that

better results are forthcoming, he will hesitate in spending the necessary funds, engaging in the travel, and so forth.

An additional element of market resistance is induced by the user's not being able to perform the analysis in his own facility, with his own trusted personnel, at his own pace, with leisure to doublecheck results and correct for errors. Instead, he is under some pressure to expedite his work at the Service Center in order to minimize the charges which run on the order of \$250 per hour.

Additional elements of impact which emerged from the survey are the following:

1. Training - Before using the remotely sensed data, the user must achieve a minimum level of understanding of their nature, purpose, and how to apply them. Lack of knowledge was found to be particularly severe among the small and medium users; one of the principal gaps is the lack of understanding of the meaning of radiometric information.
2. Software - Software for handling remotely sensed data is available to users through the COSMIC system. The development of special software specifically designed for hydrology should receive consideration.
3. Availability of Services for Foreign Users - The training and software problems are particularly severe in the case of foreign users. Software is a problem even for the sophisticated users; training is a problem for the less sophisticated users.

It is understood that uninhibited transfer of software paid for by the U.S. taxpayer would impact certain export policies. Nevertheless, consideration should be given to an appropriate software exchange program, wherein foreign users could trade their software for U.S. software.

As regards the training, efforts are under way by the Department of Interior's EROS Agency, U.S. Universities

and private companies, as well as foreign Universities and institutes. In particular, a program is currently being contemplated by the United Nations. NASA should consider an optimal policy for support of these programs.

4. Delay in Dissemination of Data - The current lapse between ordering and receipt of CCT's and ERTS imagery poses a psychological rather than a fundamental problem. In general, for hydrologic users it is not so much a problem of needing the information in real time; rather, long delays discourage taking advantage of the service.
5. Presentation of the Information - It is important to remember that most users -- particularly the numerous population of small users -- are accustomed to seeing and handling information in specific formats -- maps, graphs, and so forth. Even for users versed with interpreting aerial photography, use of LANSAT imagery and especially of CCT's is sufficiently different so that meaningful correlations are by no means automatically established in the user's mind. A significant step towards widespread acceptance of remote sensing would result if the user were presented with digested information in the format he is accustomed to handling. Experience of the writers with small users, for example, indicates that even the conventional computer printout must be made very clear and simple, avoiding overprints and unfamiliar symbols. Preferably, the format should contain only the information demanded by the model user's model: for example, if he employs a rational-formula type model, the information should be in terms of percentages of ground cover of different types.

Training is the most significant element and is worth expanding upon. Training in this context must be interpreted broadly as follows: 1) refreshing the user in the fundamentals of his applications, and showing him specific areas where remotely sensed data can make contributions; 2) familiarizing the user with the methods of processing remotely sensed data, in both imagery and CCT format, on the equipment he has available or can afford to procure; 3) outlining to the user that the overall costs of using remotely sensed information are less than those associated with conventional methods.

An overview of current training courses, both U.S. and foreign, shows that all too often the training is essentially confined to teaching the user how to process imagery or computer tapes, on the assumption that the user knows best his own field. In reality, the user experiences difficulty in relating his knowledge, which is based upon conventional practices, to the information derivable from remotely sensed data.

Frequently, the remotely sensed data contain information which is new and therefore unfamiliar and not directly incorporable into the user's models without a significant rethinking process, often innovative in nature. The writers have observed cases where the users approach the instructors with specific questions relating to the application of the remotely sensed data to specific facets of their problem. However, the instructors were primarily data processing people while the users as hydrologists were responsible for tailoring the process to the application. Clearly there is a gap between the user's discipline and the data processing procedures.

As a minimum, "User Training Manuals" are needed, specifically tailored to the utilization of remotely sensed information in water resources. They should incorporate within the training protocol practical and significant examples of water resource applications, supported by current ERTS results. It is important to provide instructors who are well-versed in both hydrology and interpretation of remote sensing products.

A valuable adjunct to a formal training course would be a well-designed student home-study course including a manual of *how to apply the technique*. This would acquaint the user with the application of remotely sensed data prior to his attending the course. A good example of such a manual is the report "Handbook of Techniques for Satellite Snow Mapping," by Barnes and Bowley, prepared under NASA Contract NAS5-21803.

The essential point is that the remote sensing technology needs to be marketed like any other new technique or product. Experience shows that products with high technological content are best sold when the seller "knows the buyer's business better than the buyer does himself."

BIBLIOGRAPHY

General

Computer Applications Plan, Fiscal Years 1973-1974. Computer Applications Management Board, Bonneville Power Administration, January 1973.

Computer Applications Plan Supplement, Fiscal Years 1973-1974, BPA 1090 Forms. Computer Applications Management Board, Bonneville Power Administration, September 1972.

Federal Water Resources Research Program for 1972. Office of Water Resources Research, Washington, D.C., 1972.

GML Computer Review. GML Corporation, Lexington, Mass., 1974.

Hydroelectric Power Resources of the U.S. - Developed and Undeveloped. Federal Power Commission, Washington, D.C., January 1, 1972.

Keydata Computer Characteristics Review, Vol. 10, No. 1, Keydata Corporation, Watertown, Mass., 1970.

OECD Informatics Studies 6: The Evaluation of the Performance of Computer Systems - A Survey of Policies and Trends in Governmental Computing. Organization for Economic Cooperation and Development, Paris, 1974.

Budgets

The Budget of the U.S. Government FY 1973. Government Printing Office, 1974.

Plan for Progress: Public Services Program FYS 75-80 and Annual Budget FY 75, Montgomery County, Md.

FY 1975 City of Baltimore Budget in Brief, Dept. of Finance.

The City of Los Angeles Budget for the Fiscal Year Ending June 30, 1975.

Budget for 1973-1974 for Dorchester County, Md., County Commissioners.

Approved Fiscal Plan, Fiscal 1975, Fairfax County, Va.

Baltimore County Operating Budget, FY 74-75, Adopted May 29, 1974.

City of Chicago Annual Appropriation Ordinance for the Year 1974.

State of New York Executive Budget for the Fiscal Year April 1, 1974 to March 31, 1975.

Models

Analog Computer Simulation of the Runoff Characteristics of an Urban Watershed. V. V. Dhruva Narayana, J. Paul Riley, and Eugene K. Israelsen, Utah State University, January 1969.

A Water Balance Program. Forest Service, USDA, July 1968.

Calibration of U.S. Geological Survey Rainfall/Runoff Model for Peak Flow Synthesis - Natural Basins. U.S. Geological Survey, October 1973.

Computer Program for Project Formulation - Hydrology (TR-20). Technical Release No. 20, Soil Conservation Service, USDA, May 1965.

COSSARR Model: Streamflow Synthesis and Reservoir Regulation. North Pacific Division, Corps of Engineers, January 1972.

Digital Simulation in Hydrology: Stanford Watershed Model IV. Norman H. Crawford and Ray K. Linsley, Technical Report No. 39, Stanford University, July 1966.

Direct Search Optimization in Mathematical Modeling and a Watershed Model Application (Hydro-12). John C. Monroe, NOAA, Dept. of Commerce, April 1971.

National Weather Service River Forecast System Forecast Procedures (NWSRFS or Hydro-14). Hydrologic Research Laboratory, NOAA, Dept. of Commerce, December 1972.

National Weather Service River Forecast System - Snow Accumulation and Ablation Model (Hydro-14). Eric A. Anderson, NOAA, Dept. of Commerce, November 1973.

SSARR Model: Streamflow Synthesis & Reservoir Regulation. North Pacific Division, Corps of Engineers, September 1972.

Numerical Simulation of Watershed Hydrology (Texas Watershed Model). B.J. Claborn, W.L. Moore, Texas University at Austin, August 1970.

USDAHL-70 Model of Watershed Hydrology. H. N. Holtan, N. C. Lopez, Agricultural Research Service, 1970.

USDAHL-74 Revised Model of Watershed Hydrology. H.N. Holtan, G.J. Stiltner, W.H. Henson, and N.C. Lopez, Plant Physiology Institute Report No. 4, Agricultural Research Service, 1974.