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USER REQUIREMENTS AND USER ACCEPTANCE OF CURRENT AND NEXT-GENERATION SATELLITE MISSION AND SENSOR COMPLEMENT, ORIENTED TOWARD THE MONITORING OF WATER RESOURCES

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16. Abstract:

Principal water resources users were surveyed to determine the applicability of remotely sensed data to their present and future requirements. Analysis of responses was used to assess the levels of adequacy of LANDSAT 1 and 2 in fulfilling hydrological functions, and to derive systems specifications for future water resources-oriented remote sensing satellite systems. The analysis indicates that water resources applications for all but the very large users require: resolutions of order 15 meters; number of radiometric levels of the same order as currently used in LANDSAT 1 (64); number of spectral bands not in excess of those used in LANDSAT 1 (4); repetition frequency of order 2 weeks.

The users had little feel for the value of new sensors: thermal IR, passive and active microwaves. What is needed in this area is to achieve specific demonstrations of the utility of these sensors and submit the results to the users to evince their judgement.

TECHNICAL REPORT STANDARD TITLE PAGE (CONT'D)

16. Abstract: (cont'd) All users indicated that the most significant information requirements are in the area of better knowledge of the characteristics of precipitation. Specifically: the temporal behavior (intensity versus time) of rainfall; its areal distribution; the statistics of succession of rain events as a function of time; and the storm travel characteristics.

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1.0 PREFACE

The Earth Resources Technology Satellite, in conjunction with information gathered from meteorological and other operational satellites, has demonstrated significant capability and promise for the application of remote sensing techniques to the area of hydrology.

ERTS investigations have indicated the feasibility of several major applications: mapping of surface water area for monitoring surface water supplies stored in lakes and reservoirs, mapping of snow-covered area for seasonal forecasts, of runoff from snowmelt, mapping of land-use or ground cover characteristics usable to determine the transfer function of watersheds for the real-time computation of the rainfall-runoff relationships, construction of hydrologic planning models to predict the unusual events of specified recurrence for the purpose of sizing waterworks, and improved delineation of flood plains.

The experience gathered from ERTS now indicates that these applications can be perfected, and that further significant results can be made possible by the use of more optimal combinations of sensors, including some advanced sensors, and novel modes of data gathering.

Typical examples of additional sensors are a 1.5 to 1.8 micron infrared instrument for purposes of objectively separating clouds from snow in a given set of observations;

a high-resolution (order 14 meters) pointable sensor; and the possible addition of a Synthetic Aperture Radar of broad swath width and moderate resolution operating at two wavelengths.

The purpose of this effort is to provide information usable for planning a second-generation satellite payload optimized for hydrologic applications; specifically, information gathered from an in-depth survey and analysis of the technical opinion and experience of the potential users.

2.0 OBJECTIVES

The general objective of this effort is to obtain an assessment and evaluation of the best structure of a water resources-oriented satellite mission by knowledgeable personnel in responsible positions in agencies with key responsibilities for water resources management, monitoring or research.

The purpose of this evaluation is to provide useful guidance as to the user's interest in remote sensing for hydrologic applications; to allow the development of a viable and credible rationale for alterations or additions to sensors and data processing procedures, and suggestions for future consultation and interaction between NASA and the water resources management community. Specific objectives are:

1. To determine the utility of satellite remote sensing for hydrologic purposes, as seen from the viewpoint of the user;

2. To synthesize the significant requirements of the users into sensor specifications and optimal configurations and characteristics of a hypothetical mission dedicated to water resources;

3. To verify the compatibility between presently proposed sensor configurations for LANDSAT-D and the desires of hydrologic users;

4. To provide guidance as to the best compromise between proposed and desired sensor characteristics, mission parameters and data formats; and

5. To indicate the structure of the NASA/user interface preferred by the hydrologic users.

3.0 CONCLUSIONS

1. Interface with, and securing of productive information from the users, is best accomplished by discussing remote sensing in the language most familiar to the users themselves. This is the best method to bridge the gap between the user's and the new technologist's differing backgrounds and experience.

2. This requires a great deal of homework on the part of the technologist: to familiarize himself with the user's techniques, and to prepare his questions in an easily answerable format.

3. One of the better tools to promote communications was found to be a "user package" depicting cogent examples of the application of remote sensing to the user requirements. Such a package promotes identification by the user with the remote sensing capabilities and techniques, and with the results achievable therefrom, and prompts the user into a lucid exposition of his problems.

4. Most hydrologic users -- especially the Federal users -- already employ remote sensing techniques in the form of aerial photography. They are interested in their expansion to LANDSAT - derived information, for reascns of economy, ease of handling, frequency of coverage, and the potential offered by the multiband radiometric information.

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5. A more effective transfer of LANDSAT - derived CCT information could be achieved by lowering the cost of the tapes. A potential remedy is available from the observation that most users are only interested in watersheds which occupy small fractions of a LANDSAT frame. Thus the technique, proposed in Reference (1), of stripping out pertinent portions of a frame, at reduced cost, should be given serious consideration.

6. The primary interests of the users surveyed are hydrologic modeling of both management and planning types, flood plain mapping, and snow cover measurements.

7. The principal measurements of interest to users and which are performable by current remote sensing technology are: Watershed area; slope distributions; surface cover, classified by Land Use Type II and III; Drainage density; Channel length; flood plain width; snowpack area.

8. All users evidenced considerable interest in additional capabilities which need be addressed by advanced remote sensing technology: temporal and spatial characteristics of rainfall; storm travel.

9. The capabilities offered by advanced sensors -- active and passive microwave devices -- are as yet not sufficiently demonstrated to evince significant user response.

10. Synthesis of the user requirements boils down to five basic types of measurements: elevations, areas, target

differences and content (discrimination and identification); width of linear features; length of linear features. This letter hinges essentially upon measurements of width.

11. Elevation measurement requirements of users are not addressable by LANDSAT. Its accomplishment requires use of other a priori information. The advisability of incorporating stereo capability in advanced satellites hinges upon its cost effectiveness, i.e. the marginal improvement over existing topographic maps.

12. Areal measurement requirements, for areas which can be geometrically mensurated (i.e. wherein discrimination or identification of area content does not present a problem as is the case with snow for example) are fulfilled by LANDSAT: 100% for the large users, 90% for the small users, 0% for the local users.

13. Areal measurement requirements for areas which cannot be geometrically mensurated (i.e. wherein discrimination or identification predominate the mensuration function), are fulfilled by LANDSAT as follows. In the inventory or aggregate mode if 98% classification accuracy is achieved: 100% for the large users, 90% for the small users, 0% for the local users. In the land use, or mapping mode: LANDSAT performance is marginal.

14. Improved geometric resolution would broaden the applicability of remote sensing to the user requirements. For example, a resolution of 15 meters would fulfill the following. In the inventory mode at 98% classification accuracy, it would satisfy the areal measurement requirements of all the large and small users, plus approximately 60% of the local users. In the land use mode, additional improvement in classification accuracy is required before increased resolution will prove beneficial.

15. Increased resolution will however also increase the pixel sample size: it should be conductive to improved quality of classification, both in the inventory and land use mode. A numerical formulation of this effect is dependent upon the availability of a sufficient body of spectral information, currently being gathered under the sponsorship of NASA.

16. Streamwidth measurements are essential for determining drainage characteristics such as streamlengths, and flood plain widths. Under the most favorable conditions, LANDSAT A can identify, from measurement of streamwidth, areas from which the streams emerge as small as approximately 2.5 Km^2. This capability approaches the requirements of the small users within a factor of two. It meets those of the large ones. Its achievement does however require the occurrence of particularly favorable

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contrast conditions: it will necessitate a significant number of LANDSAT observations on any given watershed. For some watersheds, it may not be achievable. Under more typical conditions, the identifiable area of stream emergence is approximately 30 Km^2, or 50 times larger than what the small user desires. On the average, an improvement factor of at least two, preferably as much as ten, would be beneficial. Under favorable contrast conditions, LANDSAT A performance for flood plain mapping approaches the requirements of most users. A notable exception are the small towns.

17. Based upon a limited and preliminary set of available spectral information, the general specifications for a hydrologically-oriented satellite should be oriented as follows:

    Geometric Resolution: as high as possible; 15 meters desirable.

    Radiometric Resolution: $\sim$ 100 levels

    Spectral bands in the 0.5 to 1.1 microns range: 2 or 3

18. Several important principles should guide the working relationship between the technologists (NASA) and the users. Firstly, the technologist must learn the user's business--the reverse is not necessary, since the user is the final customer.

19. It is not fruitful, in most cases, to request users to speculate and pass judgement on the potential value of applying advanced technologies to their activities. Users

should be asked only to judge results. As a minimum, potential results should be simulated as realistically as possible. The reason is that most users are accomplishing their tasks their own way, and doing it well. It is not easy for them to visualize new ways of doing their job: it is much more effective to demonstrate that the new way is better. For example, users could not judge the value of performing periodic soil moisture measurements. They are performing this function now by other means: they need to be shown specific results of the direct measurements plus costs and method of utilization in order to assess the new method. Likewise, users had difficulty in visualizing the useful product generated by radar. They need to be shown.

20. It is desirable to utilize the expertize of selected users in developing new applications. The contribution of these users should be structured within the framework of a definite working arrangement, carefully constructed so that results become visible to the user community as they develop.

4.0 APPROACH

A simple opinion poll of the user's requirements in terms of sensor and mission specifications is not an adequate method of approach. The reason is evident from the experience acquired in ERTS investigations: the problem of communication between diverse technical disciplines. The problem is best stated by example: to many users, otherwise highly competent in their field, the definition of "resolution" is obscure and unfamiliar. To engineering personnel involved in sensor design, it is obvious. The opposite is true in many cases; terms familiar to the user may not be equally familiar to aerospace engineers. It is thus important in a survey such as this one to convert the sensor payload specifications into a language and illustrative examples with which prospective users are familiar and conversant; and conversely to subsequently translate back the user's desires into technical sensor and mission specifications.

Other important problems of a psychological nature are immediately apparent to any one conducting a survey of the nature required for this effort:

1. The question, "what are your desires" or even "what are your principal problems," requires a considerable effort of thought, even for competent scientists. The time required to properly answer such a broad query generally considerably exceeds the time reasonably allowable for an interview, even of several hours.

2. Most competent users perforce tend to think in terms of improving their present methods of operation. Unless the user is quite familiar with the potential and capabilities of the new technology, it is unfair to expect him, in the brief span of an interview, to come up with new methods and procedures especially tailored to the new technology. This is, instead, the function of the technologists: namely to extrapolate from the stated user requirements to novel ways of accomplishing the user's objectives: and then, having demonstrated that the new techniques work, present them to the user for concurrence or comment.

These reasons counseled the following approach:

a. A "user familiarization" package was prepared. The intent of the package was to acquaint the users with the important principles of remote sensing, including examples of the application of LANDSAT data to the area of hydrology, or to applications closely related to hydrology. With some users, already fairly familiar with remote sensing techniques, this package turned out to be a "user refresher kit."

   It was found, however, most useful in establishing the initial communication and perspective for the subsequent interview.

b. From a survey of approximately 8 of the most employed hydrologic management models, and of approximately 100 planning models, a chart was prepared, indicating in detail the significant input parameters required by these models. Each element of the chart was then tagged with numerical entries gleaned from literature and the experience of the compilers. The entries provided initial terms of reference on which the user could comment either by concurring, or by disagreeing. In the event of disagreement, the user was asked to correct the entry or at least state the reasons for his disagreement. This method was found to work in the majority of the items about which the user was queried.

The composition of the user familiarization package was the following:

1. Verbal discussion of basics, plus questions and answers. Particular stress was placed on the radiometric aspect, upon explaining its basic difference from conventional photography and the corresponding potential for recognition.

2. A compilation of pictorial examples from selected sources, with corresponding annotations.

3. A computer printout of multispectral identification, appropriately annotated and colored to depict recognizable features, plus corresponding superimposable USGS map.

4. Several LANDSAT transparencies selected to illustrate hydrologic phenomena "as they are seen by the satellite."

5. A portable light table and photointerpretation lenses.

The details of the package are included in Appendix A. The structure of the user query chart is depicted in Figure 1.

The replies by the users and their comments elicited in the discussions were then documented in appropriate visit reports. The comments and replies were then integrated into an overall synthesis of the user's desires, including desires common to all users and requirements applicable to single categories of users. Based upon the information gathered, a ranking was made of the "intensity of user desires" as a function of the specific parameter to be measured. The procedure and results of the analysis are presented in Section 8.

Finally, the user requirements, appropriately commonalized and interpreted were translated into a set of satellite remote sensing parameters especially aimed at hydrologic users.

FIGURE I

EXAMPLE OF USER QUERY CHART

HYDROLOGIC MANAGEMENT MODEL - OPERATIONAL MODELS:

USER AGENCY:

USER OPERATIONAL LOCATION:

INTENSITY OF USE: (hrs./month)

MODEL DEVELOPMENT AGENCY:

MEASUREABLE PARAMETERS	ACCURACY		FREQUENCY		SAMPLING AREA OR ZONE		METHOD OF ACQUISITION	COST OF ACQUISITION	FORMAT	PRIORITY/WEIGHT
CURRENT TECHNOLOGY	ACHIEVED	TOLERABLE	ACHIEVED	TOLERABLE	ACHIEVED	TOLERABLE				
1. WATERSHED BOUNDARY	[illegible]		[illegible]		[illegible]		[illegible]	Low	map	
2. WATERSHED AREA	±1%		[illegible] watershed		subwatershed		stereo pairs	Low	histogram	
3. SURFACE COVER — VEGETATION	[illegible]		[illegible]		[illegible]		[illegible]	[illegible]	[illegible]	
SOIL	[illegible]		[illegible]						[illegible]	
IMPERMEABLE	[illegible]		[illegible]						[illegible]	
IMPOUNDED H2O	[illegible]		[illegible]							
4. DRAINAGE — DENSITY	±5%		[illegible]		[illegible]		[illegible]		[illegible]	
PATTERN	[illegible]		[illegible]				[illegible]		[illegible]	
5. CHANNEL WIDTH	[illegible] ±2m [illegible] ±5m		every year		every [illegible] length		[illegible]		[illegible]	
6. SNOW — AREA	[illegible]		[illegible]				[illegible]		[illegible]	
SURFACE MELT	[illegible]		[illegible]		[illegible]		[illegible]		[illegible]	
LINE ALTITUDE	±50m						[illegible]		[illegible]	
7. VEGETATIVE MOISTURE STRESS	±5m		within 1 week after flood peak		every 5 [illegible] along stream		[illegible] radiometer		[illegible]	
8. FLOOD PLAIN-WIDTH	±5m		[illegible] for each [illegible]		along stream every 20m.		traverse		[illegible]	
FUTURE TECHNOLOGY										
1. SOIL MOISTURE										
2. SLOPE										
3. RAINFALL — AREAL DISTRIB.										
TEMPORAL PATT.										
SPATIAL MOTION										
4. SURFACE TEMP. PATTERN										
5. STRUCTURES/LAND USE PLANT COVER WITHIN BOUNDARY										

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5.0 GENERAL ASSESSMENT OF THE ADEQUACY OF THE SELECTED APPROACH

The results of this survey essentially confirm observations made by the authors in similar surveys in diverse disciplines--including water resources, agricultural applications, scientific applications--over the last decade.

The scope of these past surveys embraced scientific, technical and administrative personnel belonging to at least a dozen different nationalities and with corresponding diverse backgrounds, the common thread being an interest in applying the technology of remote sensing.

As a first general observation, it became obvious that preparation prior to interfacing with users is well worth the effort. Specifically, the following points have emerged as being of principal significance:

1. The construction and, of course, presentation of a "user package" was found to essentially determine the difference between a successful exchange of quantitative information and just a generalized discussion. The only exception was represented by users already thoroughly versed in the techniques of remote sensing, in this case the personnel from USGS-EROS.

2. The spending of effort in studying and analyzing the general field of the user's application, plus the specific specialized applications, methods, models and publications by the user was also found of prime importance. In fact, items 1 and 2 above are simply two facets of the same approach: the user package is necessary to familiarize the user with the new technology; the pre-study of the user's application is required to allow the inquirer to understand and question the user's replies. The combination allows both user and inquirer to arrive at numerical conclusions, or at least to define common areas of uncertainty with precision.

3. One should allow sufficient time for the discussion. The discussion should begin with the presentation of the user package. Typically, a complete discussion will require at least three hours of which approximately one for the presentation of the remote sensing overview, the other two for discussing the user's requirements. In some cases, return visits or at least follow-up phone calls are necessary to clarify points which have not emerged in the discussion or which have remained obscure. In the case of the present survey, personal return visits were not found necessary, but only because the users had already been exposed in some measure to remote sensing techniques, either from public literature, or previous discussions with NASA personnel, or with the writers of this report.

4. In presenting the user package, one should concentrate on presenting results rather than just images, no matter how attractive. As such, care should be exercised in culling out examples of imagery or computer tapes which have been interpreted and annotated. It is not necessary that the inquirer have performed the interpretation himself; it is important that he be able to explain how it was performed.

   This point cannot be overemphasized; all too often this writer, wearing the "hat" of the user, has found himself in the position of requesting from remote sensing technologists the meaning of certain features on imagery or computer printouts, and has received the answer, "to do that you need to bring your own expert." Especially when employed with a new user, this approach can be deleterious to the credibility of remote sensing.

5. In presenting the capabilities of remote sensing from LANDSAT, it is important to be realistic. Extravagant claims or inferences--for example, on the ability to deeply penetrate subsurface phenomena--perhaps may be believed on the spot; yet as the user becomes conversant with the capabilities of the technique, they will do nothing but detract from his perception of its value--or of the competence of the presenter.

6. After presentation of the package, quering of the user in terms familiar to him, rather than in the terminology of remote sensing was found most important. In fact only one user (USGS-EROS) supplied specific answers to questions pertaining to sensor parameters, such as resolution, band location, and similar. This user has been deeply engaged in remote sensing applications for several years.

For most users, terms with which they are fimiliar such as: watershed area, length of streams, type of vegetative cover, must be employed to elicit a fruitful discussion.

7. The querier, once he has started the discussion going, must be careful to *listen* to the user. The user will sometimes bring up facts and requirements in a language different from that used by the querier. This is only natural since the backgrounds and the schools differ. For example, a highly competent user, rather than relating to "drainage density," preferred to specify this parameter in terms of "the minimum area of the watershed out of which he wanted to see a stream emerge." The querier must be sensitive to these semantic differences, and be able to make the appropriate translation. This is of course nigh-to impossible unless he has spent effort in familiarizing himself with the user's field, as already pointed out under item 2 above.

6.0 GENERAL ASSESSMENT OF USER INTEREST IN REMOTE SENSING, AND OF THE PROBLEMS RELATED TO ITS DISSEMINATION

The survey provided valuable insight into the user's receptivity to remote sensing techniques; it also revealed some problems, essentially of an economic nature whose solution the writers believe would significantly hasten the dissemination of remote sensing techniques, especially among the medium and small hydrologic users.

1. Most users--especially the Federal users--already employ remote sensing in the form of aerial photography. Several have done so for decades. They are thus quite familiar with its advantages and limitations. What they are interested in is what does the satellite offer that is better. One should thus concentrate on the aspects of frequent and readily accessible coverage (aerial photography for any one area is generally several years old; its repetition frequency is of the order of years); the capability to enhance the identification of landcover by means of the multispectral technique; cost per hectare; and so forth. In the experience of this writer, the user himself will generally ask these questions and will want a reasonably quantitative assessment of LANDSAT capabilities.

2. All users queried were significantly interested in remote sensing from LANDSAT. The problem is to show them how to use the technique, or to encourage them to using their own techniques. To this effect, it is most important to make it easy to use the LANDSAT products.

3. For those users employing computers, a method has been already pointed out in a previous report[1]: specifically to strip out from the tape of the entire 185 x 185 km LANDSAT frame the watershed subarea(s) of interest to the user, thus reducing the cost of acquisition of the tape. This cost is currently approximately $200 per scene (in four bands). The survey has shown that users wish to avail themselves of the repetition feature, available from the satellite.

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(1) "Impact of Remote Sensing Upon the Planning, Management, and Development of Water Resources," Castruccio, P.A., Loats, H.L., Fowler, T.R. and Frech, S.L., May 1975.

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Thus, they desire to obtain as many scenes as reasonably possible. For the user desiring a scene per season, for example, the price would climb to $800 which is quite high unless it can be shown to be worth the price.

The problem is aggravated for foreign users. For example, the Telespazio Company which has installed the LANDSAT ground station near Rome, Italy, is planned to charge $600 per scene.

A low-cost stripout technique transferable to foreign ground station owners should be seriously considered for development by NASA.

4. As regards imagery, a similar problem exists in a different form. The imagery cost of LANDSAT is comparable to that of aerial photography. It thus presents little problem. Although it is true that LANDSAT imagery can be analyzed with a simple light table and lens apparatus, costing perhaps $100, and thus within everyone's reach; the method, for a user with little experience in interpreting LANDSAT imagery is limited to high-contrast imagery. Much better results can be had by superimposing LANDSAT transparencies onto existing maps, such as USGS maps, or, even better, upon aerial photography. This brings out features not easy to observe with LANDSAT imagery alone. This superimposition technique is at present available only with commercial equipment costing $5000 and upwards. This capital investment is high, unless a user can be reasonably certain that the system can be fed a sufficient workload. He cannot be certain unless he tries, thus giving rise to the economic problem familiar to all who have been in the business of marketing new technologies.

It is recommended that NASA initiate a program to stimulate industry in developing low-cost apparatus, perhaps in the form of a user kit, possibly upgradable to higher capabilities as the user acquires familiarity and confidence with the technique.

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7.0 SUMMARY OF USER RESPONSES

7.1 Criteria for Selection of Users

The selection of the users to be queried was by necessity based upon a sampling scheme. The reader interested in the detailed exposition and backup documentation of the sampling procedure is referred to Reference (1), "Impact of Remote Sensing Upon the Planning, Management, and Development of Water Resources," May 1975, ECO75:C-3-III, Volumes 1 and 2. A summary of the criteria used is given here:

As regards the water resources application of the user:

1. *Share of the budget, magnitude of efforts, and scope of activities.* The major portion of water resources activities is conducted by Federal Agencies. These also motivate most of the hydrologic research conducted by Universities and State Water Research Institutes.

2. *Capillary spread of activity.* This criterion is directed at covering the large number of users not encompassed directly within the Federal Activities. These are the Local Government users, especially at the County level, whose aggregate budget is relatively modest compared to the budget of Federal Agencies, but who number in the thousands. As shown in Reference (1), local hydrologic activities also motivate most of the activities of Private Contractors.

As regards the specific hydrologic applications:

Table 1, drawn from Reference 1, ranks the important applications with known capabilities of remote sensing--which, for example, eliminates the otherwise important area of Economic Analysis and Planning--resulted in the definition of the following three major areas of application:

TABLE I

PRINCIPAL WATER RESOURCES APPLICATIONS RANKED BY USER INTEREST

CATEGORY	RANK			
	FEDERAL	STATE	WATER RESOURCE INSTITUTES	UNIVERSITY
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

1. Hydrologic Modeling, both Management and Planning;
2. Flood Plain Mapping;
3. Snowmelt runoff measurement and prediction

Because of the growing impact of remote sensing technology, of LANDSAT in particular, throughout the world, it was felt desirable to include in the sample also a foreign application: flood plain mapping for developing regions currently under development by the United Nations.

7.2 Users Selected for the Inquiry

Based on the affiliations and applications of the users, the following Agencies were selected for the query:

ARS - Agricultural Research Service of the U.S. Department of Agriculture - Management Models

SCS - Soil Conservation Service of the U.S. Department of Agriculture - Management and Planning Models

USGS - United States Geological Survey, Department of Interior - Management Models

COE - United States Army Corps of Engineers - Flood Plain Mapping - Management Models

SCS County Representatives - Soil Conservation, Waterworks Planning

United Nations Economic and Social Affairs Department - Flood Plain Mapping

The ARS represents a sophisticated user, devoted primarily to research in advanced hydrologic modeling on watersheds which are not highly urbanized. ARS is also interested in promoting the operational use of their models, and is employing some as such.

The SCS - Federal is concerned primarily with operational modeling, both for management and planning of non-highly urbanized areas. The SCS and TR-20 models have widespread application throughout the U.S.

The USGS represents primarily an operationally-oriented user, whose models are widely employed at state level, as well as at Federal level.

The COE is primarily operationally-oriented; the primary concentration in the query was upon their work on Flood Plain Mapping.

The local representatives of the SCS are located at the seat of virtually every County in the United States. Their principal concern is with determining hydrologic parameters indicative of soil erosion and sedimentation, and with the design of the appropriate waterworks to prevent or mitigate these effects.

In most counties they are responsible for approving the detailed design of projects affecting erosion and sedimentation, such as land development projects, roads. As such, they monitor most local engineering and surveying hydrological activities involved with overland flow.

The United Nations through their Economic and Social Affairs Department, Center for Natural Resources, Energy and Transport is planning a World Water Conference to be held in Buenos Aires in 1977. They have been aware of the problems caused by flooding, with special emphasis on the developing Nations, for some time. As part of the World Water Conference, they are considering a demonstration of the use of LANDSAT data in the so-called dynamic method of Flood Plain Mapping (2) (3).

7.3 Comparison and Commonalization of User Responses

7.3.1 Hydrologic Modeling

We will proceed by listing the user responses as to 1) the accuracy, 2) repetition frequency, and 3) method of accounting (whether aggregate over an area is sufficient, or whether the coordinates of the area must be related to the sought-for properties), with which the principal remotely sensible watershed parameters are desired.

7.3.1.1 Watershed Geometric Parameters

Watershed Boundary.

Users had difficulty in quantifying the accuracy with which this parameter needs to be measured. The best common answer is "commensurate with accuracies achievable from existing maps." Users preferred to think in terms of the next parameter:

Watershed Area

All users indicated that ±1% for total area was an upper limit. Lower limit: ±5% of total area. Local SCS-County work can tolerate ±10%. All users indicated that it is important to also measure subwatershed areas. Lower limit of accuracy: ±10%.

Slopes

All users consider this an important parameter. They are satisfied with the accuracies currently achievable from USGS topographic maps encompassing the watershed.

Watershed Shape

All users considered this factor as implicit in the definition of the watershed map. Their models do not take the factor "shape" into explicit account.

As regards frequency of repetition, users indicated that the watershed's geometric parameters need only be measured once, unless significant changes do occur in the watershed. Among such changes SCS includes those caused by major erosion. Major landslides or earthquake-induced changes may also be worth considering, although the occurence of significant modifications to the watershed's geometry due to these causes is rare.

As regards format of the data representing watershed geometry, users would prefer to see the product in the form to which they are most accustomed, namely as a topographic map.

7.3.1.2 Watershed Surface Cover

Vegetation

All users considered this observable of primary importance. There was general concurrence that the distinguishable classes of ground cover should be of the type: small grains, corse grains, tilled, forested, untilled and so forth.

As to the accuracy of areal measurement of cover; ±5% is considered quite good, ±10% adequate, for each class of identified ground cover. Most users would accept information on ground cover as an *aggregate*, or percent coverage, for subwatersheds or small watersheds. In other words, a detailed *description* of where the cover is located is *not required*, as long as the watershed is small, or is a relatively small subwatershed of a larger watershed unit.

A notable exception is SCS - Federal, who wishes to perform delineation of vegetative boundaries; they require *association* of the class of cover with its *geographic location*.

As regards frequency of coverage, a significant difference was encountered in user desires. ARS is interested in the dynamic changes in vegetation, which they use as an indicator of evapotranspiration and infiltration. They wish a frequency of coverage as high as possible: weekly if available, although lesser frequencies would also be acceptable.

USGS-EROS position was that if the cover is used as a semi-invariant to compute overland friction flow, frequency of coverage could probably be only seasonal. It if is used to compute evapotranspiration they would require a biweekly coverage.

SCS is interested in seasonal variations: twice yearly as a minimum, four times preferably.

The Locals are interested primarily in recording major changes, for example due to urbanization. Thus once yearly or every few years for areas in rapid development would be adequate.

Soil

There was agreement on the desire of identifying the principal soil types in terms of their hydrologic properties, particularly infiltration. Next in importance would be the capability to perform soil association, to determine the gross properties of the underlying horizons.

Frequency of coverage can be low, unless major changes do occur, such as urbanization, roadbuilding.

Impervious Areas

The accuracy of their areal measurement is a function of what fraction of the watershed they occupy. An overall accuracy of ± 5% of the total watershed area appears adequate. Most users are satisfied with an aggregate measurement for small watersheds and for subwatersheds. SCS desires their location outlined as well. Frequency of coverage is similar to that for soils.

Impounded Water

The users did separate two aspects: 1) impounded water as an impervious area, and 2) as a reservoir storage device, natural or artificial. The first aspect is included in, and treated similarly to the impervious areas above: USGS indicated desirability of measuring areas down to 10 acres. As to the second aspect, users desire to identify the existence of dams; more importantly, to measure the total storage within the impoundment. The frequency of coverage depends upon the variability of the inpoundment surface, and its importance relative to the watershed hydrology.

As regards the format of the data, the users would prefer an annotated map indicating the extent and type of cover.

Alternately, many users would accept a listing of the composition of the cover, in percent of total area, for each subwatershed.

7.3.1.3 Drainage Characteristics

Drainage Pattern

When pattern was defined as the order of bifurcation of the streams, the users felt more comfortable in discussing the subject in terms of:

Drainage Density

SCS does not use this datum in their models. The local users do neither. The other users desire to observe streams as small as those which issue from areas of 0.25 to 0.5 square miles. USGS-EROS considers this too stringent for the larger watersheds. Frequency of coverage should be sufficient to allow tracing the streams in their entirety. Some are less visible at certain seasons. Once the stream pattern is established, coverage need only be repeated if significant changes occur.

Channel Length

SCS is interested in this parameter: they feel it is generally underestimated, especially when picked from conventional maps. The local users are not. The other users do not appear particularly interested: by implication, they

wish to see the channel leading up to the 0.25 or 0.5 square mile segment, as indicated above. Frequency of repetition is similar to that covered under the above paragraph, Drainage Density.

Channel Width

Users were not sure this parameter is required for hydrologic modeling.

7.3.2 Flood Plain Mapping

There was high interest in this hydrologic application by most users. The two principal parameters discussed were accuracy of floodplain measurement, and density of measurements required along the stream axis.

Flood Plain Width

The responses differed somewhat in detail, but were essentially similar in content. Accuracies of flood plain width measurement should be expressed in percentages of the width rather than as absolute figures. ±5% appears adequate, increasing to an upper limit of ±10% for large streams. A reasonable lower bound is ±5 meters, applicable to urban work performed on 1:24,000 scale. For regional work, at scale 1:100,000, accuracies between ±50 and ±100 meters appear adequate. Exceptions exist in the small towns, of which several want the flood plain boundary carried to property lines rather than to the nearest easily-distinguishable landmark. USGS-

EROS recommends mapping the alluvial plain, as an indicator of the worst possible flood likely ever to occur. Significant input from SCS: the accuracy should be specified as a function of the use, i.e. differently for different uses.

Density of Measurements Along the Stream Axis

The figure suggested by the inquirer of one measurement every 50 meters along the stream axis was considered far too stringent by USGS-EROS. The consensus of desires is that this parameter should be made a function of the variability of the flood plain.

As regards frequency of measurements, they should occur every time there is a significant flood, with a time tolerance which is a function of the variability of the traces left by the flood.

7.3.3 Runoff from Snow

This is considered a significant hydrologic measurement by all users: with the obvious caveat that the importance varies with the region.

Snowpack Area

Areal measurement accuracy of ±5% appears adequate. SCS would like to measure the amount of snow which drifts downhill, driven by wind. Users would like to have a simple model based upon area only, if this were physically possible. SCS indicates that they feel that snowpack area is not sufficient to

predict runoff: some measure of depth or water content is desirable.

Snowline Altitude

USGS-EROS indicates that this parameter should be a function of the terrain slope. An accuracy of ±50 meters is too tight for mountainous areas, too loose for flatter areas.

Surface Melt

Users indicate that a reliable measurement of temperature would be desirable. Accuracy of ±5% of the melt appears adequate. Repetition frequency should be commensurate with the variability of the melt. A biweekly observation interval appears to be adequate, weekly desirable.

The format desired could be either: a) a table of numbers, or b) an annotated scale drawing of the snowpack area showing the temporal variations of area.

8.0 ANALYSIS OF USER RESPONSES

A considerable amount of information is contained in the set of user responses. Let us attempt to extract it, following the same order of topics used in the previous Section.

8.1 Hydrologic Modeling

8.1.1 Watershed Geometric Parameters

8.1.1.1 Watershed Boundary and Watershed Area

Whenever good maps are available, these parameters can be derived conveniently from them. In those localities where maps are not available or are of doubtful accuracy or at too small a scale, the watershed boundaries can be identified by the well-known method of measuring average distances between adjacent drainage patterns. In this case, the permissible random error in establishing the boundary can be shown to be approximately:

$$e_b \approx 100\ e_a \sqrt{A} \qquad (1)$$

where: e_b = linear dimension of one sigma random error committed in defining the watershed boundary, meters

e_a = relative desired error in the area measured, one sigma, $= \dfrac{\text{hectares measured} - \text{hectares true}}{\text{hectares true}}$

A = watershed area, hectares

Thus, for example, if the watershed area to be measured is 10,000 hectares (the median watershed of the small U.S. users), and the desired measurement error is ±5% or less, the average

error in locating the boundaries must be approximately:

$$e_b \approx 100 \times 0.05 \times \sqrt{10,000} = 500 \text{ meters}$$

The 500 meter figure should not be construed as the resolution element required. The resolution rather, must be commensurate with the *capability of observing* the smallest recognizable streams near the watershed boundary, since it is from the pattern of these streams that one determines the boundary. Thus the proper measure for the resolution required is in terms of *length of streams* This is discussed in Section 8.1.3.

Figure 2 shows the permissible error for various watershed areas of practical interest and for a practical range of user-specified errors.

8.1.1.2 Slope

The users indicate that slope measurements desired are those commensurate with existing USGS maps encompassing the watershed under study.

A fair estimation of what this means can be arrived at by making the reasonable assumption that the watershed under study covers between 1/4 and 1/2 the area depicted in the topo map. The graph of Figure 3 was constructed by correlating the area subtended in the standard USGS topo maps, and their corresponding contour intervals. Figure 3 essentially depicts the *slope determination accuracy* which a remote sensing system *should achieve* to match the user requirements.

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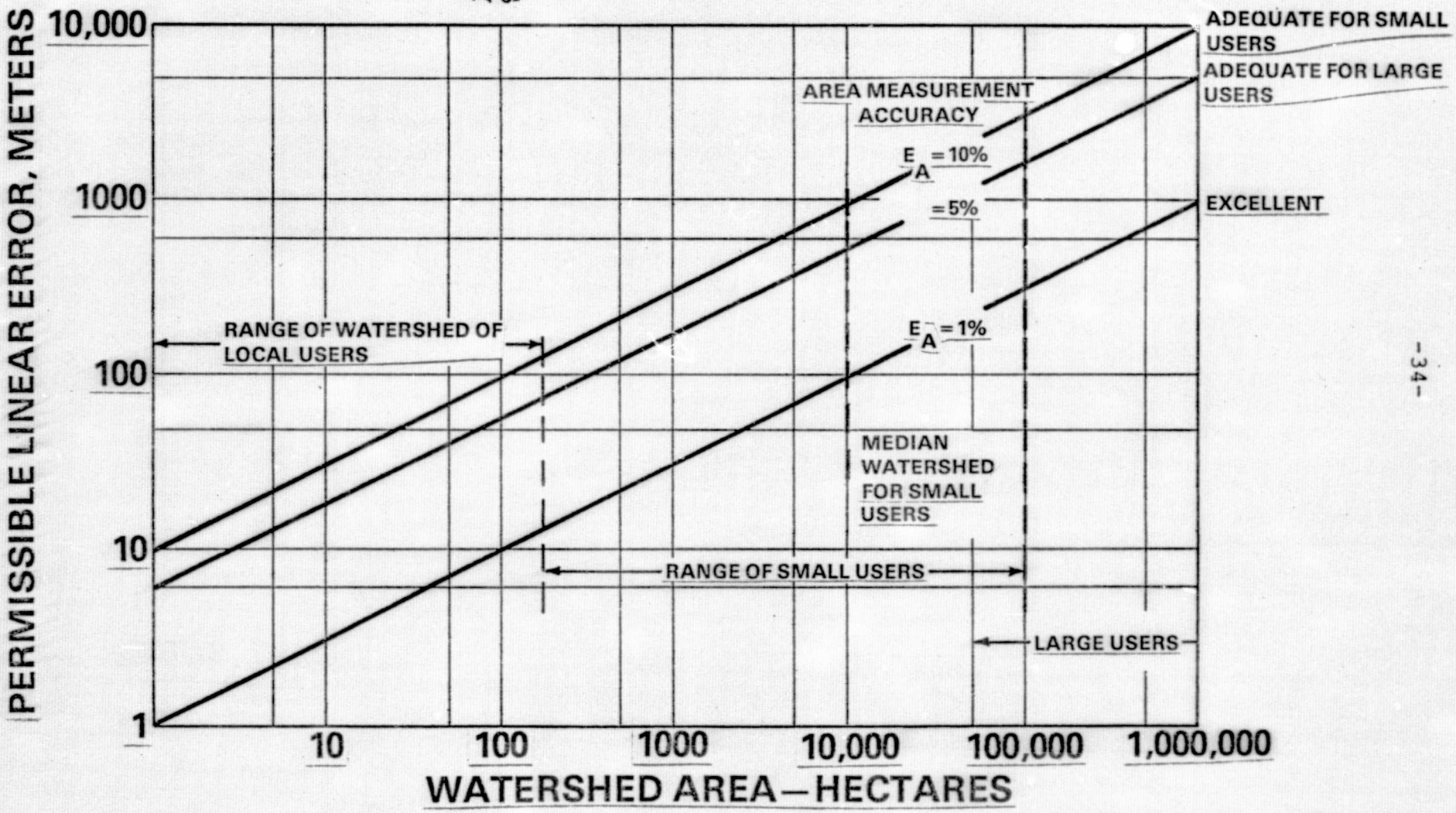

FIGURE 2 PERMISSIBLE LINEAR ERROR IN LOCATING WATERSHED BOUNDARIES

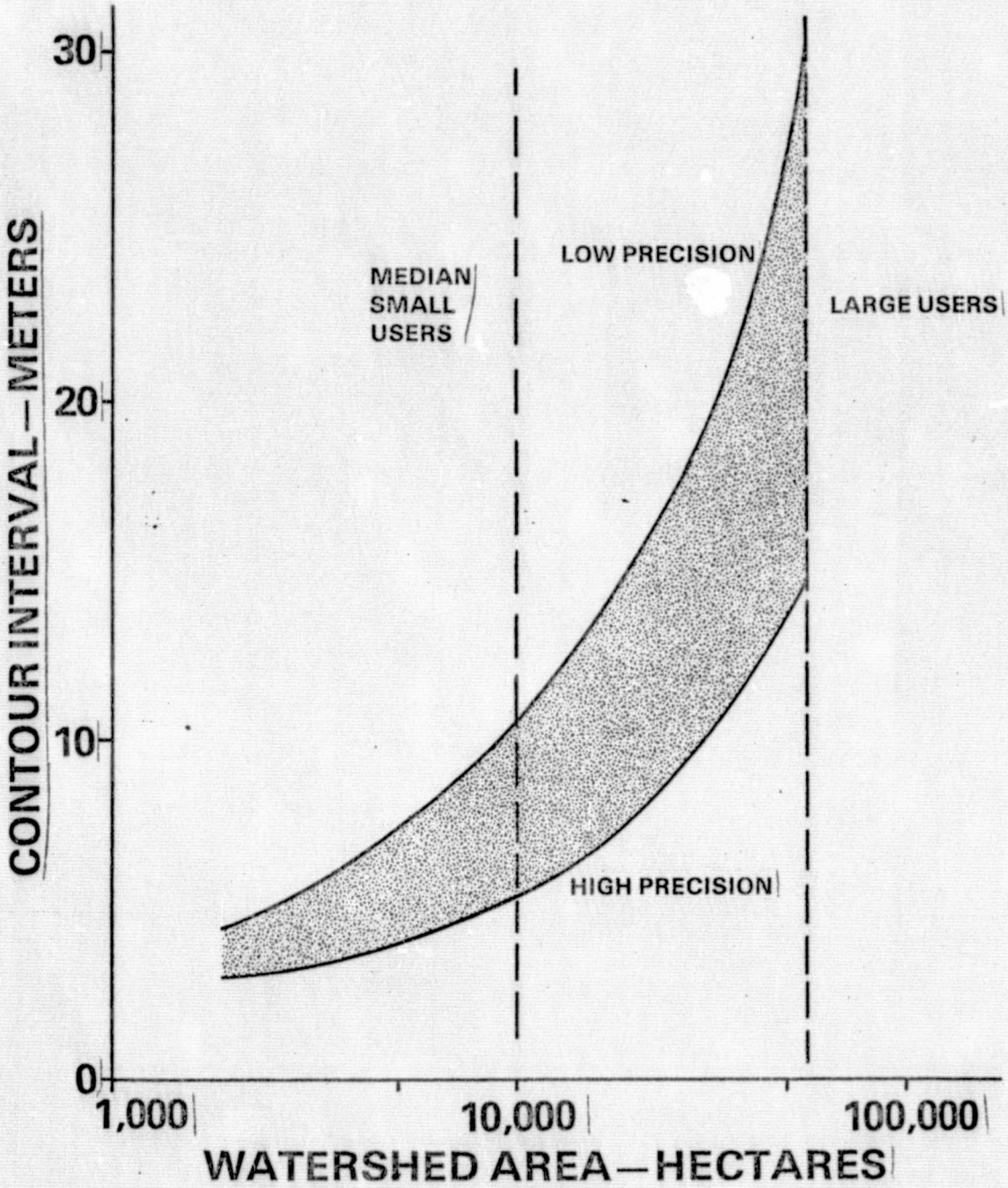

FIGURE 3 USER REQUIREMENTS FOR ACCURACY OF SLOPE MEASUREMENT

8.1.2 Watershed Surface Cover

8.1.2.1 Vegetation

The measurement of vegetative areas -- and, in fact, of cover in general - hinges upon two functions: 1) Discrimination, i.e. identification of the class of cover, and 2) mensuration, i.e. the measurement of its area. The first measurement is based upon the spectral reflectance statistics. It can be performed in two modes: 1) the land use mode, in which the identified cover is associated with its location -- in essence producing a land use map; or 2) the inventory mode, in which the constraint of location specification is relaxed, and the objective is to provide only an averaged, or aggregated, land use. In the inventory mode, the land cover is expressed in terms of "percent cover" for each class of cover. As was seen in Section 7, all users except SCS find the inventory mode adequate for subwatersheds and for the smaller watersheds. The types of distinct cover classes desired are typical of Level II and III land use classification, depicted in Figure 4. In the inventory mode, the percentage area covered with a given species is measured by ratioing the number of pixels classified into the various classes of interest to those covering the total area. It is shown in Section 10 that the error in classification combines with that of mensuration, resulting in a larger total error. The user requirements indicate that the required accuracy of mensuration, including classification, of each class of cover indicated in

FIGURE 4 LAND USE IDENTIFICATION DESIRED BY HYDROLOGIC USERS [PARTIAL SET OF USGS/NASA LAND-USE CLASSIFICATION SYSTEM]

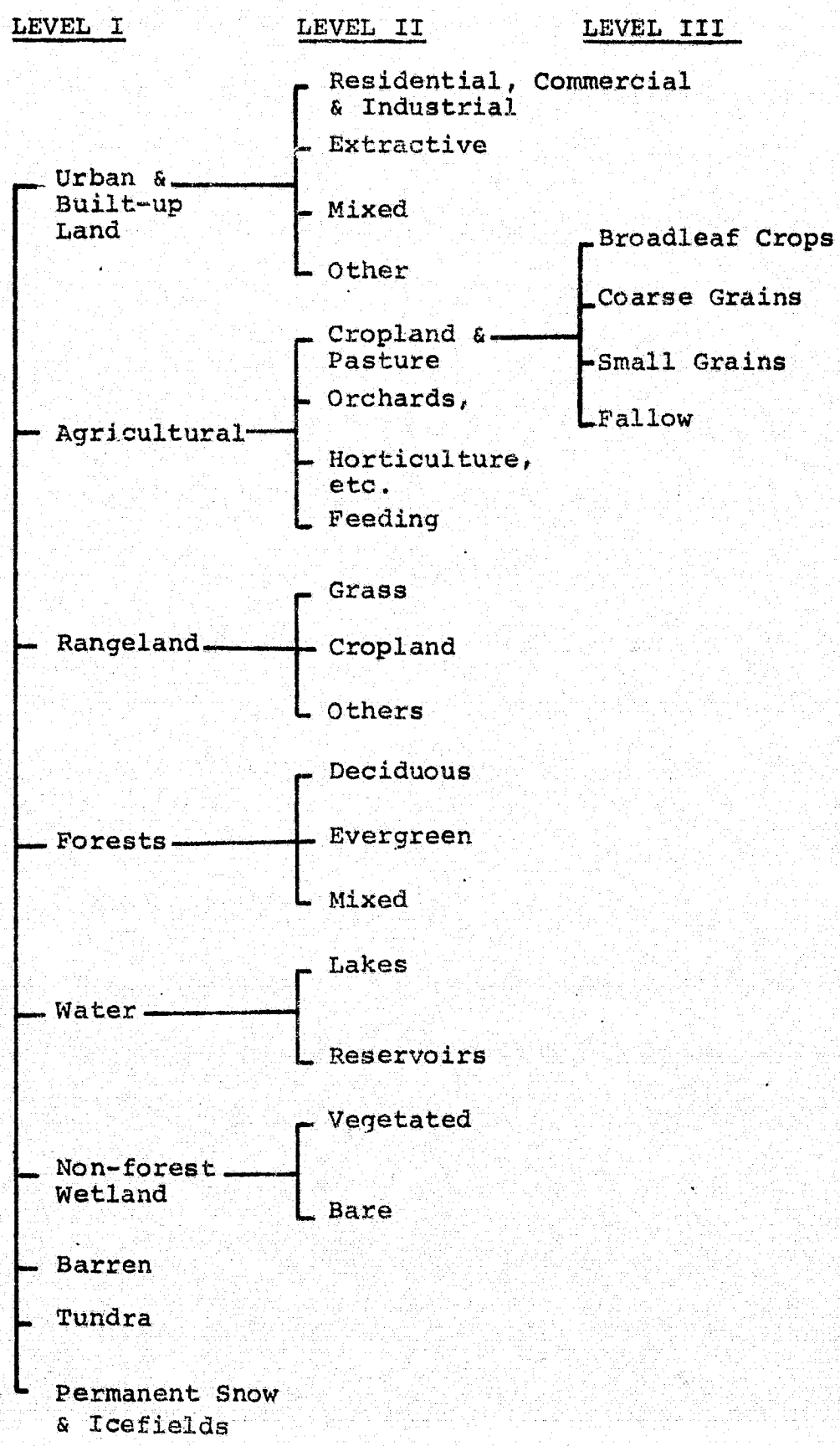

Figure 4, should be of order 90% to 95%.

The essence of the inventory mode is that errors of commission tend to balance statistically the errors of omission. This requires: 1) that the errors occur in as random a manner as possible, and 2) that the number of samples be sufficiently large to reduce the variance to a value reasonably smaller than the desired maximum error. Errors that cannot be balanced in this manner are attributable to the systematic errors, i.e. departures of the measuring method from truly random behavior. The precise definition of the number of samples required depends upon the detailed knowledge of the statistics or spectra of the cover being observed.

In the land use mode, mensuration can still be performed by counting the number of pixels classified into the various classes of interest. The required accuracies are of the same order as those indicated above, namely 90% to 95%. It should be noted that the accuracy of classification achievable is generally less than for the inventory mode. This is because the requirements for the land use type of classification are more stringent on the sensor and information extraction system than those for an aggregate, or inventory classification.

All mensuration modes present the problem of border pixels, in which classification is uncertain because the pixel straddles two covers of differing spectral characteristics. If there is no error of classification, the mode becomes geometric mensuration. Its associated error can be expressed by the approximate formula*:

$$e \approx \frac{2kr}{\sqrt{A}} \qquad (2)$$

where: e = error, percent of area mensurated

r = resolution element: linear dimension of pixel, meters

A = area mensurated, hectares

k = a coefficient which depends upon the sophistication of the mensurating algorithm, upon the contrast ratio, and upon the shape of the plane figure being mensurated.

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*In conventional property surveys, the permissible error e is specified usually as:

$$e \text{ (absolute)} = a\sqrt{A} + b\,A$$

where a, b are coefficients which vary among Countries, although not by much. The first term of the above equation represents the contribution of random errors, the second of systematic errors. Dividing the above expression by A, one obtains the relative, or fractional permissible error:

$$e \text{ (relative)} = \frac{a}{\sqrt{A}} + b$$

Typical values for a and b (Italy) are a = 0.7, b = 0.001. It is virtually certain that a systematic error appears in mensuration from LANDSAT. Its value is not known with certainty: this fact tends to indicate that it is small, otherwise chances are it would by now have been detected.

Errors for various values of k and for essentially square shapes are given in Figure 5. Assuming a value of k = 1, typical of visual interpretation and of the less sophisticated computer processing schemes and of reasonably good contrasts, the minimum area which can be mensurated to specified errors and with specified pixel sizes (resolution) is given in Figure 6.

Accuracy of mensuration, both in the inventory and land use modes, hinges upon the accuracy of classification. Figure (4) depicts the cumulative distribution of accuracies achieved by workers with LANDSAT data thus far in classifying agricultural cover. To provide a feel for typical achievable classification accuracies, it presents the results of 64 distinct "experiments," or attempts at classification. The 64 experiments were selected out of a larger population of 224, using as principal selection criterion *the controllability of the results reported by means of ground truth*. The meaning of the curves of Figure 7 is that on the average, for a sufficiently large number classification experiments, the probability of achieving 90% accuracy is 50% in the inventory mode, 20% in the land use mode.

Note that the data presented in Figure 7 pertain to discrimination of major crops, which is a Level IV problem, more complex than the Level II and III classifications required by hydrological users. Thus one should expect somewhat better performance in hydrologic applications than that indicated in Figure 7.

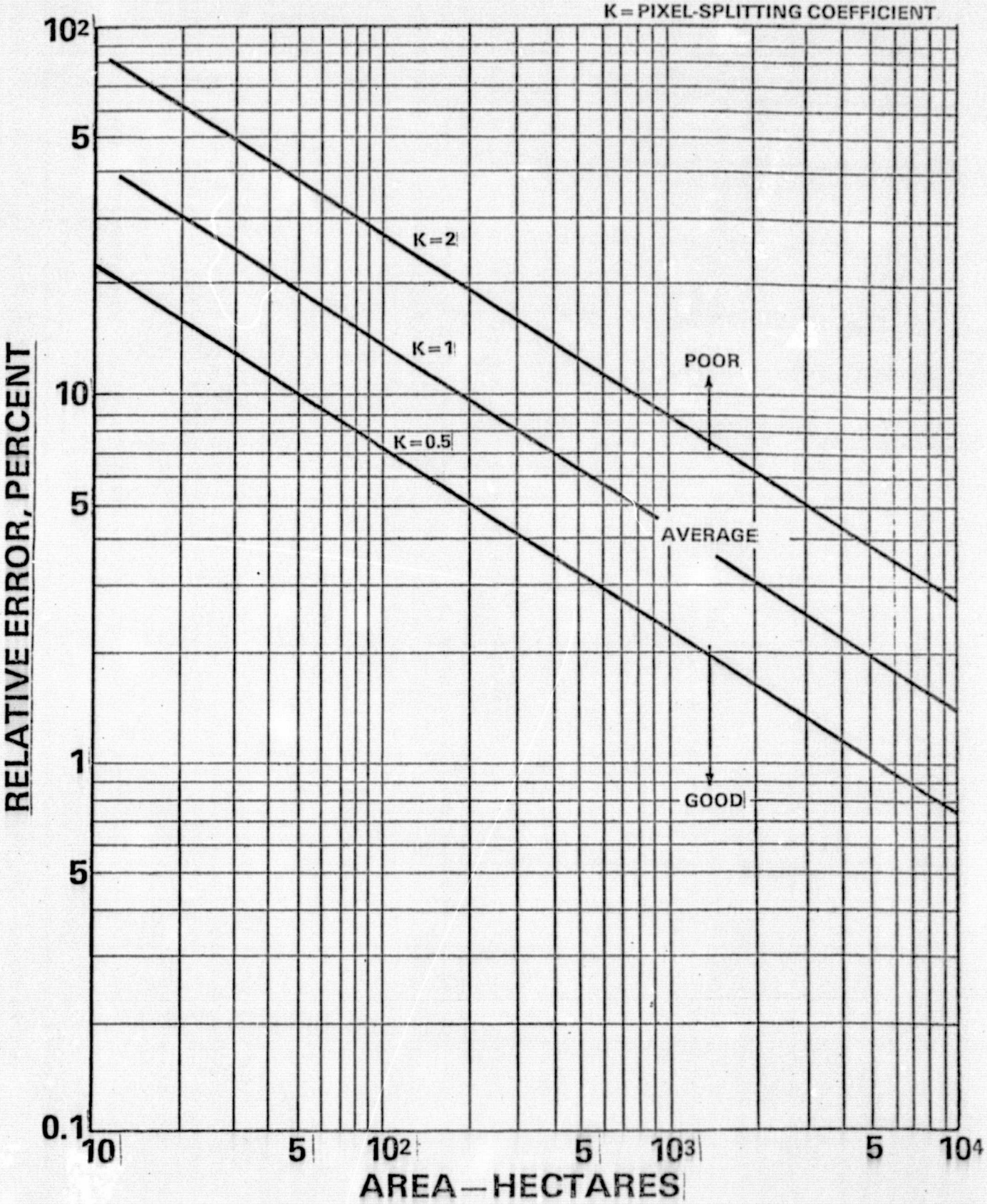


FIGURE 5 MENSURATION ACCURACIES ACHIEVABLE WITH A RESOLUTION OF 66 METERS (LANDSAT AVERAGE PIXEL DIMENSION)

ECOSYSTEMS
INTERNATIONAL INC.

FIGURE 6

MINIMUM AREA OF CONTINUOUS SNOWPACK MENSURABLE TO A ±5% ERROR AS A FUNCTION OF RESOLUTION

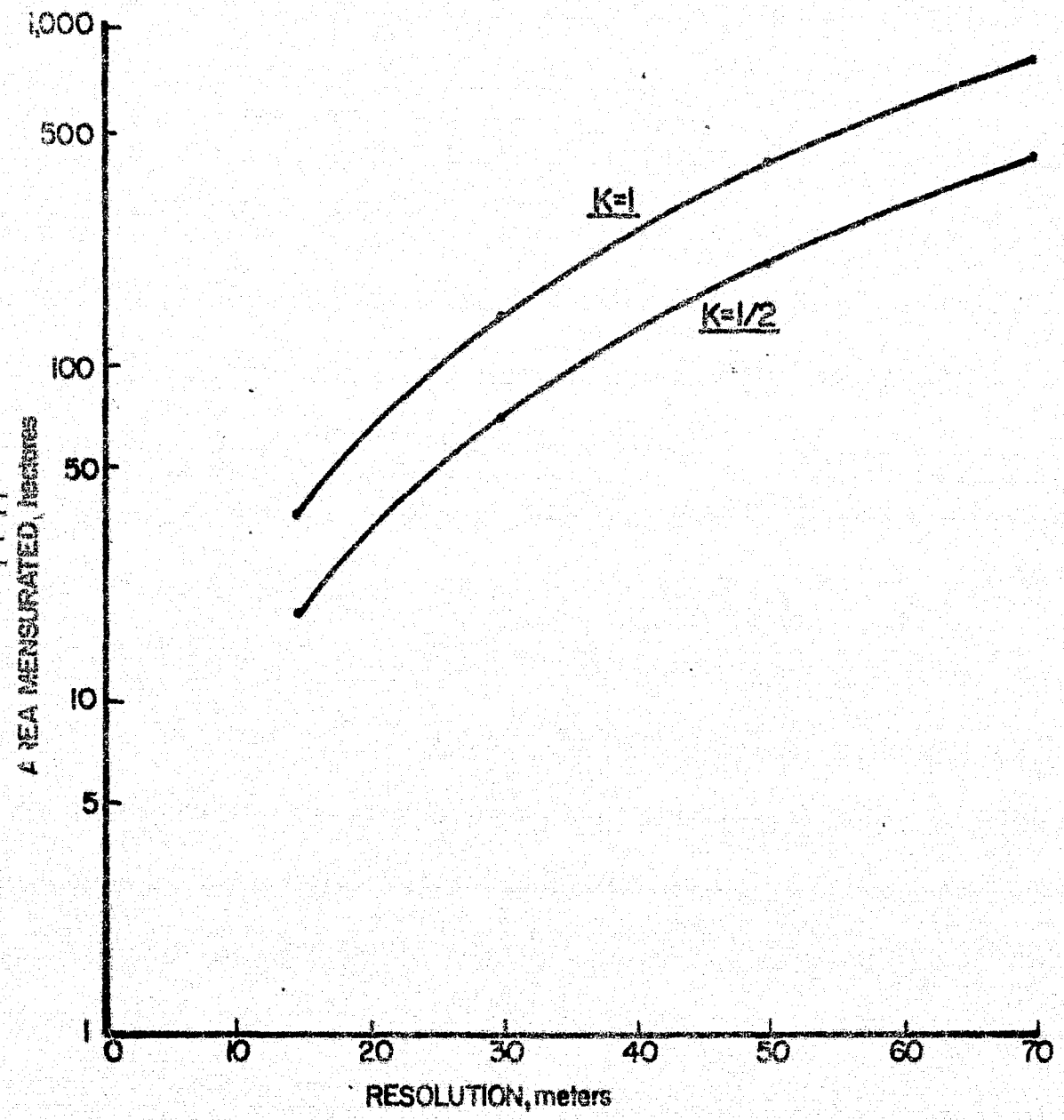
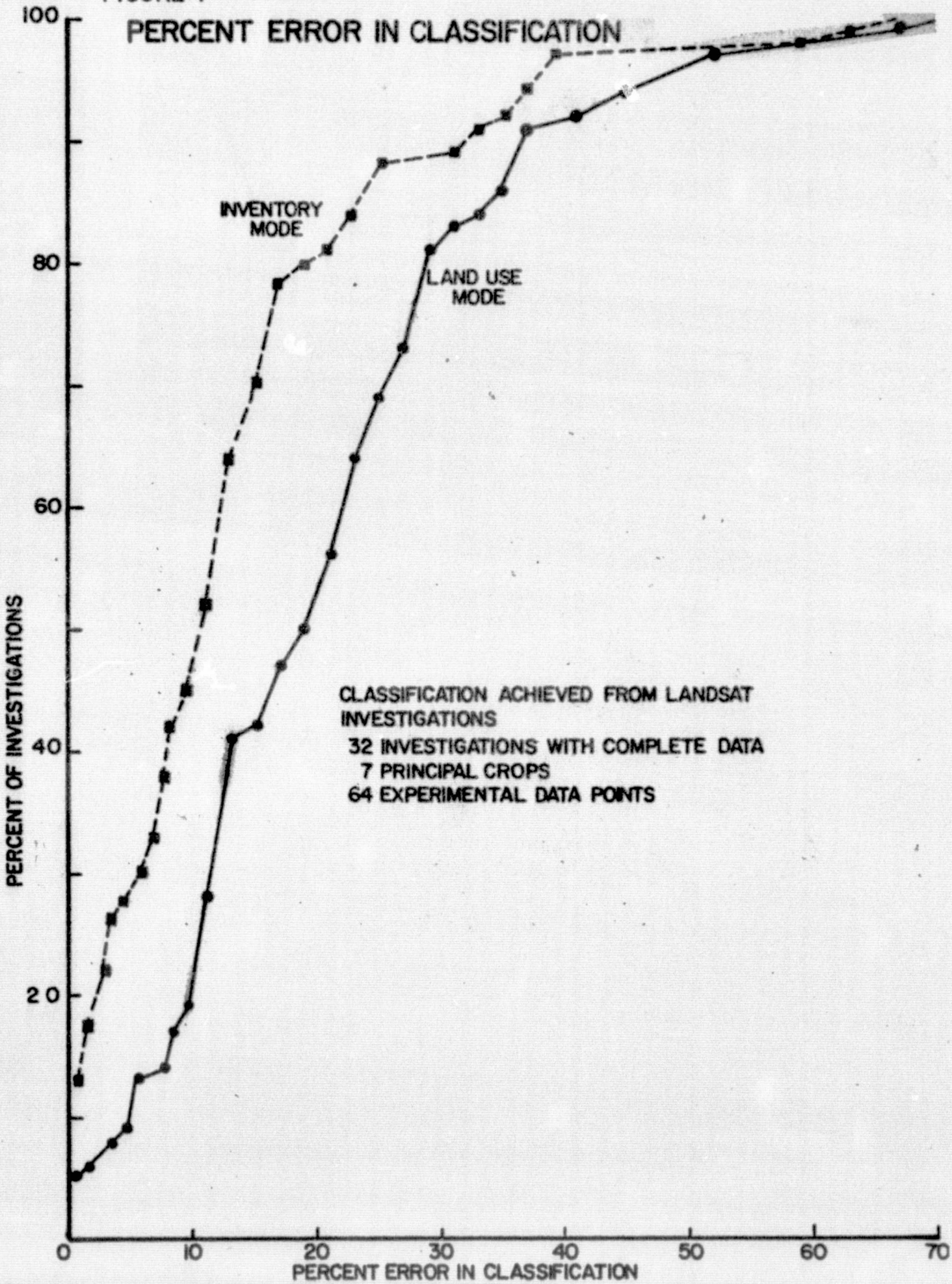


FIGURE 7


PERCENT ERROR IN CLASSIFICATION
INVENTORY MODE
LAND USE MODE
CLASSIFICATION ACHIEVED FROM LANDSAT INVESTIGATIONS
32 INVESTIGATIONS WITH COMPLETE DATA
7 PRINCIPAL CROPS
64 EXPERIMENTAL DATA POINTS
PERCENT OF INVESTIGATIONS
100
80
60
40
20
0
10
20
30
40
50
60
70
PERCENT ERROR IN CLASSIFICATION

8.1.2.1.1 Repetition Requirements for Vegetation

As regards frequency of repetition, the present biweekly coverage is adequate for all users: research-oriented users would prefer a somewhat more frequent coverage, but not critically so. Operationally-oriented users can tolerate reduced frequency.

8.1.2.2 Soil and Impervious Areas

The conclusions drawn for vegetative cover apply to these components of the cover.

8.1.2.3 Impounded Water Storage

The direct measurement of this quantity requires measurement of depth. In the case of clear and relatively shallow water this is conceivably achievable from transparency measurements. More commonly, in turbid waters, a gross measurement is achievable by mensurating the water area and coupling this measurement with physiographic knowledge of the slope of the terrain. Where the economics warrant, DCP's can be used to record water level. Water impoundment must be measured in the land use mode. Figure 6 depicts the accuracies achievable as a function of the resolution. It assumes that the areas to be mensurated have been correctly identified, a good assumption for reasonably "clean" water surfaces.

8.1.3 Drainage Characteristics

8.1.3.1 Drainage Density

The user requirements of discerning the stream which issues from a 0.25 to 0.5 mi^2 area can be translated into drainage density with reference to Figure 8. Consider a square area of side dimension d. The area is d^2. Consider a single stream splitting this area. Its length is d. The drainage density is then

$$\frac{d}{\text{Area}} = \frac{d}{d^2} = \frac{1}{d} \qquad (3)$$

Elementary computations yield:

For A = 0.25mi^2 = 647,200m^2 ≈0.65 Km^2:

Drainage density = 0.00124 meters/$meter^2$ = 1.24 Km/Km^2

For A = 0.5 mi^2 = 1,294,400m^2 ≈ 1.3 Km^2

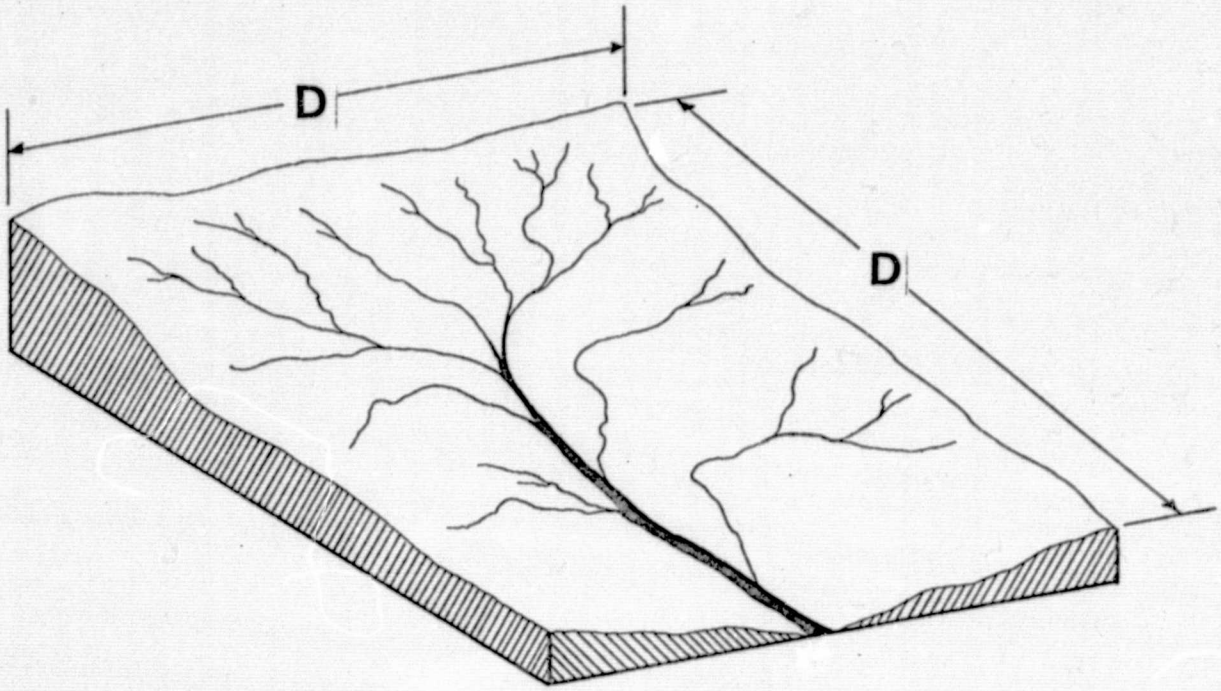
Drainage density = 0.00088 meters/$meter^2$ ≈ 0.9 Km/Km^2

The drainage density measurement required by the users thus do not exceed values comprised between 0.9 to 1.3 Km^{-1}.

The measurement of this quantity obviously depends upon the measurement of channel length, which in turn depends upon the minimum discernible channel width.

8.1.3.2 Channel Width

Channel width as a function of the channel's upstream reach depends upon the morphological characteristics of the watershed. Figure 9, adapted from Reference (5), depicts the range



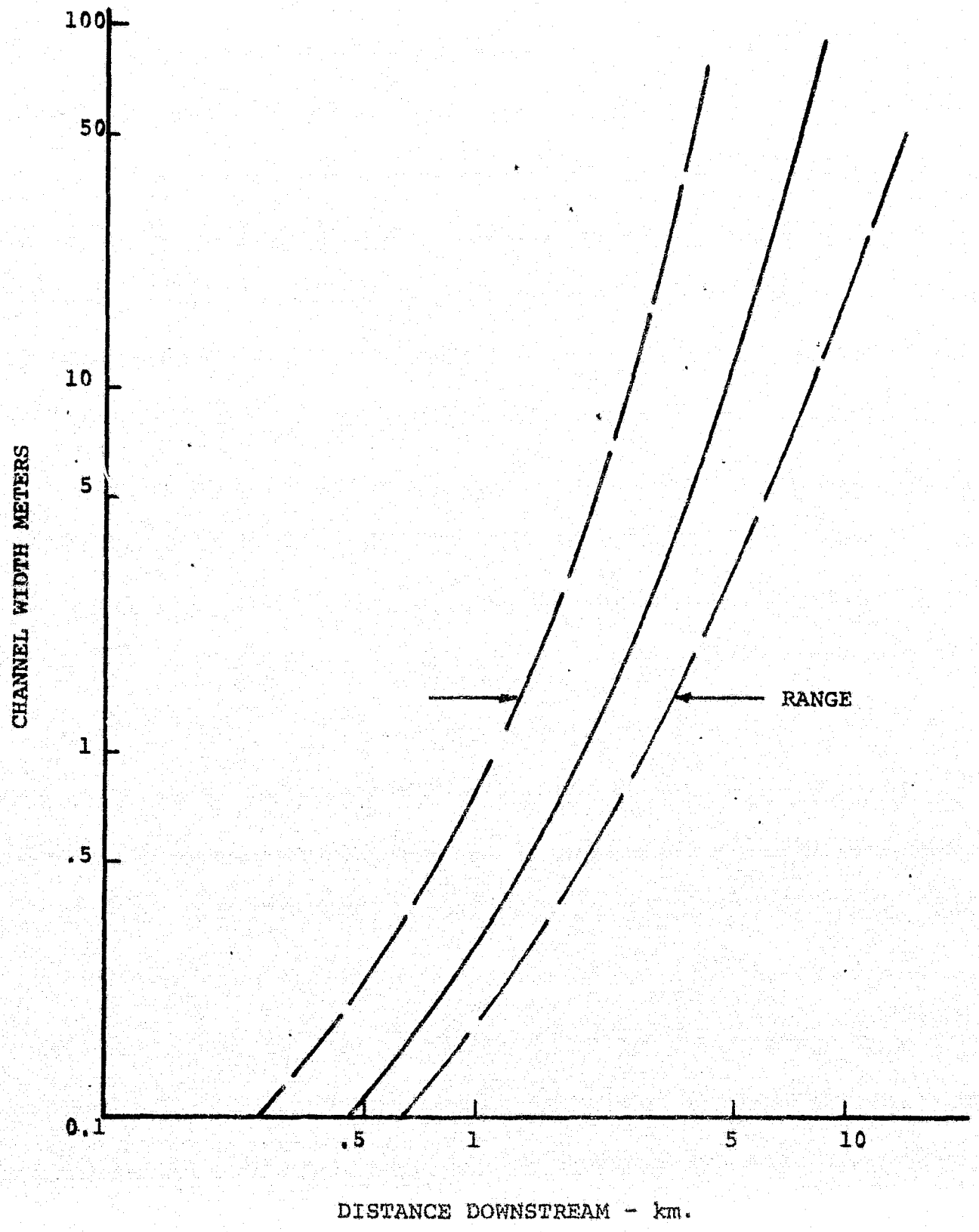
$$\text{AREA} = D^2$$

$$\text{STREAMLENGTH} = D$$

$$\text{DRAINAGE DENSITY} = \frac{D}{\text{AREA}} = \frac{D}{D^2} = \frac{1}{D}$$

FIGURE 8. SCHEMATIC MODEL FOR COMPUTING DRAINAGE DENSITY

FIG. 9 RELATIONSHIP BETWEEN STREAMWIDTH AND DISTANCE FROM STREAM ORIGIN



of channel widths which can be expected to occur over a range of typical watersheds as a function of the distance downstream. The user requirements quantified in the previous Section can be adapted to the computation of the desired discernible downstream length as follows.

As a minimum, it is desired to identify the stream issuing from a 0.25 to 0.5 mi^2 area without wishing to know what happens inside the area itself. If the area is assumed square, the downstream distance would equal the side of the square. This turns out to be:

For the 0.25 mi^2 area: 800 meters

For the 0.5 mi^2 area: 1,138 meters

A more stringent assumption is that one would wish to discern something of what goes on inside the area. This can be approximately quantified by requiring that one-half of the above distances be discernible. Combining the two requirements yields the following ranges:

For the 0.25 mi^2 area: 400-800 meters

For the 0.5 mi^2 area: 560-1,140 meters

From Figure 9, the corresponding channel widths range from 0.1 to 0.25 meters.

In regions subject to frequent flooding, and where vegetation is slow to cover up their traces, the flood traces may be visible as a "pseudo-channel" wider than the channel's actual width. In the normal case, the visibility of the channel depends upon the contrast between the channel and

and the surrounding background (6). Specifically, the resolvable channel width is given approximately by:

$$w = \frac{r}{\left|\left(n_c - n_b\right)\right|} = \frac{r}{n\left|\left(1 - \frac{n_b}{n_c}\right)\right|} \qquad (4)$$

where: w = resolvable channel width

r = resolution (pixel linear dimension)

n_c = radiometric signal-to-noise level of channel

n_b = radiometric signal-to-noise level of surrounding background

$\frac{n_b}{n_c}$ = contrast ratio between channel and background

Interpreted rigorously expression (4) indicates that the process of discernment of channel width is statistical, because the n's are statistical variables. With somewhat less rigor, but adequate for our purpose, especially so at high signal-to-noise ratios, (4) can be written:

$$w = \frac{r}{q\left|\left(\rho_c - \rho_b\right)\right|} = \frac{r}{\rho_c\, q\left|\left(1-c\right)\right|} \qquad (5)$$

where: ρ_c = reflectance of channel

ρ_b = reflectance of background

c = contrast ratio = $\frac{\rho_b}{\rho_c}$

q = Number of levels comprised between $\rho=0$ and $\rho=1$.

TABLE 2

TYPICAL REFLECTANCES AND CONTRAST RATIOS FOR CHANNELS AND THEIR SURROUNDING BACKGROUND

BAND, μm	ρ (BACKGROUND)	ρ (CHANNEL)		CONTRAST RATIO		NO. OF LEVELS
		WET	DRY	WET	DRY	q
0.5-0.6	0.15	0.15	0.30	1	0.50	64
0.6-0.7	0.20	0.10	0.35	2	0.57	64
0.7-0.8	0.35	0.08	0.40	4.37	0.87	64
0.8-1.1	0.50	0.08	0.60	6.3	0.83	128

The contrast ratio varies as a function of whether the channel is dry, in which case the reflectance of channel-bottom soil prevails, or wet in which case the reflectance of water dominates. Typical contrast ratios drawn from existing data are shown in Table 2, together with the number of levels available in LANDSAT A and B. It can be seen that the improvement factor, indicating *how much smaller an object than the resolution element can be distinguished* is:

$$\frac{r}{w} = \rho_c [(1-c)]q \qquad (6)$$

Table 3 indicates the achievable improvement factor and the effective minimum streamwidth theoretically discernible from LANDSAT, under the assumptions given. It can be seen that the current average LANDSAT resolution of 66 meters should allow recognition of channel widths no smaller than of the order of 2 meters for wet, 5 meters for typical dry channels. This in turn should allow identification of channels in the range of

TABLE 3

IMPROVEMENT FACTOR AND ACHIEVABLE LANDSAT EFFECTIVE RESOLUTION IN MEASURING STREAMWIDTH

BAND, μm	IMPROVEMENT FACTOR		EFFECTIVE RESOLUTION, METERS	
	WET	DRY	WET	DRY
0.5-0.6	0	9.6	66	7
0.6-0.7	6.4	9.6	10	7
0.7-0.8	17.3	3.3	4	20
0.8-1.1	54	13	1.2	5

approximately 1.5 to 5.5 kilometers downstream. The corresponding minimum recognizable area from which a channel emerges is of order 2.25Km^2 to 30Km^2, or approximately twice to as much as 45 as denied by the users, depending upon the season of observation.

8.2 Flood Plain Mapping

The key parameter is flood plain width.

8.2.1 Flood Plain Width

Figure 10 recapitulates the user requirements. These range from a minimum of ±5 meters for small widths, progressing to ±5% of the width for intermediate, up to ±10% for large widths, with an upper bound of ±100 meters. Note that the requirements of some of the small towns, conveyed by SCS, are not included because too stringent (measurement to property lines).

The accuracy of linear mensuration of flood plain width is given by the approximate formula:

$$e \simeq \frac{r}{\left| n_f - n_b \right|} = \frac{r}{\left| n_f \left[1 - \frac{n_b}{n_f} \right] \right|} \qquad (7)$$

where: e = error, meters

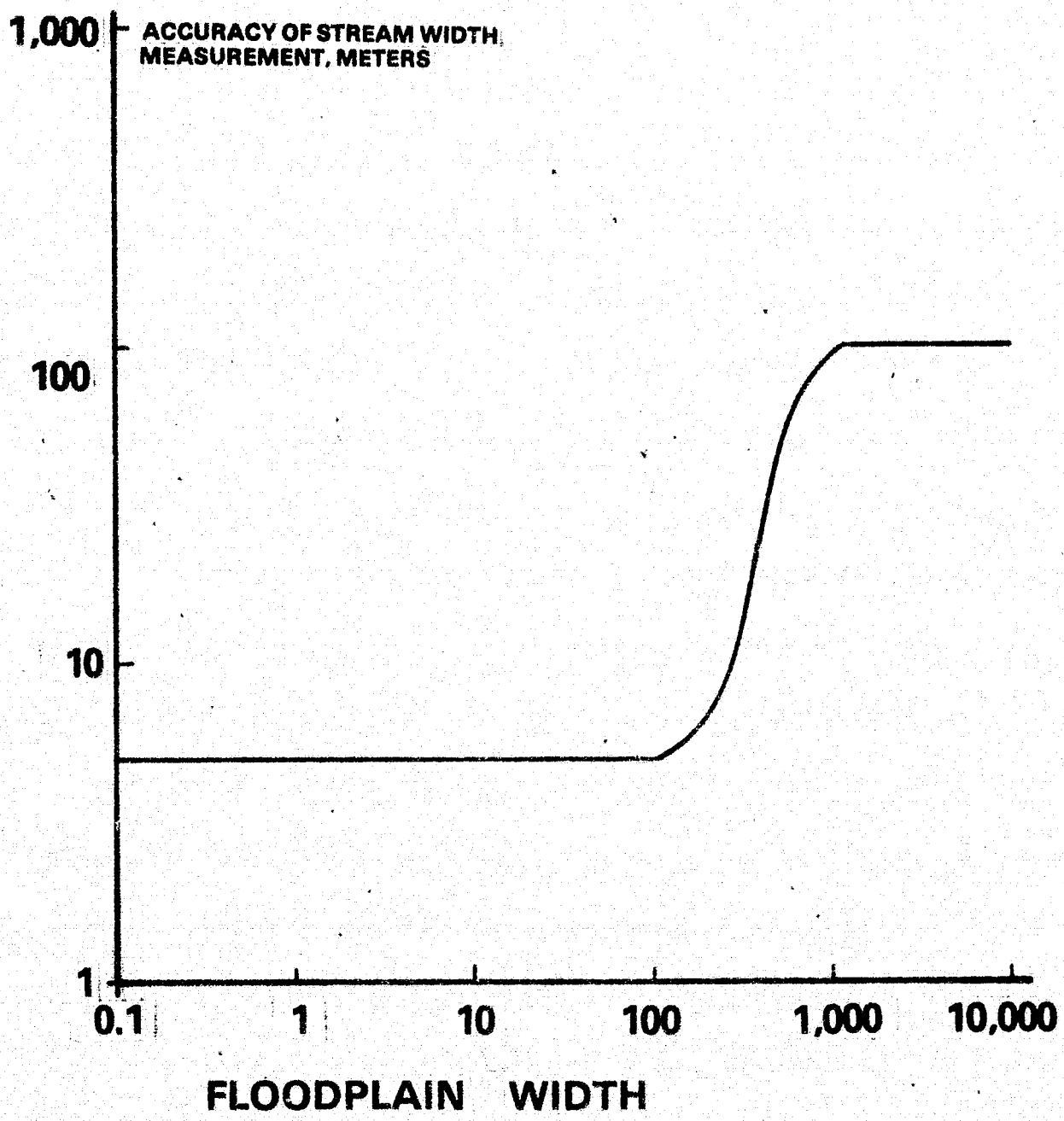
r = resolution (pixel linear dimension)

n_f = radiometric signal-to-noise level of flooded area

n_b = radiometric signal-to-noise level of surrounding background

$\frac{n_b}{n_f}$ = contrast ratio

FIGURE 10—SYNOPSIS OF USER REQUIREMENTS FOR ACCURACY OF FLOOD PLAIN WIDTH MEASUREMENT.



The contrast ratio varies as a function of whether the flood is observed at its peak, in which case generally the reflectance of water against surroundings dominates; or whether what is being observed are its traces, after the peak has passed. In this latter case the contrast is determined by the water-stressed vegetation and/or wet soil against unstressed vegetation and/or drier soil. Typical data and computational results were presented in Table 3. This indicates that effective resolutions of 2 to 5 meters should be theoretically available from LANDSAT information . It is recommended that the extent to which this theory has been translated into practice be thoroughly investigated by analyzing the available results from LANDSAT investigators.

It is important to note that expressions (4) through (7) given above apply only to conditions wherein the channel, or the edge of the flooded area, are surrounded by a homogeneous background whose width is of the order of the resolution. The effect is explained in Reference (2). It is analogous to the effect whereby an optical or radar system can detect a line, thinner than the resolution element, provided this line lies on a homogeneous background at least as wide as the resolution element itself. For floodplains which meet these conditions, mapping with current LANDSAT capabilities would meet the user requirements.

8.2.2 Density of Measurements Along the Stream Axis

User consensus is that this parameter should be a function of the variability of the width of the flood plain. This requirement in turn translates into a requirement for the slope of the floodplain contour with respect to the floodplain axis. The indicator of variability is the derivative of the slope. Thus: the larger the second derivative of the flood plain width relative to its axis, the more numerous the measurements of flood plain width required. In practice, frequent measurements are easily achievable from LANDSAT space imagery. A difficulty would arise in cases where the variability of the flood plain width is so great as to impact the resolution capabilities in the along-axis direction. Existing examples of flood plain mapping, Reference (7), indicates that this case is seldom if ever encountered in practice.

8.2.3 Repetition Frequency

This parameter should be commensurate with the period of permanence of the flood traces. References (7) and (9) indicate periods of time of order 7 days or even somewhat longer as typical measures of permanence. However, the information available in the literature addresses a limited number of streams, most of which are relatively large. Considerably more information on the permanence of flood traces must be gathered and made available before hard and fast conclusions as to optimal repetition frequency can meaningfully be drawn

for this application. At this time, available information suggests one week as a reasonable value of this parameter.

8.3 Runoff from Snow

The key element, both because it is the major indicator of snow content and the most easily observable parameter, is the area of the snowpack.

8.3.1 Snowpack Area

In general, the reflectance of snow is sufficiently high as to make the problem of discrimination from its surroundings relatively easy. In the case of exposed, visible and discriminable snow, the accuracy of area mensuration is expressed by the approximate relationship:

$$e = \frac{2kr}{\sqrt{A}} \qquad (2)$$

where:

- e = error, percent of snowpack area mensurated
- r = resolution element, linear dimension of pixel, meters
- A = area mensurated, hectares
- k = a coefficient which depends upon the sophistication of the mensuration algorithm, upon the contrast ratio, and the shape of the pack.

For typical reflectances of snow against typical backgrounds, and for visual interpretation, a value of k = 1 is reasonable; k = 0.5 should be achievable with reasonable care.

Figure 11 depicts the minimum size of *aggregate* snowpack area which can be mensurated to the user-specified accuracy of ±5%, as a function of resolution. It can be seen that snowpack areas of order 10 Km^2 are required to achieve 5% accuracy with the current LANDSAT average resolution of approximately 66 meters. Thus, the current LANDSAT resolution appears adequate for this application.

8.3.2 Snowline Altitude

The users (USGS - EROS) state that a precision of ±50 meters is too fine for mountainous regions. Assuming for these regions an average slope of 15%, a contour interval of ±50 meters implies that the measurement accuracy of the one-dimensional extent of the pack should be of order ±300 meters.

The users also state that precision of ±50 meters is too coarse for the flatter regions. Assuming a minimum slope for these regions of 1% yields a lower bound for the tolerance of the one-dimensional extent of the snowpack of order 5,000 meters. The user statements boil down to the requirement that 300 meters is too fine, 5,000 too coarse.

With the current LANDSAT resolution of 66 meters and with the simultaneous availability of topography, the snowline altitude should be measurable to the following accuracies:

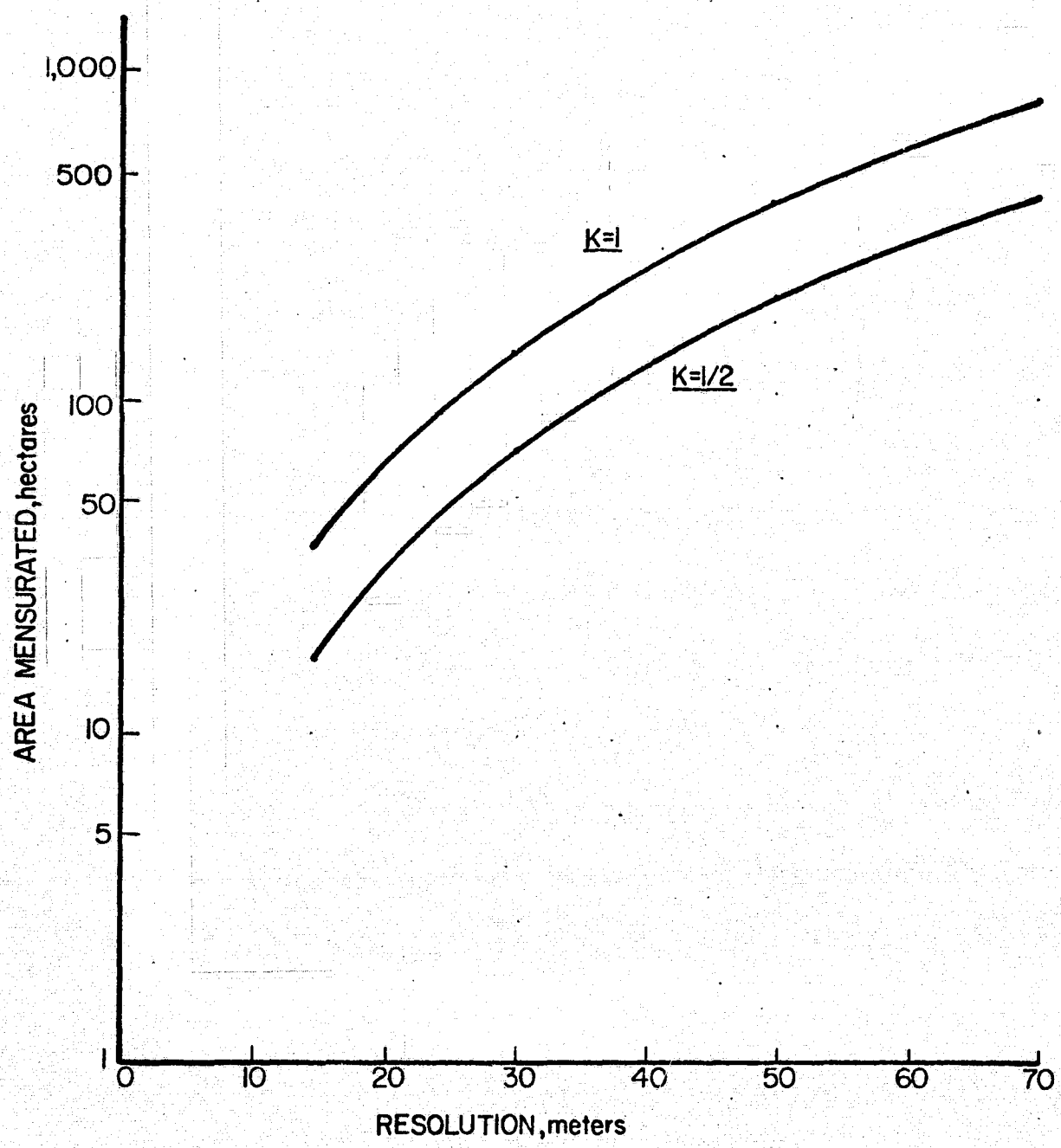
In mountainous regions with typical 15% slope: ± 10 meters.

In flat regions with typical 1% slope: less than one meter.

These values more than adequately meet the user requirements.

FIGURE 11

MINIMUM AREA OF CONTINUOUS SNOWPACK MENSURABLE TO ±5% ERROR AS A FUNCTION OF RESOLUTION



9.0 REQUIREMENTS FOR ADVANCED REMOTE SENSING CAPABILITIES

All users queried expressed desire for certain capabilities which are at present not directly available from satellite-borne remote sensing, nor planned for LANDSAT D. Since these desires may well represent the requirements for a future generation of remote sensing satellites, it is thought worthwhile to recapitulate them here.

9.1 Rainfall Characteristics

Users uniformly consider this item as one of the principal, if not the principal, physical phenomenon driving hydrology. They indicate that certain important aspects of precipitation have not thus far been sufficiently explored; and suggest that spaceborne remote sensing technology consider their exploration in the future. Of principal importance, in approximate order of priority, are the following phenomena:

9.1.1 Temporal Characteristics of Rainfall

By this are meant two types of data: 1) the statistics of the succession of significant rainfall events, sufficiently close in time so that the early events affect the later ones; 2) the behavior of the precipitation mass and rate within a single event, with particular emphasis on the high-intensity events.

The importance of the first set of data is illustrated by the example of two successive rain events, neither of which by it-

self is sufficient to cause a flood. However, if the first event wets the watershed, thereby reducing its permeability, the second can cause a flood.

The significance of the second set of data can be appreciated from Figure 12 which portrays results of simulations performed by ECOSYSTEMS. It can be seen that a "triangular" rainfall shape can cause approximately twice the peak runoff than a constant rainfall of the same mass and duration.

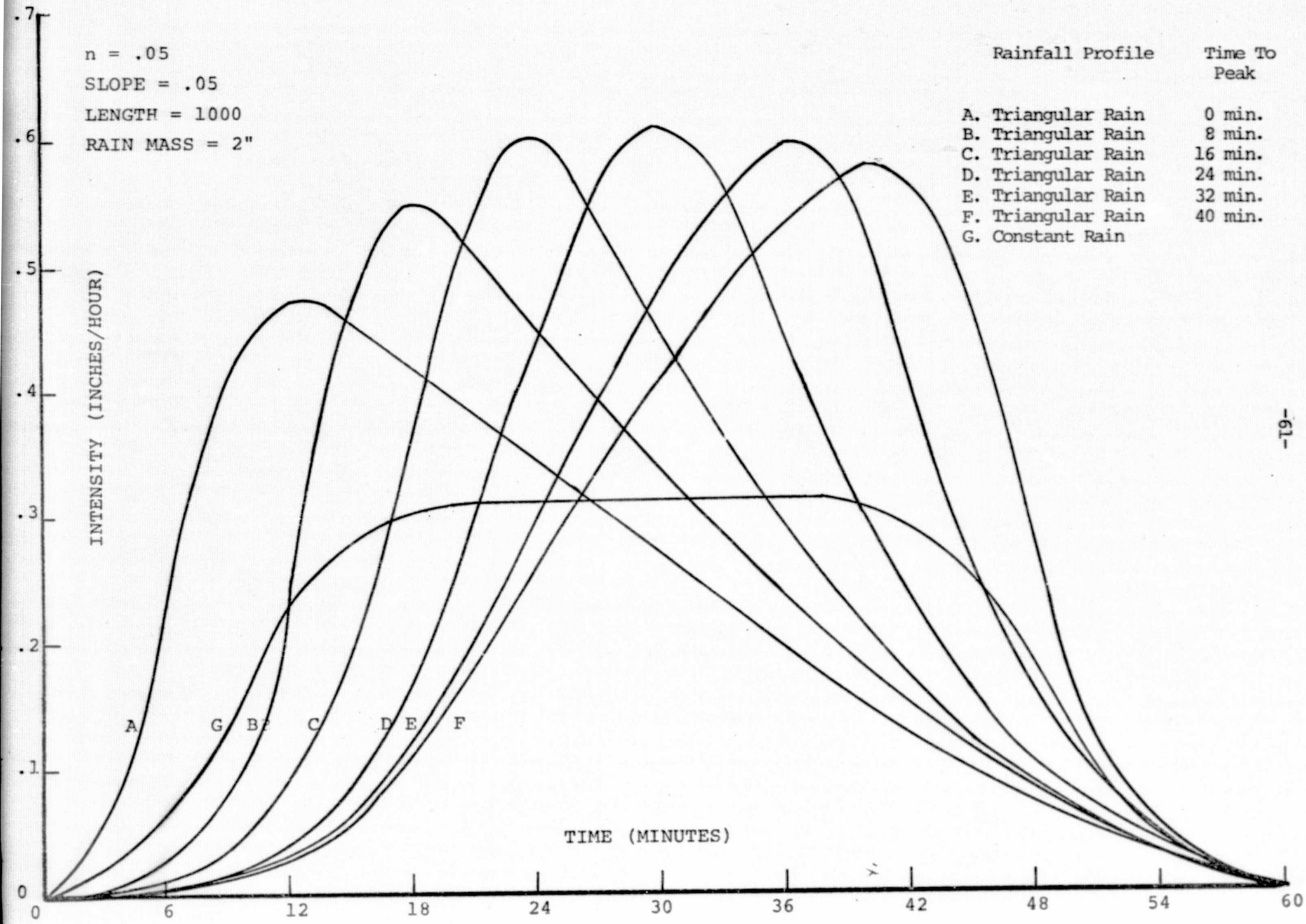
9.1.2 Areal Characteristics of Rainfall

It is well known that rainfall does not occur uniformly within an area, but rather tends to taper off from its epicenter of maximum intensity: the larger the distance away, the greater the decrement. It is also well known that little data is available to quantify this phenomenon, except in a few regions where it has been measured. For large watersheds, areal variations of rainfall can cause significant differences in runoff. Improved statistics on this phenomenon would allow higher precision in computing the runoff.

9.1.3 Storm Travel

It is known that the motion of a circumscribed rain event within a watershed can cause significant differences in runoff, even with constant rain mass and duration. The motion of the storm couples with areal non-uniformity to cause phenomena such as the

FIGURE 12 SENSITIVITY OF RUNOFF TO RAINFALL PROFILE



"missing" of certain raingages while others are hit by intense rainfall. The phenomenon can cause significant distortion of the computed outflow. Data are scarce and limited to restricted regions which have been densely instrumented for the purpose -- for example, the Chikasha, Oklahoma watershed. More information would be highly desirable. USGS-EROS indicated that possibly more data are available than have appeared in the literature. Thus, a thorough search of these data to assess the full extent of their availability, should be completed before engaging in satellite-planning activities.

9.2 Requirements for Active Sensors

The major suggestion offered by users boil down the the fact that these sensors should be considered if they can meet the two simultaneous conditions: 1) be able to operate in all-weather environment, or at least to penetrate normal cloud cover; 2) be able to perform the hydrologic surveys as with a quality comparable to that synthesized in previous Section 9 for the optical sensors. In particular, the requirement for a low-resolution, (1,000 meters), broad-swath (horizon-to-horizon), all-weather active or passive sensor was not identified as being useful. This does not necessarily mean it is not useful: simply that its usefulness has to be demonstrated. It is felt that one of the promising applications for active sensors is in gathering data on the parameters discussed in preceding Section 9.1.

10.0 TRANSLATION OF USER REQUIREMENTS INTO REMOTE SENSING PARAMETERS

From the preceding Section, the functional requirements for hydrological surveys are of six basic types:

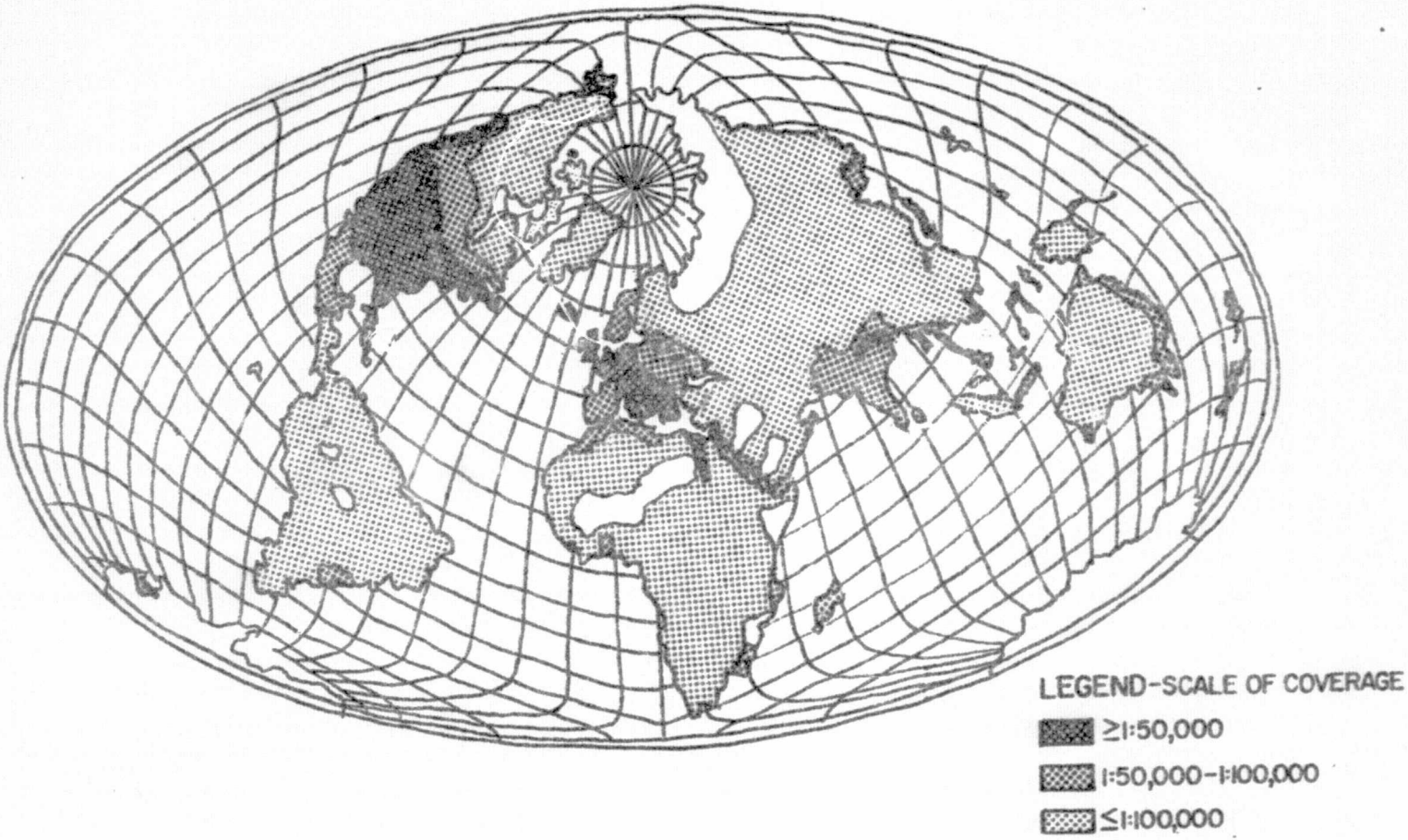
a. Measurement of elevations (for slope computations)
b. Measurement of areas (mensuration)
c. Determination of differences between targets (discrimination)
d. Determination of target content (classification)
e. Measurement of the length of linear features
f. Measurement of the width of linear features

10.1 Measurement of Elevations

The measurement of elevations is essential for hydrology. Incorporation of stereo capability into a future hydrologic satellite is strictly a matter of cost-effectiveness. Approximately 20% of the world is covered by topo maps at scales 1:50,000 or larger. Another 40% is topographically mapped at scales 1:250,000. The remaining 40% of the land surface is covered by scales of order 1:1,000,000. Many large areas are at present not sufficiently populated to require much mapping. Typical of these are tundra areas in Siberia, near-polar regions deserts. The situation is depicted in Figure 13.

In many important areas, where hydrologic information and modeling are critical, adequate to tolerable topographic coverage already appears to exist. This can be used in conjunction with remotely sensed non-stereo data to provide the relief mapping.

FIGURE 13



WORLD TOPOGRAPHIC MAP COVERAGE

10.2 Measurement of Areas

To measure the area of a target -- for example, of the forested portion of a watershed --- it is necessary to discern the area of interest from its surroundings. The minimum discernment function is to determine that the area of interest differs from its surroundings, and rely on other available information to determine its content (discrimination). The complete discernment function identifies the target's contents (identification). Depending upon the nature of the targets of interest, and the quality of the information obtained by the remote sensor, two methods are possible for measuring areas "geometric" mensuration, usable in those cases wherein discrimination or identification present no problem, and statistical mensuration, necessary in those cases wherein the problem of recognizing the target's contents cannot be solved by conventional means. Statistical mensuration subdivides into two categories: a) measurement in the inventory mode, wherein what is sought are the proportions of the area exhibiting specific differences, without seeking any information as to their geometric locations; b) measurement in the land use mode, wherein the geographic location of the differing targets is sought.

In hydrologic applications, examples of cases amenable to geometric mensuration are snow, clear water: as will be seen later, other cases have been experimentally found to exist also. Area tally in the inventory mode is employed in most

hydrologic models, at least at the level of the sub-watersheds. The land use mode is less used, but is desired by some users (SCS).

10.2.1 Geometric, or Pure, Mensuration

If the classification is perfect, the mensuration error is a function only of the uncertainty of the assignment of the boundary pixels. If there are no classification errors, the measurement of areas thus boils down to pure mensuration. This essentially affects only the geometric resolution of the system and imposes upon it the requirements shown in Table 4.

Table 4 was constructed by attaching to each category of users the range of watershed areas of interest: then estimating the approximate number of homogeneous areas (in terms of surface cover) within the typical watershed. The indicated resolutions can be considered *as an upper bound*, in the sense that the presence of classification errors will worsen the mensuration accuracy or impose more stringent requirements on the system's resolution.

The important parameter is not the geometric pixel size, but rather the "effective pixel size." By this is meant the ability of the system to locate boundaries. It is well known that with techniques of "pixel splitting," boundaries can be located to better than the geometric pixel size: this is possible whenever the radiances of the two bordering targets are constant over a distance from the boundary at least equal to the geometric

TABLE 4

RESOLUTION REQUIREMENTS FOR MENSURATION OF AREAS

USER	AREA OF WATERSHEDS OF INTEREST, ha		AVERAGE AREA TO BE MENSURATED, ha (HOMOGENEOUS AREAS)	ACCURACY REQUIRED	REQUIRED EFFECTIVE RESOLUTION, METERS
LOCAL	MINIMUM	1	0.5	10%	3.5
	MEDIAN	50	10	10%	15
	MAXIMUM	150	30	10%	27
SMALL	MINIMUM	100	20	5%	11
	MEDIAN	10,000	2,000	5%	110
	MAXIMUM	100,000	10,000	5%	250
LARGE	MINIMUM	50,000	7,000	5%	210

pixel dimension. In this case, the fraction of the geometric pixel which can be resolved is in theory approximately equal to:

$$k = \frac{r_{eff}}{r} = \frac{1}{\left[\left[n_1 - n_2\right]\right]} \qquad (8)$$

where: r = geometric resolution (pixel dimension)

r_{eff} = effective resolution

n_1, n_2 = signal-to-noise ratios of neighboring targets

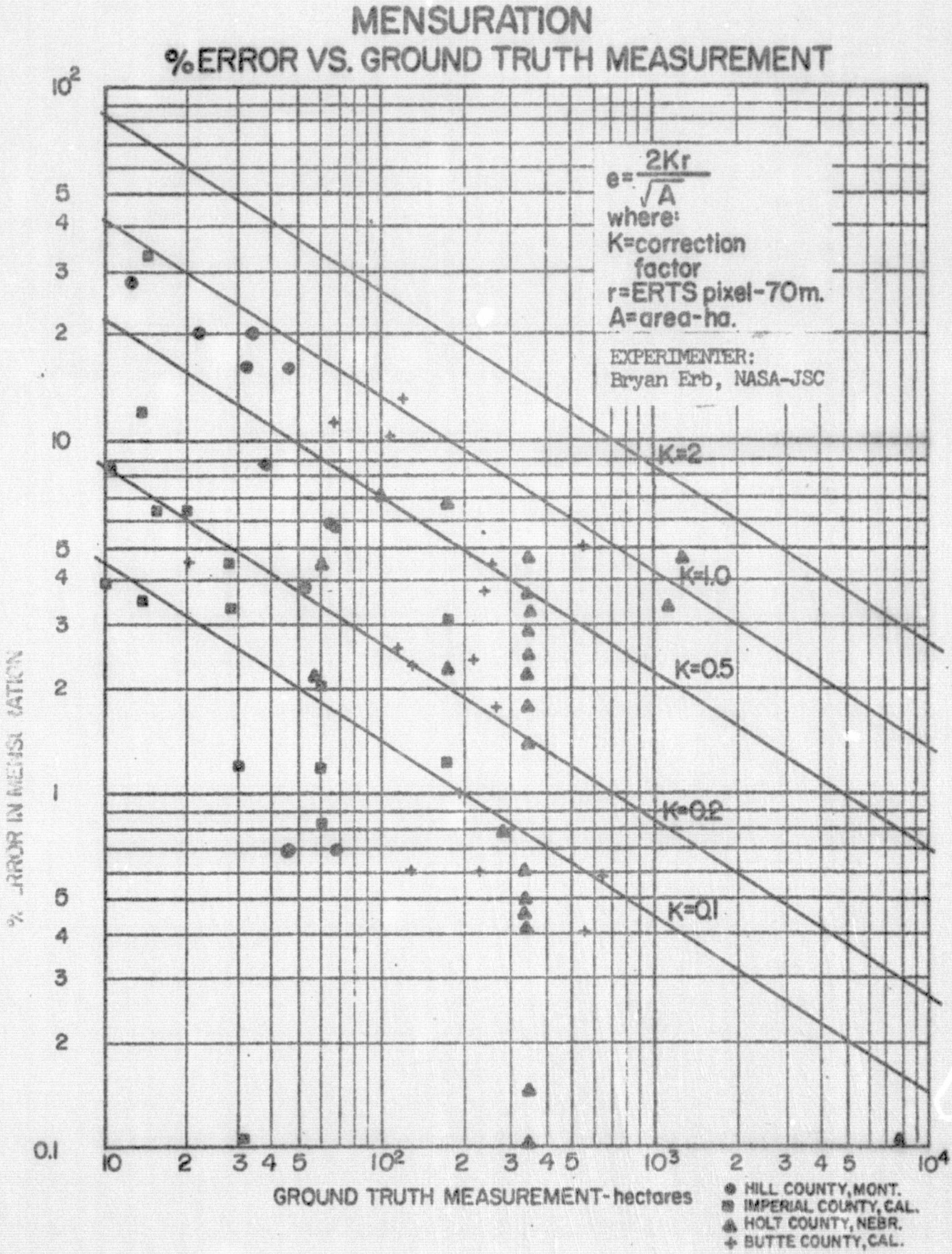
k = pixel splitting coefficient

Figure 14, which depicts a set of experimental results of mensuration from LANDSAT, Ref. 11, indicates the "pixel splitting coefficients" achievable in practice by careful mensuration. Note various instances of "pixel splitting coefficients" as low as 0.1.

In practice, if the areas to be mensurated are "clean," i.e. with well-defined boundaries, homogeneous either side of the boundary for a distance at least equal to the pixel size, and with high differential contrast, the pixel splitting coefficient will be low. Watershed areas displaying these characteristics will be mensurated more accurately than those which do not. A conservative satellite design must however consider all possible cases.

Figure 14 indicates that in this case a reasonable design value of the pixel splitting coefficient is unity. Thus the resolution figures of Table 4 apply to the full geometric resolution required by a remote sensor designed for hydrologic use. Table 4

IG. 14 EXPERIMENTAL ERRORS IN GEOMETRIC MENSURATION FROM LANDSAT IMAGERY



tells us that the current LANDSAT resolution (66 meters average) is certainly adequate for the large users. When coupled with Figure 15, it indicates that it sould serve 90% of the watersheds of the small users. It could not serve the local users.

To serve a substantial portion of the latter, the resolution would have to be improved to at least 20, preferably 15 meters. An obvious case approaching "ideal" mensuration is offered by snow, or bodies of clear water surrounded by beaches. However, as evidenced in Figure 13, similar cases are also encountered in agricultural land cover.

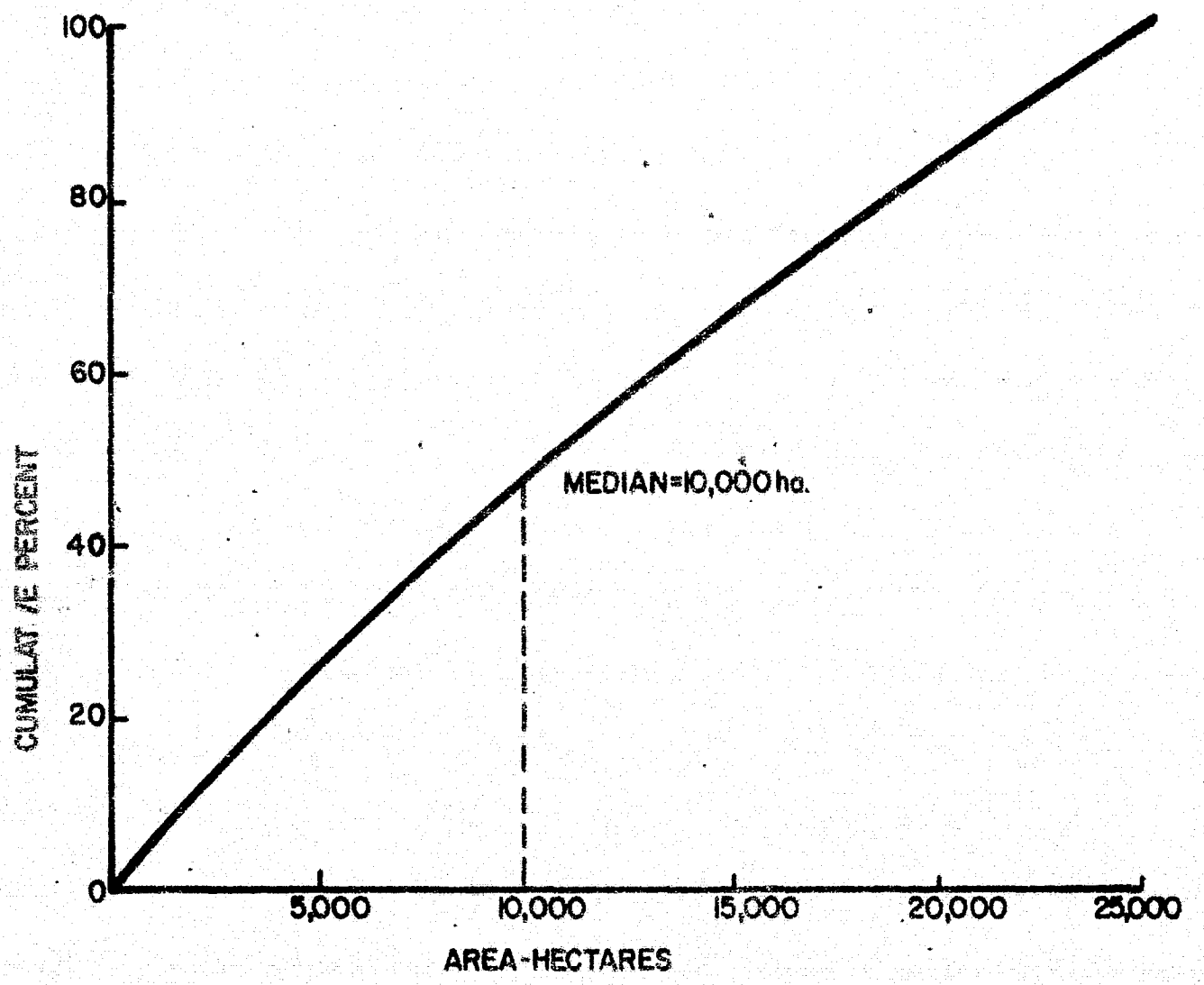
10.2.2 Measurement of Areas in the Inventory Mode

For classification in the inventory mode -- which, as reported in Section 8, is adequate for most users --- the error of mensuration essentially equals the error in discrimination or classification, *if the area classified is sufficiently large* relative to the pixel area.

The reason for this constraint is that since the process of discrimination or classification from remotely sensed data operates on statistical variables (the reflectance spectra), its end result, i.e. the accuracy of classification, is itself a statistical variable. Its value will cluster around its mean value, the closer the larger the number of samples included in the process. The number of samples required to

FIGURE 15

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



achieve a given "stability" of classification is a function of the statistical parameters of the targets -- ratio of standard deviation to means, separation between means, and, for non-Gaussian distributions, the values of the higher moments. The number of samples required per target is what determines the resolution required.

If the resolution is too low with respect to the target characteristics, another cause of error arises: the number of cases in which the pixel straddles the boundaries of adjacent but different targets increases. The straddler pixels yield erroneous information, lowering the accuracy of classification. This cause of error is the analog in the spectral domain of the border error experienced in pure mensuration.

It is relatively easy to formulate expressions for the number of samples -- and hence resolution -- required to achieve specified stabilities of the result. Their translation into practical resolution specifications requires the knowledge of spectra of the hydrologically important targets. Much of this information is currently being gathered: a precise answer must await completion of this process.

An indication of the second type of error is obtainable by assuming that the straddler pixels induce an "equivalent mensuration error" statistically independent from the classification error. In this case the total error will be approximately:

$$e_t = (e_c^2 + e_m^2)^{\frac{1}{2}} \qquad (9)^*$$

where: e_t = total error in measuring area

e_c = error in classification

e_m = equivalent error of mensuration $\approx \frac{2kr}{\sqrt{A}}$

Average errors of classification achieved in the inventory mode in 64 LANDSAT investigations are shown in Figure 7. The one-sigma (63% of the cases) error is of order 13% (87% correct classification). As mentioned previously, Fig. 7 relates to Level IV Land Use Classification, whereas most hydrologic classifications only require the simpler-to-achieve Levels II and III. A thorough survey of classification results for Levels II and III is not available: indications are that inventory mode classification accuracies of at least between 95% (one sigma) should be achievable.

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* More rigorously, expression (9) should be written:

$$e_t = (e_c^2 + e_m^2 + e_s^2)^{\frac{1}{2}}$$

where: e_s = stability error

the other symbols are as in (9)

Although precise numerical measurements of e_s are not yet available for the reasons explained before, indications are that they will not contribute much for the larger and for most of the small-user watersheds -- provided care is exerted to use a significant number of pixels in the classification. The stability error will however impact the low end of the small user waterheds, and the local user watersheds.

From expression (9) above, it is easy to see that: a) at the "worst" end of the error range, a classification accuracy of 95% (5% error), coupled with an equivalent mensuration accuracy of 90% (10% error), would yield approximately 11% total mensuration error; b) at the lower end, classification accuracy of 98% (2% error) plus equivalent mensuration accuracy of 95% (5% error) yields a total error of 5.3%; c) in the middle of the range, classification accuracy of 95% (5% error) coupled with mensuration accuracy of 95% (5% error) yields a total error of 7%.

In conclusion, the mensuration accuracies achievable in the inventory mode for hydrological use are somewhat worse, but not exceedingly so, than those achievable in the pure mensuration mode. It should be noted that, in order to strictly meet the user requirements synopsized in Table 4 (10% area measurement accuracy for the local, 5% for the small and large watersheds) the classification error must be at least as good as the required accuracies. From expression 9, Figure 16 was drawn, which depicts the mensuration accuracies achievable from the current LANDSAT (66 meter average resolution) with two levels of classification quality: 95% (5% error) and 98% (2% error). It can be seen that LANDSAT at 95% classification quality is marginal. At 98% classification quality, it meets the requirements of the large users, and approximately 90% of the requirements of the small users. It does not meet the requirements of the local users.

FIGURE 16 AREA MENSURATION ACCURACIES ACHIEVABLE FROM LANDSAT A & B INCLUDING EFFECT OF CLASSIFICATION ERRORS

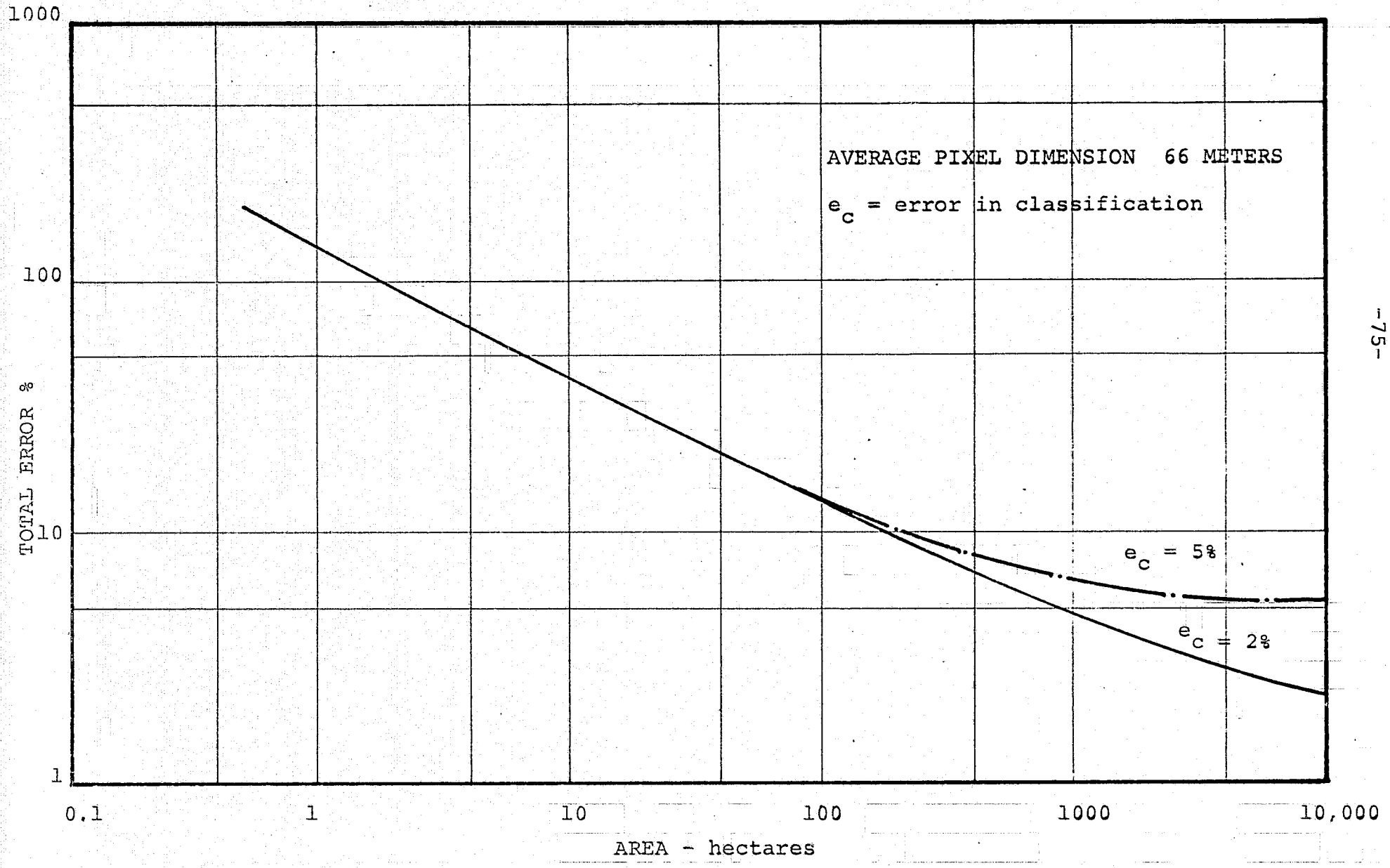
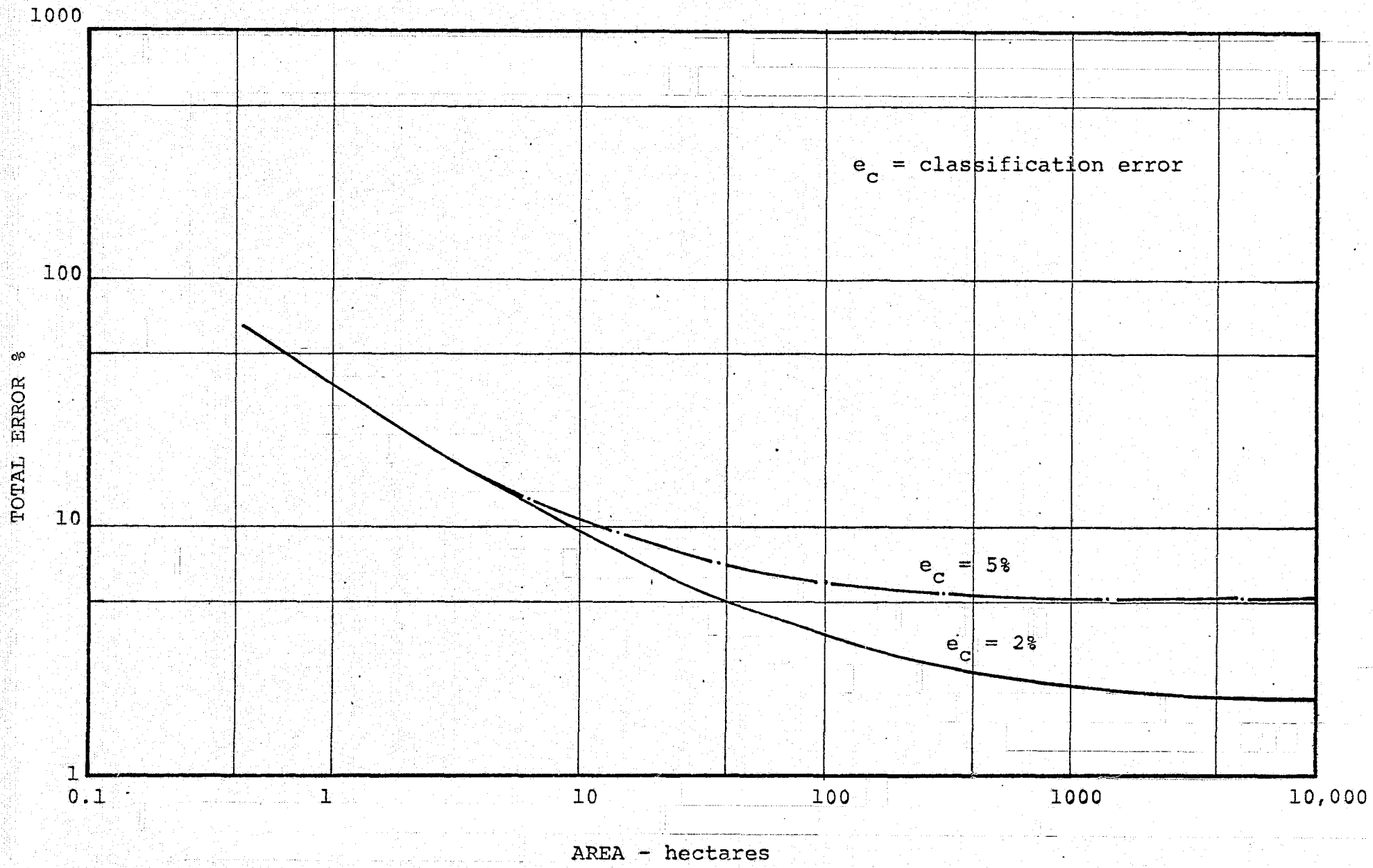


Figure 17 depicts the situation for an advanced satellite with a resolution of 15 meters. At 95% classification accuracy, this system would marginally meet the requirements of the large and small users, but it would meet approximately 50% of those of the local users (because the permissible error is greater for the locals). At 98% classification accuracy, it would meet all the requirements of the large and small users, and approximately 60% of those of the local users.

10.2.3 Measurement of Areas in the Land Use Mode

In the land use mode, which is desired only by SCS among the users queried, the situation is similar. Errors in the land use mode result in misestimation of the areas of interest: this error must be combined with the error of mensuration, resulting in an expression analogous to (9) above. The errors committed in the land use mode are larger than those for the inventory mode. As shown in Figure 7, the one sigma error for 64 Level IV investigations was approximately 23% (77% correct classification). Although, as in the preceding case, a thorough survey of Level II and III classification is missing, indications are that classification accuracies of 90% and better (one sigma) should be achievable in this mode.

FIG. 17 AREA MENSURATION ACCURACIES ACHIEVABLE AT RESOLUTION OF 15 METERS - INCLUDING EFFECT OF CLASSIFICATION ERROR



The classification errors, coupled to equivalent mensuration errors through expression (9), indicate that LANDSAT performance in the land use mode needs further improvement to meet the user desires. Improvements in resolution alone will not suffice, unless such improvements can be directly related to improvements in spectral discrimination brought about by *increased number of samples*.

10.3 Measurement of the Length and Width of Linear Features

These two measurements depend essentially on the recognition of the presence of a stream. Except for streams whose width is large with respect to the pixel dimension, the majority of the important measurements requires the use of pixel splitting techniques.

From Table 3 in the previous Section, it can be seen that typically achievable pixel-splitting coefficients, with proper choice of bands, vary from approximately 0.1 (10:1), for dry to 0.025 (40:1) for wet channels. These figures assume the availability of 64 grey levels in Bands 4, 5, 6, and 128 levels in Band 7: they further assume that the dynamic range be fully available; further, that the target be "well behaved," i.e. that the stream be surrounded by a homogeneous background, with good contrast, extending at least one pixel dimension either side of the stream axis.

It should be noted that experimental observations of LANDSAT imagery show numerous instances where the stream is not visible per se, but becomes recognizable by the presence of traces along the stream -- such as vegetation coloration, alluvial deposits, and so forth. In these cases, of course, recognition is easier.

As shown in the preceding Section, to meet the user requirements, the identification of channel widths as low as 0.1 meters is desired. Two general solutions are possible: a) maintain a relatively coarse resolution, but increase the number of grey levels (for example, in the case of LANDSAT D, bring the number of levels to approximately 600); b) improve the resolution, maintaining the number of grey levels as high as possible. Both avenues are possible with the technologies currently available for such advanced satellites as LANDSAT D. Which is the better choice? At first blush, expression (6) of the previous Section would indicate that they are equivalent. That this is however not so can immediately be deduced from the fact that the equivalence is predicated upon certain constraints impose upon the target: primarily that of homogeneous background. Increased radiometric resolution will not serve to relax these constraints: whereas increased geometric resolution will. For example, identification of a small stream with a pixel size of 60 meters implies that the background must be homogeneous for at least 60 meters either side of the stream:

whereas with a pixel size of 15 meters, the homogeneity constraint need hold only over 15 meters either side.

Thus the choice is clearly in favor of improved resolution. The computational results given in Table 5 indicate the stream widths recognizable with a pixel size of 15 meters and for the number of grey levels currently embodied in LANDSAT. This value of resolution would come close to matching the user requirements.

10.4 Choice of Spectral Band Locations and Widths

Much spectral information necessary to specify these parameters is currently being gathered, and should be available within the next six months. Some results of analysis of a preliminary, restricted set of spectral information gathered by the Goddard Institute for Space Studies (GISS) (10) are offered here. They should be construed as being only indicative, because the set of data is limited in number, confined to one region only (Imperial Valley) and to a few types of cover (soils, alfalfa, wheat and a few additional crops), and the full set of calibration data is still being collected.

1. For soils, alfalfa, wheat, Bands 4,5,6, appear to be significantly correlated. This indicates a significant level of redundancy, meaning that any one of these three bands, or even all three combined, yield most of the information necessary for discrimination and identification.

2. Band 7 is significantly decorrelated from Bands 4, 5,6, meaning that the combination of any one of these three bands with Band 7 adds significant information above that offered by either Band by itself.

TABLE 5

IMPROVEMENT FACTOR AND ACHIEVABLE EFFECTIVE RESOLUTION IN MEASURING STREAMWIDTH ACHIEVABLE WITH PIXEL DIMENSION (RESOLUTION) OF 15 METERS*

BAND µm	IMPROVEMENT FACTOR		EFFECTIVE RESOLUTION, METERS	
	WET	DRY	WET	DRY
0.5-0.6	0	9.6	15	1.6
0.6-0.7	6.4	9.6	2.4	1.6
0.7-0.8	17.3	3.3	0.9	4.5
0.8-1.1	54	13	0.3	1.2

*Number of grey levels: 64 for Bands 4, 5, 6; 128 for Band 7.

3. The spectral portion of Band 7 extending from 0.8 to 0.9 microns is significantly correlated with Bands 4, 5, 6: it is decorrelated with the remainder of Band 7 (0.9 to 1.1 microns). This indicates that the information-bearing portion of Band 7 lies between 0.9 and 1.1 microns.

4. No significant improvement in discrimination or identification capabilities was found to exist in the Band extending from 0.74 to 0.8, and from 0.8 to 0.91 microns.

If these results should be confirmed from the spectral data presently being collected, for the universe of hydrologically-important covers, they would indicate that the improvement in discrimination achieved by splitting the Band from 0.4 to 0.8 microns in three parts is attributable in large part to the increased number of available samples (factor of three). The same improvement may be obtainable by reducing the pixel area by a factor of three (thereby reducing the average linear pixel dimension from 66 meters to 38 meters).

10.5 Choice of Number of Grey Levels

Reduction of pixel area implies a corresponding reduction in the number of available grey levels. The question is whether it is better to say halve the pixel area and accept half the number of grey levels, or double both. The answer depends upon the characteristics of the target.

For "clean" targets which can be mensurated, or whose linear dimension can be estimated by pixel splitting, we have seen

that improvement in resolution is preferable to increasing the number of levels.

For targets which must be discriminated or identified based on their statistical spectral content, a numerical answer must await the availability of a sufficiently representative number of spectral data. One important point is worth making: it relates to the capability of any state-of-the-art radiometric sensor to indeed yield a large number of unequivocal levels. Discussions with the Bureau of Standards indicate that, in their experience, the best that can currently be achieved with most careful calibration is of the order of 100 levels. If this is indeed the case, it would place an upper bound on the number of grey levels achievable with current state of the art. Faced with this situation, the choice would to be to improve the resolution by reducing the pixel size to a value which would yield 100 levels. Computations performed in Reference (6) for LANDSAT, and updated for the known characteristics of LANDSAT D, indicate that the corresponding theoretical resolutions are as shown in Table 6.

10.6 Repetition Frequency

Based upon the user replies and the subsequent computations performed in Sections 7 and 8, the repetition frequency desired is of the following order:

TABLE 6

THEORETICAL RESOLUTIONS ACHIEVABLE AT MAXIMUM TARGET CONTRAST, LANDSAT A & B AND LANDSAT D

BAND	# LEVELS FULL RANGE	THEORETICAL RESOLUTION ACHIEVABLE, METERS	
		LANDSAT A & B	LANDSAT D
4	64	72	11
5	64	82	11
6	64	90	11
7	128	82	16

For operationally-oriented users: two weeks preferred, somewhat less frequent acceptable.

For research-oriented users: two weeks tolerable, one week preferred.

Thus a choice of two weeks appears to be adequate to satisfy most of the user's needs.

10.7 New Sensors

There appeared to be little feel on the part of the users for the value of novel sensors such as thermal IR, passive and active microwaves. What is needed in this area is to achieve specific demonstrations of these sensor's utility and submit these to the users to evince their judgement.

10.8 Synopsis - Preliminary Guidelines for Sensor Design

As already said, complete numerical conclusions must await the availability of spectral data, currently being gathered under the sponsorship of NASA.

The following is offered as an indicator, with the caveat that it is based to a significant extent upon preliminary data gathered by GISS, which need doublechecking and expansion to other regions, temporal periods and a greater variety of hydrologically important situations:

1. Broaden the spectral bands. For example, select one band from 0.5 to 0.9 microns, the other from 0.9 to 1.1 microns.

2. Consider the use of additional bands above 1.1 microns, after careful analysis of the data.

3. Improve the resolution to approach as close to 15 meters as possible.

4. Choose a number of grey levels consistent with sensor capabilities: probably of the order of 100.

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