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USE OF LANDSAT MULTISPECTRAL IMAGERY IN ESTIMATING SNOW AREAL EXTENT AND SNOW WATER CONTENT COST-EFFECTIVELY

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ABSTRACT

The objective of this investigation[1] is to design a general remote sensing-aided information system to provide the estimates of two important inputs to water yield forecast models. These input parameters are snow areal extent, snow water content, and cost-effectiveness analysis applied to snow water content-estimation. The techniques under development in this investigation are being tested on the water source basin for the California Water Project. This area is known as the Feather River Watershed. With the cooperation of the California Department of Water Resources and the University of California at Davis.

The general approach involves a stepwise sequence of identification of the required information, sample design, measurement/estimation, and evaluation of results. All the relevant and available information types needed in the estimation process are being defined. These include Landsat, and aircraft imagery supported with ground data where applicable.

In case of snow areal extent, the procedure developed has been applied to three dates in 1973 with satisfactory and cost-effective results. The results are maps of snow areal extent along with their variance, population ratio estimator, confidence intervals, and allowable error for each date.

In case of snow water content, the Landsat-aided system has yielded precise and cost-effective estimates of input parameters to hydrologic models over the watershed(s) of interest with sufficient accuracy. This investigation suggests that remote sensing has shown a great potential for predicting water yield and aiding water resources managers.

INTRODUCTION

The water demand for human being needs is constantly increasing with the increase in the world population and improvement in the standard of living and industry. Water is the medium of life processes and the source of their hydrogen. It flows through living matter mainly in the stream of transpiration. Water is needed for transporting ships and as a habitat for aquatic life. Water acts as a heat reservoir in cold weather and as a cooling medium in the summer. The integration of information gained in various hydrological processes enables us for water resources development and management. Because the water resources renewal depends on climatic phenomena which are very difficult to control; the proper development of water resources and its management thereafter is very important. It is precisely these extremes of flood and drought that are often of most interest to the water resources managers. Remote sensing-aided information systems which would enable us to record these changes on a basis throughout the years over the large area of interest is badly needed. Remote sensing is also able to give us information on water quality, which is equally important as its quantity.

The early prediction of the amount of runoff to be derived from the snowpack allows more efficient utilization of the limited water supply for power generation, irrigation, flood control, domestic and industrial water supplies, and recreation. The need to plan for expected water supply has led to runoff forecasting programs used by various water resources management organizations. Whether a particular runoff forecast procedure is based on some form of index method or rational method, all procedures have one thing in common: raw data are required and the costs of raw data are continually rising (Thompson, 1975).

The values of knowledge concerning the areal extent of snow has been recognized for some time. One index of runoff, which has been found useful for improving residual flow forecasts is areal snow cover. The close relationship between snow-cover, depletion and accumulation of a given basin has been well documented, (Leaf, 1971). The physical basis and the mechanisms of snow abalation have been understood and modeled for number of years (U.S. Army Corps of Engineers

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1956). These physically based models have been varified experimentally on a local scale using a snow lysimeter installed in the Andes Mountains in Chile by Amorocho and Espildora, 1966. They obtained good agreement between model prediction and experimental data. The same physical elements are used in the spatially lumped snow submodels of watershed hydrologic models such as the Sacramento RFC model, developed by Burnash and his associates.

Advanced space technology and several new satellite snow mapping procedures (Barnes and Bowley 1974, Foster and Rango 1975) promise to make satellite snow cover observations available on a dependable and routine basis. These satellite snow cover estimates used in combination with conventional snow survey data as inputs to computerized simulation models should make the problem of short-term residual volume forecasting less difficult in the very near future. Satellites possessing relatively high resolution sensors have been regularly observing snowcovered areas since 1972. Landsat-1 (previously known as Earth Resources Technology Satellite, ERTS-1) has been providing 80 m resolution, multispectral visible and near infrared observations over a 185 $185km^2$ area as often as once every 18 days since July 1972. Landsat-2 has been providing similar data since its launch in January 1975. The currently operating two satellite system effectively provides once every 9 day coverage over a given area. Landsat has shown potential use in determining areal extent of snow cover (Baren et al. 1974, Meier 1973). Imagery obtained from Landsat-1 has provided the raw data for this study. Wiesnet and McGinnis (1974) have shown that snow extent mapping is both six times faster from Landsat-1 imagery than from high altitude aerial photographic surveys, and that the cost of snow maps produced from Landsat-1 is about one-two hundredth the cost of the simplest maps made from aircraft surveys.

Even though it has been shown that snow extent can be accurately measured from Landsat-1 imagery (Barnes, Bowley, and Simmes, 1974), there has been some question about usefulness in terms of predicting snowpack yield or seasonal runoff in view of the fact that only the area covered by snow, and not snow depth or water equivalent, is observed. This is true of all visible, near infrared, or thermal infrared sensors, no matter what their resolutions.

The objective of this paper is the development of remote sensing-aided information system design for estimating input parameters for water yield forecasting models. The focus will be on watershed-wide snow quantification and water loss to the atmosphere. The snow quantification consists of snow areal extent over the watershed and snow water content. The test area used for the development of this methodology is the Feather River Watershed (FRW), Northern Sierra Nevada, California and the Spanish Creek Watershed, a sub-basin within the FRW.

MATERIALS AND METHODS

The methodology described in this section is composed of two parts: (1) Use of Landsat-1 and supporting aircraft imagery for snow areal extent estimation; and (2) Snow water content estimation based on snow areal extent data and supporting ground data along with cost-effectiveness analysis.

Procedure for Estimating Areal Extent of Snowcover:

This method is based upon the analysis of Landsat imagery in the form of simulated color infrared enhancements of band 4, 5, and 7 was used for the snowcover interpretation procedures (Katibah, 1975). Two dates of Landsat color composite imagery are used for analyzing each snowpack date. For instance, if the areal extent of snow is to be calculated for the April 4, 1973 Landsat overpass of the Feather River Watershed, a Landsat color composite of April 4, 1973 and a Landsat color composite on a cloud-free summer date such as August 13, 1972, are used.

The snow cover analysis dates are April 4, May 10, and May 29, 1973. On these (or at the most, two days thereafter) random transects were flown across the watershed to acquire large scale photography that could be used as an aid in determining the actual snow condition on the ground (i.e. "ground truth").

To estimate the areal extent of snow, the Landsat 1 images were gridded with image sample units (ISU's), each equalling approximately 400 hectares. These image sample units were then transferred to the large scale photography where applicable. The image sample units on the large scale photography was coded as follows:

Code	Snow Cover Class	Midpoints
1	No snow present with the ISU	0
2	0-20% of ISU covered by snow	.10
3	20-50% of ISU covered by snow	.35
4	50-98% of ISU covered by snow	.74
5	98-100% of ISU covered by snow	.99

The gridded Landsat color enhanced images were then interpreted, sample unit-by sample unit, and coded using the following method to account for vegetative cover and density and to some degree, aspect and elevation, (Katibah 1975).

Scale matched simulated color infrared enhancements of Landsat 1 imagery were produced for all the winter dates and the summer date in reflection print form. The April and May dates represent the snowpack and were gridded, while the August 1972 date, representing a cloud free summer image, was not gridded. The purpose of the August date was to provide a clear aerial view of actual ground relationships of vegetation/terrain features.

The Landsat-1 interpretation results were compared to the coded large scale photography where applicable. The sample-by-sample unit interpretation of the Landsat image was then used to find the estimate for the areal extent of snow in the watershed. Totals for each of the individual snow cover classes were found and multiplied by 400 hectares, the approximate area of each image sample unit on the ground. This gave the number of hectares for each class; these values were then multiplied by the appropriate snow cover class midpoints to give the total number of hectares of snow in each class. Finally, these totals were added to give the estimated areal extent of snow.

The areal extent of snow thus calculated was based solely upon the Landsat interpreation results. The calibrate this estimate, the image sample units where snow areal extent "ground truth" was obtained (from large scale aerial photography) were compared with the same image sample units on the Landsat imagery. The relationship between the snow areal extent values on the corresponding Landsat and "ground truth" sample units is the basis for the application of the ratio estimator statistical technique (Chocran, 1963). This technique not only provides a correction for the original interpretation estimate, but also allows for an estimate of the precision of this estimate through the application of confidence intervals. The 95% confidence intervals around the areal extent of snow estimates were then calculated.

Snow Water Content Estimation Procedure with Cost-Effectiveness Analysis:

The methodology in this part is described in three sections. The first section is composed of a stepwise remote sensing-aided procedure for snow water content estimation. The second section briefly describes cost-effectiveness analysis applied to this technique. Finally, cost survey of Landsat-aided and conventional (operational) systems follows.

Stepwise Remote Sensing-Aided Procedure:

The Remote Sensing-aided snow water content estimation system is designed to generate an estimate of watershed-wide snow water content and an associated statement of precision. This system employs a stratified double sampling technique based on Cochran 1963 and Raj 1968 and uses both ground snow course and Landsat data. Its objective is to combine snow water content information for the whole watershed, as obtained inexpensively from Landsat data, with that gained from a much smaller and more expensive sample of ground-based measurements at snow courses. In this way, a large amount of variability in basin snow water content is accounted for by the use of Landsat data. (Khorram et al 1976). The method is summarized in eight steps described below:

Step 1: Create Landsat color composites with appropriate image sample unit (ISU) grid over watershed(s) of interest. Black-and-white Landsat transparencies are obtained and transformed in a simulated infrared color composite based on a metholodology developed by Katibah, 1973. In the color combining process, an ISU grid is randomly placed over each image so as to cover the watershed of interest. ISU's in this study represented areas of about 400 hectares (980 acres). The Feather River Watershed covers approximately 780,000 hectares.

Step 2: Estimate snow areal extent by Landsat ISU for previous year(s) or current season snow buildup dates. Each ISU is interpreted manually as to its average snow areal extent cover class according to a snow environment-specific technique described earlier.

Step 3: Estimate snow areal extent by ISU for Landsat snow season date of interest.

Step 4: Transform snow areal extent data to snow water content data by Landsat ISU. Snow water content index is estimated from the following first order, time specific model:

$$X_i = \sum_{j=1}^{J} (M_{ij})\,(G_j) \quad \cdot K_i$$

where X_i = estimated snow water content for image sample unit i,

M_{ij} = snow cover midclass point based on photo interpretation; expressed on a scale of 0.00 to 1.00 for image sample unit i on the jth Landsat snow season date,

G_j = weight assigned (0.00-1.00) to a past M_{ij} according to the date of a current estimate,

K_i = the number of times out of j that sample unit i has greater than zero percent snow cover, and

J = total number of snow season dates considered.

To insure reasonably high correlation between X_i and corresponding ground snow water content values, there usually should be at least three snow season dates considered ($j \geq 3$). Normally, one or two dates of Landsat imagery would be required during the early snow accumulation season. Occasionally, j may be only two, such as when the first date consisits of an April 1st snow water content map based on past year's Landsat data. In all cases the sample unit grids on all dates must be in common register with respect at a base date grid location.

Step 5: Stratify ISU's into Landsat snow water content index classes, if not already performed. Then calculate by stratum the number of ground sample units (GSU's) or snow courses required to achieve the allowable error criteria for the basin snow water content estimate. The number of required ground samples may be determined (Thomas and Sharp, 1975) for individual strata according to the snow survey direct cost budget for the watershed of interest and according to the following stratum specific statistics: relative stratum size, Landsat snow water content variability, Landsat to ground correlation, and Landsat to ground sample unit cost ratio. This study employed six snow water index strata, with water content index calues ranging from less than 0.1 to over 81 Such stratification was used to control the coefficient of variation of the overall basin snow water content estimate.

Step 6: Allocate the GSU's calculated in Step 5 among snow water content strata with equal probability within strata in accordance with stratified random sampling requirements. The following table summarizes the number of image and ground sample units required in each of six snow water content strata, given a cost per ISU of 15¢ and a cost per GSU of $150.

Step 7: Calculate the estimate of watershed snow water content according to a summation of stratawide snow water content estimates generated from regression equations relating the Landsat snow water content index data in each stratum to the corresponding sample of ground snow water content measurements.

Step 8: Enter the basin snow water content into statistical or physical models to predict water yield. For example, the watershed Landsat-aided snow water content estimate could serve as a predictor variable in a regression equation developed to predict water runoff.

Cost-Effectiveness Analysis:

The side-by-side comparison of the operational and Landsat-aided snow water content estimation systems was facilitated by a blending of statistical and economic theory. Multistage sampling enables an investigator to calibrate a large number of low-cost oribital observations with a small number of ground-based measurements. Optimal sample sizes were derived using a stratified double sampling scheme, as previously described.

The statistical concept of coefficient of variation (CV) and allowable error (AE) help provide a common measure of relative performance between the competing snow water content estimation systems. Coefficient of variation describes a sample's data dispersion about its mean. Allowable error extends the CV concept by enabling the researcher to make a probabilistic decision concerning the precision of an estimated value. This is done by defining a confidence interval about the estimated mean in which the true value will fall a specified portion of the time.

This study employs one variant of cost-effectiveness analysis, known as a "system comparison study", to make a side-by-side comparison of operational and Landsat-aided snow water content estimation systems (Sharp and Thomas 1975).

Figure 1 illustrates a comparative cost-effectiveness framework by showing the effect of technological progress on the cost-capability "frontier" of an existing production system. The frontier F_0F_0 shows the maximum capability that can be expected from the present system at a given level of budget. A system producing on the frontier is defined as "cost-effective" because a decrease in cost is not possible without a decrease in capability. A technological advance would beneficially alter this relationship. A technological advance would beneficially alter this relationship: the cost-effective frontier would be pushed out to some new set of points F_1F_1. A point P_0 on the old frontier F_0F_0 would now represent an inefficient pattern of production. A set of points in the shaded area of Figure 2 would represent an improved return, with cost-effecient points now lying on F_1F_1 between P_1 and P_2. The effect of technological progress thus ranges between equivalent capability at a lower budget (P_1) and greater capability within the same budgetary constraints (P_2). The foregoing model is used for assessing the effect that Landsat imagery would have on current snow water content estimation procedure operated by California Cooperative Snow Survey, Department of Water Resources. The com-cost-effectiveness framework, because it deemphasizes the quantification of benefits, is more adapted to this current stage of work than the typically more ambitious benefit-cost analysis.

Cost Survey for Landsat-Aided and Conventional Methods

Design and evaluation of a Landsat-aided approach to snow water content estimation required an examination of the currently operational system. The California Cooperative Snow Survey (CCSS) program, the principal source of water supply forecasts in California, was examined both qualitatively and quantitatively. CCSS program budget information, although useful for examinining the snow surveys production process as a whole, does not tell us much about the costs of producing intermediate outputs like snow density and water content measurements. Moreover, we were specifically interested in the costs of producing these outputs in our study area, the Feather River Basin, rather than for the entire state.

Estimates for the direct costs of survey work were derived from discussions with DWR snow survey personnel. Based on 1974 survey information, we determined the following average cost figures:

Aerial marker survey measurement visit $15

Snow course survey measurement $150

Costs of the two survey types thus differ by about a factor of ten. Aerial marker visits are relatively inexpensive because a skilled piolet can overfly and photograph many markers in a short period of time. Snow course measurement visits, because they involve detailed ground measurements, have a higher and wider range of costs. DWR analysts estimate the direct costs of visiting the most accessible snow courses at $50 and $60 each. Some courses can be reached by road or easily by snowmobile or helicopter. Remote course accessible only by foot can represent as much as $210 each. This would include two met at $40 per day plus expenses plus maintenance of supply cabins.

Estimates of indirect costs are much harder to derive than difect costs. The challenge is to isolate only those indirect costs associated with the production of snow water content measurements. It was determined that indirect costs amounted to roughly one-third of the direct costs associated with the snow survey efforts. For the Feather River Basin in 1974, with 3 aerial marker visits and 125 snow course visits, total survey costs (C_{FRB}) were estimated as follows:

$$C_{FRW} = 1.33 \cdot (3 (\$15) + 125 (\$150)$$

$$C_{FRW} = \$25,000$$

By assuming a uniform distribution of direct and indirect costs over the snow sampling season, it is possible to estimate how much of the annual snow survey budget is consumed in a "typical" snow survey month. April and May were considered typical survey months in this study. A monthly proportionality factor was derived for April and May and applied to the basin total cost budget (Thomas and Sharp, 1975). The monthly direct costs allocated to survey work were estimated to be roughly $4,200.

Determining costs in the Landsat-aided snow water content estimation system involves mixing costs developed in both the operational and Landsat-aided approach. Since the collection of water content samples at snow courses is an activity common to both methods, it was possible to apply the same set of costs per ground sample unit. The unit costs of typical snow course measurement visits were estimated earlier at $150. Aerial marker measurements visits do not constitute a significant portion of the snow survey budget within the Feather River Watershed.

RESULTS

The results of snow areal extent estimation, snow water content estimation, and comparative cost-effectiveness analysis are discussed below respectively.

Snow Areal Extent:

The results of snowcover inventory is summarized in Table 1. In this table the areal extent of snow estimates and statistically true values along with their standard derivations, population ratio estimators, number of sampled units and the confidence intervals around the estimates are presented. The Landsat-1 images for all the dates are shown in Figures 2, 3, 4, and 5. Each grid box in gridded images equals 400 hectares.

Snow Water Content:

The number of image sample units examined in the watershed and visited on the ground for each snow water content stratum is shown in Table 2. The results of Landsat-aided snow water content estimates, based on Spanish Creek Watershed data, is shown in Table 3. This data is used to represent Feather River Basin values due to the similarity in snow water content class distribution between the two basins for the snow season dates investigated.

The correlation coefficients between the average ground-based and Landsat-based values of snow water content indecies are 0.85 and 0.77 for three dates and two dates of analysis respectively. Since more than two dates will be available in most operational snow water content estimation situations, a conservative value of 0.80 was selected as the correlation coefficient to be used in the sample size analysis.

Cost-Effectiveness Analysis:

Use of the allowable error (AE) formulation, described earlier, permits a direct cost-capability comparison of the two snow water content estimation systems. For the Landsat-based sample sizes, AE's were calculated for monthly direct cost budgets of $1,000, $3,000, $5,000 and $7,000 at confidence intervals of 80, 90, 95, and 99% respectively. For the CCSS system of snow water content estimation, AE's were calculated at four confidence levels on a monthly direct cost budget of $4,200. Results for the 95 percent confidence level are shown below in Figure 6, a diagram analogous to Figure 1. The results may be analysed from two points of view: 1) cost savings and 2) increased precision.

Figure 3 permits a cost comparison of the two production systems at many levels of effectiveness. One production possibility of the existing system is represented by point P_0 at the $4,200 monthly direct cost budget level. Point P_1 identifies an outpout of similar precision and accuracy in the Landsat-based system. The cost advantage per snow survey month is represented by the horizontal distance between P_0 and P_1. In this case, the Landsat-based system shows approximately a $2,300 savings over the existing system of snow water content estimation. Extrapolated over the full range of survey months, this would imply a savings of around 50 percent over the existing annual snow survey budget for the Feather River Basin. Advantages of the Landsat-aided systed are also apparent on the capability of effectiveness side.

Table 1

Summary of Results
Areal Estent of Snow Estimation (In Hectares)
along with the Confidence Intervals

Source	April 4, 1973	May 10, 1973	May 28, 1973
Landsat-1 estimate of the areal extent of snow	511,378	205,768	60,516
Estimate of the true areal extent of snow	501,355	195,644	57,847
Standard deviation of the areal extent of snow estimate	12,776	14,526	17,126
Population ratio estimator	.9804	.9509	.9559
Total number of hectares inventories	879,642	813,014	798,340
Total number of image sample units inventories	2,218	2,050	2,013
Total number of image sample units sampled	80	52	49
Confidence intervals (95%)	485,940 Y_R 536,816	176,601 Y_R 234,935	26,075 Y_R 94,958

Table 2
Number of Image Sample Units
Examined in Watershed and Visited on the
Ground for Each Snow Water Content Stratum

LANDSAT Snow Water Content Stratum	1	2	3	4	5	6
No. of LANDSAT ISU's Examined in Watershed	503	614	205	393	220	283
No. of ISU's Visited on Ground	0	3	1	7	4	11

Table 3. LANDSAT-BASED SNOW WATER CONTENT STATISTICS BASED ON SPANISH CREEK WATERSHED FOR APRIL 4, May 10, and May 28, 1973

Stratum Index (h)	LANDSAT Snow Water Content Estimate Range	Ave. Snow Water Content Index Per Image Sample Unit $\bar{X}_h = \frac{\sum_{i=1}^{h} X_{hi}}{l_h}$	Standard Deviation for X_{hi}	Coefficient of Variation	Total Snow Water Content Index $X_h = \sum_{i=1}^{h} X_{hi}$	Stratum Weight Based on Snow Water Content $W_h = \frac{X_h}{\sum_{i=1}^{6} X_h}$	Number of Image Sample Units for the Spanish Creek Watershed	Number of Image Sample Units for the Feather River Watershed
1	0.00- 0.10	0.0000	0.0000	0.00	0.00	0.0000	32	503
2	0.10- 0.35	0.1833	0.1194	65.14	7.15	0.0304	39	614
3	0.35- 1.00	0.7808	0.1883	24.12	10.15	0.0432	13	205
4	1.00- 3.00	2.0480	0.4404	21.50	51.20	0.2178	25	393
5	3.00- 5.00	3.9557	0.4525	11.44	55.38	0.2356	14	220
6	5.00	6.1750	0.9672	15.66	111.15	0.4729	18	283
							$N^* = 141$	N=2,218

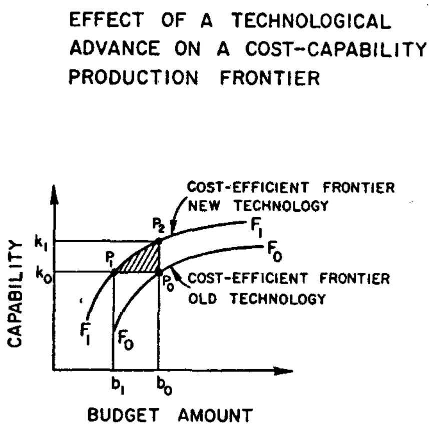

Figure 1. Effect of a technological advance on a cost capability production frontier.

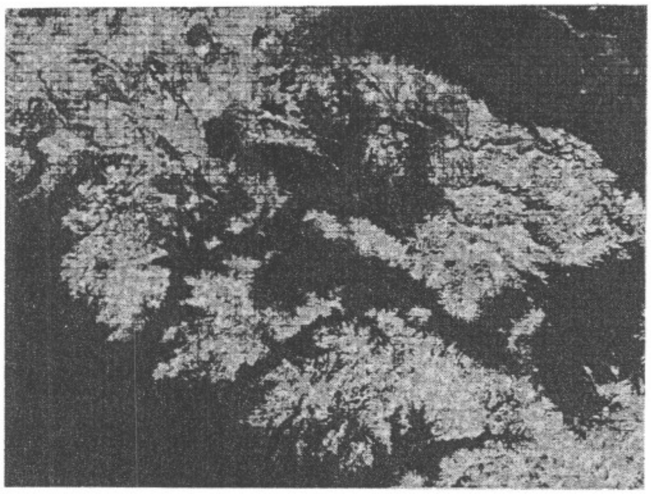

Figure 2. Landsat-1 Simulated color infrared image for April 4, 1973 over the Feather River Watershed, Northern California

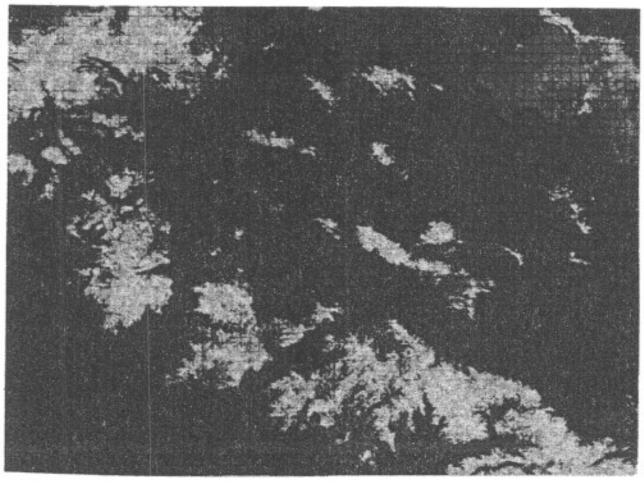

Figure 3. Landsat-1 simulated color infrared image for May 10, 1973 over the Feather River Watershed, Northern California

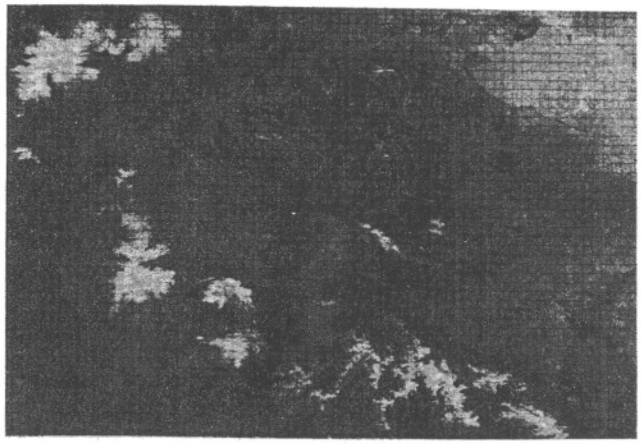

Figure 4. Landsat-1 simulated color infrared images for May 28, 1973 over the Feather River Watershed, Northern California

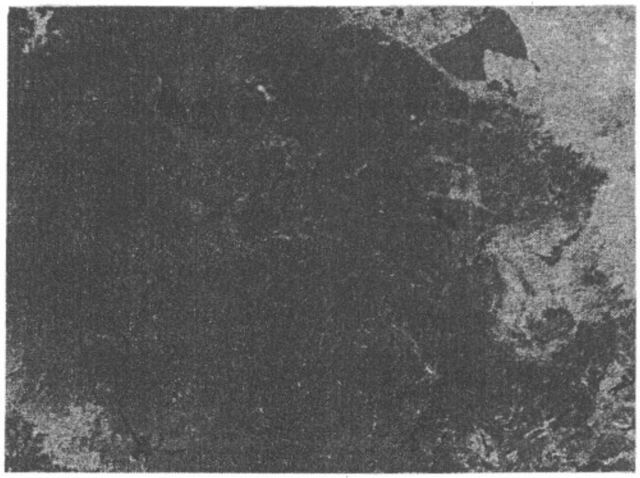

Figure 5. Landsat-1 simulated color infrared image for August 31, 1973 over the Feather River Watershed, Northern California

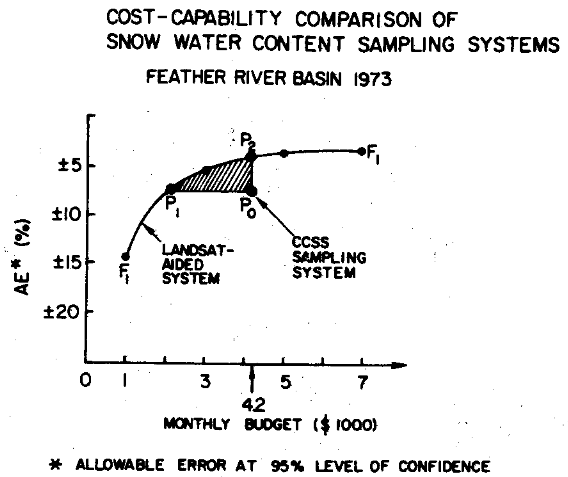

Figure 6. Cost-Capability Comparison of Snow Water Content Sampling Systems

CONCLUSIONS

Landsat-1 imagery along with supporting aircraft and ground data has provided the base information requirements for this snowcover extent and snow water content inventory.

The design of this project facilitates the performance of valid statistical analysis. This is an important factor so that future results from different approaches can be analyzed with respect to prior research. Confidence intervals were applied to all areal extent and water content of snow estimates thus providing accuracy of results figures. The double sampling method employed in this study calibrates the Landsat imagery and provides a good way of analyzing the data.

Major advantages of Landsat-aided system versus existing system for snow water content estimation could be based on the analysis of results of this investigation it could be concluded that: 1) remote sensing data can be integrated with conventional (ground snow course) data for watershed-wide estimation of snow water content; 2) In general, the Landsat-aided system yielded more precise estimates of watershed snow water content than existing procedure; 3) Advantages of the Landsat-aided system are also apparent on the capability or effectiveness side, and 4) the Landsat-aided snow water content estimation system offers several additional information such as frequent in place maps of snow water content and snow melting boundaries.

DISCUSSION

Improvement in the areal extent of snowcover inventory, as it is currently done, is possible by increasing the sample size and by optimizing the image sample unit size.

The one improvement that by itself can substantially decrease the width of the confidence intervals (and consequently the allowable errors) is that of decreasing the sample standard deviation. As already shown, the April 4th data had the smallest standard deviation, the May 10 data had the next smallest and the May 28 data had the largest. The reason for this progressive increase in sample standard deviation most likely can be attributed to the decrease in the snow pack over the three dates. The image analyst's ability to classify seems to be related to the proportion of snow cover; however, the majority of the standard deviation may not be due to the analyst, but rather to a natural state of greater snow areal extent variability among sample units over an area defined as a watershed.

The Landsat snow areal extent-snow water content transform discussed here is only a first case model. Yet it yields correlations with ground sample data on the order of .80. More sophisticated stochastic and physical transform models now being developed should push this correlation significantly higher. The result will be greater snow water content estimation precision at the same level of budget.

The precision of snow water content estimates could be improved still further by using techniques that increase the correlation of orbital to ground snow water content estimates. Smaller image sample units, more enivronment-specific snow class interpretations, and automatic processing of satellite digital data are some of the more promising of these techniques.

The results of this investigation are further enhanced by the fact that snow water runoff is one of the major sources of water supply within the California Water Plan, as well as in many other parts of the world. Improved methods of identifying, monitoring, mapping, and modeling our snow water resources at this time can lead to improved methods of predicting and managing this resource in the future. 'Landsat-based imagery, when used to augment an existing hydrological model, thus appears to resemble a classic "technological advance" as defined in a cost-effectiveness framework.'

REFERENCES

Amorocho, J, and B. Espildora. 1966, "Mathematical Simulation of the Snow Melting Processes". Water Science and Engineering Paper No. 3001, University of California, Davis, February 1966. Presented at the 15th Annual Conference Hydralic Div. ASCE, Madison Wisconsin.

Barnes, James C., Clinton J. Bowley, and David A. Simmes, 1974, "The Application of ERTS imagery to mapping snow cover in the western United States", ERTS Type III Final Report, Jan. 1974, NASA-LR-137223, National Technical Information Services E74-10400, 80 pp.

Burnash, R. J. C., R. L. Ferral and R. A. McGuire, 1973, "A Generalized Stream Flow Simulation Model". National Weather Service—California Department of Water Resources.

Cochran, W. G., 1963. "Sampling Techniques", John Wiley & Sons, Inc. New York, New York.

Katibah, E. F., 1975, "A Simple Photographic Technique for Producing Color Composites from Black-and-White Multiband Imagery with Special Reference to ERTS-1", Information Note, Remote Sensing Research Program, Berkeley, California, 16 pp.

Khorram, S., et al, 1976, "Remote Sensing-Aided Procedure for Water Yield Estimation", In Chapter 3, An Integrated Study of Earth Resources in the State of California Using Remote Sensing Techniques, Space Sciences Laboratory Series 18, Issue 5, University of California, 63 pp.

Leaf, C. F., and A. D. Haeffner, 1971, " A Model for Updating Streamflow Forecasts Based on Areal Snow Cover and Precipitation Index", Proceedings of the 39th Western Snow Conference, pp: 9-16.

Meier, M. F., 1973, "Evaluation of ERTS imagery for mapping and detection of changes of snow cover on land and on glaciers", Symposium on Significant Results Obtained from ERTS-1, NASA-Goddard Space Flight Center, NASA SP-327, pp. 863-878.

Sharp, J. M., and R. W. Thomas, 1975, "A Comparison of Operational and Landsat-Aided Water Content Estimation Systems", Proceedings of Operational Applications of Satellite Snow-Cover Observations, South Lake Tahoe, California, pp. 325-344.

Thomas, R. W., and J. M. Sharp, 1975, "A Comparative Cost Effectiveness Analysis of Existing and Landsat-Aided System for Estimating Snow Water Content", An Integrated Study of Earth Resources in the State of California Using Remote Sensing Techniques, Space Sciences, Laboratory, Series 16, Issue 34, University of California, Berkeley.

Thompson, A. G., 1975, "Utilization of Landsat Monitoring Capabilities for Snowcover Depletion Analysis", Proceedings of Operational Applications of Satellite Snowcover Observations, South Lake Tahoe, California, pp. 113-129

U.S. Army Corps of Engineers, 1956, "Snow Hydrology".

Weisnet, D. R., and D. F. McGuiness, 1974, "Snow Extent Mapping and Lake Ice Studies Using ERTS-1 MSS together with NOAA-2VHRR", Proceedings of the Third ERTS-1 Symposium, NASA Sp-351, U.S. Government Printing Office, Washington, D.C., Vol. 1, pp. 995-1009.

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