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A COMPARISON OF OPERATIONAL AND LANDSAT-AIDED SNOW WATER CONTENT ESTIMATION SYSTEMS

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ABSTRACT

This study describes how LANDSAT imagery can be cost-effectively employed to augment an operational hydrologic model. Attention is directed toward the estimation of snow water content, a major predictor variable in the volumetric runoff forecasting model presently used by the California Department of Water Resources. A stratified double sampling scheme is supplemented with qualitative and quantitative analyses of existing operations to develop a comparison between the existing and satellite-aided approaches to snow water content estimation. Results show a decided advantage for the LANDSAT-aided approach.

1.0 INTRODUCTION

Problems in managing natural resources often reduce to problems in allocating scarce time and money resources. Technological innovations like LANDSAT, by dramatically reducing the costs of gathering information, promise to beneficially alter existing time, cost, and capability relationships in many resource management areas.

This paper describes and applies a methodology for comparing different information-gathering technologies. Although the focus here is on a particular resource (water) in a particular context (snow mapping and runoff prediction) over a particular region (the Feather River Watershed of Northern California), the approach can be generalized to cover other natural resource data acquisition situations.

The overriding objective for the work described here is "to determine if remote sensing can be <u>cost-effectively integrated</u> with data presently used in the California Cooperative Snow Surveys (volumetric) model to produce potentially more precise and accurate estimates of water supply" (Thomas <u>et al</u>., 1974).

Attention in this study is directed toward the estimation of <u>snow water content</u>, a major predictor variable and intermediate

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output of this California Cooperative Snow Surveys (CCSS) volumetric yield prediction model. Normally, snow water content estimates are developed directly from ground-based snow course measurements. Instead, this study introduces a stratified double sampling approach that relates the ground-based estimates to snow areal extent data gathered from LANDSAT-1 imagery. The resulting relationships enable low-cost remotely-sensed data to account for a large portion of basin snow water content variability.

The study's major elements are summarized below in three sections. An initial section briefly describes cost-effectiveness analysis and how it can be used. A following three-part section describes general underlying assumptions and compares the two systems in terms of their sampling designs and costs. Finally, comparative results and conclusions follow.

2.0 COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness analysis is one of several techniques that attempt to apply economic rationality to public investment decision making. Benefit-cost analysis is its closest theoretical relative, although techniques used in systems analysis, operations analysis, planning, programming and budgeting systems (PPBS), and others bear strong resemblance to the cost-effectiveness appraoch. These techniques all share a common purpose: i.e., to make systematic and quantitative comparisons between alternative resource allocation options, using a logical sequence of steps that can be verified by others.

Traditional resource allocation processes have been a mixture of political, administrative, and professional judgement. Their purpose is typically to find a pattern of production which is most efficient, or lowest cost for a set of desired outputs. Without a price mechanism to allocate output, some other procedure is necessary.

The choice of appraisal methodology depends upon the nature of the investment and the information available. Both benefit-cost and cost-effectiveness analyses contain their own variants, advantages, and limitations. In benefit-cost analysis, every effort is made to quantify in commensurable monetary terms both the benefits and costs stemming from alternative actions. Physical outputs are projected, social values (positive and negative) are estimated for these outputs, and benefits and costs are compared over time, either on a gross annual basis or on a net benefit basis discounted to the present. A complete analysis includes not just immediate benefits and costs to the agency and its clients, but also the spillover benefits and costs to others not directly related to the action in question. The result is a ratio of benefits to costs for each alternative action considered.

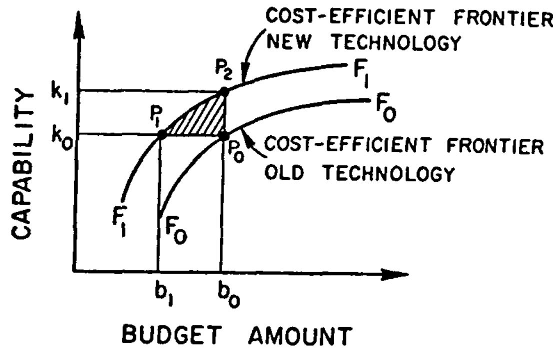
Cost-effectiveness analysis, in contrast, allows the use of multiple, non-commensurable measures on the benefit side. Economic benefits are stated in terms of cost savings. The method is specifically directed toward problems in which outputs cannot be evaluated in market prices, but where inputs can, and where the inputs are substitutable at market-developed exchange relationships. Cost-effectiveness analysis thus helps a decision-maker answer questions about how to achieve a given set of objectives at the least cost, or how to obtain the most effectiveness from a given set of resources.

Some kind of cost-effectiveness analysis is involved in any decision concerning resource allocation. In the usual case, a decision-maker relates the costs of alternative scarce resources (inputs) to specified performance standards (outputs) desired from a production process. The decision-maker may be looking for the least expensive way to meet the specifications or for a means of adjusting the specifications to fit a fixed budget. In either case, the decision-maker seeks to establish cost-capability relationships for various combinations of resource alternatives.

The system comparison type of cost-effectiveness analysis is well-suited for identifying the potential contribution of new technologies to the cost-capability relationships of existing systems. Figure 1 illustrates 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: the cost-efficient 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 1 would represent an improved return, with cost-efficient 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 procedures in California. The comparative 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.

FIGURE 1 - EFFECT OF A TECHNOLOGICAL ADVANCE ON A COST-CAPABILITY PRODUCTION FRONTIER



An identification and evaluation of the benefits stemming from improved hydrologic modeling will be part of the future work.

3.0 COMPARATIVE ANALYSIS

In addition to ample qualitative information, judgements about the cost-effectiveness of comparable systems usually require a resourceful use of quantitative methods. Comparative analyses, in other words, must be "custom-tailored" to the uniqueness of each case example. This section describes how we applied a cost-effectiveness analytic framework to the context of our snow survey example.

3.1 Assumptions

Real-world complications inevitably force applied cost-effectiveness analyses to deviate from their theoretical counterparts. On the cost side, the question is not one of perfection but of sufficiency. On the performance side, a balance must be struck between what we would like to measure and what can be measured with reasonable accuracy. Overriding both sides are questions concerning the comparability of different production systems.

Ideally, our own study would attempt to compare the existing DWR CCSS volumetric model with an identical model augmented with remotely-sensed snow survey information. Outputs of both models would be keyed to estimates of total water yield. Costs and accuracies would be estimated at least for the entire Feather River Basin, if not for the whole Sierra Nevada.

In reality, our study isolates those portions of the CCSS volumetric model that can be compared with LANDSAT-derived snow areal extent information developed in the University of California Remote Sensing Research Program (RSRP). An intermediate output--snow water content-- is used rather than water yield. This is nevertheless a critical step toward defining the applicability of remote sensing techniques to the possible improvement of water yield forecasts. By individually examining predictor variables such as snow water content, we may determine how precision increases that are made in predictor variable estimates can lead to precision increases in overall predictions. The analysis here thus compares the relative abilities of two systems to generate an intermediate output. Costs and accuracies for the existing model are based on published reports and interviews with DWR staff. Costs and accuracies for the LANDSAT-aided model are derived from concurrent RSRP work in the Spanish Creek Watershed, an area within the Feather River Basin.

The proposed LANDSAT-aided and the current CCSS Program snow water content estimation systems are, in fact, not identical. However, if the two systems' products are utilized similarly and are based on a concept concerning a representative quantification of the characteristics of watershed snow pack, then a common measure of relative system performance is possible. The intermediate products of both systems are designed to be utilized in water yield prediction. The error of either will affect the runoff prediction in a similar manner. Both are intended to characterize, at least in part, the general variability of the snow pack as it relates to water content.

A common statistical measure of performance is therefore implied. The often-used criterion of probability sampling, known as allowable error (AE) is appropriate here. Consequently, the CCSS snow course system must be considered as a random sample for comparison. To make this assumption and insure an equitable comparison requires that an especially favorable assumption toward the CCSS system be made. This additional assumption is that the CCSS snow courses are randomly located over the entire watershed. In fact, however, they are allocated only to the zone receiving snow that is resident on the ground for significant periods during the middle of the snow season. The result is that CCSS snow water content data will have a smaller coefficient of variation than would be expected if ground sample units were in fact allocated over the entire watershed.

3.2 Comparative Sampling Designs

3.2.1 The Current CCSS Program Snow Water Content Estimation Technique

3.2.1.1 Output

The objective of the California Cooperative Snow Survey Program's snow water content estimation technique (system) is to provide a snow water content index input to a watershed specific, multivariate regression water yield prediction model. Other predictor variables include runoff and precipitation quantities (Thomas, et al., 1974). Basin specific snow water content indices are generated monthly, February through May. January and June values may be produced as well.

The snow water content index is a statistically significant variable in prediction of monthly and April-July runoff quantities in California. This data give rise to the CCSS Program's ultimate product, the water yield forecast. Since 1929, the Department of Water Resources (DWR) has coordinated California's program of snow surveys and water supply forecasting. The stated objective of this program is to "reliably predict the State's snow-melt runoff as necessary to meet the annual operating needs of California's water using agencies." Water supply forecasts are published in DWR Bulletin 120 titled "Water Conditions in California" and issued five times a year. Four reports contain water supply forecasts based on snow conditions as of the beginning of February, March, April and May, respectively. The fifth report is distributed in December and summarizes the previous water year.

3.2.1.2 General Technique (System) Features

A watershed snow water content index is generated primarily from data gained by monthly visits to a set of snow courses distributed over the basin in question. Within a given area designated as a desirable snow course location, only certain positions presently satisfy course location criteria. These positions must be essentially open and free from extreme drift, melt, wind, and ponding (Bulletin 129, 1970). Annual measurements in the same locations provide an index to snow cover forecasting runoff.

The snow course itself consists of ten points spaced at 50 or 100 foot intervals in one or more transects. Snow depth and weight readings are taken at each point with a Mt. Rose snow sample device. The resulting average snow water content from ten points is then defined as the course snow water content value for the given sample date. Key snow courses are visited near the beginning of each month from January through May, while all snow courses are sampled on or about April 1.

Snow depth markers associated with snow courses and a growing network of experimental automatic snow sensors, provide supplemental information to the snow course networks.

3.2.1.3 Sample Size and Allocation

The current number of active snow courses in the Feather River watershed (880,000 ha), the study site in this research, is 29. However, this total number is only visited in the baseline month of April, the average date of maximum snow accumulation. Otherwise, 21 to 23 courses are visited at the beginning of each month in the February to May period. Thirteen snow courses are visited for January data.

The Feather River basin also has nine active depth marker for light aircraft observation. However, a combined total of only three aerial marker readings were made in the 1974 water year.

These snow courses are not currently allocated over a watershed (e.g., Feather River area) in a random fashion. Instead, the present CCSS Program snow course locations have evolved paralleling the development of snow hydrology sampling theory over the last fifty years (Howard 1974). For example, 30 to 40 years ago snow courses were located primarily according to site accessibility. The next twenty years saw criteria for new snow course location evolve to allow better areal and elevational snow zone sampling. Recently, locational criteria have emphasized snow zone positions with high runoff correlations. Some of these positions may not have been sampled previously.

The basic assumption of the CCSS Program's snow course allocation scheme is that the quantitative subjective allocation plan will provide data that can be correlated with water yield. As Bulletin 129 points out, snow course measurements should not be taken as an accurate measure of snow water content over a large area without careful study of both the snow course and the area of interest.

3.2.2 The LANDSAT-aided Snow Water Content Estimation System

3.2.2.1 Output

The proposed LANDSAT-aided snow water content estimation system is designed to generate an estimate of total watershed snow water content and an associated statement of precision, i.e., reliability. The estimate may then be related by regression equations directly to basin water yield for a given runoff period. Or the estimate may be used as another predictor variable in current snow survey runoff prediction equations.

3.2.2.2 General System Features

The snow water content estimation method utilized in this study with LANDSAT information is known as a stratified double sample. 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 snow courses. In this way, a large amount of the variability in basin snow water content is accounted for by the use of the LANDSAT data.

The desired result is that after calibration by regression of LANDSAT data on snow course data, an overall estimate of basin snow water content is possible at significantly more precise levels than available for the same cost from conventional snow course data alone. In addition, the associated gridding of LANDSAT data into an image sample unit system allows an in-place mapping of snow water content with respect to known melting environments and stream channels. Such in-place mapping is potentially very useful as an additional data type for improvement of hydrologic model accuracy.

The stratified double sampling plan is described mathematically by Thomas and Sharp (1975). The method summarized in section 3.2.2.4 generally proceeds as follows: First, black-and-white LANDSAT transparencies are obtained and transformed to a simulated infrared color composite form (Katibah, 1973). In the color combining process an image sample unit grid is randomly placed over the image so as to cover the watershed of interest. Each image sample unit is then interpreted manually as to its average snow areal extent cover class according to a snow environment-specific technique described by Draeger and Lauer (1973) and in more detail by Katibah (1975).

Snow water content is then estimated from the following first case, time specific model[1]:

$$X_i = \left(\sum_{j=1}^{J} (M_{ij})(G_j) \right) \cdot K_i \qquad \text{eq. 1}$$

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 the current estimate,

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

1. Investigation of more sophisticated stochastic model and physical model transforms is currently under way.

J = total number of snow season dates considered.

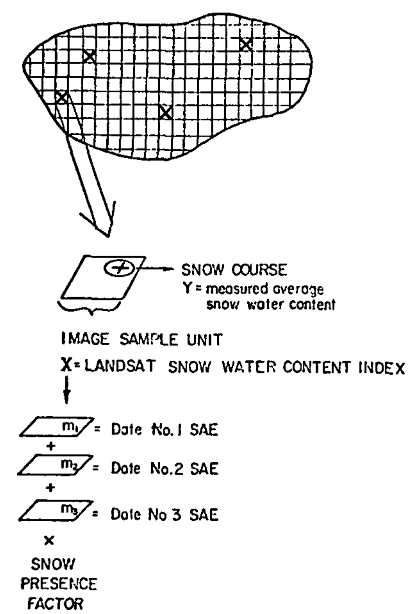
Image sample units utilized in this study represented 980 acre ground areas. Snow cover classes were defined as 0 percent, >0 - 20 percent, > 20 - 50 percent, >50 - 98 percent, and >98 - 100 percent of ground covered by snow.

In order to insure reasonably high correlation between X_i and corresponding ground water content values, y_i, j should equal at least three. As a matter of operating procedure, one or two dates of LANDSAT imagery would be required during the early snow accumulation season after which LANDSAT snow water content estimation could proceed for a given date based on a semi-sliding two, three, or more date basis. Under certain circumstances j may only be two. For instance, an early snow season date and the mid-season date of interest may give rise to acceptable LANDSAT-ground correlations. Or, more powerfully, the first date may consist of an average 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 to a base date grid location (see Figure 2).

After the snow water content index for each LANDSAT image sample unit has been determined, all such units are sorted into strata according to the size of their respective snow water content index. Stratification is used to control the coefficient of variation of the overall basin water content estimate. This is accomplished by the subsequent segregation of the population of image sample units into homogeneous environmental types tending to receive, accumulate, and lose snow at similar rates (see Figure 3). Six such strata were used in the effort reported here.

FIGURE 2

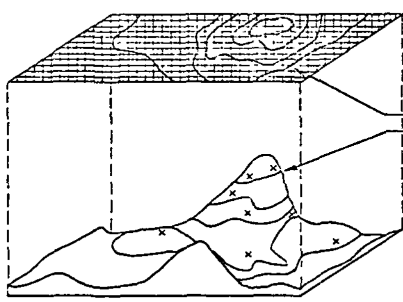
SNOW MEASUREMENTS WITHIN THE SAMPLE UNIT GRID



The total snow water content in a given stratum was obtained from a simple linear regression equation relating image and ground data. Given the average LANDSAT-image derived snow water content index and the number of sample units in that stratum, the regression equation <u>will predict</u> a total

FIGURE 3

STRATIFIED DOUBLE SAMPLING FOR WATERSHED SNOW WATER CONTENT ESTIMATION



ground-based snow water content value for the stratum. The total, ground-calibrated watershed snow water content estimate is obtained by simply summing the strata estimates.

An associated estimate standard deviation may be calculated. The total snow water content estimate can then be placed in a confidence interval in which the actual basin total snow water content is said to fall a specified percentage of the time.

3.2.2.3 Sample Size and Allocation

All watershed sample units are inexpensively examined by the photointerpreter. Ground (snow course) sample sizes 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.

Assuming the current total monthly snow survey budget of $4,200 (see section 3.3) for the Feather River watershed, an average gound sample unit cost of $150, an average image sample unit cost of $0.15, and accounting for overhead costs, ground sample unit sizes were calculated for the six snow water content strata. The accumulated LANDSAT snow water content index in each stratum represented the stratum's size. Strata definitions, variances, and other statistics are given in the table below. The table in section 4.1 summarizes the image and ground sample unit sizes. A correlation coefficient of 0.80 between image and actual ground snow water content estimates, based on spring 1973 data, was used in the sample size calculations.

LANDSAT SNOW WATER CONTENT STRATUM	1	2	3	4	5	6
SNOW WATER CONTENT INDEX RANGE	0.00-<0.10	0.10-0.35	>0.35-<1.00	1.00<3.00	3.00-5.00	>5.00
AVERAGE SNOW WATER CONTENT INDEX	0.00	0.18	0.78	2.05	3.96	6.18
RELATIVE ACCUMULATED SNOW WATER CONTENT INDEX	0%	3%	4%	22%	24%	47%
CV OF SNOW WATER CONTENT INDEX	0%	65%	24%	22%	11%	16%

Once stratum ground (snow course) sample sizes have been calculated for a fixed budget, the expected performance may be determined for the snow water content inventory. One standard statistical expression of performance is expected resulting allowable error (AE). This value was defined previously as the half width of an interval centered on the basin estimate in which the true basin water content value is expected to fall with given confidence probability. Calculation of the expected overall coefficient of variation (CV), selection of the confidence probability (represented by Student's-t), and use of the total snow course sample size (n) allows calculation of expected resulting AE according to the following formula.

$$AE = (t_{n_{total}-1}) \cdot (CV_{overall}) \qquad \text{eq. 2}$$

If the allowable error is not low enough to satisfy snow water content estimation objectives, a larger snow survey budget is required. In this case the hypotehsized larger budget level is selected and the sample size and allowable error calculation process is repeated. It should be noted that the calculation of the overall coefficient of variation would be based in part on LANDSAT data and in part on snow course data. If snow course data are not available then first year snow water content variability estimates may be based on previous LANDSAT data or supporting time coincident aircraft data alone.

After the allowable error criterion has been met, the calculated number of necessary snow courses per stratum are allocated with equal probability to image sample units within a stratum. This allocation for a given watershed may occur once during the system setup. In such a situation, sample size and AE testing should be performed for the most variable snow water content index month of the snow season. Once the snow courses were established, cost-effective basin snow water content estimation would proceed by use of the double sample regression formulae relating LANDSAT and ground data. The resulting water content estimate would then be related in combination with other independent variables to water runoff.

For basins where established snow courses already exist, the snow courses would be classified into the appropriate strata. Under this third allocation method, additional courses could then be added, subtracted, or replaced where necessary according to an annual partial course replacement strategy.

3.2.2.4 Summary of Steps to be Used in Stratified Double Sampling for Snow Water Content Estimation

(1) Create LANDSAT color composites with appropriate image sample unit grid over watershed(s) of interest.

(2) Estimate snow areal extent by LANDSAT image sample unit for previous year(s) or current season snow build-up dates(s).

(3) Estimate snow areal extent by image sample unit for LANDSAT snow season date of interest.

(4) Transform snow areal extent data to snow water content data by LANDSAT image sample unit.

(5) If not already performed, stratify image sample units into LANDSAT snow water content index classes. Then calculate stratum ground sample unit (snow course) sample sizes to achieve allowable error criteria for the basin snow water content estimate. Stratification and sample size calculation should be performed for the pre-snow season date combination having the most variable snow water content and/or containing the largest water runoff-related snow pack.

(6) If not already performed for the given snow season or snow season date, allocate ground sample units to strata with equal probability within strata.

(7) Calculate the estimate of watershed snow water content according to a summation of stratum regression relationships for LANDSAT versus ground observations.

(8) Enter the basin snow water content estimate into statistical or physical models to predict water yield.

3.3 <u>Comparative Costs</u>

3.3.1 The CCSS System

3.3.1.1 CCSS Budget

An agency's budget provides an obvious starting point for evaluating the cost of outputs produced. In the case of the snow survey and water supply forecasting activities of the DWR, we found that the entire production process has been running on an "official" annual budget of around $300,000. About 90 percent of this amount comes from State general fund support. The remainder, about $30,000 a year, consists of reimbursements from CCSS program cooperators.

The DWR snow surveys group has estimated that cooperators contribute services far in excess of their reimbursements. This occurs because many cooperators absorb the state survey costs along with their own snow survey efforts. The DWR estimates (very roughly) the value of these unaccounted services at around $200,000 per year. This implies an "unofficial" snow survey annual budget in the neighborhood of $500,000.

Program costs within the budget are allocated about 50:50 between survey support and forecast activities. The DWR's non-salary direct costs for snow survey activities in 1974/75 are budgeted at around $28,000. This includes $19,000 for contractors, $4,000 for flying services and other support, and $5,000 for sensor equipment. These costs are expected to be fully offset by contributions from cooperators. Budgets in future years are likely to contain greater outlays for sensor equipment as automatic sensors and other sophisticated measurement devices are brought into use.

3.3.1.2 Cost of Surveys

CCSS program budget information, although useful for examining the snow surveys production process as a whole, does not tell us much about the costs of producing <u>intermediate outputs</u> 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 visit ≈ $150

Costs of the two survey types thus differ by about a factor of ten. Aerial marker visits are relatively inexpensive because a skilled pilot 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. The costs of visits appear most affected by where they are and who performs them. 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 courses accessible only by foot can represent as much as $210 each. This would include two men at $40 per day plus expenses plus maintenance of supply cabins.

Estimates of indirect costs are much harder to derive than direct costs. The challenge is to isolate only those indirect costs associated with the production of snow water content measurements. Indirect costs can be distinguished in the following DWR snow survey activities:

- program direction and coordination of survey work
- communication with cooperators
- preseason aerial marker and snow course setups
- measuring equipment acquisition and maintenance
- training and safety instruction sessions
- formal recording and publication of 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:

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

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

3.3.1.3 Cost Per Survey Month

If it is assumed that direct and indirect snow survey costs accrue uniformly 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.

3.3.2 LANDSAT-Aided System

3.3.2.1 Ground Sample Unit Costs

Since the collection of samples at snow courses is an activity common to the LANDSAT-aided and the existing snow survey methods, it was possible to apply the same set of costs per ground sample unit to both systems. 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 Basin.

3.3.2.2 Image Sample Unit Costs

Costs per image sample unit, applicable to only the LANDSAT-aided survey system, were developed along with the sampling methodology described previously, and are derived from actual University RSRP snow survey work using 2218 image sample units in the Feather River Watershed.

The average cost for each of the 2218 image sample units was 13.6¢, of which about 10¢ went toward image interpretation and keypunching. Since most of the processed and unprocessed imagery is useful for later training and comparative analysis, an amortization factor was applied. It was assumed, for example, that two out of three dates of imagery developed for one occasion would be usable over a total of five separate occasions.

4.0 RESULTS AND CONCLUSIONS

4.1 Sample Sizes

The methodology behind sample size determination was described in section 3.2. The number of samples required were calculated for various budget levels, sample costs, and weighting options. The following table summarizes the number of image sample units (ISU's) and ground sample units (GSU's) required in each of six LANDSAT snow water content strata, given a cost per ISU of 15¢ and a cost per GSU of $150.

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

4.2 Performance Comparison

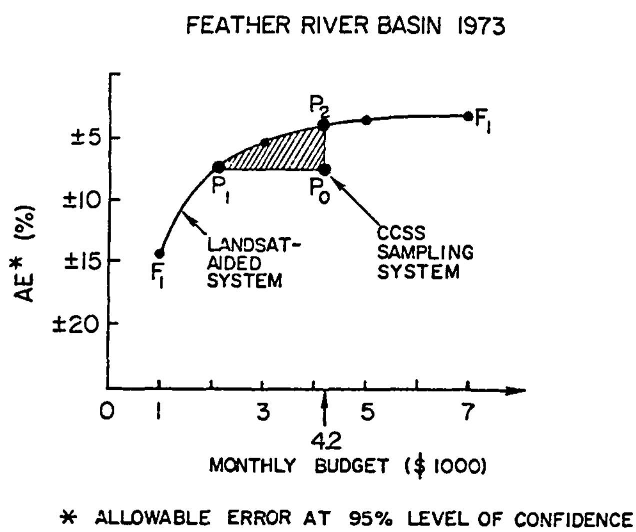
Use of the allowable error (AE) formulation described earlier permits a direct cost-capability comparison of the two snow water content estimation systems. For the LANDSAT-based sample sizes, AE's were calculated for monthly direct cost budgets of $1,000, $3,000, $4,200, $5,000, and $7,000 at confidence intervals ranging from 80% to 99%. For the CCSS system of snow water content estimation, AE's were calculated at four confidence intervals on a monthly direct cost budget of $4,200. Results for the 95 percent confidence interval are shown below in Figure 4, a diagram analogous to Figure 1.

4.3 Major Conclusions

4.3.1 Cost Savings

Figure 4 permits 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 output 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.

FIGURE 4 - COST-CAPABILITY COMPARISON OF SNOW WATER CONTENT SAMPLING SYSTEMS



4.3.2 Increased Precision

Advantages of the LANDSAT-aided system are also apparent on the capability or effectiveness side. At the $4,200 budget level, the proposed snow water content estimation produced results approximately 1.8 times more precise than the existing system.

In general. the LANDSAT-aided system yielded relatively precise estimates of total watershed snow water content. For a $4,200 monthly budget, this approach estimated true basin snow water content to within ± 3.6% ninety-five times out of a hundred. The precision of basin 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 environment-specific snow class interpretations, and automatic processing of satellite digital data are some of the more promising of these techniques.

4.3.3 Additional Abilities

The LANDSAT snow areal extent-snow water content transform presented 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 LANDSAT-to-ground correlation coefficient of .80 was achieved using satellite imagery specific to two ground survey dates plus minimal information from a third date. In an operational situation, however, detailed early-season and/or previous-snow-season LANDSAT data would be available in combination with the snow date of interest, this additional information should further increase the correlation coefficient and produce an even more cost-effective snow water content estimation.

A LANDSAT-aided snow water content estimation system offers several additional possibilities for future snow survey work:

- One biproduct of the LANDSAT-derived image sample unit data is an in-place mapping of snow water content with respect to known melting environments and stream channels. Such time- and place-specific snow melt records could be used to aid in the selection of new snow course sites or in the placement of automatic snow sensors. Snow pack and stream channel juxtaposition data could also be used in refined models of runoff timing.

- Human and automatic analysis of daily meteorological satellite data, when correlated with less frequent LANDSAT and ground data, offers the possibility of extremely frequent watershed snow water content updating.

- Hydrologic models of the future will conceivably integrate remote-sensing and meteorological data with automatic ground-based snow sensing equipment. Real-time information eventually could be generated for entire watersheds of subbasins, depending on the need to assess the impact of a major storm or a minor subdivision. The continued refinement of remote sensing-aided snow water runoff estimation procedures is likely to be a necessary input into future water resource management practices.

The foregoing conclusions suggest that remote sensing promises great potential for aiding in the snow water content estimation process. Our findings 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 fiture. LANDSAT-derived imagery, when used to augment an existing hydrologic model, thus appears to resemble a classic "technological advance" as defined in a cost-effectiveness framework.

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