BASIN DIVISION AND SNOWMELT DISCHARGE IN AN ALPINE BASIN 780-85

by

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INTRODUCTION

As population centers throughout the west expand, a reliable water source is increasingly important. Mountain snowpacks are a major contributor to annual streamflow, especially in the Rocky Mountain states (United States Army Corps of Engineers (U.S.A.C.E.), 1956; Office of Technological Assessment (O.T.A.), 1983). Yearly variations in mountain snowpacks are responsible for floods or drought. The alpine snowpack as a substantial, consistent, and efficient contributor to the seasonal mountain snowpack (Williams and Peck, 1962; Barry, 1973; Martinelli, 1975; Carroll, 1974, 1980) is the subject of this study. The 7.3 square kilometers of alpine terrain within the Green Lakes Valley watershed of the Colorado Front Range was used as the study site during the 1982 snowmelt season.

Background

Previously the recessional limb of the seasonal hydrograph has been characterized as an exponential decay curve (Leaf, 1975; Caine 1976), where streamflow follows the contraction of the snowpack. Primary interest focused on the time period prior to peak flow when it can be assumed that streamflow is primarily dependent on snowmelt. Therefore, streamflow is used to determine the nature of the expansion rate of the snowpack contributing to the snowmelt hydrograph.

Most models used to describe the influence of snowmelt on streamflow can be characterized as index models, simulation models or some combination of the two. Index models develop statistical relationships between indices of snow water equivalent or meteorological data and basin discharge. Simulation models extrapolate energy balance concepts for a point to an entire basin in order to estimate basin discharge. Often, because of physical and monetary constraints, studies lack sufficient data and are forced to make certain assumptions. Common assumptions are (1) snow accumulation and depletion characteristics are uniform for the entire basin or zones within the basin; and, (2) meteorological conditions have uniform rates of change with elevation. The accuracy of predicted streamflow is dependent on the validity of these assumptions.

In the alpine, even though the distribution of snow by wind tends to give snowcover a patchwork quality, the same pattern appears to recur annually, with local topography strongly influencing the distribution of snow (Anderson, 1972; Martinelli, 1975). The distribution of snow throughout the basin is the primary factor governing the snowmelt schedule and is important in defining the form of the snowmelt hydrograph (U.S.A.C.E., 1956, 1960; Anderson, 1972; Rango, 1983). Numerous studies have reported the importance of such factors as elevation, slope aspect, slope angle and vegetation cover in determining radiation receipts and therefore snowmelt runoff (Price and Dunne, 1976; Dunne and Leopold, 1978; Thomsen and Striffler, 1980). Investigators have divided basins into different zones in order to better describe snowmelt runoff (Carroll, 1974, 1980; Martinec, 1979; Rango, 1983). A model might more accurately describe the snowmelt/streamflow relationship if it can adequately divide the basin into groups of similar snowcover and energy environments.

OBJECTIVES

For the purposes of this study the isothermal snowpack is defined as that portion of the snowpack which is at 0°C throughout its thickness and thus contributing to snowmelt runoff. Snowcover area will be used as a surrogate for the snowpack classified isothermal. That is, the isothermal snowcover (isoarea) refers to the surface area of that portion of the snowpack which is 0°C from the snow surface to the ground surface and contributing to snowmelt streamflow.

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The study's objectives are:

(1) the division of the basin into similar snow and energy environments, with particular regard to changes in snowcover and ablation estimates; and,

(2) comparison of different isoarea expansion rates for Model 1 and Model 2. Model 1 used generated discharge estimates to approximate isoarea and compare to available snowcover. The model, based on recessional analysis of the seasonal snowmelt hydrograph, was exponential by nature of its derivation which limited its usefulness within the study. Accordingly, a second model (Model 2), modified from Garstka (1978), was developed which described daily discharge in a manner which allowed the modeller to test different isoarea expansion rates.

Study Area

The Green Lakes Valley, Figure 1, ranges in elevation from 3250m in the east at the Lake Albion townsite to 4000m in the west, along the Continental Divide. The basin can be divided into two distinct valley types. The upper valley is a high alpine environment with active talus slopes and soil development primarily limited to the valley floor. The lower valley consists of much fewer active talus slopes, a more extensive soil cover and more vegetation than the upper valley. The four lakes in the lower valley have been dammed and their levels raised while the two upper valley lakes are not actively controlled. Green Lake 2 was drawn down in the fall of 1981 and raised in the summer of 1982. Although this change in the lake level affects the basin's water storage capacity, the effect is slight and, therefore, not taken into account. Permanent snowfields can be found in both the upper and lower valleys, while approximately 5% of the entire basin within the lower valley has forest cover.

Data

As part of the University of Colorado Long-Term Ecological Research (CULTER) Program, stream discharge, meteorological records, and ablation records have been gathered and summarized. Snowcover changes were also recorded for the 1982 snowmelt season. Stream discharge was recorded at the Albion townsite (3250m) approximately 0.8km downstream of Lake Albion. Meteorological conditions were recorded at two sites along Niwot Ridge, (Saddle (3536m) and D1 (3743m)), which forms the northern border of the basin. Ablation was measured at six snow course sites on twelve occasions between June 11 and September 10. Elevation for the snow course sites ranged from 3500m to 3850m and varied in aspect from N.N.E. to S.S.E., and included one site on the valley floor. Finally, snowcover was estimated using ground photographs on six dates between May 27 and July 15.

BASIN DIVISION

The basin was divided into 188 square grid sections, approximately 190 meters on a side. Each grid section was then described by its mean elevation, slope aspect, and slope angle. A cluster program (Davis, 1973) arranged the 188 grid sections as a dendrogram based on similarity defined by a distance coefficient. The dendrogram was then arbitrarily divided into ten groups. Most groups were comprised of a core of contiguous grids and a number of satellite grids, Figure 2.

To test the ability of elevation, slope aspect and slope angle to discriminate between groups, a t-test was performed on the snowcover present on June 23, at peak flow, four weeks after snowcover estimates began. For all groups tested, the null hypothesis could not be rejected at the 95% confidence level, implying no difference in snowcover between the groups on June 23.

Ablation estimates for the six sites were regressed in a stepwise manner against their elevation, slope aspect, and slope angle for each week between June 11 and September 10. The regression coefficients, Table 1, were used with the mean elevation, slope aspect, and slope angle for each group to estimate average ablation within the group. A t-test of each regression's correlation coefficient (R) showed only one time period, July 1 - July 8, significant at the 95% confidence level. However, a larger sample ($N>6$) size would lower the critical R value which might increase the number of time periods statistically significant. Also, information gained by including slope angle is so small that its elimination should be considered. Slope angle, however, might be more important in other basins.

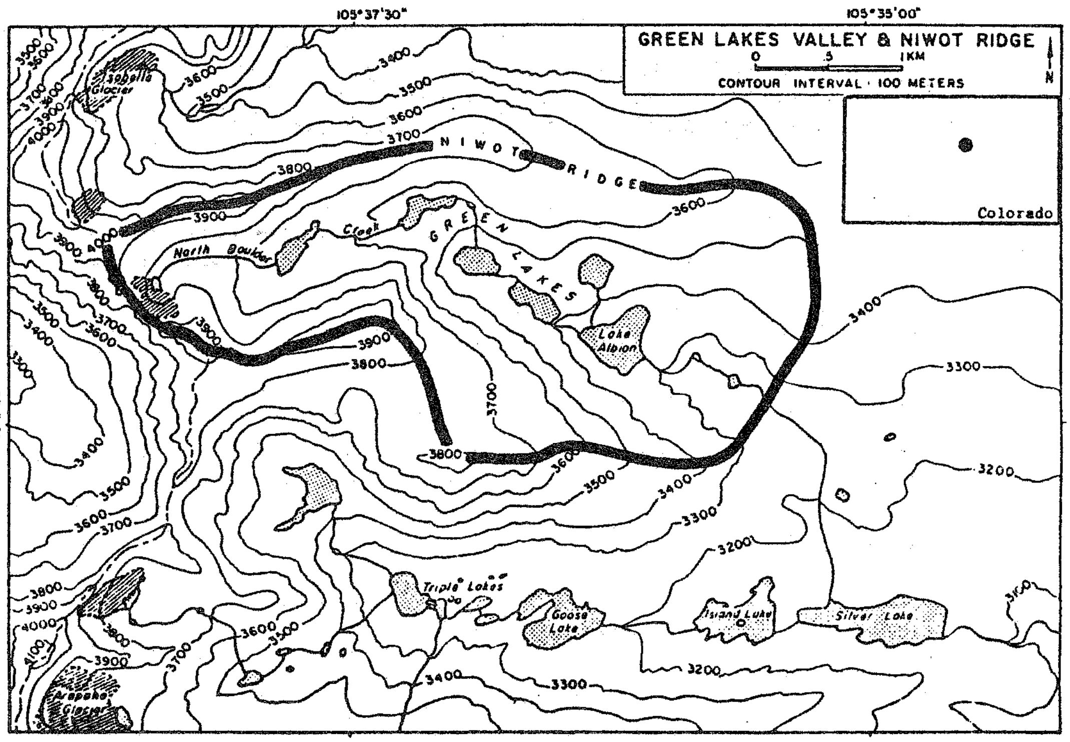

Figure 1. The Green Lakes valley, Colorado Front Range.

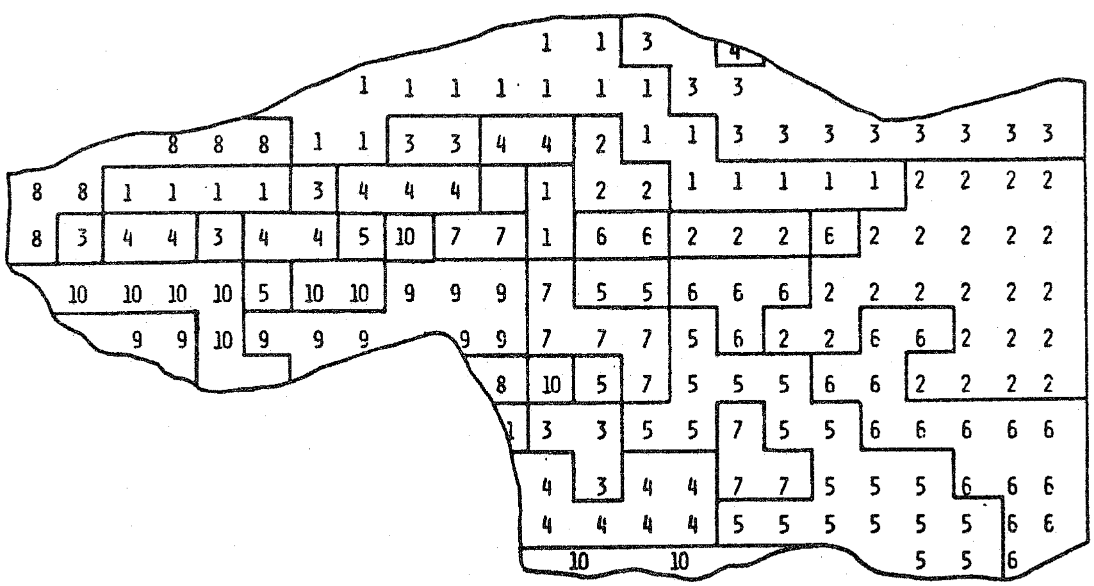

Figure 2. The basin delineated into 10 groups using a dendrogram derived from a cluster analysis of grids described by their mean elevation, slope aspect and slope angle.

Table 1. Stepwise regression analysis for elvation, slope aspect, and slope angle against ablation. T-test critical value for regression's correlation coefficient,(R), is .983.

Date	Elevation	Slope Aspect	Slope Angle	Constant	Correlation Coefficients (R)
June 11 June 24	-.03853*		.29570	171.6	.88
June 24 July 1		.032666*		41.3	.64
July 1 July 8	-.058517*			251.0	.98
July 8 July 15	-.03450*	.03260		167.1	.93
July 15 July 22	-.03385*	.02689		175.8	.90
July 22 July 29	-.03174*	.03486		161.0	.86
July 29 August 5	-.04670*	.05971	-.29510	225.0	.97
August 5 August 12	-.05913*			274.6	.80
August 12 August 19	-.04040*			206.9	.79
August 19 August 26		.14990*	-.87340	48.4	.92
August 26 August 31	-.04623*			202.5	.62
August 31 Sept. 10	-.08258*	.05856		354.8	.97.

* indicates first variable to enter the equation.

MODELLING ISOAREA EXPANSION

Background

The snowmelt which flows out of a basin in any given 24 hour period, daily discharge, is not due solely to the snow which melted during that time period. Daily discharge can be separated into two components: water from snow which melted during that day and the recessional flow from the previous days' snowmelt. Discharge generated from one day's snowmelt can be separated into two components: that portion which passes the gauging station on the first day and that portion which will leave the basin on subsequent days (Garstka, 1978). In Figure 3, daily discharge is represented by the areas A and C while generated discharge is represented by areas A and B.

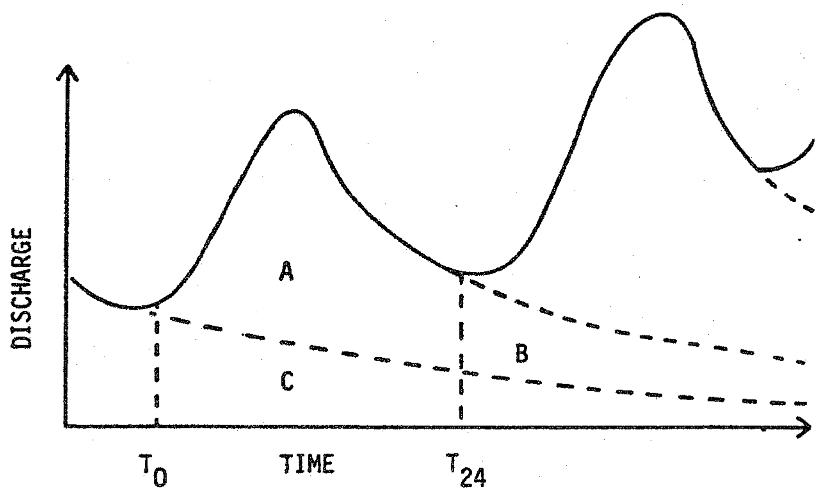

FIGURE 3. FLOW COMPONENTS.
Solid lines represent measured flow,
Area A + C = total volume for a 24hr. period
A = streamflow discharged the same day it was generated,
B = streamflow discharged on subsequent days (recessional flow).

(after Garstka, W.U., 1978, Water Resources and The National Welfare, Water Resources Publication, p. 312.

Isoarea

It is assumed that, prior to the onset of the snowmelt season, there is no substantial volume of snow contributing to streamflow, that is, isoarea equals zero. Given that streamflow follows snowcover contraction on the recessional limb of the stream hydrograph (Leaf, 1975; Caine, 1976), it appears reasonable to assume that snowmelt discharge follows the expansion of the isoarea on the rising limb. Therefore, following the start of the snowmelt season, isoarea will increase until a maximum is attained, presumably immediately preceding peak snowmelt runoff. Figure 4 illustrates the forms of the three isoarea expansion rates evaluated. The three forms chosen were the Gombertz growth curve, a positive exponential curve, and an intermediate linear increasing curve. The exponential rate was defined by fitting an exponential curve to generated discharge between June 8 and June 25. The linear curve was delimited by a May 24 starting date and an upper limit of 3,200,000 m^2 defined by total snowcover June 23. The growth curve began May 24 and had an upper limit of 3,330,000 m^2. These three curves were chosen in an effort to test a wide range of possibilities. The last objective of the study utilizes two models to describe and evaluate the progression of the isoarea for the time period preceeding peak snowmelt runoff.

Model 1

The first approach is based on the standard formulation for recessional flow and assumes the ascending limb of the seasonal streamflow hydrograph can be described as a positive exponential curve. By fitting generated discharge to an exponential curve, isoarea is calculated and compared to available snowcover. Following the equational form of recession analysis, equation (1) describes the expansion of the isoarea while (2) describes the increases in stream discharge.

$$C_t = C_o K_1^t \qquad (1)$$

$$Q_t = Q_o K_2^t \qquad (2)$$

where o represents the initial state, t represents time, and K is analogous to the standard recession coefficient and remains constant with time. The first two equations are combined to derive equation (3)

$$Q_t = b(Co K_1^t) + \alpha \qquad (3)$$

where b is a dimension conversion factor and α is a random error term. In natural log space equation (3) becomes the first model, (4).

$$Ln (Q_t - \alpha) = \ln C_o + t \ln K_1 \qquad (4)$$

Generated discharge is then transformed into natural log space, and regressed against time in order to use the discharge estimates with Model 1 to solve for isoarea. The isoarea estimates can then be compared to available snowcover. Generated discharge is backcalculated from daily discharge records using the seasonal recession coefficient. Peak generated discharge, June 25, calculated from daily discharge records, was approximately 192,450 cubic meters. Estimated generated discharge by Model 1 was 120,000 cubic meters, or two thirds the flow calculated from daily discharge. The difference between these two estimates of generated flow can be explained by the poor fit of generated flow with time. More importantly, the isoarea needed to produce the model's flow was greater than available snowcover. A similar situation is true for the four days preceeding peak flow.

Model 2

The second model, modified from Garstka (1978), attempts to describe the rising limb of the snowmelt hydrograph as the summation of daily snowmelt hydrographs where recessional flow follows an exponential decay function, Figure 5. The slope of the rising limb of the seasonal snowmelt hydrograph is primarily controlled by (1) the rate of snowmelt, and (2) the length of time necessary for a basin to discharge one days generated flow. The length of time for one days snowmelt to leave the basin is determined by the first days contribution to flow and the number of subsequent days

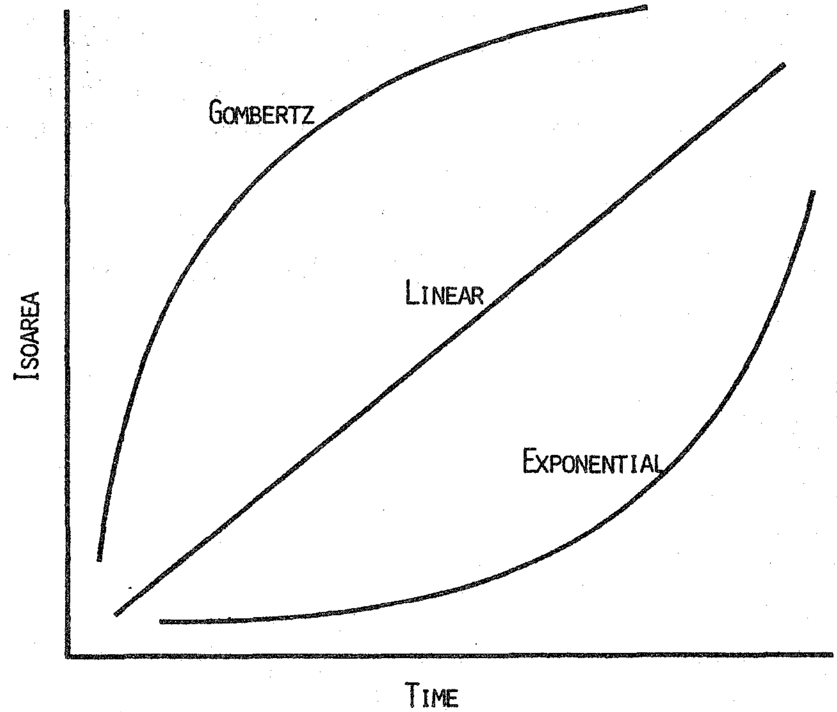

FIGURE 4. EXPANSION RATES FOR THE ISOTHERMAL SNOWPACK

$$Q_T = A + \left(\frac{C_T + SC}{CONST}\right) DP + (Q_{T-1} * RC)$$

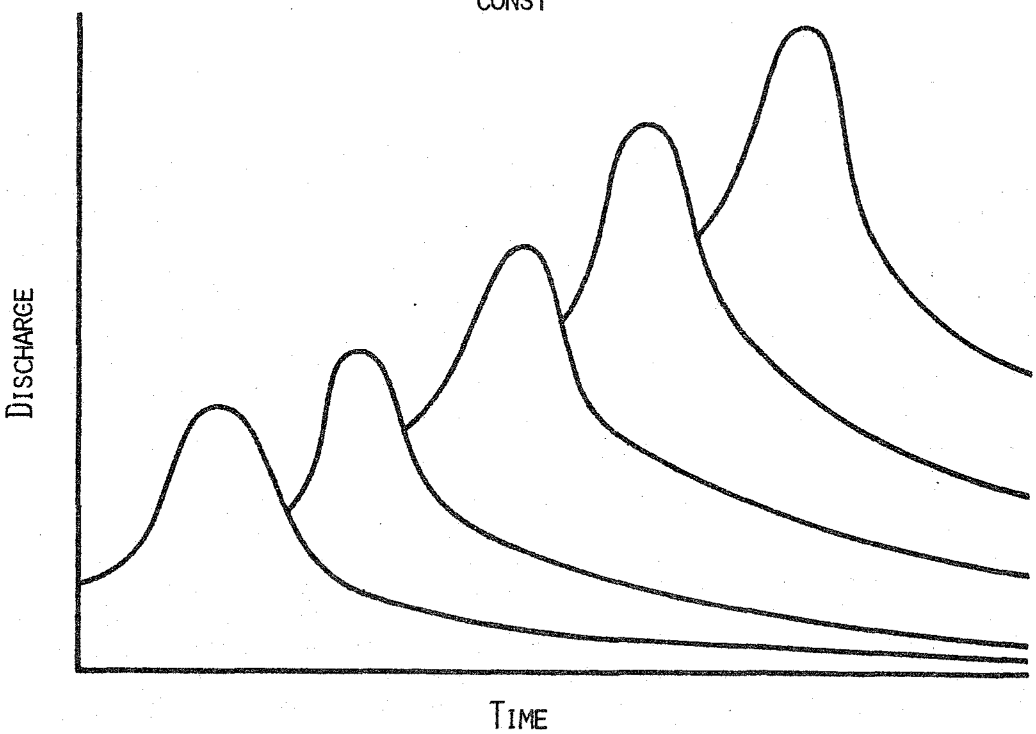

Figure 5. Model 2, the summation of daily snowmelt hydrographs, (after Garstka, W.U., 1978, Water Resources and the National Welfare, Water Resources Publication, p.312.

necessary for the remaining snowmelt to drain from the basin. The recession coefficient, which describes recessional flow, is empirically derived from the daily discharge estimates and is an indirect measure of basin size and hydroconductivity. As such it appears reasonable to assume that as basin snowmelt increases, the recession coefficient should reflect changes in the snowmelt source area and changes in the hydroconductivity of the basin.

The second model, (5), takes the form of

$$Qt = a + \left[(C_t + SC) / CONST)\right] dp + (Q_{t-1} * RC) \qquad (5)$$

where

Q = discharge at time (t),
a = baseflow
C = isoarea
SC = estimated snowcover loss
d = ablation
p = snow density
RC = recession coefficient
CONST = constant used to determine the first days contribution

Discharge estimates were derived for (1) a linear expansion of the isoarea; and, (2) a growth curve (Gombertz) expansion of isoarea. The values for RC and CONST were directly linked to changes in discharge. Isoarea is constrained within the model so that it cannot exceed available snowcover.

Results show that total discharge estimates between June 8 and June 23 for a linear increase in isoarea underestimated measured discharge by approximately 14% while a growth curve increase in isoarea overestimated measured discharge by 10.5%. The 10.5% overestimate (89.5% basin efficiency) agrees well with Carroll's (1976) estimated efficiency of 90% for the same study area. It should be noted, however, that Carroll's efficiency estimate was for an entire snowmelt season while the time period for the present study is the early snowmelt season, when basin efficiency would be expected to be greater. Nevertheless, of the three expansion rates tested, results suggest the growth curve to be the best estimate for isoarea expansion.

SUMMARY and CONCLUSIONS

The topographic characteristics (elevation, slope aspect, and slope angle) were used to divide the basin into ten distinct groups. At peak snowmelt runoff (June 23, 1982), there was no significant difference in proportionate snowcover between the ten groups. Before concluding that elevation, slope aspect and slope angle discriminate snowcover poorly, more analysis should be done. Further analyses might take the form of between-group analyses of variance for the time periods preceding peak snowmelt runoff to provide additional information regarding spatial and temporal changes in snowmelt contributing areas. The statistical significance associated with elevation, slope aspect, and slope angle used to predict ablation, although reasonable, might improve with a larger sample size (more ablation study sites). Further, a snow survey site within each group could be used to compare differences in ablation rates between groups to further test basin division by elevation, slope aspect, and slope angle.

The first part of the study emphasized the use of topographic characteristics to describe snowpack conditions. The implied assumption has been that grids 190 meters on a side were the ideal size. In fact, there is no a priori reason for choosing that size. Two factors which may be important when considering grid size is (1) the size of the basin, and (2) the scale of the local topography. For the basin studied, smaller grids, perhaps 100 m on a side, might be more suitable for monitoring changing snowpack characteristics. Regardless, the study demonstrated an ability to divide a basin into distinct units concerning snowpack conditions. The effectiveness of the division, while not entirely satisfactory, does hold promise with modifications.

The second part of the study assumed isoarea expanded by one of three rates. Two models were used to test the different expansion rates. Both models rely heavily on recessional flow analysis. Model 1 estimates generated flow. These estimates of generated flow are then compared to the generated discharge estimates backcalculated from daily discharge using the recession coefficient. Model 2 calculates daily discharge by dividing the total daily snowmelt into a first day's contribution and a recessional flow. In either case, the recession coefficient is derived from recessional analysis which takes place primarily after peak streamflow. If late season basin storage characteristics are different from early season storage characteristics, the difference should be reflected by changes in the recession coefficient. However, there are very few instances before peak flow when discharge decreases and these instances may not entirely consist of recessional flow. This makes it difficult to empirically estimate a recession coefficient for that time period before peak flow. Model 1 results tend to support a pre-peak flow recession coefficient smaller than the seasonal recession coefficient. Model 2 linked recessional analysis directly to total basin discharge. However, it is difficult to substantiate quantitative changes in recessional analysis for the pre-peak flow period until more is known about recessional flow during this time period.

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