AN ESTIMATE OF WATERSHED EFFICIENCY FOR A COLORADO ALPINE BASIN [1]

615-76

By

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Introduction

The demand for water in semiarid areas has always exceeded the readily available supply. This problem becomes critical in areas of rapid population growth and expanding economy, characteristic of the eastern slope of the Rocky Mountains today. One approach to this problem is to manage the primary water-producing areas in a way that will enhance streamflow. The alpine zone is defined as that area above natural treeline; it has been estimated that as much as eleven percent of montane Colorado is in the alpine zone. However, little is known about the snow accumulation and stream discharge from alpine areas (Martinelli, 1975). This study is an attempt to determine the water budget and basin efficiency (output expressed as a percentage of input) of an alpine basin in central Colorado.

Nature and Objectives

The project has three objectives. The first is to establish a water budget for the Green Lakes Valley in the Colorado Front Range for the period of May to October, 1973. The second is an attempt to determine the efficiency (i.e., generated discharge expressed as a percentage of snowmelt input) of an alpine basin. Intuitively, it seems that the efficiency of an alpine basin would be higher than that of a forested basin largely because of the low evapotranspiration losses associated with alpine areas. The third objective is to define the significance to water yield of areas in the basin which are based on topographic factors.

With some additional observations, the realisation of these objectives would allow computation of a water budget for the alpine area. The study can, therefore, be approached in terms of a catchment water budget:

$$Q = P - Et - \Delta S \qquad (1)$$

where Q = stream discharge;

P = one or more precipitation terms;

Et = sum of evaporation, sublimation and transpiration losses and gains;

ΔS = sum of storage changes within the basin (in the snowpack, soil and ground water and lakes).

In evaluating equation (1), all terms must be stated in the same units, usually as depths of water (cm) or as volumes (m^3). In this study, it has not been possible to define a water budget for the basin with a short time resolution although some of the terms in equation (1), particularly Q, can easily be treated on a daily, or shorter, frequency.

Equation (1) is treated here in two parts. The first concerns the input of water to the stream system and involves both summer rainfall and storage changes within the basin that occur on snowmelt. The second comprises the basin outflow, either as stream discharge or through evapotranspiration.

Field Site

The Green Lakes Valley (40° 3' N; 105° 37' W) is a glaciated valley in the Indian Peaks sector of the Front Range of central Colorado approximately twenty miles west of Boulder. The 2.08 km^2 basin runs east from the Continental Divide with an elevation of 4,087 m to the outlet of 3,554 m 2.4 km down valley. The basin has two small lakes which;

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together with areas of bogs, scrub willows, and standing water; constitute seven percent of the basin area. Tundra vegetation composes thirteen percent of the basin while eighty percent of the basin is bare rock surface of talus and bedrock. During 1973, the basin was instrumented with a hygrothermograph, a stage recorder, and a recording rain gage.

The long-term climate of the Green Lakes Valley can be estimated from the records of the D-1 station (3,750 m) located on Niwot Ridge immediately to the north of the valley. These records have been analysed by Barry (1973). They show mean temperatures of -13.2° C. in January and 8.3° C. in July with an annual mean of -3.8° C. The mean annual precipitation is 102.1 cm (based on only five years of record) with a slight maximum in winter and a minimum in the fall. An important characteristic of the D-1 site is its windiness (mean annual wind speed is 10.3 m $\sec^{-1}$) which is important in drifting and sublimation of the winter snowfall and concentrating the water stored as snow in drift situations.

Data from the three Boulder Creek snow courses maintained by the Soil Conservation Service indicate that on May 1, 1973, the snow water equivalent of the snowpack was 159 percent greater than the previous year and 132 percent greater than 1953-1967 average snow water equivalent for the same time (Washichek, 1973). The above normal snow accumulation will influence discharge values but not stratum or basin efficiencies.

Basin Stratification

A snow course of 89 points was used to estimate snow water equivalent and measure ablation. In setting out the course, the basin was stratified by elevation, slope, aspect, and estimated snow depth (Table 1). Any one of the 89 points on the snow course can be described by a four-element term which defines its characteristics.

Spring Peak Snow Water Equivalent

Depth and density measurements were made on May 18, 1973, with a Federal snow sampler at each of the 89 points of the snow course to determine the snow water equivalent held on the basin at the time of peak snow accumulation. A correction of 9.8 percent was made which compensated for the over-estimate of the sampler (Work, et al., 1965). At peak accumulation it was determined that an average 67.6 cm w.e. of snow was distributed over the basin. Table 1 also gives the mean snow water equivalent held on each of the thirteen stratifications and the number of snow course points on each stratum. Through the relatively small elevational range of density samples (372 m), density was not found to vary with elevation. However, data from the 89 points on the Green Lakes snow course suggest that in the alpine, snow water equivalent at peak accumulation increases 74.3 cm per 1000 m. Other workers have found similar results in the Rocky Mountains (Caine, 1975; Meiman, 1968; Storr and Golding, 1973).

Ablation

Ablation measurements were taken at weekly intervals during the nine weeks from June 16 to August 20, 1973, using the 89 snow course survey points as the sites of ablation stakes. An estimate of the nine week snow water equivalent contributed from each segment can be derived from the product of the ablation, snow density measured during the ablation season, and proportion of snow covered area of each segment. The ablation efficiency of a segment is some measure of how expediently the snowpack ablates from a given segment or stratum. The efficiency of a stratum is derived by dividing the percent of total melt from each stratum by the percent of total area of each stratum. This gives a basin mean efficiency of 1.00 with a minimum of 0.66 for north facing slopes and a maximum of 1.23 for south facing slopes. Both the minimum and maximum exceed ±1.64 standard deviations from the mean. Table 2 gives the ablation efficiency for each stratum. Efficiency is probably a function of ablation controls and snow accumulation patterns which may in turn be influenced by mesotopography and local wind patterns even though radiation patterns and medium snow depths are relatively uniform.

Summer Precipitation

Precipitation was measured with a shielded Belfort weigh bucket rain gage located at the lower end of the basin. The summer precipitation data was corrected in order to compensate for the systematic underestimate associated with rigidly shielded gages (Hamon, 1972; Larson and Peck 1974). From May 18 to October 31, 1973, 32.5 cm of precipitation fell; 13.1 cm of this fell in the period June 19 to August 20 when the ablation measurements were taken.

Table 1

BASIN STRATIFICATION AND SNOW WATER

EQUIVALENT AT PEAK ACCUMULATION

Elevation	four elevational zones of roughly equal area	No. of Points	SWE (cm)
1	3554 to 3566 m	12	52.7
2	3566 to 3658 m	29	63.9
3	3658 to 3780 m	26	76.0
4	3780 to 4087 m	22	51.3
Slope	three slope angle classes		
steep	over 20°	45	64.9
medium	7.5° - 20°	24	78.6
flat	less than 7.5°	20	78.8
Aspect	four aspect classes		
north facing		24	48.7
south facing		26	73.7
east facing		19	105.6
flat (same as the flat area of the slope category)		20	78.8
(Since the basin runs west to east, west facing slopes are practically absent.)			
Depth	three depth classes (based on air photos)		
deep	deep drifted areas	34	121.2
medium	areas other than deep and light	33	68.2
light	blown clean areas throughout year	22	10.9
		basin mean =	67.6

Discussion

The largest input to an alpine water budget is that of winter accumulation. In order to estimate the volume of input from the winter snowpack on a weekly basis, estimates of ablation, snow density, and snow cover are necessary. Ablation was measured at weekly intervals and snow density at monthly intervals because density is relatively invariable. Snow cover was estimated empirically from the generated discharge (U.S. Army, 1956, p.277). The product of ablation, density, and snow cover at weekly intervals gives a rough estimate of the volume of input to the water budget during the interval. The estimate of areal snow cover probably introduces most of the error into the weekly estimates of volume input. However, the error is reduced when the volume of input is considered on a greater time scale.

The second input to the water budget is summer precipitation. Weekly estimates of input from precipitation may be in error since areal variation of basin precipitation will not be compensated for in the short term. However, errors associated with areal variation of precipitation are minimized over the season. Consequently, the error of the precipitation term in the seasonal water budget is acceptably low.

Table 2

STRATUM EFFICIENCY

Main Category	Strata	% of nine week melt	% total area	Efficiency
Elevation	1	10.7	10.6	1.01
	2	23.1	23.0	1.00
	3	32.0	30.6	1.05
	4	34.2	36.5	0.94
Slope	Steep	70.8	69.6	1.02
	Medium	12.9	13.6	0.95
	Flat	16.3	16.8	0.97
Aspect	Flat	16.3	16.8	0.97
	North	21.5	32.4	0.66
	South	41.1	33.5	1.23
	East	21.1	17.3	1.22
Depth	Deep	16.1	15.0	1.07
	Medium	55.7	52.9	1.05
	Light	28.2	32.1	0.88

$\overline{X} = 1.00$

OUTPUT FROM THE SEASONAL WATER BUDGET

Stream Discharge

Stream stage was measured at a natural section (3,554 m) with a Leupold-Stevens float recorder. The section was rated with a Price current meter during the melt period. Error associated with the rating curve is less than five percent. The stage record begins approximately two days after flow began and a linear extrapolation backwards was used to estimate stream flow on these days.

Generated Discharge

Generated discharge is defined as the volume of stream flow at the gaging point produced by snowmelt. Other workers (Garstka, et al., 1958; Leaf, 1969, U.S. Army, 1956) have estimated flow generated by each snowmelt day which is defined as the period of time from one trough in the hydrograph to the next one, normally about 24 hours (Leaf, 1971). However, this requires a more accurate estimate of the recession coefficient than is available for the Green Lakes Valley. The net flow generated from each snowmelt week (i.e., seven snowmelt days) was isolated on the discharge type hydrograph by means of the recession curve (Garstka, et al., 1958; U.S. Army, 1956). Each week corresponds to the week in which ablation measurements were made throughout the basin (June 19 to August 20).

Generated runoff values (Q_{gen}) from the gaging station were computed from observed daily runoff volumes by equation (2):

$$Q_{gen} = Q_{obs} + Stg1 - Stg2 \qquad (2)$$

where Q_{obs} = the observed runoff during the snowmelt week

$Stg1$ = the initial volume of storage on the watershed at the beginning of the snowmelt week

$Stg2$ = the terminal volume of storage on the watershed at the end of the snowmelt week

Storage is used here as a groundwater or basin storage term and specifically excludes lake, stream, or snowpack storage. The volume of water in storage (Stg1 and Stg2) is a function of the discharge rate and is estimated as the integration of the area under the recession curve (Garstka, et al., 1958). In this way, basin storage can be separated from snowpack storage and each can be considered separately.

Evapotranspiration

Evapotranspiration is the second output of the water budget (Hamon, 1966; Harris, 1972; Storr, 1973). This includes evaporation from rock, stream, lake, and soil surfaces as well as the volume of transpiration from the vegetation in the basin. Different plant types transpire at different rates while moisture evaporates at different rates from different surface types. Evaporation and transpiration are combined and an attempt is made to compute potential and actual evapotranspiration for the basin. Daily values of potential evapotranspiration have been estimated from mean daily temperature observations by the procedure of Hamon (1963):

$$E_p = C\, D^2\, P_t \qquad (3)$$

where E_p = average potential evapotranspiration in cm per day

D = possible hours of sunshine in units of 12 hours

P_t = saturated water vapor density (absolute humidity) at the daily mean temperature in grams per cubic meter

C = 2.17×10^{-3} chosen to give appropriate yearly values of potential evapotranspiration as indicated by observation reported in the literature

Equation (3) allows an estimate of potential evapotranspiration for the basin but this is only useful in the parts of the basin where the water supply is unlimited. Consequently, the basin was divided into three sub-areas based on the vegetation: (1) areas where water is not limiting (e.g. lakes, areas of willow scrub and bogs), (2) areas of tundra vegetation, and (3) areas of bare rock (i.e., bedrock and talus). Actual evapotranspiration for the wet areas was assumed to be the same as potential evapotranspiration for those areas; actual evapotranspiration for areas of vegetation with medium water holding capacity was taken to be .23 times the potential. Recent work on Niwot Ridge (LeDrew, 1975), immediately north of the Green Lakes basin, indicates that actual evapotranspiration rates for a tundra vegetation can be computed from potential evapotranspiration by the use of equation (4):

$$E = \frac{.212\, E_p}{1.0 - 1.275\, E_p} \qquad (4)$$

where E = actual evapotranspiration in ly min^{-1}

E_p = potential evapotranspiration in ly min^{-1}

For the bedrock and talus areas of the basin, evaporation rates are somewhat more difficult to calculate. Little work has been done in either measuring or calculating evapotranspiration from bare or lichen covered rock surfaces. Consequently, it was assumed that evaporation from areas of bare rock accounted for the amount of surface detention, taken to be 1 mm of water, after every summer rainstorm which is followed by at least six hours with no rain. Where the storm total is less than 1 mm, it is assumed to be totally evaporated. This estimate gives a runoff coefficient of approximately .85 for the bare rock areas.

Runoff coefficients for streets and downtown business areas vary from .70 to .95 (Todd, 1970, p. 77).

The estimates used for evapotranspiration from areas of alpine tundra and alpine talus and bedrock may introduce error into total evapotranspiration term. It has been estimated that actual evapotranspiration rates from alpine tundra can vary from .83 to .27 mm per day (P. J. Webber, pers. comm., 1974). This is in good agreement with the estimate of actual evapotranspiration used in this study which was derived from potential evapotranspiration.

A second check on the evapotranspiration loss from the basin can be made from pan evaporation data. In 1969, data from four evaporation pans in the basin were collected. A high correlation between pan evaporation and actual evapotranspiration has been found (Hargreaves, 1958).

An estimate of the actual evapotranspiration for the basin based on the Hargreaves equation and the 1969 pan evaporations data is 3.2 cm and indicates that the values of actual evapotranspiration found in the 1973 study are reasonable.

In areas where water is not limiting (14.6 ha) the nine week estimate is 11.1 cm; in areas of tundra vegetation (26.6 ha) actual evapotranspiration is estimated at 2.6 cm; and in areas of bare rock (166.8 ha) the nine week estimate of actual evapotranspiration is 2.1 cm. The average nine week evapotranspiration distributed over 2.08 km^2 alpine basin is estimated at 2.8 cm while the total twenty-four week (May 17-October 29) evapotranspiration is estimated as 6.5 cm.

WATER BUDGET FOR THE GREEN LAKES VALLEY

The water budget of equation (1):

$$Q = P - E_t - \Delta S \qquad (1)$$

can be redefined using the units considered already as:

$$Q_{gen} = S_n + P - E \qquad (5)$$

where Q_{gen} = generated discharge

S_n = snowmelt from winter accumulation

P = precipitation

E = basin wide evapotranspiration

Generated discharge has previously been defined as simply discharge resulting from snowmelt. However, in using generated discharge to compute a water budget, precipitation and evapotranspiration must be considered. Consequently, generated discharge here includes the evaporation and precipitation term as well as the snowmelt term. The change of storage term of equation (1) is included in the Q_{gen} term of equation (5). When a large portion of the input to a water budget is derived from snowpack depletion, it is useful to evaluate the water budget in terms of equation (5).

The weekly estimates of snowmelt and precipitation were used as inputs to the water budget. Summer precipitation contributions are relatively straight forward and have been discussed. However, estimates of contributions from snowmelt are more difficult to quantify. From density and snowpack lowering measurements it is possible to estimate ablation over snow covered areas.

The major outflow from the water budget is that of generated discharge. Snowmelt and precipitation during a given period contributes to groundwater recharge and observed discharge, both of which constitute generated runoff.

Watershed efficiency (generated runoff expressed as a percentage of snowmelt and precipitation input) was computed also for the first five weeks (June 19-July 23), the first nine weeks (June 19-August 20), and for the entire season (May 17-October 29). Calculated efficiencies exceeded 90 percent in all cases (Table 3).

Table 3

WATER BUDGET (cm)

Weeks	Q_{gen} 1	Snow-melt 2	P 3	E (wet) 4	E (medium) 5	E (unveg.) 6	Error	Efficiency (Percent)
1-5	63.50	59.46	8.54	.45	.13	1.04	-2.88	93.4
1-9	79.65	66.54	13.12	.78	.23	1.68	2.68	99.9
Year (May 18-Oct. 31)	94.53	67.63	32.48	1.54	.45	4.33	.73	94.4

Note: The evapotranspiration term is the estimate from each of the three areas distributed over the total basin.

Error = 1 - (2 + 3 - 4 - 5 - 6)

$$\text{Efficiency} = \frac{1}{2 + 3} \times 100$$

Conclusion

A water budget of the basin was computed for three time intervals; two of the intervals represent a composite of field ablation measurements taken in order to use a snowmelt input term. The snowmelt input term for the seasonal interval was computed as the total snow water equivalent held on the basin at peak accumulation. Generated discharge was also computed for the same intervals. As seen in Table 3, more than two thirds of the seasonal stream flow volume was generated during the first five week period (June 19-July 23). Snowmelt produced virtually all of the runoff from this alpine basin.

In contrast, other studies have indicated a much lower efficiency for subalpine basins. For the period from 1943 to 1954 Fool Creek in the Fraser Experimental Forest in Colorado has a mean efficiency of 39 percent while Deadhorse Creek averaged 39 percent efficiency in 1969. Deadhorse Creek is divided into an upper and lower basin; during 1969 the average efficiency of the upper basin was 54 percent while the average efficiency of the lower basin was only 20 percent. The Fool Creek and Deadhorse stream gages are at 2926 m and 2880 m respectively.

It has been estimated that other alpine basins in Colorado have efficiencies also in excess of 90 percent (Leaf, 1975). The high efficiency of many alpine basins is apparently the result of: (1) a high snow cover at the time when seasonal snowmelt rates are near a maximum on all aspects, (2) a delayed and short snow cover depletion season, (3) relatively low recharge, and (4) evapotranspiration losses which are in part, compensated for by condensation on alpine snowfields during some months (Martinelli, 1975).

Partially as a result of the high watershed efficiencies found in alpine areas, it has been suggested that these areas might be used as to increase water supply to lower populated areas of the western United States. For the past twenty years, Martinelli (1975) has experimented with snowfences as a means of augmenting the alpine snowpack. Other techniques are available and include: (1) terrain modification; (2) intentional avalanching; and (3) artificially creating massive accumulations of ice from winter streamflow (Martinelli, 1975).

It may soon become feasible to utilize some of the above techniques to improve water yields from alpine zones largely because of the high watershed efficiencies which characterize areas above treeline in the Rocky Mountains.

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