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Computation of water budget of a snow bound river basin

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सार — इस शोध–पत्र में सतलुज नदी के बर्फीले जलग्रहण क्षेत्र के माध्यम से मासिक जलबजट की गणना करने की तकनीक बताई गई है। जलबजट के माध्यम से कुल अपवाह आकलित किया गया है। सतलुज का जलग्रहण क्षेत्र, जिसका कुल क्षेत्रफल 57,244 वर्ग कि० मी० है (22,310 वर्ग कि० मी० भारतीय क्षेत्र में है) और क्षेत्र का लगभग 70 प्रतिशत भाग सर्दियों में हिमाच्छादित रहता है। इसका औसत वर्षण 40 चुने हुए स्थानों पर 17 वर्ष के आंकड़ों से प्राप्त किया गया है। शिमला के लिए विभव वाष्पीकरण वाष्पोत्सर्जन का मान पैनमैन (1948) के समीकरण से निकाला गया है और इससे जलग्रहण क्षेत्र के लिए प्रयुक्त किया गया है। शिमला के विकिरण, तापमान, मेघाच्छन्नता, पवन और आर्द्रता के आंकड़ों की मदद से ऊर्जा बजट की धारणा पर हिमगलन की दर परिकलित की गई है।

ABSTRACT. In this paper, the snow bound catchment of river *Sutlej* has been chosen to illustrate the technique of computing monthly water budget and estimating total runoff. This catchment covers an area of 22,310 km² in the Indian territory (total area 57,244 km²), about 70% of which remains under seasonal snow during winter. The average areal precipitation has been estimated by using 17 years' data of 40 selected stations. The potential evapotranspiration for the station Shimla computed by using Penman (1948) equation is taken to be representative for the catchment. The snowmelt rates are worked out by energy budget concept with the help of normals of radiation, temperature, cloudiness, wind and humidity data recorded at Shimla.

1. Introduction

The computation of water budget in a snow bound catchment becomes a complicated problem as it involved the estimation of seasonal snow cover variations and processes of glacier melt. The main difficulty is due to non-availability of representative ground observations of related parameters. A general equation of water balance is expressed as :

$$P - Q - E - \triangle S - \eta = 0 \qquad (1)$$

where, P : Precipitation, Q : Discharge, E : Evaporation, $\triangle S$: Change in water storage, η : Error term.

$\triangle S$ consists of the following sub-components :

(a) change in soil moisture storage ($\triangle M$), (b) change in ground water storage ($\triangle G$), (c) change in storage of seasonal snow cover ($\triangle S_n$) and (d) glacier mass balance sub-component ($\triangle G_l$). If we are evaluating monthly or other long-term water budget, the retention of surface water in micro depressions may be neglected. Therefore,

$$\triangle S = \triangle M + \triangle G + \triangle S_n + \triangle G_l \qquad (2)$$

Another complexity arises due to the fact that precipitation occurs in solid form over higher reaches of the catchment and at the same time in liquid form over the lower reaches. The delineation between these two areas is necessary as there is large time lag in respect of water yield as runoff. The observations of snow lines and freezing levels are very inadequate in the mountainous watershed.

The mass balance studies of glaciers are just in the initial stage and insignificant informations are available in this regard. Even the surface area of glaciers (or permanent snow fields) are very roughly known for the Himalayan river basins. Nevertheless, the importance of water balance study of snow bound catchment cannot be ignored.

For the basins without snow, the water balance equation is normally utilized for the evaluation of actual evaporation losses or runoff after estimating other components. For snow bound watersheds evaluation of $\triangle S_n$ and $\triangle G_l$ poses more challenging problem, where Eqns. (1) and (2) could be useful. For this purpose an alternative method has to be adopted for computing E. We should also have long term runoff data for estimating Q. In this paper, however, all the components have been independently worked out in order to check the balance. The procedures of estimation in the absence of relevant data have also been suggested. An illustration of the procedure is provided using snow, meteorological and physiographic data of Sutlej basin. Sutlej catchment covers an area of 57,244 km² upto Bhakra dam of which 3 934 km² lies in Tibet, 11% (Dhir and Singh 1956) of this area remains under permanent snow and glaciers throughout the year. During winter the snow line comes down to an elevation of 1600 m a.s.l. and about 75% of the Indian area becomes snow bound (Upadhyay 1983).

TABLE 1

Mean and variability of monthly discharges in *Sutlej* at Bhakra (1925-71)

Month	Mean (cumec)	C.V. (%)	Equivalent depth of water over Indian part of basin (cm)
Jan	127	21	1.5
Feb	129	27	1.5
Mar	137	18	1.6
Apr	194	16	2.2
May	534	62	6.2
Jun	883	27	10.2
Jul	1432	23	16.6
Aug	1521	23	17.7
Sep	644	28	7.5
Oct	290	45	3.4
Nov	171	18	2.0
Dec	136	15	1.6

TABLE 2

Distribution of areas in relation to snow cover

Month	Snow-line (m)	Freezing level	% area (fraction)		
			A_1	A_2	$A_3=(A_1-A_2)$
Jan	1600	1750	.84	.81	.03
Feb	1500	1990	.82	.75	.07
Mar	1800	2940	.80	.65	.15
Apr	2500	3540	.70	.59	.11
May	3500	4080	.59	.51	.08
Jun	4200	4680	.48	.34	.14
Jul	4800	5250	.31	.16	.15
Aug	5200	5400	.20	.16	.04
Sep	5200	4480	.20	.39	—.19
Oct	4500	3510	.39	.59	—.20
Nov	3600	3030	.58	.65	—.07
Dec	2200	2100	.73	.74	—.01

NOTE : Areas refer to the Indian part of the Sutlej catchment.
A_1 = Percentage area above snowline.
A_2 = Percentage area above freezing level.
A_3 = Percentage area between snowline and freezing level.

2. Data used

Monthly rainfall observations of about 40 stations for 17 years (1951-67), in and around Sutlej catchment have been utilized to estimate the monthly catchment precipitation (P) for the Indian part of the basin. 47 years (1925-71) 10-day discharge observations of *Sutlej* recorded at Bhakra dam site have been considered for the evaluation of runoff component (Q). As there are not many meteorological stations having temperature and wind records for a long term, the data of Shimla are used for computing potential evapotranspiration. Area-elevation curve alongwith other topographic and upper air meteorological features such as freezing level have been analysed to determine the areas of snow cover, glaciers and melting zones of the catchment. Radiation and other components of heat-budget equation (convective and sensible) have been evaluated with the help of related meteorological parameters such as cloudiness, humidity, wind and temperatures.

3. Computation of the components

(a) *Monthly areal precipitation* (P)

Mean monthly rainfall data of 40 stations were worked out for a period of 17 years. The arithmetic mean of these 40 stations have been taken as the estimate of normal areal rainfall of the Indian part of the catchment. A weighted mean worked out by isohyetal analysis is normally considered more appropriate, but in this case the network being sufficiently dense, the arithmetic mean gives comparable results.

(b) *Mean monthly discharges* (Q)

For this catchment long-term records (1925 onwards) of daily discharge are available for Bhakra dam site. These data represent the runoff features of the entire catchment upstream of this point. The arithmetic mean of these observations will provide reasonable estimate of Q.

The mean values have been converted into depth of water on the basin in the units of cm (Col. 4 of Table 1) and used in the equation of water balance.

It may be interesting to note that the variability is very high in the months of May and October, when there is abrupt change in flow rates; in May due to sudden increase in snowmelt and in October due to withdrawal of southwest monsoon.

(c) *Evaporation* (E)

Evapotranspiration from an open surface depends upon field capacity, actual moisture content of the soil and routing depth of vegetation. The potential evapotranspiration can theoretically be estimated using Penman's equation. It requires the input of radiation, wind, temperature, vapour pressure and cloudiness. Shimla is the only station which has long term observations on these parameters. Thus, PE of Shimla has been taken as the representative for the Indian part of the basin. For evaluation of actual evaporation, the change in soil moisture storage has been worked as under. If F is the field capacity, the soil moisture storage (M) is given by :

$$M = F e^{-\frac{\Sigma (P - PE)}{F}} \tag{3}$$

where, Σ (P—PE) is cumulative sum of successive differences for the months when $P < PE$.

According to the experiments performed by Lutz and Chandler (1956) on various types of soil, the maximum quantity of gravity water held by soil per foot of depth is as follows :

Type of soil	*Field capacity/Foot* (cm)
Sand	4
Silt loam	8
Clay	11

TABLE 3

Monthly energy budget — Shimla (1y/day)

Month	Q_{rs}	Q_{rl}	Q_c	Q_e	Net energy input (H)
Jan	54	—90	5	—9	—40
Feb	105	—83	10	—7	25
Mar	175	—61	17	—5	126
Apr	268	—34	22	0	256
May	388	—4	28	13	425
Jun	394	11	25	43	473
Jul	274	—5	17	81	367
Aug	260	—8	14	74	340
Sep	315	—16	15	6	320
Oct	290	—42	15	16	279
Nov	188	—68	11	07	138
Dec	109	—81	9	—10	27

Q_{rs} : Absorbed solar radiation.
Q_{rl} : Net long-wave radiation exchanged between snowpack and surroundings.
Q_c : Convective transfer of heat between air and snowpack.
Q_e : Latent heat of condensation/evaporation.

Considering soil moisture storage up to 2-3 feet depth, we may take an average field capacity of 20 cm (for silt type soil) for the present study.

Actual evaporation (AE) is given by

$$AE = P + |\triangle M|, \quad \text{when } P < PE$$
$$= PE \quad \text{when } P > PE$$

where, $\triangle M$ is the change in storage ($M_i - M_{i-1}$), M_i being the soil moisture storage of i^{th} month.

(d) *Change in storage* ($\triangle S$) :

$\triangle S$ has 3 components, *i.e.*,

$\triangle S = \triangle M + \triangle S_n + \triangle G_l$, where,

$\triangle M$ = Change in soil moisture

$\triangle S_n$ = Change in water content of seasonal snow cover.

G_l = Change in water content of glaciers.

Sutlej catchment has seasonal snow cover and permanent glaciated areas. Seasonal snow cover builds up in early December and ablates away by the end of June/July. The mean freezing level and the altitude of snowline have been estimated from upper air temperature data of Srinagar and Delhi. These estimates are only approximations which have been used in this study. The area lying between freezing level and snowline will only contribute to the snowmelt. Above freezing level, there is no melt due to low temperature and below snowline no significant snow cover exists.

The percentage areas lying above snowline (A_1), above freezing level (A_2) and between snowline and freezing level (A_3) are provided in Table 2.

TABLE 4

Monthly water budget for Sutlej basin
(Unit . cm)

Month	P	Q	E	$\triangle M$	$\triangle S_n$	$\triangle G_l$	η
Jan	8.4	1.5	3.3	0	0.3	0	3.3
Feb	7.5	1.5	4.4	0	0.4	0	1.2
Mar	8.4	1.6	7.5	0	—2.5	0	1.8
Apr	4.1	2.2	9.3	—5.2	—4.2	0	2.0
May	5.1	6.2	9.9	—4.8	—5.1	0	—1.1
Jun	9.8	10.2	11.0	—1.2	—7.4	0	—2.8
Jul	30.7	16.6	8.4	11.2	—4.1	—2.4	1.0
Aug	27.0	17.7	7.2	0	0	—3.3	5.4
Sep	14.7	7.5	7.5	0	0	—3.0	2.7
Oct	8.4	3.4	6.6	—0.2	0	—4.0	2.6
Nov	1.6	2.0	3.4	—1.8	0	—2.5	0.5
Dec	5.1	1.6	3.0	2.0	0	—1.9	0.4
Annual	130.8	72.0	81.5	0	—22.6	—17.1	17.0
Percentage	100	55.0	62	0	—17	—13	13

P—Precipitation, Q—Discharge, E—Evaporation, $\triangle M$—Change in soil moisture, $\triangle S_n$—Change in snow cover, $\triangle G_l$—Change in glacier, η—Error term.

For snowmelt computation energy budget of Shimla (31° 06′N, 77°10′E, ht 2202 m) have been worked out. It is given in Table 3.

The mean rates of snowmelt have been multiplied by A_3 for its inclusion in the water balance equation as an estimate of $\triangle S_n$.

The snowmelt quantity is given by :

$$S_n = \frac{H}{80}$$

considering the thermal quantity to be 1. Normally the thermal quantity is slightly less than 1 (.95 to .99).

The glacier surfaces are also covered by seasonal snow. Hence, the actual contribution from glacier starts only after all seasonal snow has melted away. G_l has been considered to be effective from July to November. The glaciated areas have been estimated using data on permanent snowline and topography. The corresponding estimates of G_l are provided in Table 4.

4. Results and conclusion

The various components of water balance equation of Sutlej basin have been computed as described in section 3 and the results are provided in Table 4. Maximum contribution from rain occurs in July and August. The river runoff increases abruptly from March till August and falls sharply, thereafter, maximum evaporation occurs in May-June. Rapid loss of soil moisture is observed from April to June which is recharged by excessive precipitation in July. The snowmelt rate increases to a maximum in June (7.4 cm). Negative melt rate during winter months indicates the rate of condensation — due to low temperature. The glacier melt is maximum in October (4 cm) and minimum in December. The October maxima may be due to the exposure of glacier surfaces to insolation as glacier surfaces are totally free from seasonal snow during this month.

The large error (η) are observed during January and August. The abrupt change in soil moisture storage ($\triangle M$) seems to be responsible factor for this. The last row of Table 4 indicates that annually each 100 cm of precipitation in the basin yields a discharge of 55 cm and evaporation loss of 62 cm. The evaporated moisture sublimates over snow (17 cm) and glacier (13 cm). Thus, the balance is maintained with an error of 13%.

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