Snow accumulation, melting and runoff in the warm climate of Japan

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ABSTRACT Models of snowmelt and runoff in the snow accumulation and melting seasons may be constructed of the following series of sub-systems: snowfall and rainfall • transformation system I -*• snowpack -»- transformation system II -*• snowmelt -*• transformation system III -»• streamflow. In this study models concerned with snow accumulation and melting processes are run on an hourly basis for prediction. We can continuously compute the snowpack depth, snow density and water equivalent as model outputs. Other outputs, namely the snowmelt water and the excess water reaching the ground surface, are estimated after calibration of the model by comparison between the predicted and observed data on snowpack depth, snow density and water equivalent. Finally the excess water is used as the input data for the runoff system model. The model was applied to the years 1983 (little snow) and 1984 (heavy snow). The results are in good agreement with the observed data on snowpack depth, snow density, water equivalent, streamflow and so on for different time intervals and areas.

L'accumulation de neige, le dégel et l'écoulement dans la zone tempérée du Japon

RESUME Les modèles du dégel et de l'écoulement dans la saison de l'accumulation et du dégel peuvent se composer de la série du système suivant. La chute de neige et pluie -> le système de transformation I -> l'accumulation de neige -> le système de transformation II -> le dégel -> le système de transformation III -> l'écoulement. Dans cette étude, les modèles concernant les processus d'accumulation et de fonte de neige sont exécutés sur une base horaire pour les prévisions. Et nous pouvons calculer continuellement la profondeur de l'accumulation de neige, la densité de neige et l'équivalent en eau comme "sorties" du modèle. L'eau du dégel et l'excédent d'eau arrivant à
la surface du sol, qui sont les autres "sorties" sont estimés après étalonnage du modèle par comparaison entre les données prévues et observées de la profondeur de l'accumulation de neige, de la densité de neige et de l'équivalent en eau. Et finalement, l'excédent d'eau est utilisé comme entrée au modèle du système de l'écoulement. Ces modèles ont été appliqués à l'année 1983 (peu de neige) et 1984 (beaucoup de neige). Ces résultats concordent bien avec les données observées de la profondeur de l'accumulation de neige, de la densité de neige, de l'équivalent en eau, de l'écoulement etc. dans des intervalles de temps et superficies différents.

**NOTATION**

<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC</td>
<td>amount of free liquid water equivalent to the heat required for refreezing and cooling process (mm)</td>
</tr>
<tr>
<td>ALB</td>
<td>albedo of snowpack (%)</td>
</tr>
<tr>
<td>BDHF</td>
<td>snowmelt parameter (mm °C⁻¹h⁻¹)</td>
</tr>
<tr>
<td>CC</td>
<td>cold content (mm)</td>
</tr>
<tr>
<td>DN</td>
<td>snow density (%)</td>
</tr>
<tr>
<td>DNS</td>
<td>snow density of new snow (%)</td>
</tr>
<tr>
<td>DP</td>
<td>snowpack depth (mm)</td>
</tr>
<tr>
<td>DPNS</td>
<td>snow depth of new snow (mm)</td>
</tr>
<tr>
<td>HG</td>
<td>amount of melted water due to the heat transfer from the ground (mm)</td>
</tr>
<tr>
<td>HR</td>
<td>amount of melted water due to the heat content of rainfall (mm)</td>
</tr>
<tr>
<td>HTI</td>
<td>amount of melted water due to net heat transfer excluding the heat from rainfall and from the ground (mm)</td>
</tr>
<tr>
<td>HT</td>
<td>total amount of snowmelt water (mm)</td>
</tr>
<tr>
<td>NDX</td>
<td>age of the snow surface (days)</td>
</tr>
<tr>
<td>PC</td>
<td>percentage of a given amount of melt at the surface that reaches the ground in each subsequent hour (%)</td>
</tr>
<tr>
<td>PR</td>
<td>rainfall (mm)</td>
</tr>
<tr>
<td>PP</td>
<td>precipitation (mm)</td>
</tr>
<tr>
<td>QT</td>
<td>thermal quality (%)</td>
</tr>
<tr>
<td>RAD</td>
<td>radiation (ly day⁻¹)</td>
</tr>
<tr>
<td>REDUCT</td>
<td>reduction in depth of the old pack due to compaction (mm)</td>
</tr>
<tr>
<td>RM</td>
<td>amount of free liquid water equivalent to the heat required to raise the snow temperature and melt the snowpack (mm)</td>
</tr>
<tr>
<td>TNS</td>
<td>temperature of new snow (°C)</td>
</tr>
<tr>
<td>TP</td>
<td>snow temperature (°C)</td>
</tr>
<tr>
<td>TA1</td>
<td>air temperature above 0°C (°C)</td>
</tr>
<tr>
<td>TA2</td>
<td>air temperature below 0°C (°C)</td>
</tr>
<tr>
<td>TR</td>
<td>temperature of rainfall (°C)</td>
</tr>
<tr>
<td>WC</td>
<td>liquid water storage (mm)</td>
</tr>
<tr>
<td>WEQ</td>
<td>water equivalent (mm)</td>
</tr>
<tr>
<td>WHC</td>
<td>liquid water holding capacity (%)</td>
</tr>
<tr>
<td>α</td>
<td>increased rate of precipitation with elevation (mm m⁻¹)</td>
</tr>
<tr>
<td>β</td>
<td>lapse rate of air temperature with elevation (°C/100m)</td>
</tr>
<tr>
<td>ΔT</td>
<td>computation time step (h)</td>
</tr>
</tbody>
</table>
INTRODUCTION

The increase and uneven distribution of water demand require an effective and efficient utilization of river water. In particular, there is a great difference in the distribution of water demand and water resources between regions along the Pacific Ocean side of the country and the Sea of Japan side. The large amount of snow in the regions along the Sea of Japan side is attractive as a water resource. It is necessary to do research on the snowmelt and runoff processes in order to utilize the snow as a water resource.

In general, because of the relative inaccessibility of catchment areas and the difficulty of observation, construction of models based on knowledge of the physics of snow has made slower progress than construction of models for the rainfall-runoff system. Model construction for the snow accumulation and melting seasons may be dealt with by the following series of systems (Ikebuchi, 1982).

\[
\text{snowmelting factors} \downarrow
\]
\[
\text{snowfall} \rightarrow \text{transformation} \rightarrow \text{snowpack} \rightarrow \text{transformation} \rightarrow \text{snowmelt- and rainfall system I system II}
\]
\[
\text{streamflow} \leftarrow \text{transformation}
\]
\[
\text{system III}
\]

In this case, the transformation system represents the operation performed by the system on the input and the throughput in order to transfer it into output. The transformation system I mainly describes the snow accumulation process and renews the depth of snow based on the addition of the new snow and reduction in depth of the old pack due to its compaction. The transformation system II describes the process whereby the heat from radiation, rainfall and the ground etc. is transferred to the snowpack. As a result, the water melted on the snow surface percolates through the snowpack and reaches the ground surface. Lastly, the transformation system III describes the process whereby the snowmelt water which reaches the ground surface discharges into the river as overland, interflow and groundwater runoff.

The snowmelt and runoff system models developed in this study are primarily concerned with considering the above processes on as physical a basis as possible and at the same time representing these processes in the best way given the available data and in the light of practical modelling considerations.

The observation area, the Ohura River basin, is located in the northern part of Lake Biwa basin (Lake Biwa is the biggest lake in Japan). It is in the warm climate zone of Japan and 13.8 km\(^2\) in area. The snow falling in this zone, in particular, undergoes rapid metamorphosis and the processes of accumulation, melting and disappearance are repeated several times during winter and early spring. A continuous snow cover is not maintained.

Meteorological and hydrological data such as snowpack depth, air temperature, snow temperature, ground temperature, radiation and net radiation, humidity, wind speed, snowfall and rainfall, groundwater
level, river stage and streamflow are collected. Models concerned with snow accumulation and melting processes are run on an hourly basis for prediction. The snowpack depth, snow density and water equivalent are continuously computed as model outputs. Snowmelt and the excess water reaching the ground surface are estimated through the calibration process of comparison between the calculated and observed data of snowpack depth, snow density and water equivalent. Finally the excess water is used as the input data for the runoff system model.

The models were applied to the years 1983 (with little snow) and 1984 (heavy snow). The results are in good agreement with the observed data on snowpack depth, snow density, water equivalent, streamflow and so on for different time intervals and areas.

THE FIELD SITE AND FIELD OBSERVATIONS

Characteristics of the field site

The Ohura River basin is located at the northern end of Lake Biwa (Fig.1). The climate of the northern part of Lake Biwa is characterized by a cold snowy winter with mean temperatures from December to March of 4.7°C and a short mild summer during July and August with temperatures averaging 25.8°C. These figures are derived from a long record (1951-1980) from the Hikone meteorological station in the neighbourhood. The annual precipitation, on the average, is 1971 mm and the distribution of precipitation is characterized by a winter season with total snowfall and rainfall of 421 mm from December to March, and a rainy season during June and July with a total rainfall 459 mm. Because the observation area is higher in altitude and north of the Hikone station, its temperature is lower and precipitation much greater than the values given above.
Under these conditions the snow in this area undergoes rapid metamorphosis and the processes of accumulation, melting and disappearance are repeated during winter and early spring. A continuous snow cover is not preserved. This area is classified as part of the area covered by coarse-grained, refrozen and fine-grained, compact snows (Fig.1).

The Ohura River basin is 13.8 km² in area and ranges in elevation from 92 to 657 m above mean sea level. It is lightly forested with Japanese red pine and has some paddy fields along the river.

Observation system

The physical layout of the Ohura River basin and the location of stations where data readings were taken are shown in Fig.2. Figure 3 shows the observation system at base camp (B.C.). The depth of snowpack in centimetres above the ground was determined at hourly intervals from sunrise to sunset by the optical type of snowpack depth meter. This is self-recording and works by reading the traces on photopaper sensitive to sunlight sent through a fibre bundle.
inserted in a snowtube. River stage or streamflow was measured at three sub-basins (a small basin near B.C., 0.01 km²; Yamakado basin, 5.7 km²; Syo basin, 13.8 km²) in order to estimate the effect of scale on the snowmelt and runoff systems.

In order to estimate the effect of time scale on the models and to perform simulation computations over any specified time interval, many data were collected on an hourly basis.

Characteristics of the observed data

Figure 4 shows the comparison between the snowpack depths observed by the optical snowpack depth meter and by eye at B.C. As they are in good agreement, the snowpack depth at other points located in higher altitudes was measured by the same optical system because of the relative inaccessibility of the stations and the difficulty in maintaining adequate monitoring due to bad weather conditions and over longer periods such as a winter season.

Figure 5 shows some daily observed meteorological and hydrological data from the years 1983 and 1984. The former corresponds to a light snow year and the latter to a heavy snow year.
DEVELOPMENT OF SNOWMELT AND RUNOFF SYSTEM MODELS

General mode of operation of the models

The models developed in this study are shown in a basic block diagram (Fig.6) illustrating the major components in which the various processes are considered. A detailed description of those components is given in the next section. The main characteristics of the model are as follows.

(a) The models compute or simulate the snow accumulation, melting and runoff processes on a continuous basis in time.

(b) Understanding of the physics of the processes is used to produce lumped-parameter models in the light of practical hydrolo-
(c) The models have an ability to perform simulation computations over any specified time interval according to the availability of input data.

(d) As we can compute the snowpack depth, snow density and water equivalent continuously as model outputs, the snowmelt and the excess water reaching the ground surface are identified through the calibration process of comparison between the computed and observed data of snowpack depth, snow density and water equivalent. The excess water reaching the ground surface is used as the input data into the runoff system model.

Snow accumulation and melt processes

Model parameters are identified by calibration using the computed and observed data on snowpack depth, snow density and water equivalent. The model, therefore, was designed to compute the snowpack depth, snow density and water equivalent. As the snowpack depth was continuously observed, stress was placed on a good agreement between the computed and observed data of the snowpack depth during the calibration process.

The snowpack depth has spatial variability due to elevation effects of variables such as air temperature and precipitation. This spatial variability is considered in a later section. We first
develop a lumped-parameter model in which the inputs and snowpack parameters are assumed to be uniform over the area they represent.

The first step is to determine if precipitation has occurred during the current time step. If not, the procedure passes to Block 6 which decides whether there was snow on the ground or not. If precipitation did occur, it is necessary to determine the form of precipitation, rain or snow (Block 2). Figure 7 shows the percentage occurrences of both forms for various surface air temperatures at B.C. We judged the index temperature for differentiating rain from snow to be 2.1°C at which their percentage occurrences are both equal to 50%. Thus precipitation is taken to occur in the form of snow whenever the surface air temperature is less than 2.1°C.

![Fig. 7 Frequency of occurrence of rain and snow at various temperatures.](image)

If the precipitation is in the form of snow, the procedure goes to Blocks 3, 4 and 5. The properties of newly fallen snow become an important aspect in these blocks. To determine the effect of an accumulation of new snow on the parameters of an existing snowpack (Block 7), the density and depth of the new snow were estimated by the following relationships (Anderson & Crawford, 1964) by

\[
DNS = a + \left\{ \frac{(1.8 \cdot TNS + 32)}{100} \right\}^b \\
\]

\[
DPNS = PP/DNS \\
\]

where the temperature of the new snow, TNS, was estimated by setting it equal to surface air temperature TT. The parameters a and b were identified using the rate of increase in depth of newly fallen snow. The values for a and b were 0.03 and 2.2.

The effect of new snow or rainfall on an old snowpack, on the other hand, was expressed as follows (Anderson & Crawford, 1964)

\[
REDUCT = PP \cdot DP'/WEQ'(DP'/10)^{-0.35} \cdot 0.3244 \\
\]

where DP' and WEQ' are the snowpack depth and water equivalent before the addition of the new snow or rainfall, respectively. From
these properties of the new snow, the parameters of the resulting snowpack can be computed from the following equations:

\[ DP = DP' - \text{REDUCT} + DPNS \]  (4)

\[ \text{WEQ} = \text{WEQ}' + PP \]  (5)

\[ \text{DN} = \frac{\text{WEQ}}{DP} \]  (6)

The unprimed quantities represent values for the resultant snowpack.

The total heat flux applied to the snowpack to induce snowmelt can be expressed as follows:

\[ H = H_{\text{rs}} + H_{\text{re}} + H_{\text{cv}} + H_{\text{cn}} + H_r + H_g \]  (7)

where \( H_{\text{rs}} \) is absorbed shortwave radiation; \( H_{\text{re}} \), net longwave radiation exchange between the pack and its environment; \( H_{\text{cv}} \), convective heat transfer from the air; \( H_{\text{cn}} \), heat supplied by condensation; \( H_r \) the heat content of the rainfall and \( H_g \) is heat conducted from the ground. It is convenient to express the effect of this heat on the snowpack in terms of the number of millimetres of liquid water that may be frozen or melted by this amount of heat.

Firstly we consider the melted water by positive heat transfer (Block 8). The melted water, \( H_R \), due to the heat content of the rainfall \( H \) is given by,

\[ H_R = PR \cdot TR / 80 \]  (8)

where \( TR \) is the temperature of the rainfall estimated using the air temperature by assuming that they are equal. The latent heat of fusion of pure ice at 0°C is 80 cal cm\(^{-3}\). The heat transfer from the ground, \( H_g \), was assumed to be constant throughout the snow season. The meltwater, \( H_g \), from this constant heat transfer was estimated to be 0.02 (mm h\(^{-1}\)).

In situations when there are not sufficient data to estimate the total effect of the remaining components of equation (7), the air temperature is used as an index of those components. The procedure used in this study is to use the temperature as an index for the heat available for snowmelt taking radiation into account (Laramie & Schaake, 1972).

\[ HTI = BDHF \cdot \text{RAD} / 359 \cdot (1 - \text{ALB}) \cdot TA1 \]  (9)

where \( TA1 \) is the air temperature above 0°C, and 359 is the daily average of RAD for the most intense spring-time insolation (occurring in April in this area).

The coefficient, BDHF, is an important parameter identified by comparison of computed and observed data of snowpack depth, snow density and water equivalent. The snowpack albedo, \( \text{ALB} \), was estimated from the actual measurements by albedo meter as follows:

\[ \text{ALB} = -0.041 \cdot NDX + 0.873 \quad \text{NDX} \leq 6 \\
-0.0065 \cdot NDX + 0.666 \quad \text{NDX} > 6 \]  (10)
The value of $BDHF \cdot RAD/359 \cdot (1 - ALB)$ in equation (9) is what is called the melt factor or the degree-hour factor. The change in the melt factor over the snow season gives greater melt in the spring than in the winter. The product of radiation and temperature leads to rapid snowmelt in the warm climate zone.

**Refreezing and cooling processes**

If the air temperature is less than $0^\circ C$, heat is lost from the snowpack. This heat loss will freeze any liquid water present and lower the snow temperature (Block 13). The heat transferred for the freezing process is estimated in terms of millimetres of liquid water as follows:

$$HTI = WEQ \cdot (TA2 - TP) \cdot 0.5/80$$  (11)

In transformation from this heat to the refreezing and cooling processes, the concept of cold content (Eagleson, 1970) was introduced into the model. The cold content, $CC$, was expressed as follows:

$$CC = -0.5/80 \cdot DP \cdot DN \cdot TP$$  (12)

When the snow temperature is at $0^\circ C$, the cold content is zero. If heat is removed, some or all of the liquid water in the snowpack is frozen. If more heat is removed than is required to freeze all of the water, any remaining loss produces a heat deficit (cold content).

**Liquid water storage and excess water reaching ground surface**

If the sum total $HT$ of $HTI$ ($HT = HTI + HR$) is positive and at the same time the cold content $CC$ is positive, some or all of $HT$ is applied to reduce the cold content until it equals zero. After the cold content reaches zero (i.e. when the snow temperature $TP = 0$), the remaining $HT$ produces melt and increases the stored liquid water in the snowpack.

On the other hand, negative $HT$ is used to freeze any liquid water present, increase the cold content and lower the snow temperature below $0^\circ C$. The concept of thermal quality of snow (Eagleson, 1970) was introduced in order to indicate the amount of free liquid water that is being held by the snowpack. The amount of water being frozen for a negative $HT$, or being melted for a positive $HT$, is given by the following equations:

$$RM = HT/QT \quad HT > 0$$  (13)

$$ACC = -HT/QT \quad HT < 0$$  (14)

where

$$QT = 1 + 0.5/80 (-TP) \quad TP < 0$$  (15)

$$QT = 1 - WC/WEQ \quad TP = 0$$  (16)
RM and ACC are introduced in the change in the liquid water storage (Block 10).

As the change in the liquid water storage has been determined, let us now consider the amount of liquid water that the snowpack can hold as storage (Block 11). From the soil analogy the amount of liquid water that the snowpack can hold was assumed to be limited by its liquid water holding capacity. As it is difficult to measure and determine the liquid water holding capacity, WHC (% by water equivalent), we assumed the relationship to be correlated with the snow density, as follows

\[ WHC = 0.136 \cdot \exp(-3.05 \cdot DN) \quad (17) \]

If the liquid water stored in the snowpack at any time exceeds the value of WHC, the excess can no longer be held against gravity and percolates through the snowpack to eventually reach the ground to become runoff (Block 12).

As for the percolation of water through a snowpack of given depth, we assumed an empirical expression (Anderson, 1968):

\[ PC = \frac{553}{(DP + 553)} \quad (18) \]

This excess water and the snowmelt water from the ground heat is supplied to the runoff model described later.

**Computation of final snowpack parameters**

The final step in each interval is to compute new snowpack parameters (Block 14). Based on the changes that have occurred, the parameters were recomputed in the following ways:

- \( DN \) by equation (6)
- \( TP = -CC \cdot 80/(0.5 \cdot DN \cdot DP) \)
- \( WHC \) by equation (17)
- \( QT \) by equations (15) and (16)

**Elevation effects on areal estimation**

In order to extend the above concepts and equations to larger areas that are not quite uniform, the spatial variation due to elevation effects of variables such as air temperature, precipitation and snow water equivalent have to be accounted for.

The air temperature was assumed to vary with elevation according to the lapse rate, as follows:

\[ T_h = T_o - \beta (h - h_o) / 100 \quad (19) \]

where \( T_h \), \( T_o \), the air temperature at elevation \( h \) (m) and \( h_o \) (m), and the lapse rate \( \beta \) was identified as 0.6 from correlation analysis between the observed data of air temperature at B.C. and higher elevation stations. The further assumption that this lapse rate may be different in day time and at night was not considered in the model.

The precipitation is generally greater at higher elevations due
to orographic cooling effects. This effect was estimated by the ratio of the cumulative precipitation over the area to that at the measuring station:

$$P_h = P_0 \left(1 + \alpha(h - h_0)\right)$$  \hspace{1cm} (20)

where $P_h$, $P_0$ (mm h$^{-1}$) are the precipitation rates at the elevations $h$ and $h_0$ respectively. The increase rate $\alpha$ was identified as 0.0009 from data at $h_0$(245 m, No.8) and $h$(471 m). This rate $\alpha$, applied to each occurrence of precipitation as measured at the station, will account for the variation of precipitation with elevation in an approximate way.

APPLICATION OF THE MODEL ON SNOW ACCUMULATION AND SNOWMELT PROCESSES

Snowmelt processes

At first the model of snow accumulation and snowmelt processes was applied to base camp (B.C.), representative of a small basin area. As the parameters necessary for model simulation had already been decided, the remaining parameter BDHF was identified through comparison between the observed and the simulated snowpack depths based on a pre-assumed value of BDHF. This process of identification was continued until the simulated result was in good agreement with the observed data. The parameter BDHF was finally identified as 1.5 (mm $^\circ$C$^{-1}$h$^{-1}$).

Figure 8 shows a comparison of simulated and observed snow depth at B.C. for the years 1983 and 1984 respectively. The years 1983 and 1984 were used for calibration and validation of the model. The two results suggest that the time distribution and the magnitude of snowpack depth are reasonably accurately simulated. In addition to the snowpack depth, the model can simulate the snow water equivalent and the snow density. Figure 9 shows a comparison between the observed and simulated snow water equivalent. Precipitation, excess water and streamflow are presented in cumulative form.

On the basis of the good agreement of these and similar results for other locations with the observations, we concluded that our model could simulate the distribution and magnitude in time and space of snowpack depth, snow density and water equivalent.

Availability of model for different computation time steps

In order to demonstrate that the above model was capable of accurately simulating the actual accumulation and melting processes using several different sets of input data, the effect of the computation time step on the results obtained was examined. The chosen sets of input data were the average values in air temperature and precipitation at different time steps such as 3, 6, 12, and 24 h. The parameter BDHF was identified by comparison between the observed and simulated snowpack depths for different time steps. Its value was found to be:

$$BDHF = 0.86 \cdot \Delta T + 0.5$$  \hspace{1cm} (21)
We can, therefore, simulate the snowpack depth with reasonable accuracy for different computation time steps by varying the parameter BDHF according to equation (21). Figure 10 shows a comparison of the simulated water excess reaching the ground surface for 1-h and 24-h time steps. The lower line represents the total sum over 24 h of the 1-h time step results. The upper line represents the average value based on the 24-h time step.

COMPUTATION OF STREAMFLOWS

For practical and engineering use of a model of snow accumulation and melting processes, it is important to be able to simulate streamflow.

To do this, it is necessary firstly to make an areal estimation of the supplied snowmelt water to the ground surface. The basin was divided into contour intervals of 50 m. The sub-basins or zones between each contour line were considered to be relatively uniform with respect to the snowpack parameters affected by elevation, given by equations (19) and (20). Their different characteristics were assumed to be dependent on the spatial variation of air temperature and precipitation. The computed snowmelt water in each zone was weighted by the zone area to give an areal average as the input for simulating the streamflow.
Snow accumulation, melting and runoff

Fig. 9 Observed and simulated water equivalent and excess water etc.: (a) 1983, (b) 1984.

Fig. 10 Simulated excess water reaching the ground surface for various computation intervals.
The transformation process from rainfall to streamflow is represented by the runoff system model. In this case the runoff system model relates the computed areal average of supplied snowmelt water and the streamflow. The runoff system model selected for this purpose was the Tank model developed by Sugawara (1983).

The Tank model generally consists of four tanks as shown in Fig.11. The snowmelt water supply is put into the top tank. The water in each tank partly infiltrates through the bottom outlet and partly discharges through the side outlet or outlets. The sum of the outputs from side outlets is the computed streamflow. In the Tank model, there are many parameters such as the runoff and infiltration coefficients on side and bottom outlets, and the positions of side outlets. In this study those parameters were identified by minimizing the value of the criterion ER where

$$ER = \frac{1}{N} \sum \left| Q_c(i) - Q_o(i) \right| / \sqrt{Q_o(i)}$$

FIG.11 Parameters of the Tank model.

$Q_o(i)$ are the observed streamflows, $Q_c(i)$ the computed streamflows for a given set of model parameters, and $N$ is the number of data.

Figure 11 shows the Tank model parameters determined on an hourly basis using observed data on rainfall and streamflow at Syo basin during a season with no snow. Figure 12 shows a comparison between the observed and simulated streamflows with the same parameters. The agreement is good in the year 1983 and somewhat worse in the year 1984. From these and other results based on a daily timescale and for different sized basins, we concluded that our model for snow accumulation, melting and runoff was generally applicable for practical purposes.

CONCLUSIONS AND FUTURE RESEARCH

The snowmelt and runoff system models developed in this study were primarily concerned with considering the snow accumulation, melting and runoff processes on as physical a basis as possible through
FIG. 12 Observed and simulated hourly streamflows: (a) 1983, and (b) 1984.
detailed observation of the meteorological and hydrological elements. In addition we tried to extend the applicability of these models over a wide range of input data.

From the results of application of these models it was found that the computed or simulated snow depth, water equivalent, snow density and streamflows were in adequate agreement with the observed data.

The applicability of data input to the model was successfully extended by varying the parameter BDHF with the computed time step.

At the same time the following areas are suggested for future research:

(a) Investigation of the process by which the snowmelt water percolates through the snowpack, for example the development of better relationships between the liquid water holding capacity and the snow density, and between the coefficient for routing meltwater through the snowpack and the snow depth by observing the amount of melt formed at the surface directly.

(b) Investigation of the influence of topographic factors such as elevation, slope, aspect, exposure and vegetation on the radiation, and hence on snowmelt.

(c) Improvement of the existing runoff system model.

(d) Application of the model to larger basins such as the whole basin of Lake Biwa.

REFERENCES