Simulation of runoff processes of a continental mountain glacier in the Tian Shan, China

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Abstract Based on calculations of energy, water and mass balance and on measurements of water routine, a model is developed to simulate glacial runoff processes for Glacier No. 1, a continental mountain glacier at the source of the Urumqi River in the Chinese Tian Shan. The melt at the equilibrium line is related to the mean melt of the glacier. The drainage system of the ablation area consists mainly of surface water channels, with some intra- and subglacial tributaries. The glacier surface melt is simulated by an energy-water balance model. The energy inputs are simulated by parameterized heat flux expressions. The rainfall is simulated by a separate precipitation routine which divides precipitation into solid and liquid form. The water routine processes of the glacier are simulated by a tank model which accounts for both routing processes on the glacial surface and in the intra- and subglacial drainage system. Finally, daily hydrological discharge from the glacier is simulated and tested by measured discharge for five ablation seasons.

INTRODUCTION

The mountain glaciers at the middle and low latitudes are not only sensitive to climate change, but are also important in the regulation of water resources. In order to understand the runoff processes of glaciers, a small glacier, Glacier No. 1 (43°06'N and 86°50'E) at the source of the Urumqi River in the Tian Shan, was chosen. Glacier No. 1 is a cirque-valley glacier with almost no moraine-covered area and is divided into the east branch, 1.19 km², and the west branch, 0.68 km² (Fig. 1). The Glacier No. 1 basin covers 3.34 km² and the water flow from the basin is controlled by a hydrometric station (3695 m a.s.l.) at a distance of 315 m from the terminus (Kang et al., 1992). The nonglacierized part of the basin consists of bare rock and moraine. The Daxigou meteorological station (3539 m a.s.l.) is located at a distance of 2 km from the terminus. On the basis of measurements of mass balance on Glacier No. 1 carried out regularly on its two branches since 1979 and on experiments of energy balance, water balance, and salt tracer from 1986 to 1989 (Fig. 1; Ohmura et al., 1990; Kang et al., 1992; Kang, 1994), a glacier runoff model is developed to simulate the response of a glacier to climatic variables, surface conditions, and water routing.
GLACIER MELT AND WATER ROUTING

Specific melt

On the basis of mass balance measurement by stakes on Glacier No. 1 (Fig. 1) from 1980 to 1989, the annual specific melt is averaged separately at different altitudes over the 10 years from 1980 to 1989. The specific melt is then related to altitude by regression analysis. The specific melt decreases with increasing altitude, as follows:

for the east branch:\[ Ms(z) = 29487.6 - 7.2z, \]

for the west branch:\[ Ms(z) = 32509.4 - 7.8z, \]

where \( Ms(z) \) is annual specific melt (kg m\(^{-2}\)) at altitude \( z \) (m) of the glacier surface. The contour line at the geometric mean altitude is defined as the mean altitude line and is calculated for both the east and west branch of the glacier (Table 1). Similarly, the

![Fig. 1 Locations of the mass balance stakes and the salt tracer experiments of Glacier No. 1 (The contour lines are expressed by the dashed lines in m a.s.l.).](image-url)
Table 1 The relationship between equilibrium line, mean melt line and mean altitude line of Glacier No. 1 (averaged from 1980 to 1989).

<table>
<thead>
<tr>
<th>Glacier No. 1</th>
<th>Equilibrium line</th>
<th>Mean melt line</th>
<th>Mean altitude line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Altitude (m)</td>
<td>Specific melt (kg m(^{-2}))</td>
<td>Altitude (m)</td>
</tr>
<tr>
<td>East branch</td>
<td>4005</td>
<td>652</td>
<td>3970</td>
</tr>
<tr>
<td>West branch</td>
<td>4095</td>
<td>568</td>
<td>4069</td>
</tr>
</tbody>
</table>

contour line at which the meltwater depth equals the mean melt depth is defined as the mean melt line and is also calculated for each branch of the glacier (Table 1). Table 1 therefore shows the relationship between the altitudes of the equilibrium line, mean melt line, and mean altitude line of both branches of Glacier No. 1. The melt at the mean altitude line is influenced by the geometry of the glacier. The mean altitude line could be higher or lower than the equilibrium line. The west branch has a higher equilibrium line, and it has less melt there than the east branch. The melt at the equilibrium line of the east branch is 72% of the melt at the mean melt line, and that of west branch is 74% of the melt at the mean melt line. Therefore, the melt at the equilibrium line is strongly related to the mean melt of the glacier. It is desirable to take the equilibrium line as the standard position to which the meteorological elements are attributed and heat input to the glacier is calculated. In this study, the daily energy balance at the equilibrium line is approximated by that at 3910 m on the glacier, at which the measurement was carried out during ablation season of 1986 and 1987 (Ohmura et al., 1990).

The mechanism of water routing

A preliminary understanding of the mechanism of water routing can be drawn from a series of salt tracer experiments, which were carried out on Glacier No. 1 during 11-24 August 1989 (Fig. 1; Kang, 1994), when the drainage system of the glacier had completely developed. Salt solution is injected into the selected positions on the glacier surface, then the arrival time and the duration of the solute migration are measured by a conductivity meter at the cross section of the Glacier No. 1 hydrometric station; the recovered salt is then calculated.

In the ablation area during July and August, the drainage channels develop on the surface and at the side of the glacier, and most of the runoff flows in the channels. Some of the surface meltwater flows into the glacier along crevasses and moulins. Some water from the side streams also flows into and under the glacier. Therefore, the drainage system of the ablation area of Glacier No. 1 consists mainly of surface water channels, with some intra- and subglacial tributaries. The convergence of the meltwater is rapid in the ablation area. For example, at the salt injection points IJ4, IJ5, and IJ6 (Fig. 1), it takes 30 to 40 min for the meltwater on the ice surface to arrive at the hydrometric station during the most intense melt period. The time taken for meltwater to flow through the firn and snow layer is much longer. For example, at the salt injection point IJ7, a 10 to 20 cm snow cover at a distance of about 100 m can delay the flowing time by more than 2 h (Kang, 1994). Therefore, the glacier cannot store much meltwater in
the ablation area. The intra- and subglacial water channels develop in a rather singular
and straightforward way, because the rather low ice temperature prohibits the
development of branches and anabranches (Cai et al., 1988).

SIMULATION OF RUNOFF GENERATION

Runoff generation

In a glacierized basin, the equations of the energy balance (Kang, 1994) can be written as

\[ H_M = H_{NR} + H_S + H_L \]  

(3)

where: \( H_M \) is melt heat of snow and ice, \( H_{NR} \) is net radiation, \( H_S \) is sensible heat flux, and \( H_L \) is latent heat flux of evaporation.

The runoff (\( R \)) from the glacierized area can be expressed as

\[ R = \frac{\tau}{L_M} (H_{NR} + H_S) - \frac{L_E}{L_M} E + P_L \]  

(4)

where: \( \tau \) is time period considered, \( L_M \) is latent heat of melt, \( L_E \) is latent heat of evaporation, \( P \) is precipitation, and \( E \) evaporation. Equation (4) is the energy-water balance model of a glacier during the ablation season. On the ice and snow-free ground surface, the runoff generation is calculated from: \( R = P - E \).

Energy inputs

The energy balance components measured at 3910 m a.s.l. near the mean altitude of
equilibrium line of Glacier No. 1 (Ohmura et al., 1990) are related to the meteorological
elements at the Daxigou meteorological station (Kang, 1994). It is found that, among the
meteorological elements, air temperature has the best significant correlation to albedo,
and the relation is different between snow and ice. This can be explained by the fact that
glacier albedo varies with the surface conditions, which are controlled by heat
conditions. The calculation of energy fluxes in equation (4) for the melting glacier
surface is then carried out using the following parameterized heat flux expressions by
the standard meteorological elements (Kang, 1994).

\[ H_{NR} = R_G(1 - \alpha) + \varepsilon_a \sigma T_a^4 - \varepsilon_a \sigma T_a^4 \]  

(5)

\[ \frac{R_G}{R_{scd}} = 0.2319 + 0.5354 \frac{HD}{HD_c} \]  

(6)

\[ \alpha = 0.82 - 0.03Tm - 1.74 \times 10^{-3}Tm^2 - 1.14 \times 10^{-4}Tm^3 \]  

(snow)  

(7)

\[ \alpha = 0.27 - 0.01Tm \]  

(ice)  

(8)

\[ \varepsilon_a = 0.69(1 + 0.42C) \]  

(9)
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\[ \varepsilon_a = 0.97 \]  
\[ H_s = 0.97 U_m T_m \]  
\[ LE = 2.73 U_m (6.11 - P_{me}) \]

where: \( R_G \) is global radiation (W m\(^{-2}\)), \( \alpha \) albedo, \( \varepsilon_a \) atmosphere emissivity, \( \varepsilon_e \) surface emissivity or absorption coefficient, \( \sigma \) Stefan-Boltzmann constant (0.5667 \( \times \) 10\(^{-7}\) W m\(^{-2}\) K\(^{-4}\)), \( T_a \) atmospheric temperature (K), \( T_e \) surface temperature (K), \( R_{sec} \) daily extra-atmospheric solar radiation, \( HD \) measured daily sunshine duration hours, \( HD_c \), calculated daily potential sunshine duration hours, \( C \) cover ratio of low cloud (\( C = 0.0 \) for clear sky, \( C = 1.0 \) for overcast skies), \( H_s \) (W m\(^2\)) and \( LE \) (W m\(^2\)) are as defined before, \( T_m \) (°C), \( U_m \) (m s\(^{-1}\)), \( P_{me} \) (mb) are daily mean air temperature, wind velocity, and vapor pressure at the Daxigou meteorological station.

Table 2 shows the monthly mean values of the simulated energy balance components on Glacier No. 1 and the comparison with the values measured during 1986 and 1987.

**Water inputs**

After the correction of systematic error of precipitation measurement (Yang *et al.*, 1992), the daily precipitation on the glacier is obtained by the altitude gradient and the measured precipitation at the Daxigou meteorological station (Kang, 1994). It is found in the Urumqi River basin that precipitation increase with altitude occurs mainly in summer, other seasons do not have an obvious increase with altitude (Kang *et al.*, 1992). The altitude gradient of monthly precipitation in the source area of the Urumqi River is 5.4 mm 100 m\(^{-1}\) for May, 6.5 mm 100 m\(^{-1}\) for June and 7.4 mm 100 m\(^{-1}\) for August (calculated by the average precipitation at the Daxigou meteorological station from 1959 to 1989). The July air temperature is the highest of the summer months; this may cause strong convection and the normal altitude dependency of precipitation may be destroyed during July. The daily precipitation gradients \( PG(n, M) \) are calculated as follows for May to September, which changes with the daily precipitation, \( M = 5, \ldots, 9 \):

\[ PG(n, 5) = 8.3\% \ P_{md}(n)/100 \ m, \]
\[ PG(n, 6) = 5.5\% \ P_{md}(n)/100 \ m, \]
\[ PG(n, 7) = 0.0\% \ P_{md}(n)/100 \ m, \]
\[ PG(n, 8) = 7.2\% \ P_{md}(n)/100 \ m, \]
\[ PG(n, 9) = 0.0\% \ P_{md}(n)/100 \ m, \]

where, \( P_{md}(n) \) is the error corrected daily precipitation at the Daxigou meteorological station, the day \( n \) belongs to the month \( M \).

The snow cover is approximated by the separation of precipitation form. There are two criteria temperature \( TL \) and \( TS \) for liquid and solid precipitation. On the basis of
Table 2 Monthly mean values of the simulated energy balance components on Glacier No. 1 (3910 m a.s.l.).

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>$R_G$ (W/m²)</th>
<th>$-aR_G$ (W/m²)</th>
<th>$I\downarrow$ (W/m²)</th>
<th>$I\uparrow$ (W/m²)</th>
<th>$H_S$ (W/m²)</th>
<th>$H_L$ (W/m²)</th>
<th>$H_M$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>June</td>
<td>227.5</td>
<td>237.0</td>
<td>-169.7</td>
<td>-179.0</td>
<td>267.0</td>
<td>-308.4</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>213.7</td>
<td>221.0</td>
<td>-83.2</td>
<td>-100.0</td>
<td>273.7</td>
<td>-308.4</td>
<td>14.4</td>
</tr>
<tr>
<td></td>
<td>Aug.</td>
<td>205.7</td>
<td>228.0</td>
<td>-88.1</td>
<td>-91.0</td>
<td>265.8</td>
<td>-308.4</td>
<td>13.6</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>215.6</td>
<td>228.7</td>
<td>-113.7</td>
<td>-123.0</td>
<td>268.8</td>
<td>-308.4</td>
<td>10.8</td>
</tr>
<tr>
<td>1987</td>
<td>June</td>
<td>229.2</td>
<td>249.0</td>
<td>-169.5</td>
<td>-192.0</td>
<td>268.8</td>
<td>277.0</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>July</td>
<td>214.1</td>
<td>224.0</td>
<td>-102.5</td>
<td>-128.0</td>
<td>284.8</td>
<td>275.0</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>Aug.</td>
<td>234.1</td>
<td>233.0</td>
<td>-90.0</td>
<td>-93.0</td>
<td>267.6</td>
<td>258.0</td>
<td>15.7</td>
</tr>
<tr>
<td></td>
<td>mean</td>
<td>225.8</td>
<td>235.3</td>
<td>-120.7</td>
<td>-137.7</td>
<td>273.7</td>
<td>270.0</td>
<td>10.9</td>
</tr>
<tr>
<td>Total mean</td>
<td>220.7</td>
<td>232.0</td>
<td>-117.2</td>
<td>-130.4</td>
<td>271.3</td>
<td>270.0</td>
<td>-308.4</td>
<td>-308.7</td>
</tr>
</tbody>
</table>

* Calculated by the glacier melt model.
** Measured by Calanca and Herberger and Konselmann (Ohmura et al., 1990).
$I\downarrow$, $I\uparrow$ = Long-wave incoming and outgoing radiation.
observations at the Daxigou meteorological station, the values for \( TL \) and \( TS \) are determined as \( TL = 5.5^\circ C \), \( TS = 2.8^\circ C \). When the daily minimum air temperature \( Tmin \geq TL \), precipitation is liquid, when the daily maximum air temperature \( Tmax \leq TS \), it is solid. If the daily temperature variation is between \( TL \) and \( TS \), that is, \( Tmax < TL \) and \( Tmin > TS \), the daily mean air temperature is \( Td \), then the following equation is used to calculate the ratio of daily solid precipitation \( Ps \) to the daily precipitation \( P \): \[
P_s = \frac{1}{TL - TS} \left( TL - \frac{Td}{2} - \frac{Tmax}{4} - \frac{Tmin}{4} \right)
\] (13)

During the periods from May to September of the years from 1986 to 1990, the averaged solid precipitation ratio is 0.67 at 3539 m a.s.l., 0.86 at 3900 m a.s.l. of the nonglacierized area, and 0.93 at 4010 m a.s.l. on Glacier No. 1.

The evaporation from the ice- and snow-free surface must be calculated to give the effective liquid precipitation in the nonglacierized area of the Glacier No. 1 drainage basin. From the water balance calculation (Kang et al., 1992), it is estimated by the evaporation from the alpine meadow. On the basis of the measured data (Zhang et al., 1992), the daily evaporation rate \( Et \) (mm day\(^{-1}\)) from the alpine meadow at the Daxigou meteorological station during the period from May to September is determined by the daily mean wind velocity, vapor pressure, and saturation vapor pressure \( e_{sa} \) (mb) measured at the Daxigou meteorological station from:

\[
Et = 0.33 \left( U_m (e_{sa} - P_{me}) \right)^{0.97}
\] (14)

SIMULATION OF HYDROLOGICAL DISCHARGE

Because of the seasonal changes in the conditions for both melt and water routing in a glacierized basin, the ablation season is divided into a low melt period and a high melt period (Kang, 1991). The low melt period is generally in May, June and September, while the high melt period generally consists of the months of July and August in the Tian Shan. Discharge simulation is carried out separately for the two periods.

The energy inputs to the glacier are simulated at 3910 m a.s.l. in the ablation area. From equations (1) and (2) and Table 1, the annual melt at that altitude is more than the mean melt of the glacier. For the runoff calculation from the whole glacier, a multiplication factor \( FC \) is calibrated for both the low melt period and high melt period in order to transfer the water inputs to the standard position at 3910 m a.s.l. of the basin into those to the whole basin. The water inputs to the standard position can sometimes be over- or underestimated by about 10 to 60% for the whole basin. This uncertainty could be caused by the yearly variation of precipitation gradient (Kang et al., 1992), uneven distribution of snow cover, and melt heat on the complex topography of the basin. For the discharge simulation of the Glacier No. 1 basin in 1990, \( FC \) is 1.1 for the low melt period and 0.4 for the high melt period (Kang, 1994).

Because the surface conditions of the glaciers in the Tian Shan are very changeable, the daily variation of the snow area and ice area is difficult to track. Therefore, the calculation of the daily meltwater production is adjusted by another multiplication factor \( CMf \). The daily meltwater from a glacier is influenced by the change of melt area and albedo, and this change can be related to daily air temperature. It is found that
In a glacierized basin, the surface consists of a glacierized part and a nonglacierized part. The tank model (Sugawara et al., 1984) is used to simulate the processes of water routine, through a glacierized basin, the structure of which is shown in Fig. 2. It consists of two vertically-connected tanks. The upper tank with two side outlets and a bottom outlet is used to simulate the processes on the glacier surface and the ground surface, while the lower tank is used to simulate those of the intra- and subglacial drainage system and the active layer of the permafrost. The daily runoff generation in a glacierized basin is simulated based on equation (4) and adjusted by the two multiplication factors $FC$ and $CMf$, and then taken as the net water input to the tank runoff transformation model. The discharge from the basin outlet is the sum of the discharges from the side outlets of the tank model. The discharge from the bottom outlet of the upper tank indicates infiltration.

Through the calibration for the years from 1986 to 1989, the heights of the side outlets and the drainage coefficients for all the outlets of the tank runoff transformation model are obtained for the Glacier No. 1 basin (Table 3). The two side outlets of the upper tank are located at different heights. This indicates that the runoff transformation of the Glacier No. 1 basin shows some nonlinear properties. When the melt and effective rainfall is more than a certain height, the discharge can increase more rapidly. The heights of the upper outlets are related to the snow depth and the development of the surface drainage system. During the low melt period, the discharge is very small, and the runoff is generated from the surface at the lower altitude, therefore the infiltration and the discharge from the lower tank are very small, and the drainage coefficients of
Table 3 Parameters of the tank runoff transformation model of the Glacier No. 1 basin at the source of the Urumqi River.

<table>
<thead>
<tr>
<th>Melt period</th>
<th>H2 (mm)</th>
<th>H1 (mm)</th>
<th>A2</th>
<th>A1</th>
<th>A0</th>
<th>B1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low melt</td>
<td>5.00</td>
<td>0.00</td>
<td>0.247</td>
<td>0.191</td>
<td>0.021</td>
<td>0.004</td>
</tr>
<tr>
<td>High melt</td>
<td>10.00</td>
<td>0.00</td>
<td>0.165</td>
<td>0.151</td>
<td>0.153</td>
<td>0.146</td>
</tr>
</tbody>
</table>

Table 4 The evaluation criteria for the discharge modelling of the Glacier No. 1 basin during the months of May to September.

<table>
<thead>
<tr>
<th>Year</th>
<th>Measured mean discharge (mm day(^{-1}))</th>
<th>Simulated mean discharge (mm day(^{-1}))</th>
<th>CR</th>
<th>MSEQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986</td>
<td>6.6</td>
<td>6.8</td>
<td>0.441</td>
<td>0.571</td>
</tr>
<tr>
<td>1987</td>
<td>2.7</td>
<td>3.2</td>
<td>0.511</td>
<td>0.605</td>
</tr>
<tr>
<td>1988</td>
<td>5.3</td>
<td>5.4</td>
<td>0.401</td>
<td>0.471</td>
</tr>
<tr>
<td>1989</td>
<td>3.7</td>
<td>3.9</td>
<td>0.419</td>
<td>0.485</td>
</tr>
<tr>
<td>1990</td>
<td>3.4</td>
<td>4.0</td>
<td>0.584</td>
<td>0.761</td>
</tr>
</tbody>
</table>

the upper tank are larger than those of the intense melt period because of the quicker transit of the water flow to the basin outlet. During the high melt period, the infiltration coefficients and the drainage coefficients of the lower tank are large because of the development of the intra- and subglacial drainage system. The meltwater runoff from the glacierized area is dominant during this period. From the drainage coefficients (Table 2), the average time of the surface storage (Sugawara et al., 1984) for the whole basin can be 2 to 3 d. The ratio of accumulation area to ablation area is 0.42 for the east branch and 0.45 for the west branch of Glacier No. 1. According to Golubev (1973), the runoff transformation from the ablation area is much faster than that from the accumulation area. While the former occurs in a few hours, the latter can take a few days. Furthermore, the moraine of the nonglacierized area of the basin can delay the water running time. Therefore, the runoff transformation time of the basin can be several days.

The discharge simulation is evaluated by the tank model evaluation criterion, CR and the standard mean square error of discharge, MSEQ (Sugawara et al., 1984). The results of the simulation are evaluated in Table 4 for the calibration years (1986 - 1989) and a test year (1990). Figure 3 shows the comparison of the simulated daily discharge (Qg) hydrographs and the measured hydrographs for the Glacier No. 1 hydrometric station for 1987 and 1990. The time series of the basic meteorological elements which are measured at the Daxigou meteorological station are shown beneath the hydrographs. During the low melt period, the air temperature and vapor pressure are low, and the solar radiation \( R_{scd} \) is low (equation (6)). Therefore, even though precipitation is high, the discharge is usually very small. During the high melt period, the discharge is large, and fluctuates concurrently with air temperature and vapor pressure because the runoff is mainly fed by ice and snow meltwater.
Fig. 3 Daily discharge Qg simulation of the Glacier No. 1 hydrometric station (1987 is the year for the parameter calibration of the tank runoff transformation model, and 1990 is the year for model test.

REFERENCES


