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Relationship between runoff and meteorological factors and its simulation in a Tianshan glacierized basin

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ABSTRACT The runoff from a high mountain glacierized basin situated in the inland arid area of Asia is analyzed on its relationship to meteorological factors observed at a standard meteorological station. The daily discharge from the glacierised area has good correlation to air temperature and vapour pressure , but that from the ice-free area is positively correlated to precipitation. Taking the meteorological factors with 0 - 4 days time lag as independent variables, the daily discharge is simulated by means of the multiple regression model.

INTRODUCTION

In the source area of the Urumqi River Basin of the Chinese Tianshan Mountains, systematic observations and experiments on the processes of mountain glaciers, climatology and hydrology have been carried out by Lanzhou Institute of Glaciology and Geocryology, Academia Sinica since 1980. To understand their interrelationship, a comprehensive analysis of the existing data is undertaken.

The general water balance equation for the earth's surface can be employed to express the water revenue and expenditure in a high mountain basin, the former is precipitation and the latter is evaporation and runoff. The analysis and estimation of the runoff are the important aspects in hydrology from the view point of water resources in the high mountainous area. This paper presents the results of research works in the basin(Fig.1) which is situated at the source area of the Urumqi River Basin(43° 00' - 44° 07' E and 86° 45' - 97° 56' E). The altitude of the basin ranges from

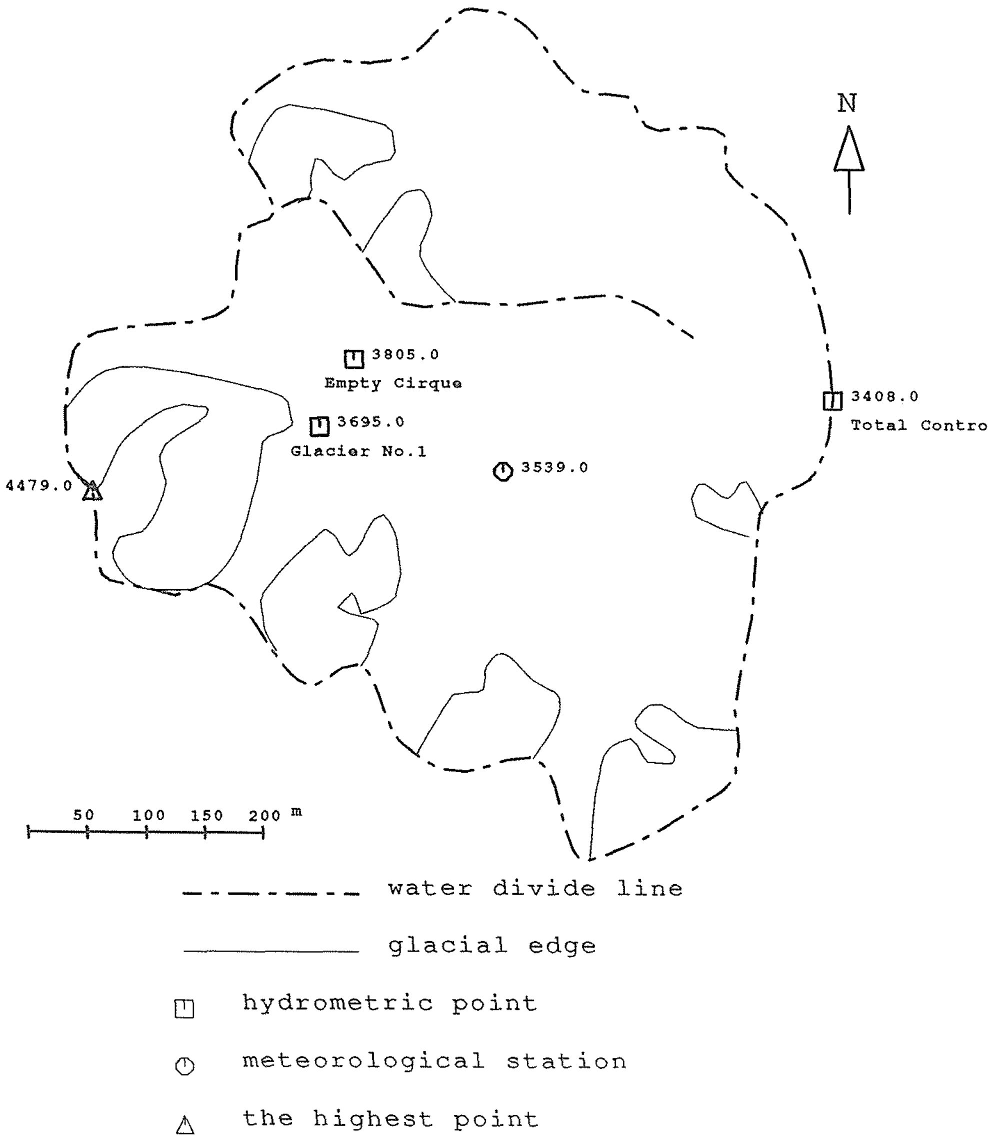

FIG. 1 The source basin of the Urumqi River.

3403m to 4479m a.s.l., with glaciers, bare rocks, moraines and alpine meadow. There are three hydrometric points and a meteorological station distributed in the basin, which are shown in Fig.1 and Table1.

The research work on the high mountain runoff include glacial runoff, snow melt runoff, rainfall runoff. The runoff production is controlled not only by precipitation and heat conditions, but also by the different underlying surfaces and the active layer of the

TABLE 1 Hydrometric points in the source basin of the Urumqi River.

name of hydrometric point	drainage area (km^2)	glacier covered ratio (%)	mean specific discharge during May-September ($l/s.km^2$)	years for statistics
Glacier No.1	3.34	55.1	41.8	1983-1987
Empty Cirque	1.68	0.0	29.8	1983-1987
Total Control	28.9	19.7	31.9	1983-1987

frozen ground. Our knowledge on the physical processes of the high mountain runoff production is limited by the difficulty and limitation of the observation condition. Hence, from the view point of practical requirement, the question is raised as to how to calculate the high mountain runoff by means of the standard meteorological elements, based on the relationship between runoff and meteorological factors. Through this, it is intended to provide the basis and methods for the estimation and forecasting of high mountain runoff, and to make foundation for the further understanding of the high mountain runoff processes.

There is uncertainty existing in the relationship between runoff and meteorological factors, they belong to stochastic variables, but some objective relation and regularity do exist in the relationship. In order to find them, statistical and regression analysis is a powerful mathematical tool(Oestrem, G.,1973). This paper uses the multiple correlation and regression method to analyze the relationship between the runoff from Glacier No.1 basin, the Empty Cirque and the Total Control high mountain basin at the source of the Urumqi River, and the meteorological factors observed at the meteorological station. In the computation, daily discharge is taken as dependent variable, and air temperature, air temperature daily range, relative humidity, vapour pressure, precipitation, wind velocity with different time lag days, as the independent variables. The meteorological factors which are closely related to the runoff are chosen, and the inquiry of the runoff simulation is carried out.

The hydrological and meteorological factors analyzed in this paper are listed in Table 2.

TABLE 2 Hydrological and Meteorological Factors for Statistical Analysis.

Measurement Points	Altitude (m)	Hydrological and Meteorological Factors
Glacier No.1 Hydrometric Point	3695	discharge Qg(m^3/s)
Empty Cirque Hydrometric Point	3820	discharge Qe(M^3/s)
Total Control Hydrometric Point	3403	discharge Qc(M^3/s)
Meteorological Station	3539	air temperature Tm(^{0}C) air temperature range Tmd(^{0}C) vapour presure Pme(mb) relative humidity Hm(%) precipitation Pm(mm) wind velocity Vm(m/s)

ANNUAL RUNOFF PROCESS AND DIVIDING OF THE STATISTICAL SAMPLES

The high mountain runoff production during May - September is shown in percentage distribution in Table 3. The most runoff is prodused in the summer months of June - August, but the glacial runoff is highly concentrated in July and August.

Fig. 2 shows the specific discharge hydrographs of the three hydrometric points and the daily air temperature and precipitation course of the meteorological station, the following characteristics can be concluded.

(a) The highly glacierized basin has the much larger specific discharge during summer as compared to the less glacierized basin, the ice-free basin has the least specific discharge.

(b) The runoff produces mainly in the period when the mean daily air temperature is above 0°C. The daily specific discharge from the Glacier No.1 basin varies in a much larger range as compared with the other two. When the daily precipitation

TABLE 3 The Annual Runoff Percentage Distribution in the Source Basin of the Urumqi River.

hydrometric points	May	June	July	August	September
Glacier No.1	1.0	12.0	42.2	41.7	3.1
Empty Cirque	11.3	26.6	34.8	20.8	6.5
Total Control	6.6	19.5	38.3	31.2	4.4

amount is large, the air temperature is low, the discharge from the Glacier No.1 basin is usually minimum.

(c) The daily specific discharge from the Empty Cirque basin increases not so much as those from the other two when summer comes, the peak values correspond often positively to precipitation.

(d) When the air temperature has gone up, after the melt season starts, and has gone down, before the melt season stops, there is a small discharge period, which symbolizes the period of ascending and descending of the seasonal snow line respectively.

During the ablation season, the conditions for the runoff production in the basin are changing. In spring, the basin is covered by seasonal snow deposit with large albedo, without glacial ice melt, on the ice-free surface of the basin, the ground active layer is not yet formed. In this period, the seasonal snow cover starts to be melted, forming a small discharge period at the beginning of the melt season, until the snow cover is melted out. At the end of summer, the glacier melt is reduced, the seasonal snow starts to cover the glacial surface and the whole basin, the discharge decreases, another period of small discharge comes again. After the glacial ice starts to be melted out, the albedo reduces, the glacial water system develops, the ground active layer is formed. During this period, air temperature is high, heat flux to the basin is abundant. After a time of precipitation, the basin is temporarily covered with snow, but it is melted out soon, forming some of the hydrograph fluctuations during the large discharge period.

When the statistical analysis is employed to the runoff from glacierized basins, Jensen and Lang clarified the necessity of dividing the melt season into different periods(Jensen, H., Lang,

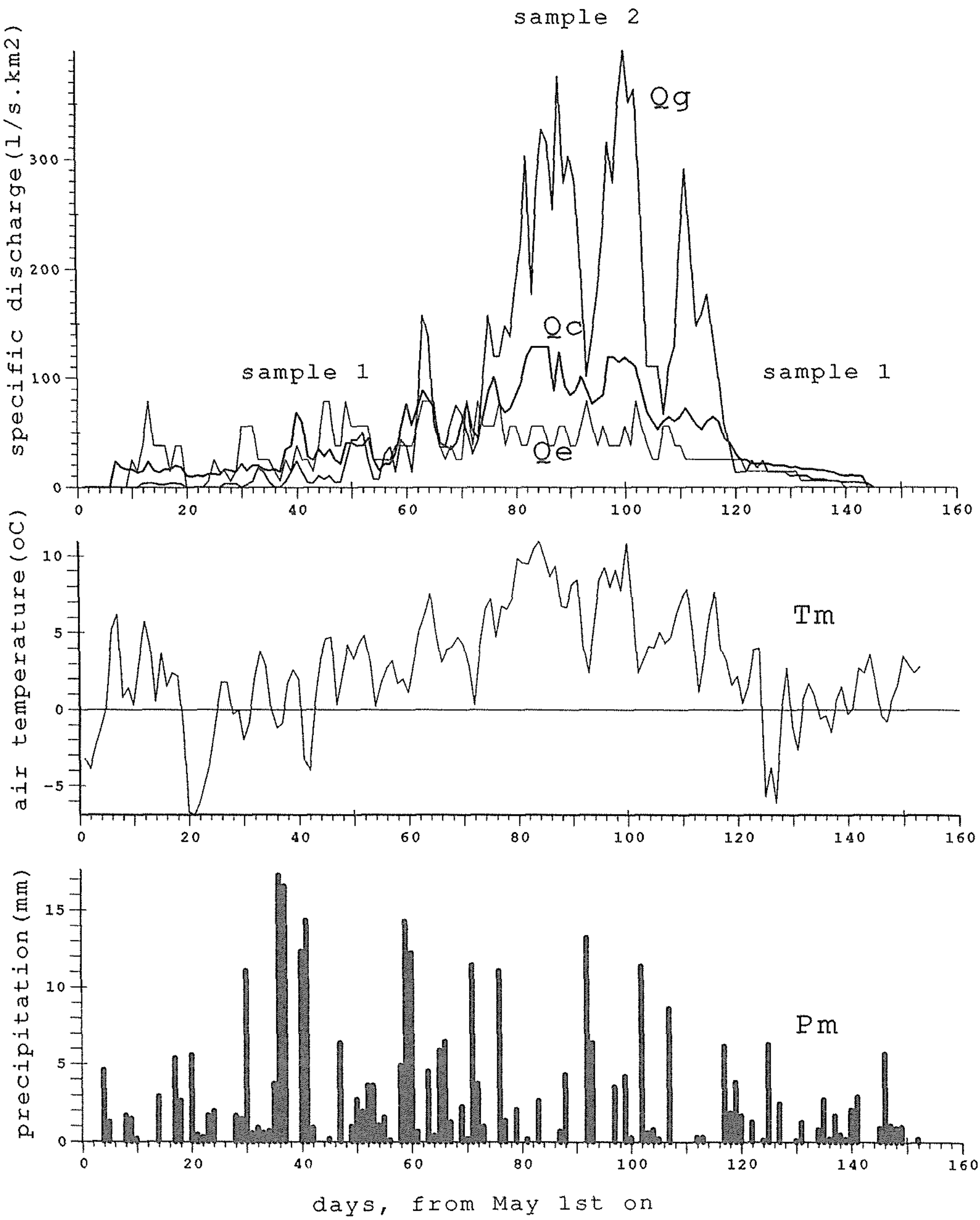

FIG. 2 Daily discharge hydrographs at the source basin of the Urumqi River.

H.,1972). The author carried out a similar dividing and runoff modelling in the Alps(Kang, E., Jensen, H., 1987). The source area of the Urumqi River is a mountain glacierized basin in the continental arid area of monsoon climate. According to the hydrograph features and the field observations, the periods of the seasonal snow line ascending to the firn line and that of the seasonal snow line descending to cover the whole basin again are separated to symbolize the small discharge period, forming sample 1; the left periods of glacial ice melt symbolize the large discharge period, forming sample 2(Fig. 1). The calculation on the data during 1983 - 1987 is carried out .

RELATIONSHIP BETWEEN RUNOFF AND METEOROLOGICAL FACTORS

All the factors are daily mean values with time lag 0 - 4 days. Because the runoff precesses are concentrated mainly during the glacial ablation period, the analysis is mainly carried out for Sample 2.

Relationship between the Glacier No.1 runoff and meteorological factors(Fig.3)

The glacial discharge has a positive correlation with air temperature, vapour pressure and air temperature daily range, but a negative correlation with precipitation, relative humidity and wind speed. The glacial runoff production is mainly determined by the heat conditions on the glacial surface(Lang, H., 1973, 1980), therefore, the runoff has good correlation to air temperature, and next to vapour pressure. Because vapour pressure is directly proportional to air temperature and absolute humidity which is a suppressor of evaporation, has rather strong ability to emit long wave radiation, and increases the atmospheric counter radiation, it has rather good correlation to glacial runoff. Precipitation reduces the glacial heat income, and relative humidity varies coincidentally with precipitation, and appositely with air temperature, therefore, they have negative correlation to glacial discharge. Daily air temperature range is related to cloudiness and radiation, influences the discharge positively. Wind velocity has complex relation to synoptic conditions, and is very changeable with time and space.

In terms of the different time lags, air temperature and vapour pressure without time lag have better correlation to discharge than those with time lags, it shows that in such a small glacierized basin, the heat condition of a day influences largely the discharge at the outlet in the same day. The air temperature and vapour pressure of the preceding days also correlated to the discharge. The precipitation with different time lags has rather even influence to the discharge, it shows also the influence of

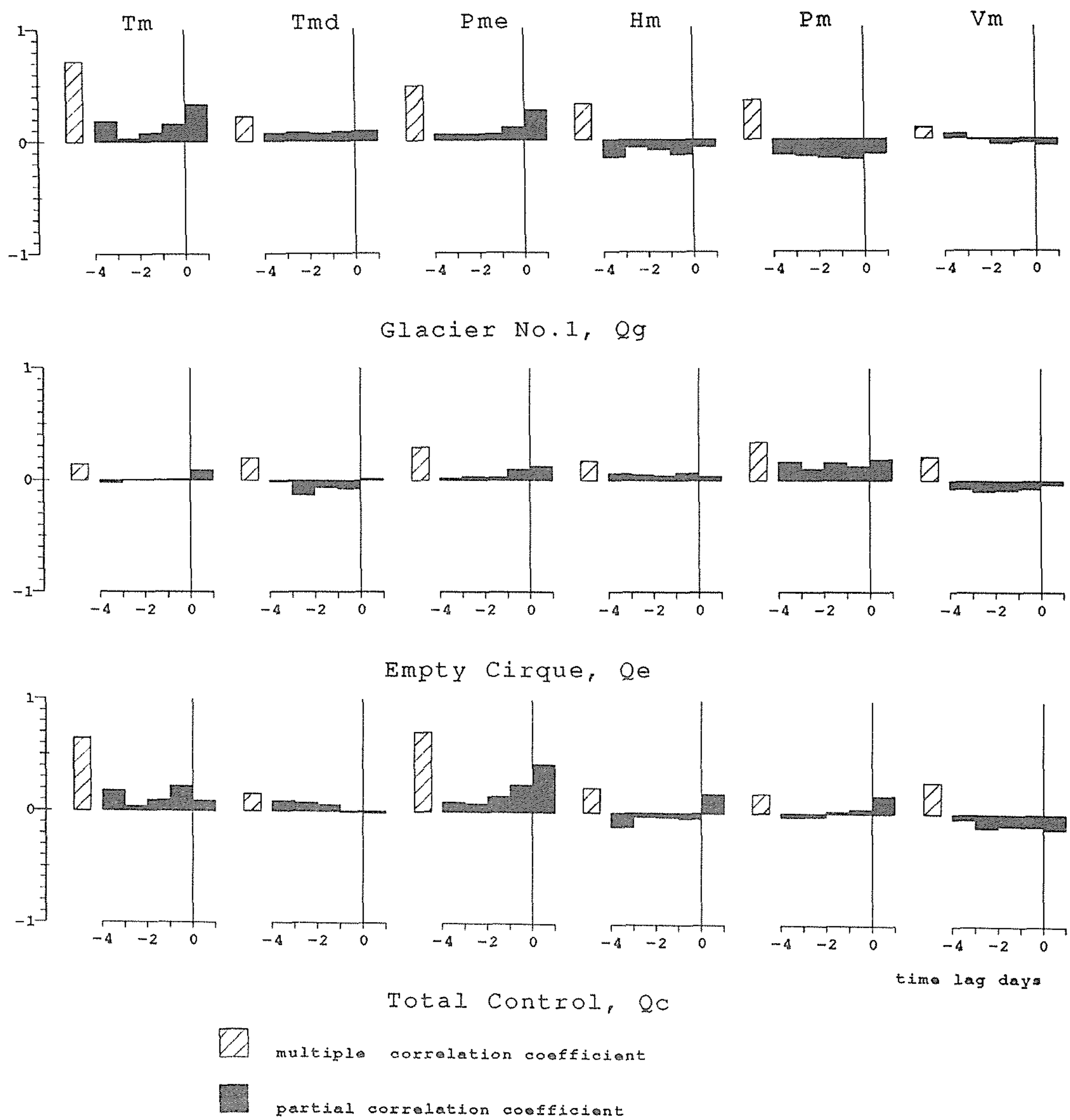

FIG. 3 Correlation of the daily discharge to the meteorological factors at the source basin of the Urumqi River (sample 2, n = 265 days).

precipitation in the preceding days to the discharge. The relative humidity with time lags 1 - 4 days has the coincident influence to discharge with air temperature, but the function is negative.

Relationship between the Empty Cirque runoff and meteorological factors(Fig.3)

The Empty Cirque runoff represents the runoff from the ice-free area of the partially glacierized basin. In the Chinese Tianshan , precipitation is concentrated in the summer months, when it is the glacial ablation season. The low albedo of the ground surface and the rather high air temperature during this season makes the snow deposit only exist in a short time. The runoff from the Empty Cirque is better related to precipitation and vapour pressure, next to relative humidity, rather weekly related to air temperature, and negatively related to air temperature daily range and wind speed. Therefore, the runoff production of the Empty Cirque is mainly decided by the amount of precipitation, next by vapour pressure and air temperature..

Relationship between the Total Control runoff and meteorological factors(Fig.3)

The runoff from the high mountain area consists of glacial runoff, snowmelt runoff and the runoff from the ice-free area. The discharge has a positive correlation to vapour pressure, air temperature, air temperature daily range with different time lags, and precipitation and relative humidity at the same day, but wind speed is negatively correlated. The best correlated meteorological factor to the discharge is vapour pressure, and a maximum at lag 0. In addition to vapour pressure, air temperature has also good correlation to discharge. Among the analyzed meteorological factors, vapour pressure is a synthetical index showing the water and heat conditions on the high mountains, that's why it has better correlation to the discharge. The positive correlation of precipitation and relative humidity expresses that the runoff from the ice-free area also contributes to the total runoff. The negative correlation of wind speed to the discharge can be explained by the fact that, when it is windy, it is accompanied with the weather which is unfavorable to the ice and snow melt. The correlation of the high mountain discharge to vapour pressure and air temperature coincides with that of the glacial discharge because the ice and snow meltwater runoff is the most important component of the total high mountain runoff in this region.

Multiple regression analysis between discharge and meteorological factors

The multiple regression analysis is employed on the discharge at the 3 hydrometric points, taking Qg, Qe and Qc as dependent variables, and air temperature Tm, air temperature daily range

Tmd, vapour pressure Pme, relative humidity Hm, precipitation Pm and wind velocity Vm as independent variables with time lags of 0 - 4 days.

The discharge and the meteorological factors have a linear regression relationship at 0.01 level of F-test. Through the comparison of standard regression coefficient, partial correlation coefficient, and the square sum of partial regression for the independent variables, it is clarified that vapour pressure plays an important role in the estimation of the discharge, and air temperature is important in the estimation of the discharge of the glacier No.1 and the Total Control runoff, precipitation is important in the estimation of discharge of the Empty Cirque and the Total Control basin. Other meteorological factors, such as air temperature daily range, relative humidity and wind velocity plays a certain role in the discharge calculation.

The above mentioned relationships are decided by the water and heat conditions in the high cold regions. The formation of glacial and snow meltwater runoff needs heat condition, air temperature, vapour pressure and air temperature daily range can be used as the indexes of the amount of heat for melting. The runoff formation of the high mountains also controlled by precipitation which is related positively to vapour pressure and relative humidity. Wind velocity is related to the synoptic precess and influences the heat exchange between atmosphere and the underlying surface. During the ablation season, when the snow falls on the ground and is melted out soon, the runoff is mostly influenced by precipitation.

About the relationship between glacial discharge and vapour pressure, it is clarified in the high mountains of maritime climate(Lang, H., 1967). This paper shows the case for the glacial and high mountain runoff in the continental climate environment. It is reasonable to use vapour pressure as one of the independent variables to estimate the high mountain runoff, e.g., in combination with air temperature.

SIMULATION OF THE DISCHARGE HYDROGRAPHS WITH METEOROLOGICAL FACTORS

Here, the daily discharge hydrographs of the Total Control hydrometric point are simulated with the meteorological factors observed at the meteorological station with the time lags of 1 - 4 days by means of the multiple regression model. The chosen equations are as following:

Sample 1 ($n=190$, $\overline{Q_c} = 0.586\ m^3/s$)

$$Q_c(t) = -1.1114 + 0.0483T_m(t) + 0.0036 \sum_{i=1}^{4} T_m(t-i) + 0.1584P_{me}(t) + $$
$$+0.0446 \sum_{i=1}^{4} P_{me}(t-i) + 0.0179P_m(t) + 0.0170 \sum_{i=1}^{4} P_m(t-i) \quad (1)$$

where t is the time in days, the standard regression sum is 0.637, the standard residual is $0.322 m^3/s$.

Sample 2 ($n=265$, $\overline{Q_c} = 1.672\ m^3/s$)

$$Q_c(t) = -2.3370 + 0.1113T_m(t) + 0.0298 \sum_{i=1}^{4} T_m(t-i) + 0.2221P_{me}(t) +$$
$$+0.0550\sum_{i=1}^{4} Pme(t-i) + 0.0348P_m(t) + 0.0207\sum_{i=1}^{4} P_m(t-i) \quad (2)$$

where the standard regression sum is 0.665, the standard residual is $0.490 m^3/s$.

In order to evaluate the fitness of the equations to the observed discharge hydrograph, the R2 - fitting standard is used(Sten Bergstron,1976) as following:

$$R^2 = (F_0^2 - F^2) / F_0^2 \quad (3)$$

where:

$$F^2 = \sum_{t=0}^{\tau} (Q(t) - Q_{cal}(t))^2 \quad (4)$$

where: $Q(t)$ is the observed discharge, t is time , τ is the time period, $Q_{cal}(t)$ is the calculated discharge.

$$F_0^2 = \sum_{t=0}^{\tau} (Q(t) - \overline{Q_\tau})^2 \quad (5)$$

where: $\overline{Q_\tau}$ is the average of the observed discharge during period τ. When the calculated value is completely fitting the observed discharge, $R^2 = 1$.

Using equation (1) and (2) to simulate the daily discharge of the Total Control hydrometric point , the hydrographs are then obtained during 1983 - 1987 of calibration periods, the average R^2 value is 0.70. Taking the melt season of 1988 as the forecast period, the simulated daily hydrograph has the R^2 value 0.74. The

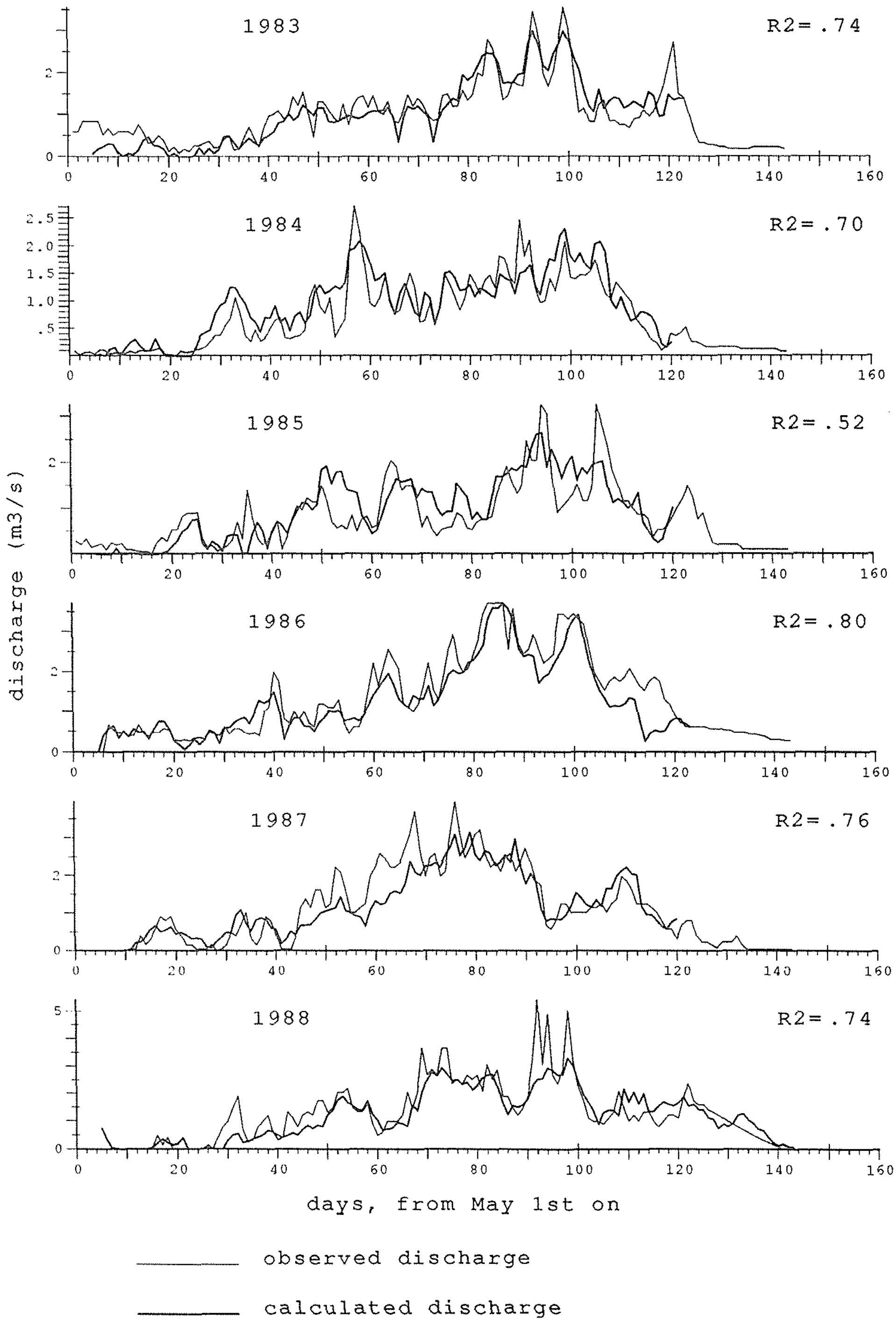

FIG. 4 Daily discharge simulation at the Total Control hydrometric point based on the meteorological factors (1983-1987 for calibration, 1988 for simulation).

comparison between the simulated and observed hydrographs(Fig.4) clarifies that, taking the daily air temperature,water vapor and precipitation with the time lags of 0 - 4 days as the independent variables to form the multiple regression equations, the simulated hydrographs of the high mountain discharge correspond basically with the observed ones. Therefore, air temperature, vapor pressure and precipitation at the standard mountain meteorological stations can be used as predictors for the discharge simulation at the inland high mountain glacierized areas.

CONCLUSIONS

(a) In the continental high mountain glacierized basins, during the ablation season, the runoff producing conditions are changing. According to the runoff characteristics in the source area of the Urumqi River, the runoff producing season is divided into small discharge periods at the beginning and end of the melt season, when the seasonal snow line is ascending to the firn line and descending to the terminus of the glacier basin, and the large discharge periods of glacial melt, forming 2 samples for discharge simulation.

(b) The runoff production from the Glacier No.1 basin is mainly decided by the heat conditions in the glacierized area. The discharge is positively correlated to air temperature, vapor pressure and air temperature daily range, and negatively correlated to precipitation, relative humidity and wind velocity.

(c) The relationship of the runoff from the Empty Cirque basin during summer to the meteorological factors is controlled by the heat and precipitation conditions . When the heat is enough for the snow to be melted after it falls on the ground, the discharge has good positive correlation to precipitation.

(d) The discharge from the Total Control basin is best correlated to vapor pressure and air temperature. It indicates that the heat conditions play an important role in the formation of the high mountain runoff.

(e) In addition to air temperature, vapor pressure is also an important index symbolizing the heat and water conditions in the high mountain glacierized area.

(f) The runoff from the glacierized high mountain area can be simulated with the meteorological factors observed at a standard meteorological station in the mountains. Taking air temperature,vapor pressure and precipitation with time lags of 0- 4 days as regression independent variables, the discharge hydrographs from the source area of the Urumqi River Basin are simulated , correspond basically with the observed ones.

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REFERENCES

Bergstrom, S. (1976) Development and application of a conceptual runoff model for Scandinavian catchments. Department of Water Resources Engineering, Lund Institute of Technology/University of Lund. Bulletin Series A No.52, Lund, 13 -15.

Brandt, S. (1983) Statistical and computational methods in data analysis. North - Holand Publishing company, New york, 401 - 404.

Jensen, H. & Lang, H. (1972) Forecasting discharge from a glaciated basin in the Swiss Alps. International symposia on the role of snow and ice in hydrology. Symposium on Operational Practice. WMO - UNESCO - IAHS. Banff, 1047 - 1054.

Kang, E. & Jensen, H. (1987) A glacial discharge modelling in the Swiss Alps. Glaciology and Geocryology, 9(1), 1 - 14.

Kasser, P. & Jensen, H. (1971) Basic principles used for the forecasts. Nr.2 Mitteilung der VAW, ETH, Zürich, 97 - 109.

Lang, H. (1973) Variations in the relation between glacier discharge and meteorological elements. Symposia on the hydrology of Glaciers, Cambridge 1969. IAHS, publ. No. 95, 85 - 94.

Lang, H. (1980) Theoretical and practical aspects in the computation of runoff from glacier areas, Data of Glaciological Studies, publ.No. 38, Academy of Science of the U.S.S.R., Moscow, 187 - 194.

Ostrem, G. (1972) Runoff forecasts for highly glacierized basin. IAHS Publ. No. 107, Vol. 2,1111 - 1129.