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Simulation of Snow and Glacier Runoff in Central Asia Alpine Watersheds

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I. PARTICIPANTS

The investigators from the Department of Geography at the University of California Santa Barbara undertook this project: Dr. Vladimir Aizen (50% of time, 24 months during the project), Dr. Elena Loktionova-Aizen (50% of time, 24 months during the project), and Dr. Hugo Loaiciga (100% of time two months during the project).

Dr. Vladimir B. Aizen has provided the background information on precipitation, snow accumulation, solar radiation, temperature, humidity, atmospheric pressure, river runoff and synoptic-scale patterns of atmospheric circulation in the study region based on data developed for the Central Asia DataBase and new data collected in Central Asia Hydrometeorological organizations in Tashkent (Uzbekistan) and Bishkek (Kyrgyzstan). The study was focused on the Ala Archa (northern Tien Shan and Oigaing (western Tien Shan) river basins, located within the Aral-Caspian hydrographic basin. He also analyzed long-term changes in precipitation and air temperature regime over the last few centuries based on dendrochronological data and changes in glacier mass-balance during last 80 years using unique glaciological and hydrometeorological records in Ala Archa River basin. Using this data Dr. Vladimir Aizen, Dr. Elena Aizen-Loktionova and Dr. Hugo Loaiciga developed, calibrated and validated two models of river runoff. The focus of the simulation models is snow and ice runoff from glaciated and non-glaciated basins during periods comprising normal and extreme years. Dr. Aizen has developed the website of the project researches and general promotion and scope of interests in details.

Dr. Elena M. Aizen-Loktionova evaluated the impact of changes in large-scale patterns of atmospheric circulation on precipitation regime. She estimated the role of zonal and meridional atmospheric circulation patterns, North Atlantic Circulation Oscillation, and West Pacific Oscillation as well as the seasonal differences in hydro-climatic regimes and developed simulation algorithms for the runoff models. This part of the study has yielded regional-scale statistical relationships linking large-scale circulation processes and regional-scale hydro-climatology. Dr. Aizen-Loktionova analyzed heat exchange during snowmelt and also determined the suitability of archived hydrological data for applications of hydrograph models. She developed regional classifications of observations in the AsiaDataBase structure.

Dr. Hugo A. Loaiciga assisted in the preparation of two articles, which were written based on the data assembled and gathered in this study.

The researchers from Central Asia (Dr. Gleb Glazirin, Dr. Valeriy Kuzmichenok, Maria Glazirina and Dr. Vladimir Komissarov), and one from St. Petersburg, Russia (Eugene Doukaev) were involved in the collection of data from National archives, typing and transferring data to USA through the Internet. Dr. Gleb Glazirin and Maria Glazirina also evaluated and validated the simulated models based on independent data set.

II. ACTIVITIES AND FINDING

1. Activities

An extended description of the work so far accomplished can be found in a web site created for this project under the address http://www.icess.ucsb.edu/~aizen/aizen.html**.** Interested readers are encouraged to visit our web site for a more in depth analysis of our results. A current summary of the database assembled for this project can be found on the page specifically devoted to the Central Asia Database (CADB) at http://www.icess.ucsb.edu/ ~aizen/centralasia/CADB.

Objective and Goals

Recent international efforts in the study of land-surface heat-water exchange have identified alpine river basins as one of the environments for which there is pressing need for properly calibrated hydro-climatic models (*World Meteorological Organization, 1988*). A **primary objective** of this study was the analysis of long-term water balance dynamics in mountainous river basins of Central Asia. The importance of this research in practical use to understand the Earth systems and the effects of natural changes on the regional environment, to analyze the process of long-term variation in river runoff and to predict the further regional climate and water resources change in Central Asia. Based on the ground hydro-meteorological data we use a combination of geophysical methods including hydrological, models of hydrologic processes, climatological, atmospheric dynamics and paleo-reconstruction. In order to fulfill the study's objective, several tasks were completed:

- Providing the background information on precipitation, snow accumulation, solar radiation, temperature, cloudiness, wind speed, atmospheric pressure, humidity and runoff in the study regions. This portion of study was focused on the Ala Archa and Oigaing river basins (**Fig.1, 2, 3**), located within the Aral-Caspian hydrographic basin to make available the data set on annual, monthly, and daily meteorological and hydrological characteristic (see **Tien Shan Database**).
- Development and implementation of physical models for snow and glacier melt runoff in the Tien Shan river basins of Central Asia with subsequent calibration and validation, using hydro-meteorological information throughout the Ala Archa and Oigaing hydrographic basins. The focus of simulation model is the snow and ice melt runoff from glaciated and non-glaciated basins during periods comprising normal, dry and wet years (see **Hydrological Modeling**)
- Estimation of energy losses from snowmelt and the impact of seasonal snow melt on air temperature in Central Asian plains and mountains (see **Heat Exchange during Snowmelt).**
- Understanding the coupling between large-scale climatic change patterns and modifications of regional-scale hydro-climatic regimes at mid-latitudes of Asia. (see **Precipitation and Atmospheric Circulation Patterns**).
- Reconstruction of climatic changes in remote, mid-latitude, continental mountains based on dendrochronological data. (see **Reconstructed Climatic Characteristics based on Dendrochronological Data**).

Hydrologic Modeling

The **first stage** of this research was focused on simulation of snow and glacier runoff in the northern and western Tien Shan river basins.

A two-component model of river runoff simulation in alpine regions of Central Asia has been developed and implemented. The first component was devoted to the estimation of daily surface runoff. The second component converts surface runoff to river runoff hydrograph.

Simulation of Daily Water Output from a Watershed

Two methods of runoff simulation in alpine river basins of Central Asia are being developed in this work. The first method is based on mean daily air temperature, daily precipitation, and elevation data to carry out surface runoff simulation (*Aizen et al., 1999a*). The second method considers daily short-wave radiation, mean daily air temperature, and daily precipitation to calculate surface runoff in alpine watersheds (*Aizen and Aizen 1998; Aizen et al., 1999b*). Elevation, aspect and slope as the topographical parameters also considered in the second method.

Air temperature was modeled as a linear function of altitude. The intra-annual mean altitudinal temperature gradient was approximated by a cosine function of the month of the year. The altitudinal distribution of daily precipitation was approximated by a power function. Liquid and solid precipitation is differentiated based on a threshold air temperature, which depends on altitude. The threshold temperature above which precipitation was liquid was developed and expressed as a function of altitude. Surface conditions that can be snow covered or snow free, and either condition was determined on the basis of air temperature and precipitation. The first method of snowmelt calculation based on air temperature took into account the main components of snow-surface heat balance, therefore the mean altitudinal gradient of air temperature, and parameters in the methods of precipitation and snowmelt calculation depend on the season and latitude.

We have developed a model for the spatial variation in solar radiation at the surface within a watershed *(Aizen and Aizen 1998;Aizen et al., 1999b)*. These fluxes drive the second type of snow and glacier melt simulation, which based on solar radiation characteristics. In this method, the spatial variation of solar radiation at the surface was considered as a function of average surface slope and aspect for a given latitude.. The parameters for calculation of incoming total solar radiation on surfaces with different aspects are coefficients of transition from the incoming solar radiation on the vertical surface, with different aspects to the incoming solar radiation on the horizontal surface. In case of absent data on insolation we got statistically significant relations between the net short wave radiation with duration of solar radiance or with total cloudiness. The mean solar radiation gradients obtained from (*Barry, 1981*) were depending on cloudiness. Field observations in the Ala Archa (*Aizen, 1988*) and Inylchek (*Aizen et al., 1997*) basins in the Tien Shan support the data on altitudinal distribution of total insolation. Albedo was approximated as a function of the radiant flux onto the snow ″t″ days after the last snowfall.

Water balances in glaciated surfaces were considered analogous to those in non-glaciated surfaces, except for a volume of refrozen water from snowmelt.

Particular characters of the developed simulations from existent conceptual models (*Rango and Martinec, 1979; Leavesley, et al, 1983; WMO, 1986; Harrington, et al., 1995*) are that both simulation methods take into account the water retention capacity of the snow pack, the amount of refrozen melt water, ice melt under glacier’s moraine, and distribution of solar radiation characteristics. The volume of refrozen water is calculated as a function of temperature. Calculation of the ice melt under glacier’s moraine was based on the altitudinal distribution of moraine-covered areas and on the altitudinal distribution of moraine thickness at the tongue of glaciers that was described as a function of moraine-covered area on glaciers and the area of the ablation zone in glaciers.

Basin topographic characteristics (watershed, glacial, and moraine areas) were quantified by means of digital elevational models for the Ala Archa and Oigaing river basins based on 1:25000 topographical maps. Digital elevational models (DEM) for the Ala Archa (**Fig. 2**) and Oigaing (**Fig. 3**) river basins were developed based on these maps created in 1976 and 1991 aerial photographs.

The description of computation of daily water output from watershed including applied parameters can be found at: www.icess.ucsb.edu/~aizen/centralasia/CADB.html The flow diagram of surface runoff generation from snow/glacier melt, rain on snow covered areas, and glaciated surfaces is shown in **Figure 4. Figure 5** summarizes the processes of snow accumulation and snow/glacier ablation modeling. Applying the pixel analyses smoothed simulation of snow water output and increased it at the beginning and end of melt season. Employing spatially variable regional modeling of snow melt based on solar radiation data and pixel scale analysis improves the river runoff simulation during dry years and partly during the normal years at the beginning of summer and autumn (**Figure 6**). Based on our results, it is recommended that solar radiation parameters for pixels with the same elevation, slope, and aspect be applied in the simulation of snowmelt in regions where the ablation season does not coincide with maximum precipitation and cloudiness, as is the case in the western and northern Tien Shan watersheds, specially during dry years.

Simulation of River Runoff Hydrograph

Once surface water is generated on the surface of an alpine watershed the next step was to synthesize the river runoff hydrograph at a desired location. River runoff was simulated at daily time steps by means of "unit response models", which are linked and interact so as to approximate the actual runoff generation processes that occur in the study watersheds. The transformation of surface runoff to river runoff hydrograph was described in terms of linear ordinary differential equations applied to elementary volumes in which water balances were defined. The method of hydrograph derivation was based on single– and two-reservoir models (**Figure 7**). The parameters in both the single-reservoir and two-reservoir hydrograph derivation methods were estimated by the least-squares technique subject to a constraint imposed on the estimated total runoff volume. Calibration and validation of the river runoff simulation model were done for the Oigaing (Uzbekistan) and Ala Archa (Kyrgystan) alpine drainage river basins of Central Asia.

The surface water transformational model was calibrated on the basis of daily data for dry, wet, and normal year. The calibration periods consisted of daily runoff data as follows: for the Oigaing River basin (1) from October to September 1973 through October 1974 (dry water year, with annual mean of river runoff $Q_{Oigaing} = 9.5$ m^3 s^{-1}), (2) water year 1978 – 1979 (wet conditions, $Q_{Oigaing} = 17.3$ m^3 s^{-1}), and (3) normal water year 1979-1980 ($Q_{Oigaing} = 12.4$ m^3 s^{-1}); and for the Ala Archa River basin: (1) dry water year 1956-1957 ($Q_{AlaArcha} = 3.7$ m^3 s^{-1}), (2) wet water year 1960– 1961 ($Q_{AlaArcha} = 4.6$ m^3 s^{-1}), and (3) normal water year 1962-1963 ($Q_{AlaArcha} = 4.2$ m^3 s^{-1}). The mathematical details of the parameter calibration method are presented in the (*Aizen et al., 1999a*) and in CADB web site http://www.icess.ucsb.edu/~aizen/centralasia/CADB.html
The validation periods for the single-reservoir and two-reservoir models were: water year 1964 –1965 ($Q_{Oigaing} = 10.9$ m^3 s^{-1}), 1971 –1972 ($Q_{Oigaing} = 10.0$ m^3 s^{-1}), and 1972-1973 ($Q_{Oigaing} = 14.9$ m^3 s^{-1}). The models were also validated on the basis of data from the Ala Archa watershed for water year 1957 – 1958 ($Q_{AlaArcha} = 4.3$ m^3 s^{-1}), 1959-1960 ($Q_{AlaArcha} = 4.0$ m^3 s^{-1}), 1961-1962 ($Q_{AlaArcha} = 4.5$ m^3 s^{-1}), and 1963-1964 ($Q_{AlaArcha} = 4.0$ m^3 s^{-1}). Simulation results of surface runoff and river runoff hydrograph in the Oigaing and Ala Archa basins are presented in **Figures 8** and in **Table 1**.

The more complex two-reservoir hydrograph model produced also accuracy of minor improvements in prediction as compared with the single-reservoir runoff hydrograph method. Specifically, the three-year mean estimation error of calculated Oigaing river runoff decreased from 6.76 m^{3}s^{-1} in the single-reservoir method to 6.54 m^3 s^{-1} in the two-reservoir method, and from 1.65 to 1.62 m^3 s^{-1} in the Ala Archa basin. The maximum relative error of river runoff simulation reached 18%, simulation errors increase with increasing annual river runoff and depend on snowmelt, glacier runoff, the amount of precipitation, and air temperature. The simulated river runoff was less than observed values during autumn-winter while in can be either larger or smaller than actual stream flow in summer months. In years with large glacier melt and in which the basin had a significant glacier-covered area the simulated river runoff underestimated observed values.

Replacement of constant annual parameters with monthly means in the runoff hydrograph simulation decreased by more that 50% the room mean square error in the improved model (*Aizen et al., 1999b*).

Applying of nonlinear response functions for hydrograph generation instead of the linear counterparts could give more accurate estimation of developed simulation. These is an area of future research.

Tien Shan Database

The development of the Central Asian Data Base (CADB) is one of the primary objectives of this project. We are making available a data set on the present and past variability changes in water resources in the Tien Shan, identifying the response of mountain regional scale climate and water resources changes to global-scale forcing, and examining possible causal mechanisms. Description of the data, and general parameters are available from Internet web site: http://www.icess.ucsb.edu/~aizen/centralasia/CADB.html (password is: xyz to access data and abcrep to access the project reports)

The Tien Shan is divided into the western, northern, central and eastern. We are loading data mostly for the northern and western regions totally for **230** stations, stream gauges and precipitation sites. The database includes basic characteristics and maps of regions: geography and geology, landscape, climatic features, and hydrological regime. The regions include basins of first, second and third order. There are maps of regions and basins, DEM of basins with resolution 50 and 100 m, short descriptions of basins with information about size, altitude, range, which basins are part of larger system and which basins are nested. Station data include information about altitude, latitude, and longitude of the station, date of the observation beginning, location, and names of the rivers. There is also information about precipitation sites and points in snow survey routes related to each meteorological station. Stream gauge data include information on river name, nearest meteorological station name, area of drainage basin, year of the observation beginning and end, available hydrological information.

The observations include solar radiation (short wave incoming radiation, solar radiance duration), air temperature, wind speed, atmospheric pressure, cloudiness (total and low), humidity, precipitation, snow cover (duration, days of appearing and disappearing, thickness, helicopter observations of snow line), river runoff. There is section on type of data with information about measurements, regularity, instruments and methods of observations.

For each meteorological and hydrological characteristic there are annual and daily sections. Annual includes monthly data for each year of observations. Daily represents averaged for the day and ten day's period of observation.

Daily data are collected for the period from 1960 to 1980, with emphasis on the extreme dry year of 1964-1965, 1973-1974; extreme wet years of 1962-1963, 1972-1973; 1978-1979; extreme cold year of 1971-1972 and normal years of 1960-1961, 1979-1980.

Annual monthly data are collected for the total observational period from the beginning of this century through 1991 for meteorological stations, stream gauges, and precipitation sites located in the northern and western Tien Shan.

Morphologic characteristics include the distribution of watershed area, glacier covered area, and moraine covered area via altitude, aspect and slope angle. Topographic maps (1:25 000 and 1:100 000 scale) are used to develop the DEM.

Glaciers. There is information about altitudinal distributions of more than 3000 glaciers, their numbers and areas in each regions and basins, genetic classification, location of lower and upper level of glaciers, average firn line position, data of glacier tongues and glacial surface changes measured by topography and aircraft-photo-survey, and main morphometric characteristics. Data about glaciers includes observations from 1943 to present. There is information of location of some glacier tongues from the end of last century. There is hydrometeorological information measured during expeditions on the Northern Tien Shan's glaciers. There are photographs of some glaciers.

Data control. The data was checked for homogeneity of observational series, representativeness, and the presence of random errors. Each time series was plotted and inspected for 'gross' errors. Data quality control was implemented in this study following *Peterson and Easterling (1994), Easterling and Peterson (1995), Easterling et al. (1995)* recommendations on meteorological quality control/assurance.

Heat Exchange during Snowmelt

The role of snow cover on the climatic system in general, and on air temperature, in particular, is determined by its energy exchange with the atmosphere. Viewing snow as important feedback to the earth's heat balance, the cooling of the troposphere has not been evaluated as a result of energy used to snowmelt at a macro-scale. Heat losses for ten-day periods from snow melt over the plains and mountains were estimated (*Aizen et al., 1999*c). Rates of snow water equivalent (SWE) decrease and a map of snowmelt duration (**Figure 9**) were obtained from long-term data from 189 stations. Maps of energy losses from snowmelt were developed and the volume of air-cooled 5°C by snowmelt was estimated for the end of each ten days period.

Stations were grouped by dates of snow loss and beginning of melt. To calculate the melted share of maximum SWE for any station, amount of melted snow for the ten-day period was normalized by the maximum mean SWE at a station and averaged throughout stations with the same dates of snow loss and beginning of snow melt. We plotted the melted share of maximum SWE as a function of time for each ten days period (**Figure 10**). The rms error of melted snow calculated by curves compared to observations at a station was on average 14%.

On plains and foothills, up to 80% of snow melts during the last ten days of snow cover. Snowmelt duration in mountains exceeds by at least twenty days that found in the continental plains and reaches up to seventy days in the high mountains of the western and northern Tien Shan. The shortest duration of the snowmelt period is observed in the eastern Tien Shan where small snow accumulation and relatively high air temperatures occur. At low altitudes the maximum snowmelt takes place during the last ten-day period of its melt. At high altitudes, the maximum amount of snow, about 40%, melts during the penultimate periods.

To obtain exact estimates, components of the heat balance were calculated for the four selected regions. The amount of energy lost via snowmelt is of the same order as the other combined components of the heat budget (**Table 2**). Heating of the atmosphere would have been three times higher if snowmelt had not occurred. Over the continental plains, maximum energy loss from snowmelt occurs in the beginning of April. Over the mountains, maximum specific energy loss from snowmelt is observed in the northern and western Tien Shan from the end of May to the middle of June. The heat loss from snowmelt in mountains amounts about 1/3 of heat loss in the plains, and air volume cooled by snow melt in mountains amounts about 1/2 of air volume over plains. The process of snowmelt and atmospheric cooling in mountains occurs more slowly and without abrupt changes observed on the plains, and energy losses in mountains smooth the general processes of atmospheric cooling prolonging it until the beginning of August.

Our approach allows evaluating the impact of a larger or smaller snow accumulation on atmospheric heating. Extant long-term mean estimations of snow accumulation (*Kotlyakov, 1998*) and air temperature at the continental scale could be the basis for forecasting air temperature deviation from average because of snow accumulation anomalies, and heat energy used to melt snow.

Satellite observations since early 1970s (*Robinson et al., 1991*) suggest a decrease in mean snow cover for spring and summer in Eurasia. The decrease of snow cover and consequently snow melting during the past twenty years is related to change in snow cover feedback affecting atmospheric cooling and leading to an increase of global temperatures more pronounced during springtime (*Jones and Briffa, 1992*) when maximum snow melt occurs over the plains. Tien Shan observations for the past fifty years revealed a decrease in snow occurred almost everywhere in the mountains (*Aizen et al., 1997*). The feedback of the spring and summer snowmelt can explain the long-term rise in air temperatures more pronounced from June to August (*Aizen et al., 1997*) when maximum energy losses from snowmelt occurs over the Tien Shan.

Precipitation and Atmospheric Circulation Patterns

The majority of investigations on atmospheric circulation patterns and climate dependence have been undertaken at the mid- to low latitudes of American and European continents. None to our knowledge have been done from mid-latitudes of the Asian continent including central Asian mountains. Analyses of the coupling between large-scale atmospheric patterns and modifications of regional precipitation regimes at seasonal and annual time scales in different terrain of mid-latitudes of Asia including western Siberia, Tien Shan and Pamir mountains, and plains of middle Asia were examined based on data from 57 and 88 hydro-climatic stations with 100 and 60 year records (*Aizen et al., 1999d*).

To describe large-scale atmospheric circulation patterns that can potentially influence on climate at mid-latitudes of Asia we used different approaches: Zonal and Meridional indices, a description of atmospheric pressure distribution through North Atlantic Oscillation, Pacific-North American (PNA), Western Pacific Oscillation (WPO), and Northern Asian (NA). Our analysis on temporal trends in precipitation includes statistical evaluation of their means, variances, moving-averaged time series patterns, and patterns of spatial and temporal correlation. To identify a possible association, three categorizations of precipitation were counted in accordance to three categorizations of the annual and seasonal circulation patterns. The associated probability of below or above average occurrence was calculated (**Table 3**).

We have shown that long-term changes and trends in general atmospheric circulation patterns could be recognized on the basis of analysis of precipitation variability. For the past 100 years, a positive trend in precipitation was revealed in western Siberia, and northern regions of Tien Shan. During the years with predominance of Zonal atmospheric patterns, negative deviations in annual, seasonal and monthly maximum amount of precipitation occurred everywhere in middle Asia. We suggest that during the last century, impacts of the western jet stream increased in the northern regions of Tien Shan. There is a suggestion that the further west location of Siberian high during development of ‘meridional one’ pattern is more favorable for precipitation development over continental regions of Asia, than the location of Siberian High more east. During dominant development of zonal atmospheric pattern decreasing the annual and seasonal precipitation observed over the most regions in continental Asia. The influence of atmospheric circulation on precipitation is strongest in peripheral northern or western regions of mountains and weakest in central Tien Shan.

NAO is one of the main atmospheric circulation patterns influencing the wetness condition at mid-latitudes of continental Asia and annual and winter precipitation deviations could be predicted based on its variability. During positive NAO phases, the strong westerlies bringing intensive precipitation to the limited northwestern region of Europe decrease winter precipitation at low to-mid latitudes of continental Eurasia (e.g., western Siberia, Tien Shan and Pamir, and plains of middle Asia). The probability of occurrence above average winter precipitation during positive phases of NAO is only 7% in Tien Shan and Pamir. WPO is also one of the main atmospheric circulation pattern influencing the wetness conditions at mid-latitudes of continental Asia. In the WPO pattern, large areas of positive anomalies in geopotential height field that are observed in the northern region of the Far East strengthens the Siberian High and decreases the winter precipitation in Tien Shan and Pamir and western Siberia. We did not find any significant impact of PNA, NA on precipitation in the middle Asia.

Reconstructed Climatic Characteristics based on Dendrochronological Data

To reconstruct climatic changes in remote, mid-latitude, continental mountains, we selected the Ala Archa glacier basin in the northern Tien Shan and Inilchek glacier basin in the central Tien Shan (*Aizen et al., 1999e*).

Fourteen samples of Juniperus turkestanica and 22 samples of Picea schrenkiana from the Ala Archa basin and 26 samples of Picea schrenkiana from the Inilchek basin were selected for the analysis. Annual rings were dated using the technique of crossdating. Annual ring widths were standardized to remove the effect of tree age on mean ring width and to produce a transformed annual index series. The appropriate mathematical functions for trend removal from Juniperus turkestanica and Tien Shan, Picea schrenkiana were decreasing exponential curves. We did not find transient trends and long-wave length fluctuations in Juniperus turkestanica and Picea schrenkiana. Low-order serial correlation, present in the annual index series of Picea schrenkiana was removed from each tree ring chronology using autoregressive procedures. The residual ring-width index chronologies for Ala Archa and Inilchek sites were then obtained by arithmetic averaging of all detrended and delagged index series.

To establish a significant statistical link between ring-width variations and variations in climate we used response functional analysis combined with regression analysis. This technique provides a least square equation maximizing the linear relation between two sets of data. Regression analysis has shown statistically significant relationships exist between Picea schrenkiana ring indices and annual precipitation, and between Juniperus turkestanica ring indices and mean summer air temperatures. A data-splitting procedure was used to validate the stability of the regression models developed to calibrate the tree ring and summer air temperature and annual precipitation.

The annual growth of Juniperus turkestanica is related to summer air temperature. The Picea schrenkiana indices reveal significant correlation with total sum of precipitation for the hydrological year. **Figure 11** presents reconstructed mean summer air temperatures and total precipitation at altitudes of 3440 m and 2100 in the Ala Archa basin, and shows reconstructed annual precipitation at the altitude of 3614 m in the Inilchek basin. According to reconstructed data for the Ala Archa basin, the summer air temperatures have increased about 0.8°C during the past 200 years, and annual precipitation has decreased, particularly during the period from 1821 to 1933. In the central Tien Shan near the Inilchek glacier, statistically significant trends in the annual precipitation reconstruction were not found during the past 300 years. The beginning of nineteenth-century had an increased amount of annual precipitation both in the northern and central Tien Shan. The minimum precipitation occurred in the middle of the 1800s in the central Tien Shan, about 250-mm/yr., and around 1930 in the northern Tien Shan, about 500 mm/yr. During the second half of the twentieth century the total precipitation for a hydrological year increased to 300-350 mm in the central Tien Shan, and to 600 mm in the northern Tien Shan. Favorable periods of glacier advance, in the northern and central Tien Shan, occurred at the end of the eighteenth, and beginning of the nineteenth centuries when annual precipitation increased and summer air temperature decreased.

FIGURES

Fig. 1. Location map of the Ala Archa and Oigaing river basins in the Central Asia

Fig. 2. Ala Archa watershed (northern Tien Shan)

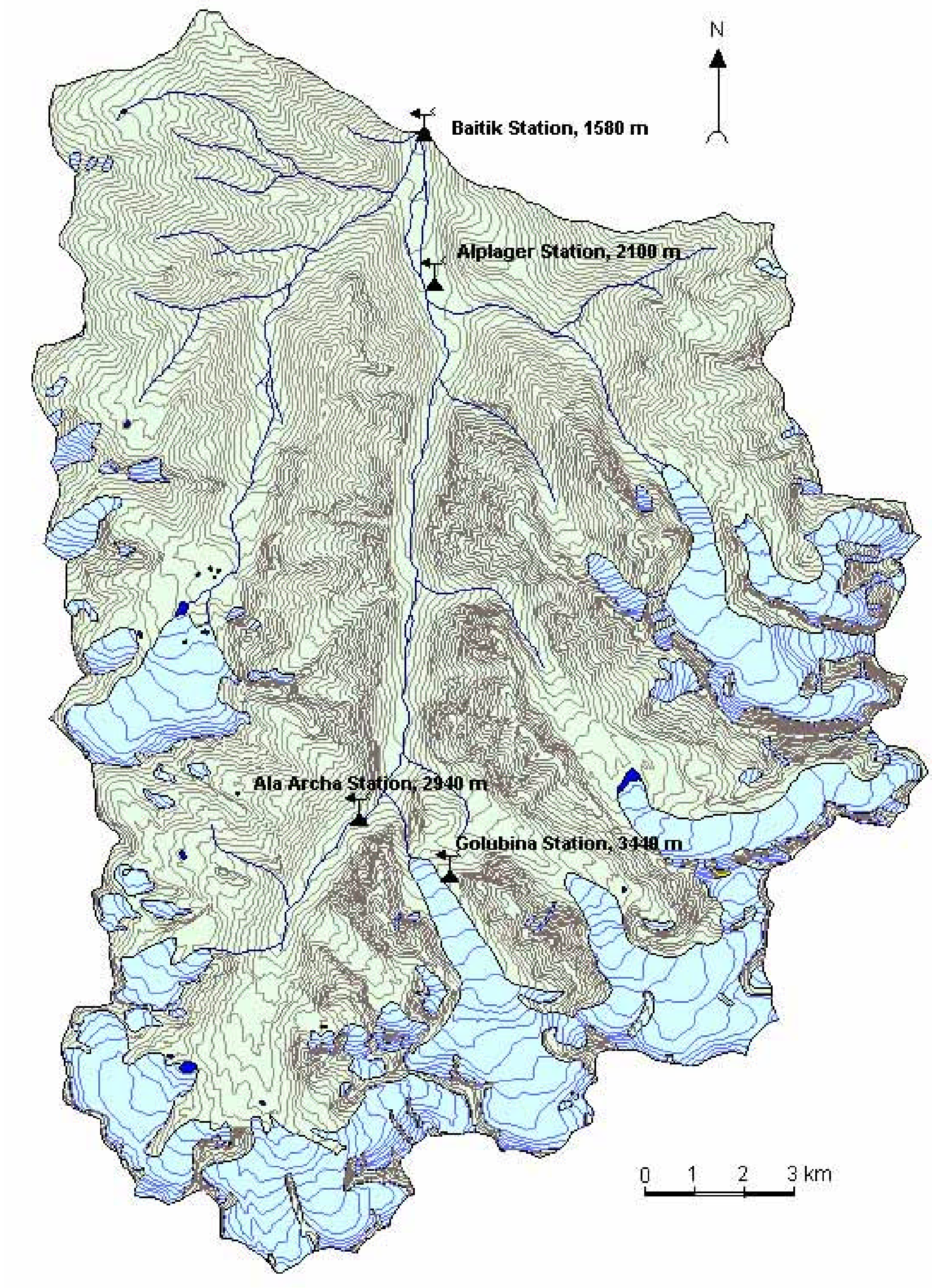


Fig. 3. Oigaing watershed (western Tien Shan)

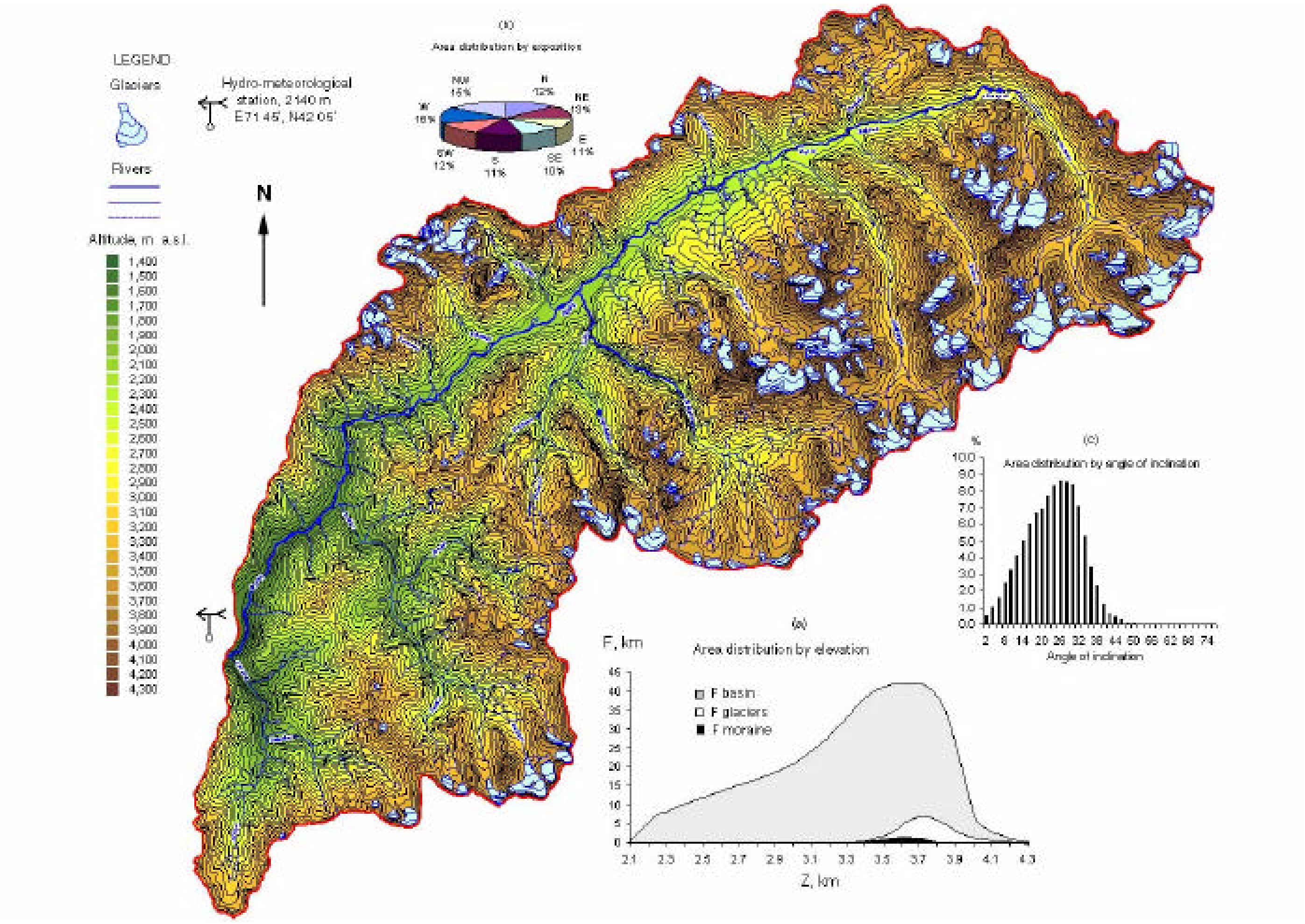


Fig. 4. Simulated surface runoff from snow and glacier melt, and rain on snow-covered and glacier surfaces.

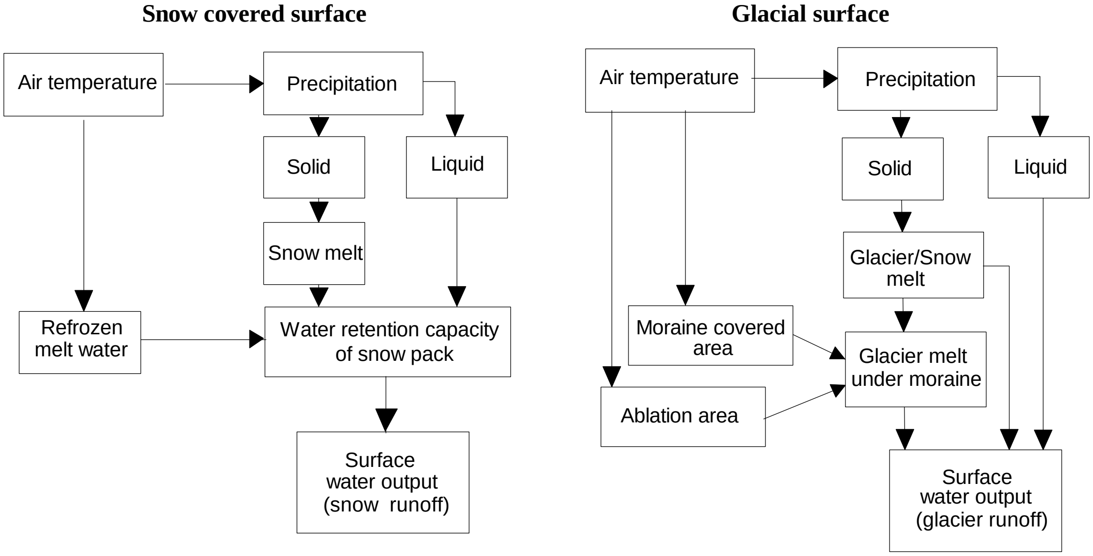
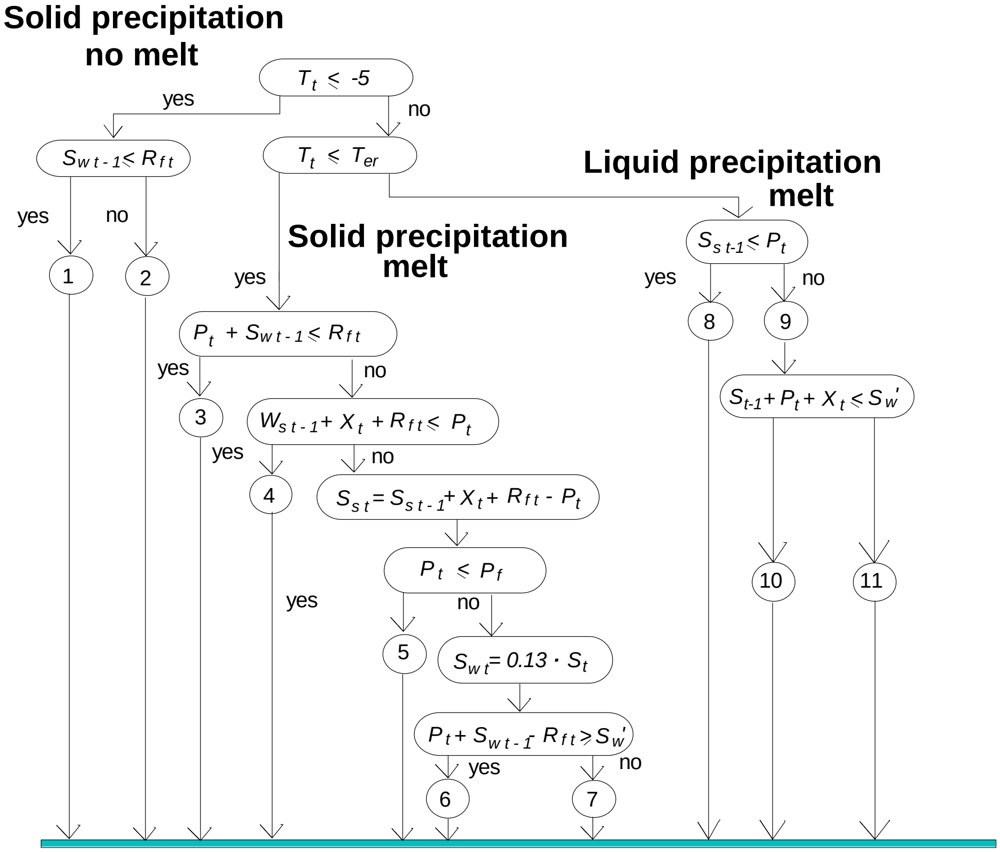
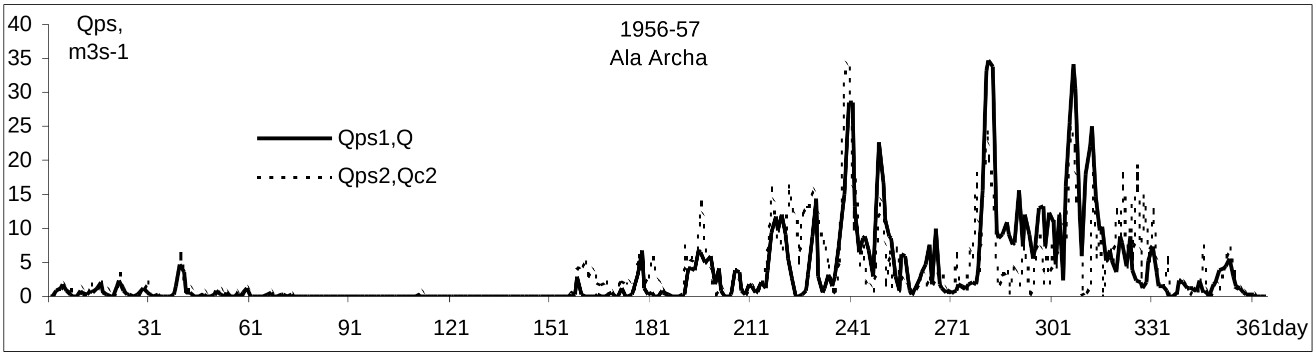


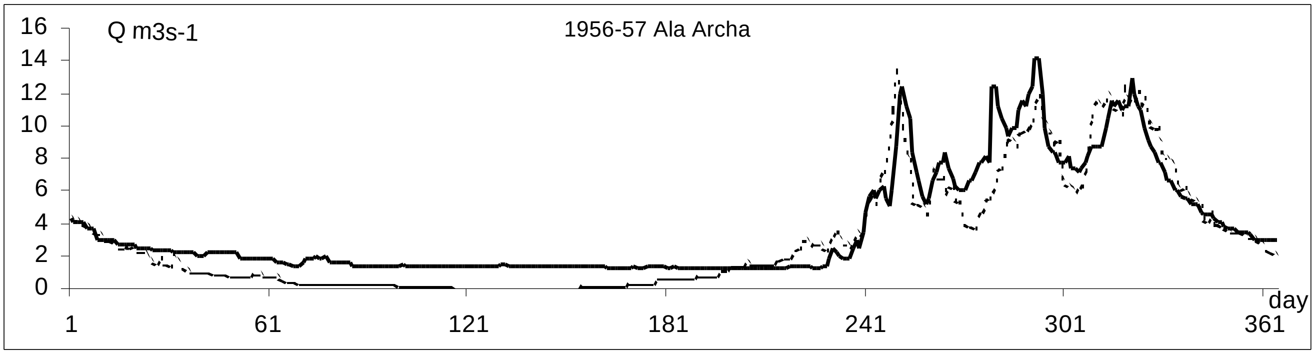
Fig. 5. Simulation of snowmelt water dynamics based on energy balance for the t-th day in the j-pixel over the entire basin. Ss = snow water equivalent of solid share in snow (without water), mm; Sw = snow water equivalent of liquid share in snow, mm; X = amount of daily precipitation, mm; Rf = amount of frozen water at a point, mm; P = intensity of snowmelt at a point, mm; $\varepsilon s = 0.13$ = water retention capacity in the snow pack; $S'w = \varepsilon s \cdot Ss$ the fraction of liquid water content in snow when water output begins after the snowpack becomes saturated, mm; qps = is water output on surface of the i-th pixel, mm; F_j = area of j-th pixel, m^2, within i altitudinal belt. For the whole basin: Qps = calculated snow water output generated from the n altitudinal belts, $m^3 s^{-1}$; m = 4 is the number of aspects that pixels can have (northern, southern, western or eastern and horizontal); n is number of altitudinal belts within basin; 1/K is a coefficient of units conversion.



1. $S_{st} = S_{st-1} + X_t + S_{wt-1}$; $S_{wt} = 0$; $qps_{it} = 0$
2. $S_{st} = S_{st-1} + R_{ft} + X_t$; $S_{wt} = S_{wt-1} - R_{ft}$; $qps_t = 0$
3. $S_{st} = S_{st-1} + S_{wt-1} + X_t$; $S_{wt} = 0$; $qps_t = 0$
4. $S_{st} = 0$; $S_{wt} = 0$; $qps_t = S_{st-1} + S_{wt-1} + X_t$
5. $S_{wt} = 0$; $qps_t = 0$
6. $S_{wt} = S'_{wt}$; $qps_t = P_t + S_{wt-1} - S'_{wt} - R_{ft}$
7. $S_{wt} = S_{wt-1} + P_t - R_{ft}$; $qps_t = 0$
8. $S_{st} = 0$; $S_{wt} = 0$; $qps_t = S_{st-1} + S_{wt-1} + X_t$
9. $S_{st} = S_{st-1} - P_t$; $S'_{wt} = 0.13 * S_{st}$
10. $S_{wt} = S_{wt-1} + P_t + X_t$; $qps_t = 0$
11. $S_{wt} = S'_{wt}$; $qps_t = P_t + S_{wt-1} - X_t - S'_{wt}$
12. $Qps_t = 1/K \cdot \sum_{i=1}^{n} \sum_{j=1}^{4} F_j \cdot qps_{jt}$

Fig. 6. Simulated river runoff (Qc) using simulated water output from snow on watershed's surface (Qps) based on elevational (1) (*Aizen et al., 1999a*) and pixel (2) (*Aizen et al., 1999b*) analyses in the Oigaing and Ala Archa river basins. Q is measured river runoff.





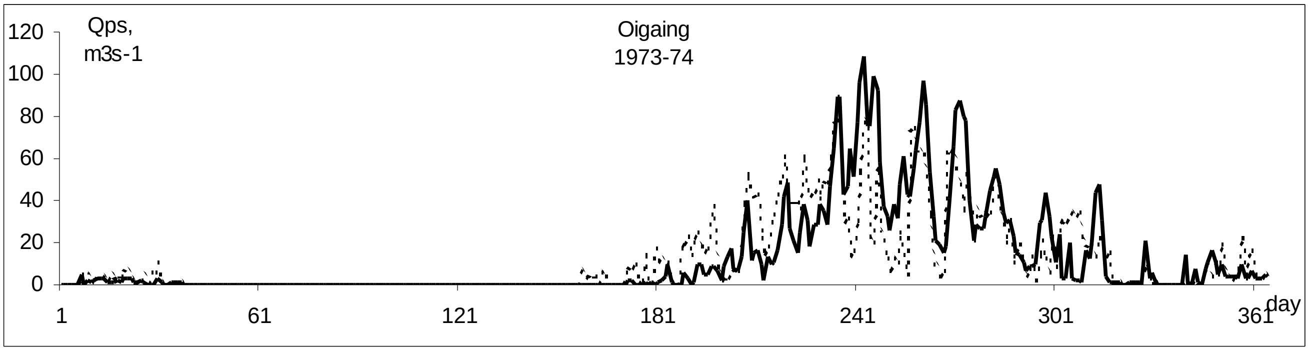


Fig. 7. Single-reservoir (a) and two-reservoir (b) models of river runoff hydrograph.

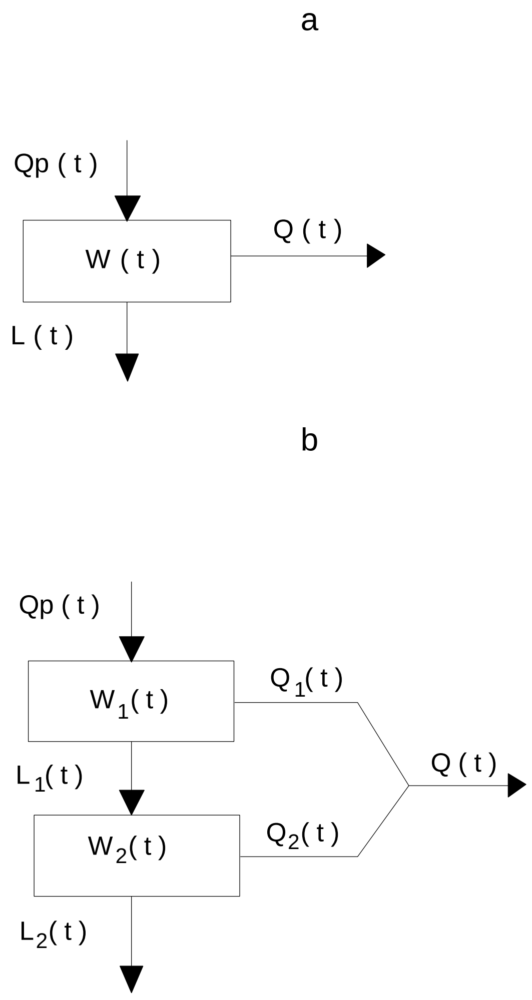


Fig. 8. Simulated river runoff based on air temperature (T, °C) precipitation (P), using single-reservoir (Qc1) and two-reservoir (Qc2) models in the Oigaing and Ala Archa river basins. Q is measured river runoff.

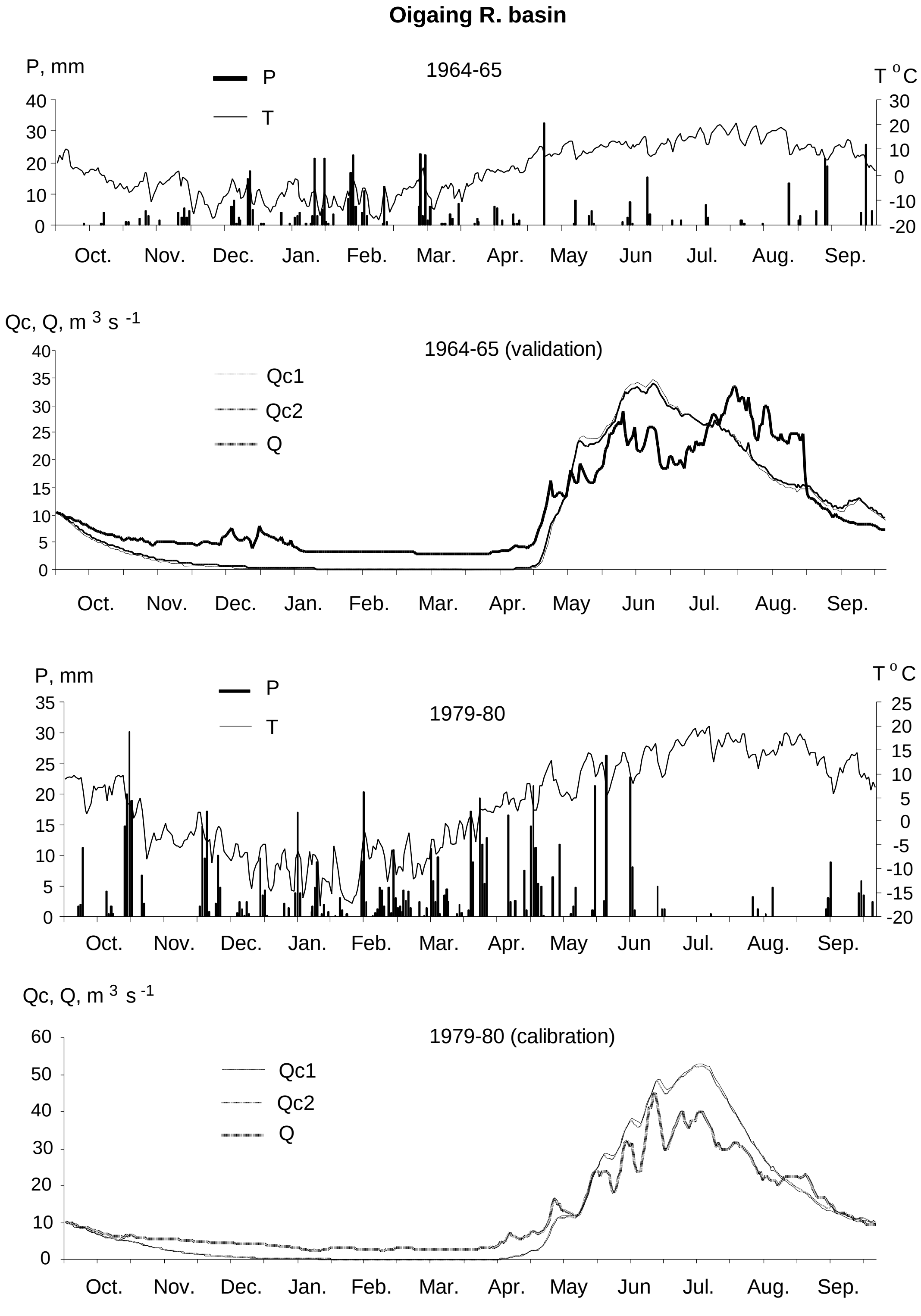


Fig. 8 (continuation)

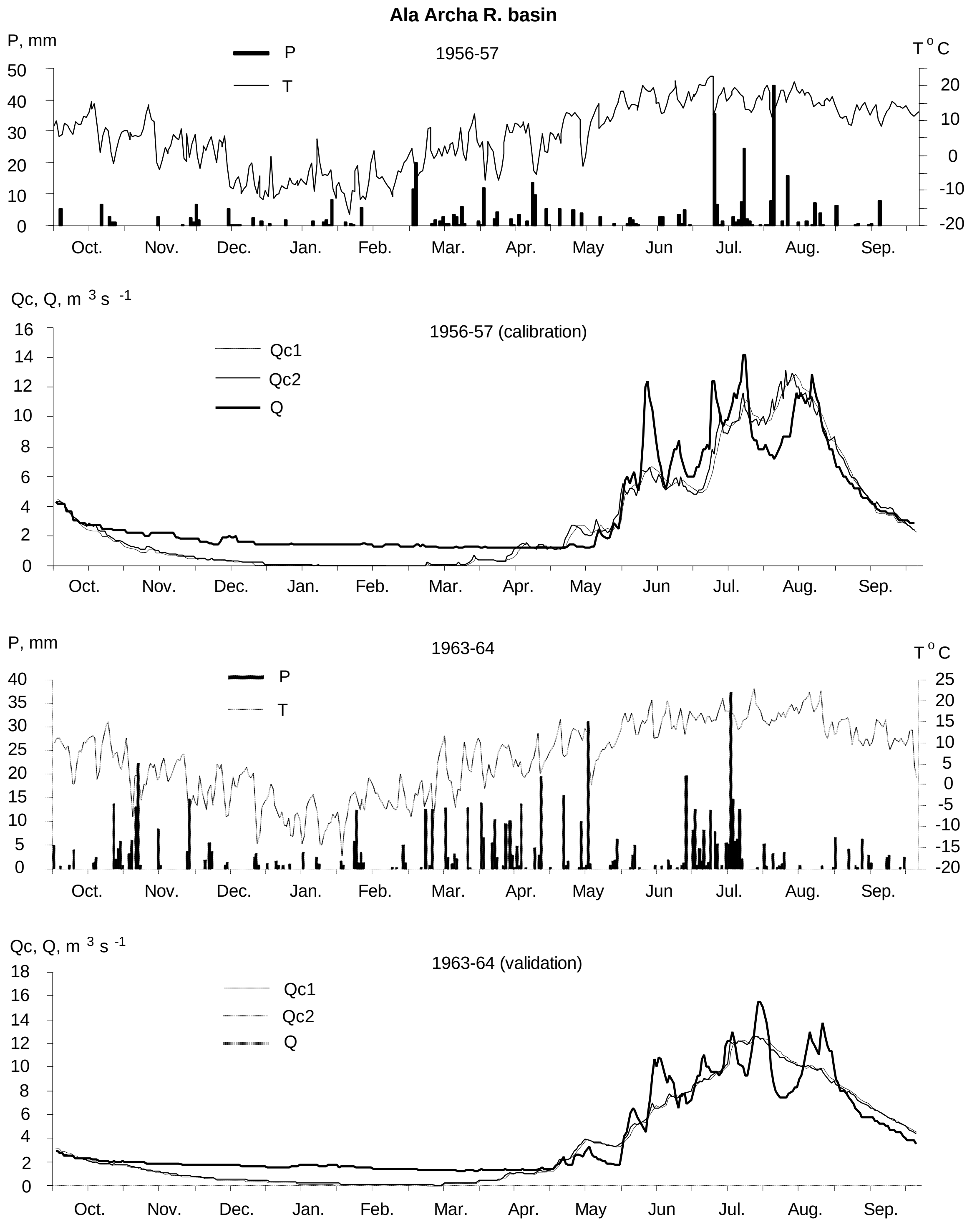


Fig. 9. Duration of snow melt period, days

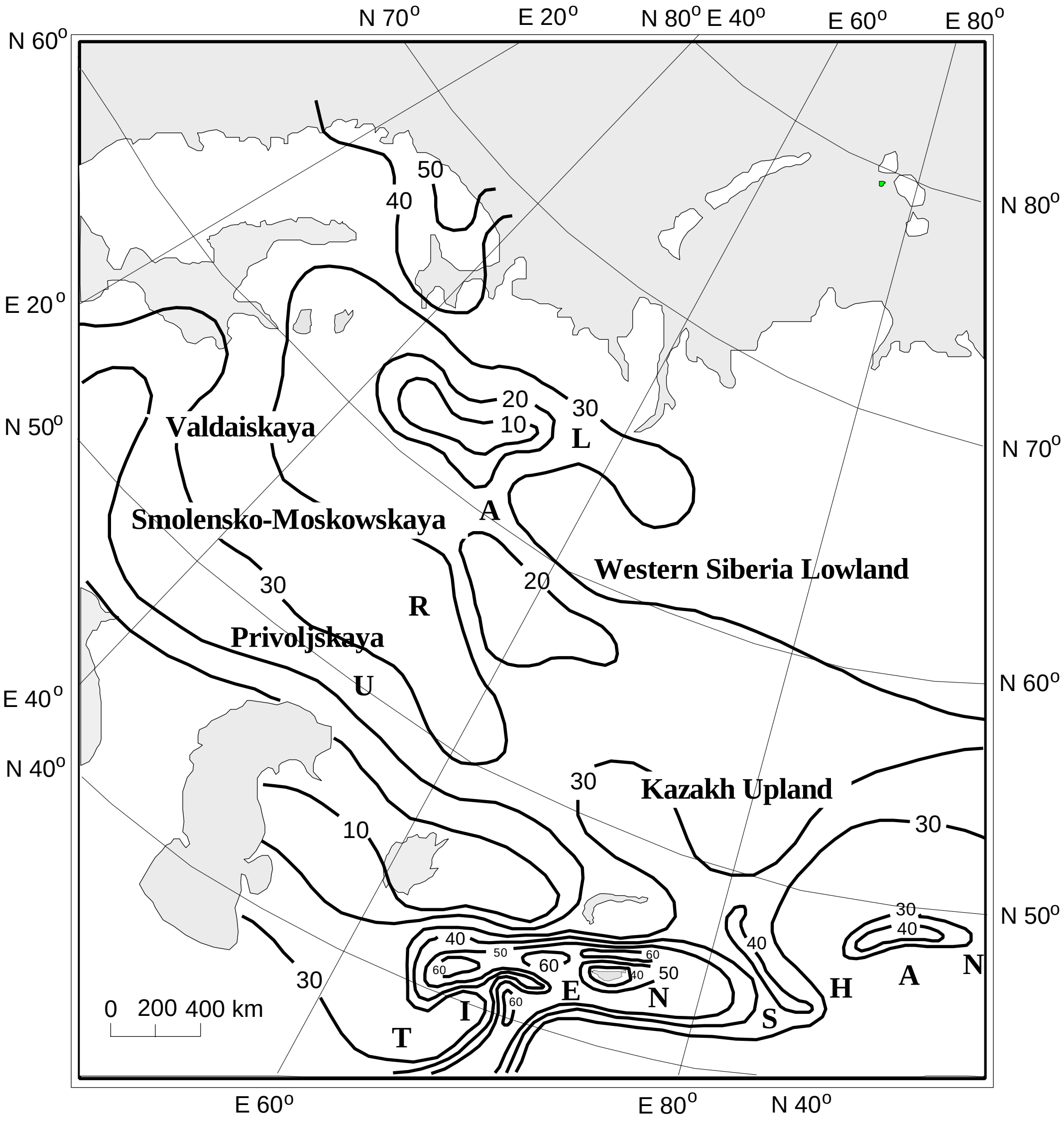


Fig. 10. The melt curves in continental plains (a) and mountains (b) classified in accordance to date of snow loss. ΔW', expressed as a fraction, is melted share of SWE for ten day period (TDP). Arabic characters mark number of TDP; Roman characters mark month.

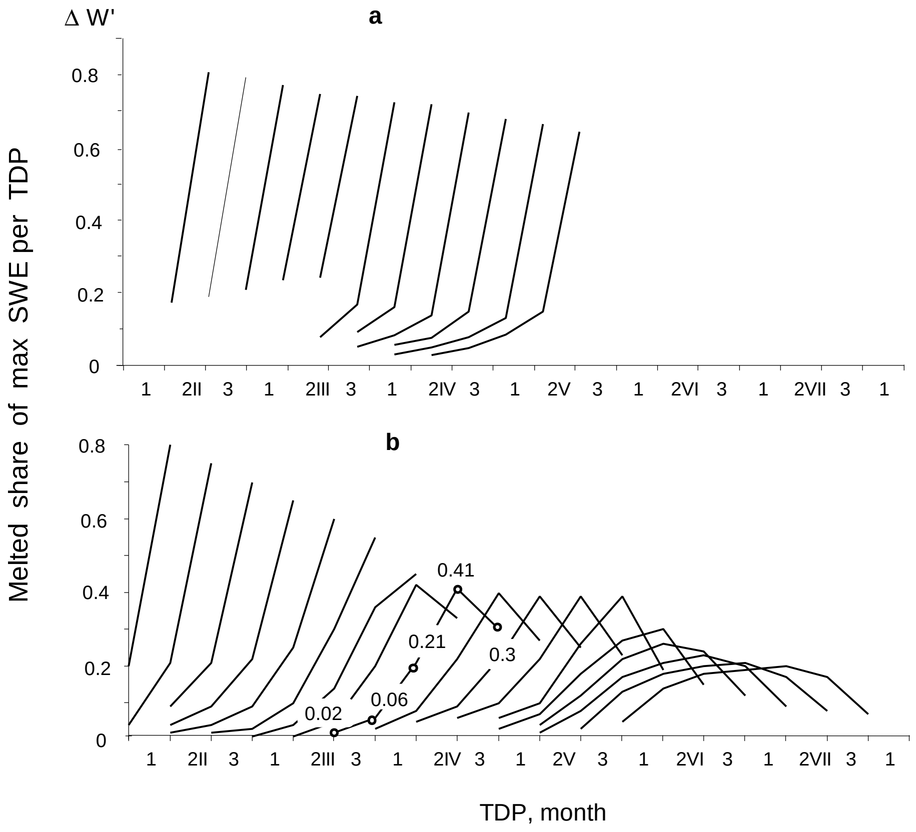


Fig. 11. Reconstructed annual precipitation (P), summer air temperatures (T) (1) and their five year running means (2) in the Ala Archa basin (a) and around the Inilchek Valley (b).

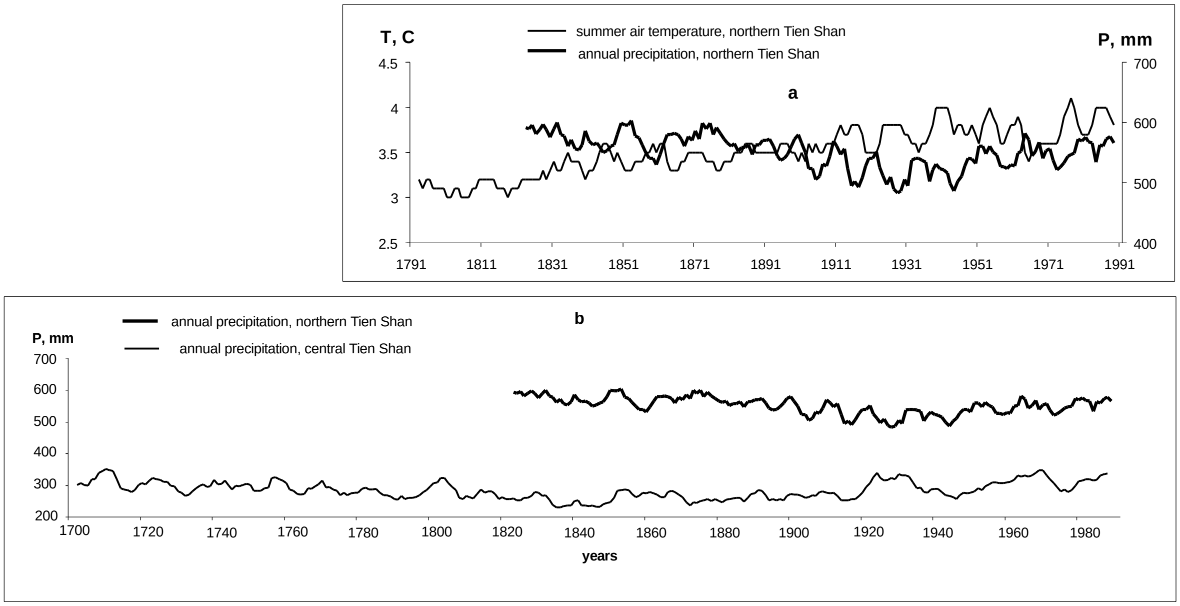


Table 1. Estimation of runoff simulation. R = root mean square error; X = annual amount of precipitation; T(°C) = annual average air temperature; Qps, Qpg, Qpr = annual mean of calculated surface runoff from snow, glacier melt, and rain (in $m^3\ s^{-1}$), respectively; Qp, Qc1, Qc2 = total mean annual runoff, and calculated hydrograph runoff based on one- and two-reservoir models (in $m^3\ s^{-1}$), respectively; Q = mean annual measured river runoff; r correlation coefficient between mean-square error (R) and other parameters

Year	R	X,mm	T	Qps	Qpr	Qpg	Qp	Qc1	Qc2	Q
					Oigaing River					
1964-65	4.98	539	2	10.9	0.6	1.1	12.5	9.4	9.3	10.9
1971-72	6.35	833	1.4	15.3	1	0	16.3	12	11.9	10.1
1972-73	4.75	710	2.8	16	0.2	1.4	17.7	13.3	13.3	14.9
1973-74	3.41	587	2.9	12.2	1.1	0.6	13.9	9.5	9.6	9.5
1978-79	8.67	952	2.7	20.8	0.4	0.1	21.4	17.3	17.1	17.3
1979-80	5.3	702	3.4	15.7	0.7	1	17.4	12.5	12.5	12.4
r		0.9	-0.2	0.8	-0.4	-0.6	0.8			0.7
					Ala Archa River					
1956-57	1.37	416	6.1	3.2	0.7	0.7	4.7	3.0	3.1	3.7
1957-58	1.65	695	6.3	4.8	1.1	0.3	6.2	3.9	3.9	4.3
1959-60	1.51	540	5.8	3.9	0.5	0.9	5.3	3.9	4.0	4.0
1960-61	2.22	486	6.7	3.3	0.8	1.3	5.5	4.3	4.3	4.6
1961-62	2.45	553	7.0	3.9	0.8	1.2	5.8	4.5	4.4	4.5
1962-63	1.28	616	6.8	4.4	1.0	0.7	6.0	3.8	3.8	4.2
1963-64	1.30	655	6.2	4.3	1.1	0.4	5.8	3.5	3.5	4.0
r		-0.2	0.6	-0.3	-0.2	0.8	0.3			0.8

Table 2. Mean ratios between heat losses during snow melt (Q_Σ) and heat balance components. $\mathrm{div}(C_P\ \rho T\nu)$ is advective energy of air masses; $\partial(C_p\ \rho T)/\partial\ t$ is change of heat amount in the atmosphere with time (warming or cooling). Arabic characters mark number of TDP; Roman characters mark month.

TDP Month	Head balance component	REGIONS* 1	2	3	4
3 III	$Q_\Sigma/\mathrm{div}(C_P\rho T\nu)$	0.34	0.32	0.44	0.28
1 IV	$Q_\Sigma/\mathrm{div}(C_P\rho T\nu)$		0.29	0.84	0.91
2 IV	$Q_\Sigma/\mathrm{div}(C_P\rho T\nu)$				0.62
3 III	$Q_\Sigma/\ \partial(C_P\rho T)/\partial t$	3.6	2.20	2.60	1.40
1 IV	$Q_\Sigma/\ \partial(C_P\rho T)/\partial t$		0.94	3.80	3.00
2 IV	$Q_\Sigma/\ \partial(C_P\rho T)/\partial t$				1.50

*Regions

Longitude	Latitude	
	50 - 55° N	55-60° N
30 - 40° E	Region 1	region 2
40 - 50° E	Region 3	region 4

Table 3. Association between deviation from norm of ACP indices and annual (P_a) winter (P_w) precipitation in the Tien Shan and Pamir (n_a, years). H is 'High/Dry' phase of ENSO; L is 'Low/Wet' phase of ENSO. E is east phase of QBO; W is west phase of QBA. Σ is total number of years with positive, normal and negative deviations in ACP.

	Tien Shan and Pamir								
	Northern			Western			Central		
ΔZonal ACP									
ΔPa	+	0	-	+	0	-	+	0	-
+	3	4	7	1	8	3	3	5	4
0	5	3	5	4	3	8	2	4	7
-	2	8	6	5	4	6	5	6	6
Σ yrs	10	15	17	10	15	17	10	15	17
ΔNorth Atlantic Oscillation									
ΔPw	+	0	-	+	0	-	+	0	-
+		2	8	1	2	10	1	3	8
0	8	4	5	4	3	3	8	2	4
-	6	2	7	9	3	7	5	3	8
Σ yrs	14	8	20	14	8	20	14	8	20
ΔSouthern Oscillation Index									
ΔPw	+	0	-	+	0	-	+	0	-
+	2	3	4	2	3	4	2	3	5
0	3	4	6	2	2	3	3	4	3
-	4	4	1	5	6	4	4	4	3
Σ yrs	9	11	11	9	11	11	9	11	11
El Nino/Southern Oscillation									
Pw	H	0	L	H	0	L	H	0	L
+	2	4	3	1	5	3	3	4	3
0	3	5	5	1	4	2	2	5	3
-	2	7		5	7	3	2	7	2
Σ yrs	7	16	8	7	16	8	7	16	8
ΔPacific- North American									
ΔPw	+	0	-	+	0	-	+	0	-
+	2	2	6	7	2	4	3	2	7
0	11	3	3	6	2	2	12	1	1
-	8	3	4	8	4	7	6	5	5
Σ	21	8	13	21	8	13	21	8	13
ΔWestern Pacific Oscilation									
ΔPw	+	0	-	+	0	-	+	0	-
+	4	4	2	3	4	6	2	6	4
0	8	4	5	5		5	9	2	3
-	7	1	7	11	5	3	8	1	7
Σ yrs	19	9	14	19	9	14	19	9	14
ΔNorthern Asian									
ΔPw	+	0	-	+	0	-	+	0	-
+	4	5	1	4	5	4	5	6	1
0	7	3	7	5	1	4	9	2	3
-	7	3	5	9	5	5	4	3	9
Σ yrs	18	11	13	18	12	13	18	11	13

	Tien Shan and Pamir											
	Northern				Western				Central			
Sunspot Number												
	Low		High		Low		High		Low		High	
Quasi-Number Oscillation												
ΔPw	E	W	E	W	E	W	E	W	E	W	E	W
+	4	1	1	3	2	1	1	4	3	1	1	3
0	4	3	3	3	3	2	3		4	2	3	2
-	1	5	2	1	4	6	2	3	2	6	2	2
Σ yrs	9	9	6	7	9	9	6	7	9	9	6	7

2. Finding

Physical modeling

We developed the physical simulation of river runoff in the alpine watersheds in Central Tien Shan as a foundation for further research on climatic and water resources changes (*Aizen et al., 1999a*). A two-component model has been developed and implemented. The first component was devoted to the estimation of daily surface runoff. The second component converts surface runoff to river runoff hydrograph. Particular characters of the developed simulations from existent conceptual models are that the simulation methods take into account the water retention capacity of the snow pack, the amount of refrozen melt water, ice melt under glacier's moraine, and distribution of solar radiation characteristics. We have developed a model for the spatial variation in solar radiation at the surface within a watershed *Aizen and Aizen (1998)*. The method for estimating the distribution of glacier covered area versus altitude with the use of limited surface information was also developed (*Aizen et al., 1999f*).

We found that: (1) the more complex two-reservoir model of hydrograph generation yielded only minor improvements in river runoff simulation relative to the one-reservoir model; (2) the simulation associated with the year-to-year parameter estimates was less than that associated with the (three-year) average parameters; (3) application of different space parameters (e.g. slope, aspect, and elevation) in calculation of snow and glacier melt based on solar radiation characteristics improves the surface water income simulation only during the dry years in a basin with significant glacier-covered area; (4) the absolute errors of simulation were found to increase with increasing annual river runoff. In the river basin where snow melt contributes over 90% to river runoff, errors increased with increasing surface snowmelt and precipitation, and decreased with increasing glacier runoff. In the river basin, where glacier melt is a significant component of river runoff, simulation errors increased with the rise of (i) air temperature and (ii) glacier contribution to runoff; (5) the simulated river runoff underestimated measured runoff during autumn-winter month; (6) the most accurate results have been received in simulation applied snow/ice melt calculations based on air temperature and calculations of river runoff hydrograph with monthly generation parameters. The developed simulation which based on air temperatures, precipitation, is the strong foundation for the evaluation of water resources changes in the alpine watersheds.

Tien Shan Database

A long term and experimental data set were the basis for our analysis. These data have become accessible to scientists outside of the former USSR. A brief description of CADB and data are available on our world wide web site at: http://www.icess.ucsb.edu/~aizen/aizen.html The CADB was extended with meteorological, hydrological, glaciological, morphological data from the northern region (mainly from the Ala Archa river basin) and western region (mainly from the Oigaing-Pskem river basin) of the Tien Shan. **Development of CADB** in to a GIS format requires to load and generalize the Tien Shan remainder data we have in paper sheets and micro-films, and further evolution in the structure with regional description, and classification of observations. Information is to be described for easy use of collected data in calculations and simulations

Heat exchange during snowmelt

First of all, the cooling of the troposphere has been evaluated as a result of energy losses from snowmelt, heat losses for ten-day periods from snow melt over the plains and mountains were estimated (*Aizen et al., 1999*c). A map of snowmelt duration was obtained from long-term data from 189 stations. Maps of energy losses from snowmelt were developed and the volume of air-cooled 5°C by snowmelt was estimated for the end of each ten days period. We assessed that heating of the atmosphere would have been three times higher if snowmelt had not occurred. The heat loss from snowmelt in mountains amounts about 1/3 of heat loss in the plains, and air volume cooled by snow melt in mountains amounts about 1/2 of air volume over plains. The process of snowmelt and atmospheric cooling in mountains occurs more slowly and without abrupt changes observed on the plains, and energy losses in mountains smooth the general processes of atmospheric cooling prolonging it until the beginning of August.

We revealed that persistence of snow cover in the south retards snowmelt in the north, since snow melting in the southern latitudes influences the snow melt in the regions located to the north. Therefore we suggest that floods in the high latitudes be not expected when an abnormally large amount of snow has accumulated in the southern areas.

Long-term mean estimations of snow accumulation and air temperature could be the basis for forecasting air temperature deviation from average because of snow accumulation anomalies, and heat energy lost because of variations in snowmelt. Our approaches allow evaluating the impact of an early or late loss of snow on atmospheric heating.

Precipitation and Atmospheric Circulation Patterns

The coupling between large-scale atmospheric patterns and modifications of regional precipitation regimes at seasonal and annual time scales in different terrain of mid-latitudes of Asia including western Siberia, Tien Shan and Pamir mountains, and plains of middle Asia were found based on data from 35 hydro-climatic stations with 100 year records. For the past 100 years, a positive trend in precipitation was revealed in western Siberia, and northern regions of Tien Shan. We suggest that during the last century, impacts of the western jet stream increased in the northern regions of Tien Shan. During the years with Zonal pattern predominance, negative deviations in annual, seasonal and monthly maximum amount of precipitation occurred everywhere in middle Asia, and western Siberia. Development of both meridional patterns is favorable for winter precipitation increase in the mountains and plains of middle Asia and Western Siberia. Location of Siberian High further east during the prevalence of M_1ACP is most favorable for annual precipitation increase in the mountains and plains of middle Asia. During dominant development of zonal atmospheric pattern with essentially rapid movements of small-amplitude waves from the west to east decreasing the annual and seasonal precipitation observed over the most regions in continental.

North Atlantic Oscillation and West Pacific Oscillation indices have inverse associations with average amount of precipitation in western Siberia and in mountains and plains of middle Asia. We did not find significant impact of Pacific-North American or Northern Asian patterns on precipitation in middle Asia. Our results suggest that NAO and WPO are potentially useful prognostic tools for precipitation over mid-latitudinal Asia.

Reconstructed Climatic Characteristics based on Dendrochronological Data

Tree-ring data from Picea schrenkiana and Juniperus turkestanica from the Ala Archa basin on the northern slope of Kyrgyzskiy Alatoo and from the Inilchek valley of the Kok Shaal Too allowed to reconstruct summer air temperatures for the past 200 years and annual precipitation for the past 150-300 years. Regression analysis has shown statistically significant relationships exist between Picea schrenkiana ring indices and annual precipitation, and between Juniperus turkestanica ring indices and mean summer air temperatures. Favorable periods of glacier advance, in the northern and central Tien Shan, occurred at the end of the eighteenth, and beginning of the nineteenth centuries when annual precipitation increased and summer air temperature decreased. According to reconstructed data for the Ala Archa basin, the summer air temperatures have increased about 0.8°C during the past 200 years, and annual precipitation has decreased, particularly during the period from 1821 to 1933. In the central

Tien Shan near the Inilchek glacier, statistically significant trends in the annual precipitation reconstruction were not found during the past 300 years.

3. Training and Development

At the University of California, Santa Barbara, Dr. Hugo Loaiciga and Dr. Vladimir Aizen have used project developed materials in general graduate and undergraduate courses. Researchers: Dr. Elena Aizen-Loktionova (the University of California Santa Barbara), Dr. Gleb Glazirin (Central Asian Hydrometeorological Research Institute), Dr. Vladimir Komissarov (Kyrgyz-Slavonic State University), Eugene Davkaev (the Main Hydrological Institute at St. Petersburg) participated in the Project and in development of Central Asian DataBase. During 1997/1998 and 1998/1999 we were participating at the National and International Conferences and Seminars presenting our results. Dr. Aizen had five invited lectures: at the Geographisches Institut, ETH, Zurich (SWITZERLAND), at the University of Alaska, Fairbanks, at Martin Lockheed National Laboratory (ENEEL), Idaho Falls, at the USGS Headquarter, Washington DC, at the NSF Global Change Committee, Washington DC where he presented the results of current research and new proposed research development. Dr. Aizen also presented our model with application of different space parameters (e.g. slope, aspect, and elevation) in calculation of snow and glacier melt based on solar radiation characteristics at the International Symposium "WaterHead'98", Merano, Italy.

Dr. Hugo A. Loaiciga merged the research activities associated with this project to a simultaneous project funded by the USEPA on the effect of climate change on regional ground water basins and created a large database on the integrated effect of global climate on regional aquifer basins of the southwestern USA.

4. Outreach Activities

Dr. Aizen gave two lectures on the methods of mathematical modeling of runoff in alpine watersheds in the Kyrgyz-Slavonic State University at Bishkek in time of his 1998 field trip to Tien Shan. Dr. Loaiciga presented six international seminars whose contents were partly funded by this project.

III. PUBLICATIONS AND PRODUCTS

1. Publications

PUBLISHED

Aizen, V.B., E.M. Aizen, J.M. H. Loaiciga, and G. E. Glazirin. **1999**a. Simulation of daily runoff in Central Asian alpine watersheds. *J. Hydrology (in press, 2000)*

Aizen, E.M., V.B. Aizen, J.M. Melack, and A. Krenke, **1999**c. Heat exchange during snow melt in Plains and Mountains of Eurasia. *J. Geophysical Research-Atmospheres (in press, 2000)*

Loaiciga, H.A. and Leipnik, R. B. **1999**. Closed-form solutions for aquifer management: theory and case study. Journal of Water Resour. Plann. & Management 126(1), 30-35.

Aizen, V.B., E.M. Aizen, J.M., and H. Loaiciga. **1999**b. Improved model of daily surface runoff in Central Asian alpine watersheds (based on solar radiation data). *Proceeding 4th USA/CIS Joint Conference on Environmental Hydrology and Hydrogeology.* San Francisco, 1999.

Aizen, V.B., E.M. Aizen. **1998**. Estimation of glacial runoff to the Tarim River, Central Tien Shan. *Proceedings of International Symposium. "WaterHead'98",* Merano, ITALY. pp.191-199

Skop, E. and Loaiciga, H.A. **1998**. Investigating catchment hydrology and low-flow characteristics using GIS. Nordic Hydrology 29, 105-128

SUBMITTED

Aizen, V.B., E.M. Aizen, J.M. M.G.Glazrina, and H. Loaiciga. **1999**b. Improved model of daily river runoff in Central Asian alpine watersheds. *Water Resources Bulletin.*

Aizen, E.M., V.B. Aizen, J.M. Melack, T. Nakamura, and T. Ohta. **1999**d. Precipitation and atmospheric Circulation Patterns at Mid-latitudes of Asia. *International J.of Climatology*.

IN PROCESS

Aizen, V.B., and E.M. Aizen, **1999**. Mass balance and dynamics of Golubin Glacier (northern Tien Shan), 1914-1999.

Aizen, V.B., E.M. Aizen, G. E. Glazirin, and J.M. Melack. **1999**f. Estimations of mountain glacier's distribution based on the surface data.

Aizen, E.M., V.B.,Aizen, and J.M. Melack.

2. Web site

We have developed the 'Central Asian Exploration' Web site, that includes description of scientific activities, the main results of our research and central Asian Database:
http://www.icess.ucsb.edu/~aizen/aizen.html

3. Database

During two years of research we have developed the Tien Shan Database. The development of the Central Asian Data Base (CADB) is one of the primary objectives of this project. We are making available a data set on the present and past variability changes in water resources in the Tien Shan, identifying the response of mountain regional scale climate and water resources changes to global-scale forcing, and examining possible causal mechanisms. Description of the data, and general parameters are available from Internet web site: http://www.icess.ucsb.edu/~aizen/centralasia/CADB.html

We have developed a Digital Elevation Model for the Ala Archa River basin based on topographic maps 1: 25 000.

We have developed programs in Fortran and Quick Basic for simulation of river runoff in the alpine watersheds.

IV. CONTRIBUTIONS

1. The principal discipline(s) of project

Seasonally snow-covered areas of the Earth's mountains are an important component of the Earth's hydrologic cycle. The total flow of water resources forming within the Tien Shan comprises approximately 80 billion cubic meters per year. The World largest closed drainage basins of the Tien Shan mountains receive and retain annually at least 10% of the western external atmospheric moisture incoming into the Aral-Caspian, Balkhash, Issik Kul and Tarim hydrographic systems, which are the major water reservoirs deriving water from the mountains. Moreover, the studied regions are sensitive to changes in climate. Among the changes in climate, changes in the amount of snow and in the form of precipitation—rain or snow—affect those areas of moderate winter temperatures and of seasonal snow cover. A warmer climate would affect both water supply and flood magnitude and frequency. We examine how the combination of climate affects the surface hydrology—the flow of water. Hence:

- Innovative coupled water and energy balance models of hydrologic response in high-altitude watersheds, is being a significant contribution to the study of *Hydrology, Hydrological Modeling, Snow and ice, Seasonal Snow Covered Alpine Drainage Basin.* Particular characters of the developed simulations from existent conceptual models are that the simulation methods take into account the water retention capacity of the snow pack, the amount of refrozen melt water, ice melt under glacier's moraine, and distribution of solar radiation characteristics. The developed simulation is the strong foundation for the evaluation of water resources changes in the alpine watersheds.
- Evaluation the cooling of the troposphere as a result of energy losses from snowmelt over the plains and mountains offering important development in studying *Land/Atmosphere interaction, Water/energy interactions, Snow and ice.* Long-term mean estimations of snow accumulation and air temperature could be the basis for forecasting air temperature deviation from average because of snow accumulation anomalies, and heat energy lost because of variations in snowmelt. Our approaches allow evaluating the impact of an early or late loss of snow on atmospheric heating.
- Development the predictive relationship among hydro-climatic model parameters and atmospheric circulation patterns in the mountains and plains of Tien Shan provides an important clue to *Atmospheric Dynamics*, *Land/Atmosphere interaction* linking large-scale climatic change patterns and regional-scale hydrologic regimes in continental, mid-latitudinal, alpine watersheds.
- Long-term, hydrometeorological data sets for continental alpine river basins was produced and made available to the global change research community

The study of *Hydrology, Hydrological Modeling, Land/Atmosphere interaction, Water/energy interactions, Snow and ice, Seasonal Snow Covered Alpine Drainage Basins* fits in the "Physical Climate and Hydrology" components of Global Change Research Program. In terms of *Earth Science Enterprise*, we contribute to the hydrologic aspects of Seasonal to Interannual Climate Variability, Long-Term Climate Change, gaining an understanding of the complexities of climatic, hydrological, and glaciological systems at local, regional, and global levels.

2. Other discipline of science or engineering

The Tien Shan holds the greatest concentration of snow and ice in the low-mid latitudes and constitute a vital sources of water supply for large population of Kyrgizstan, Tadjikistan, Kazakhstan, Uzbekistan, Turkmenistan, Afghanistan and Xinziang where population reached up to 100,000,000 people at the end of 1990s. The complexity of the problems associated with management of our environment has led to the need of water where huge population is settling. For example, the well-known drying of Central Asia in the 20th century has captured a large share of the attention afforded to environmental problems in the Aralo-Caspian basin (*Kira*, *1995*). Since that the produced results on estimation of long-term water balance dynamics in mountainous river basins of Central Asia and developed Tien Shan Data Base is extremely useful in economics, agriculture and engineering of irrigation systems in completion of natural and human ecosystems. Findings in our research is the foundation of complicated mathematical models integrating the laboratory investigations, remote sensing, observations of human interactions, and processes, along with a knowledge of the physical, biological, economic and social dimensions.

3. Contribution to Human Resources Development

Innovative coupled water and energy balance models of hydrologic response in high-altitude watersheds and evaluation the cooling of the troposphere as a result of energy losses from snowmelt are the basis for the developing and disseminating them as educational materials for the graduate and post-graduate students.

Developed results provide opportunity for the further research by following tasks:
(i) further improvement of the developed simulation with applying of nonlinear response functions for hydrograph generation instead of the linear counterparts; (ii) Developing a model of river runoff using both hydro-meteorological data, morphometric and satellite information (iii) validation of the developed simulation in other alpine watersheds with snow and glacier nourishing; (iv) obtaining the long-term dynamics of water balance components and their response to past climatic changes over the Tien Shan Mountains with providing monthly, annual hydrometeorological, stream-chemistry, topographical and remotely sensed data; (v) monitoring the long-term changes of solute content in stream chemistry; (vi) estimations on air temperature deviation from average because of snow accumulation anomalies and heat energy lost during exceptional variations in snowmelt; (viii) distinguishing whether associations exist between surface climate, streamflow and large-scale features, and if so, to evaluate the magnitude and the nature of the relationship.

4. Contribution to Resources for Researches and Education

Based on the project fund we have extended the computer and software resources in our group applying purchasing PC Pentium II DeskTop and Toshiba Satellite-Pro LapTop computers, Polaroid Film Scanner and software (ArcInfo, Fortran Power Station and IDL 5.01) which we are using in our current research and the teaching process. Courses which benefited from this hardware are: Environmental Hydrology (Geography 112), Water Quality (Geography 162), Advanced Hydrologic Models (Geography 246) and Water Resources Systems (208), all taught at UCSB.