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Preface

Basic knowledge on assessment, simulation and forecast of water resources at the central Asia World largest closed drainage basins is a critical aspect during a time of persistent droughts and increasing water demand due to population growth, agricultural and industrial development. This project has been focused on the Tien Shan highlands that supply of water to the western, northern and eastern central Asia oasis's. Finally, the results of this research enable us to evaluate long-term dynamic of water cycle components in the World's largest closed drainage system that has not been examined in details before. Therefore, the presented research is a first comprehensive investigation over the Tien Shan alpine watersheds based on rich long-term data-set over the region collected by the UI research team. The authors are sincerely acknowledging the NSF Hydrology Program for kind support in 1997 ATM - 9711491, and in 2003 ATM-0233583 to make this interesting research available.

1. Project Activities

The main purpose of our research was analysis, simulation, and forecasting the natural impact of climate change on water cycle variability in the Tien Shan Mountains.

To reach this goal we collected large observational data set on precipitation, air temperature, evaporation, total river runoff and snow/glacier/permafrost runoff, and water chemistry over five river basins located in western, northern and central Tien Shan Mountains. After one year since this project has been finished and final papers will be published, all data will be released for free public use at the research team web site in University of Idaho (http://www.sci.uidaho.edu/cae/index.html). The collected historical data (50 to 150 years) greatly improve our knowledge about the effects of global changes on regional climate and water resources [*Aizen, 2003; Aizen and Aizen, 1998; 1999; 2001; 2003; 2006a; 2006b; Aizen et al, 1995a; 1995b; 1996a; 1996b; 1997a; 1997b; 1997c; 1997d; 1997e; 1997f; 1997g; 1997h; 2001; 2000a; 2000b; 2004a; 2004b; 2005; 2006a; 2006b; 2006c; 2006d; 2006e; Barlow, et al, 2005; Surazakov, et al, 2005; Kreutz, et al, 2003; Kreutz, et al, 2004; Pruett, et al, 2004*]

Using this data we evaluated the role of water cycle components (i.e., type and quantity of precipitation, snow accumulation, evaporation, total river runoff and snow/glacier/permafrost runoff) [*Aizen and Aizen, 2003; 2006a; 2006b; Aizen et al, 2005; 2006a; 2006d; 2004a; 2004b;]*, and long-term changes in these components, characterized the physical processes and mechanisms controlling water cycle variability [*Aizen et all, 2005; 2004a; 2006d*].

Using long-term and in-situ data we discovered that water chemistry in alpine rivers controlled by changes in glacier, snow, and permafrost runoff components. The water chemistry of the Tien Shan rivers, including major ions, pH, conductivity, and dissolved oxygen is defining the input/output chemical budget of alpine ecosystems [*Aizen and Aizen, 2006a; 2006b; Kreutz, et al, 2003; Pruett, et al, 2004; Kattelmann, et al, 2005*].

The received results allowed us to develop and validate the Regional Climate-Runoff-Model, build numerical simulations of observed water cycle variability over the selected river basins and develop a transition from small alpine hydrological units to large and complex Tien Shan mountains system [*Aizen, et al, 2006d*].

The climate scenarios, as an effect of global warming, and their possible impact on water resources has been modeled [*Aizen, et al, 2006a; 2006b; 2006c; 2006d*].

Field research in Tien Shan watersheds has been accomplished in 2003 and 2005 with the University of Idaho (UI) and International support. During two summer trips, we collected long-term data in Kyrgyzstan national archives, collected snow, ice and permafrost melt water samples for geo-chemical analysis, and performed GPS survey on the northern and central Tien Shan glaciers to coordinate the glacier historical topographic maps and compute the glacier changes using the modern aerial photographs and satellite remote sensing data.

The Tien Shan watersheds Digital Elevation Models (DEM) 100 m resolution were developed using 1:25 000 scale military topographic maps and generated point-by-point stereophotogrammetric measurements for estimation of surface changes. The DEM vertical accuracies of 2.8 m for 1943 and 2.7 m for 1977 were estimated by repeat measurements and comparison along map sheet boundaries. The present positions of the glacier termini were corrected using large-scale aerial photographs 1995, acquired from AeroMap U.S. Inc.[*Aizen, et al., 2006b; 2006c; Surazakov, et all, 2005*]

The sow, glacier ice, precipitation, permafrost melt water, and stream water samples were processed at the University of Idaho and University of Maine dedicated laboratories [*Kreutz, et al, 2003; Pruett, et al, 2004; Aizen, et al, 2004a; 2005; 2006a; Aizen and Aizen, 2006a*] .

During three years of the project the Global Change and Alpine Ecosystems Research/Educational Program has been developed and implemented in College of Science at the University of Idaho (http://www.sci.uidaho.edu/cae/index.html). In a frame of this program, two new courses have been developed and taught in Department of Geography of the UI: **Geog 404/504** Glaciology and Alpine Environment; **Geog 591** Alpine Research Seminar. The results of our research were also presented at the National and International Meetings and the large Internet web media.

1.1. Scientific Meetings and Invited Lectures

Aizen, V.B.and E.M Aizen. **2006**. (*Invited*) Climate and Central Asia Glaciers, Changes and Consequences. CliC 1st Asian Symposium, Yokohama, **Japan**

Aizen, V.B. **2006**. (*Invited*) Glaciers of Central Asia Mountain System. AAAS Symposium, St. Louis, **U.S.A.**

Aizen, V.B., E.M. Aizen, V.A. Kuzmichenok. **2006**. Estimation of seasonal snow cover and glacial area changes in central Asia (Tien Shan). International Institute for Applied Systems Analysis (IIASA), Laxenburg, **AUSTRIA.**

Aizen, V.B. **2006**. (*Invited Lecture*) The Glaciers of the Central Asian Mountain System (Tien Shan, Altai, Pamir, Himalayas, and Tibet, Karakoram). Nagoya University, **JAPAN**

Aizen, V.B., E.M. Aizen, V.A. Kuzmichenok, A.B. Surazakov. **2005**. **(***Invited***)** Glacier changes in central and northern Tien Shan during the last 150 years based on surface and remote sensing data. IGS Symposium, Lanzhou, **CHINA**

Aizen, V.B., E.M. Aizen, D.R. Joswiak. **2005**. Climatic and atmospheric Circulation Pattern Variability from Ice-core isotope/geochemistry Records (Altai, Tien Shan and Tibet). International Glaciological Society Symposium, Lanzhou, **CHINA**.

Aizen, V.B., E.M. Aizen, V.A. Kuzmichenok. **2005.** Simulation and stochastic forecasting of water cycle components in Central Asian alpine basins. American Meteorological Society Meeting, San Diego, **U.S.A.**

Aizen, V.B. and E.M. Aizen. **2005.** Global Change Research Educational Program. NSF sponsored workshop on the hydrology of Central Southwest Asia. San Diego, **U.S.A.**

Aizen, V.B., E.M. Aizen. **2004**. (*Invited*) Past century variability of water cycle over the central Asia from ice-core isotope-geochemistry records. AGU San Francisco Fall Meeting, **U.S.A.**

Aizen, E.M., V.B.Aizen. **2004**. Assessment, Changes, and Prediction of Water Cycle Components in Central Asian Alpine Basins. AGU San Francisco Fall Meeting, **U.S.A.**

Surazakov, A.B., V.B. Aizen, V.A. Kuzmichenok. **2004**. Shuttle Radar Topography Mission DEM, ASTER Image and Aerial Photography in Evaluation of Mountain Glacier Volume and Area Changes. AGU San Francisco Fall Meeting, **U.S.A.**

Joswiak, D.R., E.M. Aizen, V.B. Aizen. **2004.** Isotope/Air Temperature Relationships From Snow-Firn Core Time Series at the Northern and Southern Periphery of the Central Asian Mountain System. AGU San Francisco Fall Meeting, **U.S.A.**

Aizen, V.B. and E.M. Aizen. **2004.** (*Invited Lecture*) Non-Polar Glaciers in a Focus of Global Changes. Scott Polar Research Institute, Cambridge, **U.K.**

Aizen, V.B. and E.M. Aizen. **2004**. (*Invited Lecture*) The central Asia glaciers in a focus of Global Changes. University of Heidelberg, Heidelberg, **GERMANY**

Aizen, V.B., E.M. Aizen, V.A. Kuzmichenok, A.B. Surazakov. 2004. Assessment of Glacial Area and Volume Change in Tien Shan (Central Asia) During the Last 150 years Using Geodetic, Aerial Photo, ASTER and STRM Data. Wengen-2004 International and Interdisciplinary Workshop: "Mountain Glaciers and Society", Wengen, **SWITZERLAND**.

Aizen, V.B., E.M. Aizen, D.R. Joswiak, K.Fujita, K.J. Kreutz. **2004.** Oceanic and internal moisture contribution to Tien Shan, Altai and southeastern Tibet glaciers based on isotope-geochemistry firn ice-core records. EGU Meeting, Nice, **FRANCE.**

Aizen, V.B. and E.M. Aizen. **2004.** Global Change Research Educational Program. INRA Workshop, Baseman, **U.S.A.**

Aizen, E.M. and V.B. Aizen. **2003**. (*Invited*) Spatial and temporal variability of precipitation and snow pack in Central Asia (Tien Shan), Japanese Islands and North America (Sierra Nevada) Mountains. International Symposium on Snow and Ice, Niigata, **JAPAN**

Joswiak, D.R., E.M. Aizen, V.B. Aizen. **2003.** Spatial variation of ionic and isotopic records from snow pits and shallow ice cores in Central and Southeast Asia. AGU San Francisco Fall Meeting, **U.S.A.**

Aizen, V.B., E.M. Aizen. **2003**. Tien Shan glacier's recession since the end of 19th century. AGU San Francisco Fall Meeting, **U.S.A.**

1.2. Media

"Glacier Melt Could Signal Faster Rise in Ocean Levels" by *Shankar Vedantam*
Washington Post Staff Writer, Friday, February 17, 2006; Page A01
"UI Glacier Expert Joins Researchers Documenting Loss of World's Ice"
(www.today.uidaho.edu/details.aspx?id=3418&sctn=news), 2006
KUOI News (http://kuoi.asui.uidaho.edu/news/?cat=1), 2006
TODAY@IDAHO (*www.today.uidaho.edu*), 2006
REGISTER, University of Idaho, V.17, N 17, August 12, 2005
FROZEN GROUND, November 27, 2003.
University of Idaho Magazine, Spring 2003.

2. Project Findings

To achieve the proposed research and complete the required simulation, the folloowing project activities and implications were implemented at an earlier project stage in year one and year two. The results of this research is greatly contributed to the NSF U.S. Global Change Research Program (USGCRP), the World Climate Research Program (WCRP), United Nation Environmental Program (UNEP), Climate Criosphere-Litosphere Program (CliC), Past Global Changes Program (PAGES), North Eurasia Environmental Science Partnership Initiative (NEESPI) and other International Programs. The results of this research have been published in more than 20 peer-reviewed papers in scientific journals and proceedings of the scientific meetings *(see list of publications below).*

2.1. Understanding a role of synoptic processes in climate regime and precipitation in particularly over the Tien Shan

(1) The technique of coupling synoptic climatology and meteorological data with $\delta^{18}O$ and major ion content recorded in firn cores from Tien Shan glaciers was developed in order to determine climate-related signals and to identify the origin and trajectories of moisture [*Aizen and Aizen,, 2003; Aizen, et al, 2004a; 2005*].

(2) The sources of moisture and the trajectories of air masses bringing precipitation to the Tien Shan were inferred by evaluation of the physical processes controlling the oxygen isotope content in snow accumulation with special emphasis on synoptic weather patterns. The $\delta^{18}O$ relationship for precipitation accumulated during air mass influxes entering from the west corresponded to evaporation from the ocean under conditions near equilibrium [*Dansgaard, 1964*]. More negative values of $\delta^{18}O$ were observed in snow precipitated from air masses originating over the Atlantic Ocean when moisture is transferred at higher latitudes and altitudes, than in snow due to other synoptic processes, which brought water vapor from closer sources, over lower latitudes and altitudes [*Aizen, et al, 2004a; 2005; 2006a*].

(3) In addition to the analysis of oxygen isotope content, identification of synoptic patterns through major ion records has inferred the locations of the moisture sources and trajectories of air masses, which brought precipitation to the Tien Shan. The lowest annual $\delta^{18}O$ values of snow deposited in the firn-ice core and highest annual solute content of terrestrially derived calcium, potassium and magnesium are associated with development of the southeastern periphery of the Siberian High in winter and related to water vapor originating over the region around the Aral and Caspian seas. The high solute content of calcium, magnesium and potassium in spring and autumn layers indicate development of southern cyclones, which transport moisture from the south of the Caspian Sea. The highest annual $\delta^{18}O$ values and high solute contents of calcium, potassium and magnesium occurred in summer samples and indicate development of a large thermal depression when mineral dust from the central Asia deserts is transferred eastward over the region. Influxes of air masses from the west and western cyclones are the dominant synoptic modes in the central Tien Shan, and these air masses bring a significant portion of marine-derived precipitation from the Atlantic Ocean, Mediterranean and Black seas with the highest annual values of $\delta^{18}O$, maximum concentrations of sodium and chloride, and minimum concentrations of potassium, magnesium and calcium [*Aizen, et al, 2004; 2005; 2006a*].

(4) The re-cycled annual amount of Tien Shan accumulation reached up to 87% of total, with the highest d-excess values. Precipitation, which is re-cycled from the Aral-Caspian basin contributed 55% and Mediterranean and Black seas produced about 30% to the Tien Shan mean annual accumulation. Only 13% of annual snow accumulation with low d-excess and most enriched $\delta^{18}O$ values is brought from the North Atlantic [*Aizen, et al, 2004a; 2006a*].

(5) The technique used in our research complements a well-known method for determining the precipitation origin through the deuterium excess was used for climatic and environmental reconstruction of snow accumulation, air temperature variations, moisture origin, atmospheric circulation and anthropogenic pollution in the region over the last century [*Aizen, et al, 2004a; 2005; 2006a*].

2.2. Tien Shan river water suluble components in study of the watershed chemistry cycle

Evaluation of long-term changes in stream flow, water temperature and solute content of surface water in the Tien Shan and Pamiro-Alai watershed was done based annual monthly data collected from gauging stations for over twenty years. The analysis was done for the basins with and without glacierized areas and permafrost distribution.

(1) Analyses of solute concentration and content of ionic components revealed three formation zones: a) alpine, high elevated, b) sub-alpine, forest and meadows, and c) transitional, at the foothills. At alpine zone, maximum solute concentration observed in May before intensive snow, glaciers and permafrost melt and flood peak. In two other zones the maximum occurs in April, because snow melt and rains begins early at lower altitudes. The minimum solute concentration in stream water has revealed in June in all three zones, coinciding with maximum river discharge, diluting the solute concentrations.

The glaciers and permafrost intensive melt in summer doesn't effect the Tien Shan river water solute concentration. Monthly variations in solute concentration are associated with both changes in anions and cations components. *[Katellmann, et al, 1995; Aizen and Aizen, 2006a]*.

(2) Variability in content of ionic components, solute concentration and pH affected by river runoff during both periods of maximum and minimum solute concentration. Increases in river discharge decreases the content of most ionic components and solute concentration. The pH values ranged from 7.6 to 8.0, indicating neutral to slightly alkaline stream water. The current study analyses a natural variability in the solute content determined that the stream water has uniform ion composition of bicarbonate HCO_3^- and group of calcium reflecting the state of rocks. The lowest solute concentration of stream water of 64.5 mg L^{-1} was observed at alpine zones where we found very small content of $Na^+ + K^+$ of 1 mg L^{-1} [*Aizen and Aizen, 2006a*].

(3) The water in streams and rivers at sub-alpine zone also contains phosphate, iron and silicon. The river waters in the sub-alpine zones have greater solute concentration than at high elevation and contain bicarbonate and Ca^{2+} but the relative composition of ions decreases while absolute and relative composition of Mg^+ and SO_4^{2-} increases. The Cl^- ions were also detected at sub-alpine zone [*Aizen and Aizen, 2006a*].

(4) At the low elevations, the transitional zone, water streams notching through large alluvium depositions have maximum solute concentration. Ions of NO_3^- were found only at this altitudinal zone. To pick up an anthropogenic component in long-term ionic changes, we took into account the ratio between the river runoff for two periods with human impact and without it. Besides, we calculated the ratio between ionic concentration of HCO_3^- and concentration other ions as criteria of human impact on stream chemistry assuming only natural variability in the hydrocarbon. Statistical analyses did detect associated changes of river runoff, their different components (glacier, snow and permafrost), water temperatures and its solute content. Separation of anthropogenic and natural variability revealed increased concentration of SO^{2-}, Ca^{2+} and $Na^+ + K^+$ ions since the middle of 1970 in transitional zone, which occurred simultaneously with intensification of agricultural development in Central Asia [*Aizen and Aizen, 2006a*].

2.3. Changes in glaciers ice volume and glaciers area distribution

This research presents a precise evaluation of the Tien Shan glaciers recession based on data of geodetic surveys 1861-1869, aerial photographs from 1943, 1963, 1977 and 1981, 1:25,000 scale topographic maps and Shuttle Radar Thematic Mission (SRTM) and ASTER data from 2000/2003. The Tien Shan glaciers retreated as much as 3 km from the 1860s to 2003. Area shrinkage was 4.2% in central Tien Shan and 5.1% in northern Tien Shan from 1943 to 1977 and it was 8.7% and 10.6%, respectively, from 1977 to 2003. The volume of Tien Shan glaciers was reduced on 5.5% from 1943 to 1977 and 7.4% from 1977 to 2000. The total reduction of the Tien Shan glacier is 14.2% during the last 60 years (1943-2003). The Tien Shan have not experienced a significant increase of precipitation during the last 100 years, but it has experienced an increase in summer air temperatures, especially observable since the 1970s, which caused an acceleration in the recession of the Tien Shan glaciers. Hence, continuous increase of warm season air temperatures in Tien Shan without increase of precipitation may further accelerate glacier recession and intensify desertification processes in central Asia, Kazkhstan, and northwestern China.

(1) A long-term (about 140 years) estimation of the northern and central Tien Shan glacier changes computed based on a complex of geodetic ground surveys and remote sensing data, which quantified the spatial and temporal regime of the glaciers [*Aizen, et al., 2006b; Surazakov and Aizen, 2005*]

(2) There has been a definite trend of the glacier recession over the last 140 years and especially since the middle of the 1970s, which indicates an abrupt climate change effect [*Aizen, et al, 2006b*].

(3) The main factor controlling the glacier regime is the impact of air temperature that affects the type of precipitation, the duration, and the intensity of snow and ice melt throughout altitudinal belts. The modern increase of air temperature, which is also observed in the Tien Shan's alpine areas, extends the period and intensity of melt and the glacier recession [*Aizen, et al, 1997c; 1997g; 1997h; 2000a; Aizen, 2003; Aizen et al, 2006b]*.

(4) Analysis of data from stations located Tien Shan alpine and sub-alpine zones shows no significant trends in observed annual precipitation or warm season (from May to September) temperature for the periods from 1913 to 2000. However, significant negative trend in annual precipitation is observed during the period from 1963 to 1981 (29% of average), while air temperature significantly increased during the last twenty years from 1981 to 2000 (0.93^{o}C), which extends the period of glacier ablation and consequently accelerates glacier recession [*Aizen, et al, 2006b; 2006c*].

2.4. Changes of the Tien Shan permafrost state

(1) The data on permafrost observations from Tien Shan alpine stations indicates 0.03°C rising trend in the permafrost temperature for the period of 1974-2000, which correspond with annual air temperature growth during the same period by 1.2^{o}C.

(2) The performed mathematical simulation of possible permafrost changes with increasing of air temperature by 0.04 – 0.05^{o}C a year revealed that Tien Shan permafrost boundary may be uplifted to 200-250 m higher and decrease permafrost area by 20% during the next 10-15 years. Based on simulation of the Tien Shan permafrost state the permafrost area distribution has been incorporated in 1:100 000 scale DEM for further runoff simulation and predictions.

2.5. Improved model of Daily River Runoff in Tien Shan Alpine Watersheds

The previously funded (1997-2000) by NSF-MMIA (ATM – 9711491) project on 'Simulation of Snow and Glacier Runoff in Central Asia Alpine Watersheds' gave us an opportunity to develop two-component model of river runoff simulation based on mean daily air temperature and daily precipitation at a reference meteorological stations, and on the distribution of air temperature, precipitation, and watershed area as a function of elevation. This runoff simulation method took into account the water retention capacity of the snow, the amount of refrozen melt water, and the ice melt under glacial moraines. The method of hydrograph derivation developed based on single- and two-reservoir models. Calibration and validation of the river runoff simulation model were done for the Oigaing and Ala Archa alpine drainage river basins in northern and western Tien Shan. The two-reservoir hydrograph model produced minor improvements in prediction as compared with the single-reservoir runoff hydrograph method but requiring some further development because the. simulation errors increased with increasing annual river runoff and depend on snowmelt, glacier runoff, the amount of precipitation, and air temperature *[Aizen and Aizen, 1997f; 1997h; 1998; 1999; Aizen, et al, 1995a; 1995b; 1997b; 1997c; 1997d;* 1997g; *2000a; 2000b;2006b; 2006d; Barlow, et al, 2005*].

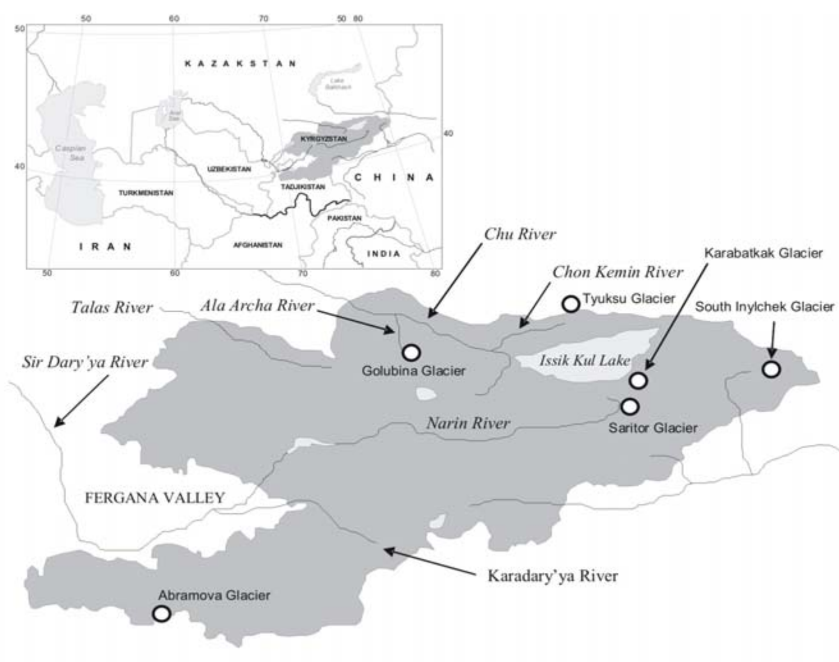

Fig. 1. Map of the studied area

In the new project we have developed above model involving additionally solar radiation characteristics, topographical parameters (e.g., slope and aspect) in the calculation of snow melt. The runoff model validation was based on data sets other than those used in model calibration. Employing physical regional modeling of snow melt based on solar radiation data and pixel scale analysis improves generally the river runoff simulation during the dry years (up to 1.6 times) and partly during the normal years at the beginning of summer and autumn. Replacement of constant annual optimal parameters to monthly means in the runoff hydrograph simulation decreased more half as much mean of standard square deviation in the improved model [*Aizen, et al 2000b; Aizen and Aizen, 2006b*]

3. Effect of Changes in Climate, Snow Pack, Glaciers, and Permafrost on River Runoff in Tien Shan, Central Asia

The applicable GIS-based Tien Shan digital distributed models: Digital Model of Mean Air Temperatures (DMMAT); Digital Model of Annual Mean Precipitation (DMAMP); Digital Model of Annual Mean Potential Evaporation (DMAMPE, and DMAMET); Digital Model of Snow, Glacier and Permafrost Area Distribution (DMSGPAD) were developed and calibrated in several western, central and northern Tien Shan watersheds (Oigaing, Chon Kemin, Ala Archa, and Narin -Sir'Darya River) (Fig. 1) based on 1:100,000 topographic maps.

3.1. Data and Methods

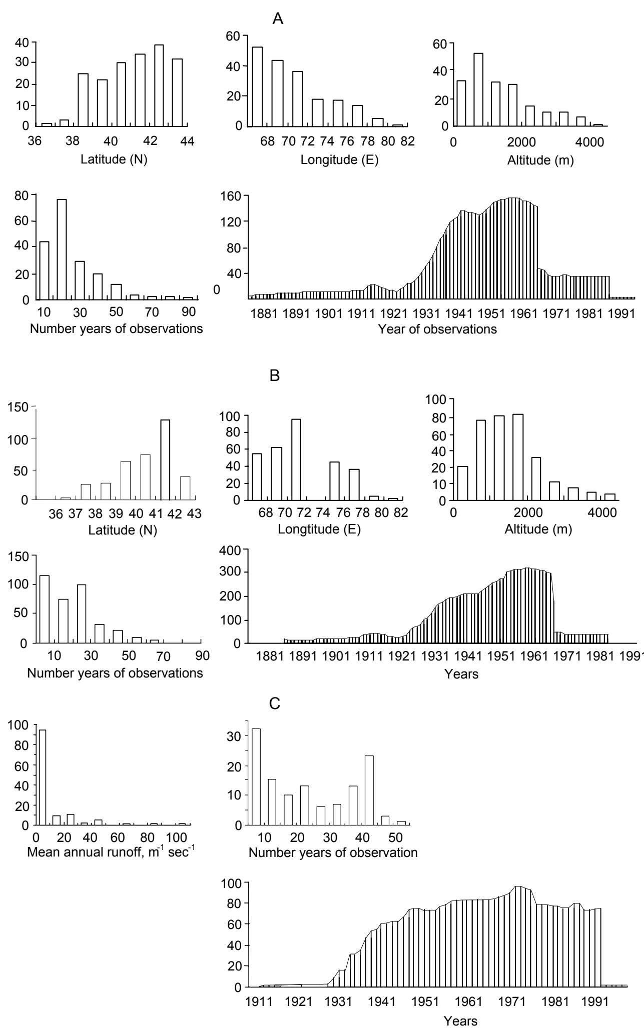

Fig. 2. *Distribution of meteorological stations (ms), precipitation sites (ps), stream gauges (sg), measured air temperature (A), precipitation (B), and river runoff (C) in the Tien Shan*

Topographic, meteorological, hydrological, and glaciological data [*Applied Reference Book on Climate, 1989; Reference Book on Climate 1966-1969; Catalogue of Glaciers in the USSR.1970; Glacier Inventory of China. III., 1986a,b,c; 1987*] used in the simulation (Fig. 2) are a part of the Central Asian Database (CADB) developed at the University of California in 1997-2000 and moved to the University of Idaho in 2001.

Hydro-meteorological observations were obtained using standard meteorological instruments and methods that are used in all meteorological network stations approved by the World Meteorological Organization. All data collected for this research project were checked for homogeneity of observational series, representativeness, and the presence of random errors. Each time series were plotted and inspected for "gross" errors. Data quality control implemented the recommendations of [*Easterling et al. 1995*].

3.2. Topography

The Digital Elevation Model (DEM) of the Tien Shan topography was developed with 500 m grid resolution based on a 1:500,000 map. The following parameters were digitized: elevation of a grid point (*H*), angle of slope (*U*), exposure (*Ex*), angle of orientation (*O*), and index of orientation (I_0). Angle of orientation is the angle between the normal vector to the surface and the direction to the sun at local noon of midsummer. The cosine of this angle (i.e. index of orientation) characterizes the total solar radiance of surface [*Kuzmichonok*, *1979*]. The findings were simulated over the Tien Shan relief using orthogonal coordinates of the equivalent cone projection with standard parallels using the Digital Elevation Model that covers 800,000 knotted points. The accuracy in determining the station coordinates was 0.1-0.5 km with a maximum of 2 km for stations located at the Chinese Tien Shan.

3.3. Digital Model of Mean Air Temperatures (DMMAT) (seasonal and annual)

The DMMAT was based on data from 212 stations from the Tien Shan and surrounding territory. The distribution of stations along latitudes, longitudes, elevations, and periods of air temperature observations is shown in the Fig. 2. Triangulation Irregular Network (TIN) without gaps and interpenetration completely covering the mountain territory with 176 triangles was developed (Fig. 3a). The optimization method of random set triangulation [*Kuzmichonok, 1993a; b*] was implemented using the criteria of minimum angles in pare of contiguous triangles. Monthly and annual air temperature linear changes by elevation and the mean square errors of approximation were computed using the least square method [*Aizen et al., 2005a*]. The correlation coefficient between air temperature and elevation (-0.90) and square error (0.17°C km^1) showed the reliability of the DMMAT.

Long-term mean annual/monthly air temperatures at any simulated point (*sp*) of the Tien Shan Mountains were estimated with the following procedure: The coordinates of the bounding points *A,B,C* at a specified triangle (Fig. 3b) were determined using the TIN (Fig. 3a). The air temperature means from three meteorological stations (*A, B, C*) shaped the triangle ABC (Fig. 3b) were extrapolated to sea level (*H=0*) through empirically developed coefficients [*Aizen et al., 2005a*]. Air temperature at the simulated sea level points (A_1,B_1,C_1) was
linearly interpolated to a new virtual point (sp_1) located inside the simulated sea level points at the triangle A_1,B_1,C_1 (Fig. 3 b). The air temperature from the virtual point sp_1 was extrapolated through linear air temperature/elevation relationship to the real point *sp* projected on the surface topography.

3.4. Digital Model of Annual Mean Precipitation (DMAMP)

Numerous studies have investigated the spatial distribution of precipitation in the Tien Shan basins [*Getker, 1985; Bakirov 1988; Aizen and Aizen, 1998; Aizen et al., 1996a,b; 1997a; 2000b; 2001; 2004a*]. However, more than 90% of the meteorological stations are located below 2500 m (Fig. 2), so they are lower than the average altitude of the Tien

Shan (Table 1). Furthermore, significant regional, spatial, and altitudinal variability of precipitation complicates the mathematical simulation of the precipitation distribution at high micro-scale resolution. All the available data related to precipitation estimation were applied to develop the DMAMP. This included data from 304 meteorological stations,

	Sir Dar'ya R.	Talas R.	Chu R.	Narin R.	Karadar'ya R.	N. Fergana V.	S. Fergana V.	T. Shan
S	111448	10794	22309	58462	25494	9828	17664	255999
K_U	445815	43160	89222	233837	102008	39309	70661	
W_l	0.61	0.15	0.14	1.05	0.24	0.05	0.00	0.55
W_f	6.80	1.71	2.23	4.73	12.06	4.34	7.43	6.2
H	2541.6	2178.8	2166.4	2735.4	2270.4	2485.3	2328.9	2683
U	10.38	9.64	8.59	9.61	10.25	11.77	12.35	9.2
C	-0.00092	0.00017	-0.00002	-0.00090	-0.00048	-0.00160	-0.00120	
Io	0.9284	0.9184	0.9179	0.9322	0.9320	0.9289	0.9108	0.930
T	0.92	1.87	2.45	-1.69	3.91	1.96	4.57	0.0
P	634/70.6	578/ 6.2	552/12.3	590/34.5	718/18.3	743/ 7.3	594/10.5	614
E^*	934	915	976	738	1158	1015	1263	
E	389/43.1	361/ 3.9	371/ 8.3	344/20.1	468/11.9	440/ 4.3	384/ 6.8	
R	249/27.5	217/2.3	181/ 4.0	246/14.4	250/ 6.4	303/ 3.0	210/ 3.7	
$D=P/E^*$	0.661	0.631	0.566	0.799	0.620	0.732	0.470	

Table 1. *Annual means of simulated water balance characteristics of the Tien Shan river basins. S, km*^{2} *is area;* K_u *is number of grid-points;* W_l*, % is share of the lake's area;* W_f *, % is share of the forested area; H, m is elevation; U° is angle of slope; C, km*$^{-1}$ *is surface flexion;* I_0 *is index of orientation; T°C is air temperature; P, mm/km*^{3} *is precipitation;* E^**, mm is potential evaporation; E, mm/km*^{3} *is evapotranspiration; R, mm/km*^{3} *is river runoff; D is index of moisture.*

Glacier	S, km^2	$\bar{H}_{e.l.}$, m	$Ts_{el.}$°C	P, mm	Data from
Tuyksu	3.8	3830	2,23	989	[*Kotlyakov, 1988; Makarevich, 1985*]
Golubina	9.4	3840	2,29	954	[*Aizen 1985; Aizen and Aizen, 1997*]
Kara-Batkak	4.5	3770	3,03	1037	[*Dikikh and Mikhailova,1976*]
Sari-Tor	3.3	4260	-0.,46	728	[*Duyrgerov et al., 1992*]
Inylchek	223.6	4500	-0,72	643	[*Dikikh and Dikikh, 1985; Aizen et al., 1997b*]
Abramova	22.8	4260	2,54	1000	[*Glazirin et al., 1993*]

Table 2. *Long-term mean of summer air temperature (*$Ts_{e.l.}$*) and annual precipitation (P) at the glacier equilibrium line altitude (* $\bar{H}_{e.l.}$*)*

23 precipitation sites [*Applied Reference Book on Climate, 1989; Reference Book on Climate 1966-1969*], 328 high altitudinal points where annual precipitation was estimated using in-situ glaciological measurements [*Dikikh, et al., 1976; Aizen 1985; Kotlyakov, 1988; Makarevich, 1985; Glazirin et al., 1993*], and 103 interpolation points. Precipitation data with a period of more than ten continuous years were used.

3.5 Estimation of precipitation through glaciological measurements

Glaciological measurements were used to estimate precipitation, and this was based on the assumption that, the annual amount of accumulation melts during summer at the equilibrium line altitude (ELA) being a function of the summer average air temperatures [*Krenke and Khodakov, 1966*]. Data from six basic glaciers (Fig. 1, Table 2) were used to develop the relationship between precipitation and summer air temperatures. The mean square error of approximation was 21 mm.

The 328 high altitudinal points, where the annual precipitation was estimated, were determined based on the glacier, meteorological, and topographic data. The ELA ($H_{e.l.}''$,

m) was calculated for the points located at a distance less than 20 km from each glacier and corrected by average glacier exposure through the compass points [*Aizen et al., 2005a*]. The long-term mean annual precipitation at a point simulated through the summer air temperature (DMMAT) takes into account exposure/orientation because it is based on instrument data from three meteorological stations place to form the specified triangle (Fig. 3). These stations are closely located near to a point where ELA was calculated and accordingly the air temperature regime took into account topographical variation.

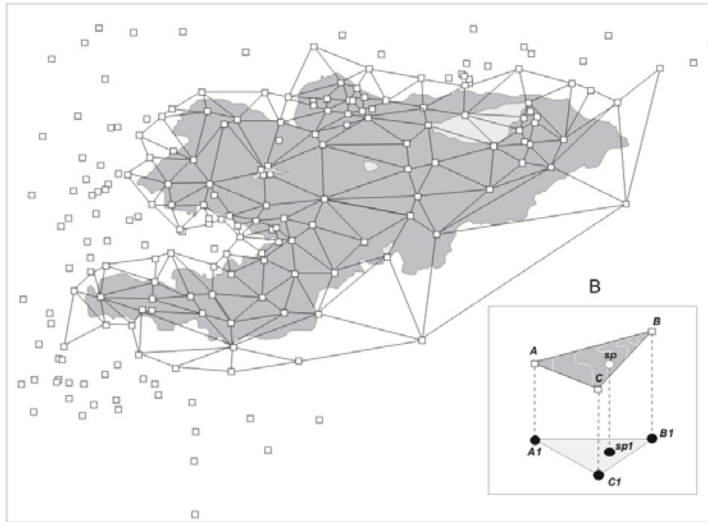

Fig. 3. *Triangulation Irregular Network, and meteorological stations used in simulation of air temperature throughout the central and western Tien Shan (A); Method of air temperature extrapolation (B).*

3.6. Interpolation of precipitation data

The interpolation technique was used for the points, which were located at the talweg with a sparse net of meteorological stations and precipitation sites, and at mountain passes where there are no glaciers.

At the valley lines, interpolation occurred along the lines connecting precipitation sites. At mountain passes, interpolation occurred over the area determined by existing meteorological stations [*Aizen et al., 2005a*] using the least square method.

3.7. Triangle irregular network in the DMAMP

The DMAMP's triangular irregular network completely covers the Tien Shan mountain territory and interpenetration was made with 1454 triangles. The triangle network was developed based on data from 758 sites where annual mean precipitation data were available (Fig. 4). The following conditions were defined under developing the TIN: sites of a triangle should not cross the mountain ridges and intermontane valleys, and the formation of a triangle should not be fully based on points where precipitation was computed through glaciological measurements. The altitudinal gradient of precipitation was computed for each developed triangle by the least square method. The gradients of annual precipitation in TIN ranged from -102 to 832 mm km^{-1} [*Aizen et al., 2005a*]

The long-term mean annual precipitation at a simulated point was estimated using the following procedure:

1. The bounding points coordinates for the specified and adjacent triangles were determined (Fig. 4).

2. The primary estimate of the annual precipitation from the specified triangle was determined through linear interpolation at simulated point (*sp*).
3. The altitude for a specified triangle was interpolated and difference between real and simulated altitudes were calculated.
4. The primary estimate of the annual precipitation at *sp* was corrected according to the altitudinal difference using altitudinal gradients in the specified and adjacent triangles. The gradient was calculated as an average weighted value.

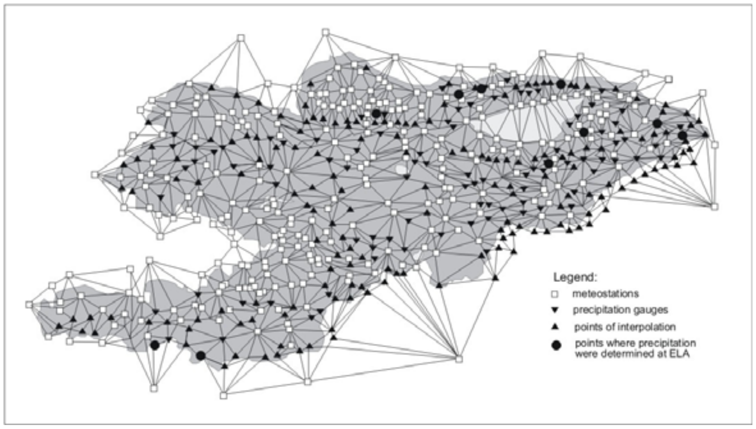

Fig. 4. *Triangulation Irregular Network and observational sites used in simulation of annual precipitation over the Tien Shan.*

3.8. Digital Model of Annual Mean Potential Evaporation (DMAMPE)

Parameters	Chon Kemin		Ala Archa	References
	Ch. 1	Ch. 2		
Area (km^2)	1037.33	1815.31	236.97	DEM, Current simulation
Perimeter (km)	193.99	307.97	73.79	DEM, Current simulation
Mean elevation (m)	3412	3006	3272	DEM, Current simulation
Mean slope (grad)	12.6	12.2	16.7	DEM, Current simulation
Mean curvature of surface(km^{-1})	-0,00123	+0,00049	-0.00166	DEM, Current simulation
Mean exposition	0.915	0.915	0.877	DEM, Current simulation
Glacier covered areas (km^2)	134.01	135.6	52.8	*Maximiv and Bajev, 1973*
Lake areas (km^2)	0.48	0.76	0.15	Atlas of the Kyrgyzstan, 1987
Rock areas (km^2)	49.30	69.46	39.2	DEM, Current simulation
Areas of water-logged ground (km^2)	0.50	0.77	0	*Natural resours. of Kyrgyz SSR, 1986*
Forest areas (km^2)	13.65	68.90	1.7	*Natural resours. of Kyrgyz SSR, 1986*
Elfin wood areas (km^2)	3.34	3.34	0	*Natural resours. of Kyrgyz SSR, 1986*
Open forest areas (km^2)		0.1	0	*Natural resours. of Kyrgyz SSR, 1986*
Bush covered areas (km^2)	0.97	4.77	29.4	*Natural resours. of Kyrgyz SSR, 1986*
Garden covered areas (km^2)		0.60	0	*Natural resours. of Kyrgyz SSR, 1986*
Meliorated areas (km^2)		66.27	0	Map: *'Irrigated Lands' 'Soils', 2003*

*Without taking into account transpiration and irrigation

Table 3. *Parameters: Chon Kemin River basin (stream gauges - Ch.1 and Ch. 2), Ala Archa River*

The amended *Ivanov's [1985]* method was used to estimate the annual potential evaporation (E^*, mm) by using annual mean air temperatures (TºC). Annual precipitation (P, m) data was used instead of relative humidity, and topography (H, m) was used instead of atmospheric pressure. The measurements from [*Sevast'yanov, et al., 1986*] were used to compute the approximation of potential evaporation by the least square method (Eq. 1) based on the 54 initial values of potential evaporation. The approximation of potential evaporation through Eq. 1 had a least mean square error of 97 mm among the 10 different considered types.

$$E^{*}=0.05581\cdot(27.24+T)^{3.0889}\cdot(0.7956+115.5\cdot H\cdot e^{327.9\cdot H})\cdot(0.3622+0.00483\cdot P^{-0.9043}). \quad (1)$$

3.9. Digital Model of the Annual Mean Evapotranspiration (DMAMET)

DMAMET was based on DEM (2.1), DMAMP (2.3.), and DMAMPE (2.4.), and digital mapping of forested areas (on the scale of 1:500,000) [*Natural resources of Kyrgyz SSR, 1986*]. Data on annual river runoff [*Kyrgyz National Hydrometeorological Archive*] was gathered from 123 stream gauges (Fig. 2) located at the stream sites in the mountains before water is distributed for irrigation. Digitizing the watershed boundaries by GeoDraw GIS was based on the map of 'Surface Waters' (1:500,000) [*Natural resources of Kyrgyz SSR, 1986*].

The annual precipitation was estimated by DMAMP. In the glacial basins, the total annual runoff was corrected with the glacier component by taking into account long-tern data on mass balance from six glaciers (Table 3). Mean precipitation was decreased by the mean value of potential evaporation if large and middle lakes are in a watershed.

The difference between precipitation and river runoff was considered to be evapotranspiration. Mean annual evaporation (*E*) for each bounding point was approximated by the least square method (Eq. 2) based on the measured characteristics in 123 river basins.

$$E=(P\vee E^{*})[0.625(2.658-ch^{1.063}U)+0.226thC-(0\vee 0.795)]/\{1+0.902P^{0.941}/[E^{*}+0.088(I_0-0.94)]^{0.556}\}^{0.731} \quad (2)$$

where C is the mean surface flexion, km^{-1}; I_0 is the index of orientation; $\vee$ is the logical *OR* operation; *ch* is the hyperbolic cosine; *th* is the hyperbolic tangent; $P\vee E^{*}$ is the minor; $0\vee 0.7955$ is the meaningful coefficient of the *sp* as related to forested area. Coefficients in Eq. 2 were determined by the'Monte Carlo' deterministic method. The minor annual precipitation or potential evaporation at *sp*, (i.e., $E<=E^{*}$ *if* $E^{*}<P$ *and* $E<=P$ *if* $P< E^{*}$) is the basic value of evapotranspiration. The error of approximation of the annual evaporation was less 72 mm for the basin areas with less 1,000 km^2, and the error decreased as the basin area increased. As the basin area increased, the number of grid points increased, and the accuracy in the approximation became more precise.

3.10. Validation of Simulations

The mean annual runoff was calculated as a difference between the annual volume of precipitation and the annual volume of evapotranspiration. The annual variability in glacier mass balance was taken into account.

The water losses for additional evaporation from the irrigated lands were computed as the difference between the two values of evaporation simulated by Eq. 1.

The first was calculated through precipitation, and the second was simulated with precipitation plus an additional water layer given for irrigation. Part of this irrigated water returns back to the river as runoff, and the rest is lost through evaporation from irrigated lands. Simulation of the annual river runoff was run for the period from 1957 to 1993 and for each grid point was related to its point in the various basins. For the first sub-basin,

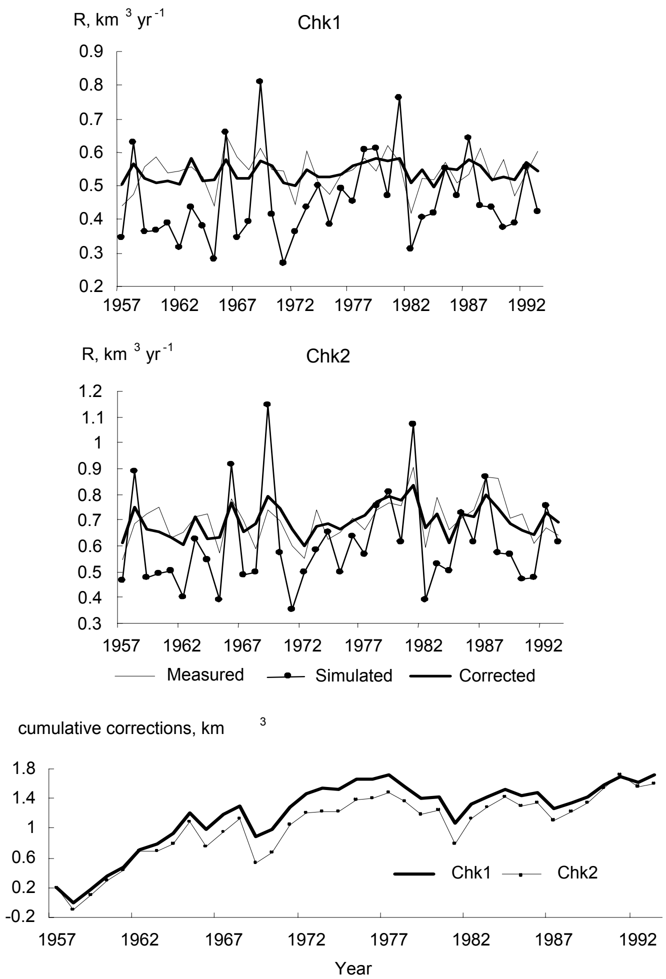

***Fig. 5.** Measured, simulated and corrected annual river runoff (R) in Chon Kemin R. basins (A); and cumulative corrections of the river runoff (B).*

the mean measured annual runoff was 0.6971 km^3 and calculated mean was 0.6099 km^3. For the second sub-basin the measured mean was 0.5496 km^3 and calculated mean 0.4671 km^3.

To optimize simulation, the discrepancy in measured and simulated river runoff was approximated by different combinations of parameters [*Aizen et al., 2005a*]. The amount of precipitation for the current year correlated most significantly (r = 0.73) with the discrepancy in simulated-measured runoff because of substantial spatial and altitudinal variability of precipitation. Another parameter that correlated significantly with the discrepancy in simulated-measured river runoff was the first derivative of the annual river runoff for the pervious year because the aquifers replenish river runoff in years of low water, and correspondingly, the river runoff replenishes the aquifers during the years with an abundance of water. The assessments of the mean residual square errors for the discrepancy caused by different parameters revealed the linear approximation of annual precipitation (*P*), glacier mass balance (*B*), river runoff and first derivative of river runoff (R, R') for the current (*i*) and previous (*i-1*) years [*Aizen et al., 2005a*]. Before correction, for the first sub-basin the mean square error between the simulated and the measured annual runoff was 0.142 km^3 (24%) with a mean square variability of 0.054 km^3, and for the second sub-basin the results were 0.172 km^3 (26%) and 0.083 km^3, respectively.

The corrections decreased the mean square error between the simulated and measured annual runoff to 0.046 km^3 for the first sub-basin and to 0.057 km^3 for the second sub-basin, i.e., more than three times from 24% to 8% (Fig. 2). After correction, the mean calculated runoff was 0.6971 km^3 and 0.5496 km^3 for the first and second sub-basins, respectively.

Similar procedures of validation and optimization of developed simulation were preformed for the Ala Archa river basin in the northern Tien Shan.

3.11. Assessment of Water Resources Characteristics

(Table 1). The mean annual air temperature over the Tien Shan was about 0ºC with a maximum of 4.57ºC at the southwestern Tien Shan (S. Fergana Valley watersheds) and minimum of -1.69ºC in central Tien Shan (Narin River basin). The mean annual precipitation amounted to 614 mm, and it varied from 743 mm in the western Tien Shan (N. Fergana Valley watersheds) to 552 mm in the northern Tien Shan (Chu River basin). The mean indexes of moisture varied from 0.8 in the Narin River basin (central Tien Shan) to 0.47 in the southern part of the Fergana Valley watersheds (Table 1). The mean annual precipitation varies inversely compared to the mean air temperature. The mean values of evapotranspiration exceed the river runoff up to two times in the Chu and Karadar'ya watersheds in the north and western the Tien Shan (Table 1). If in the northern Tien Shan, the relatively small precipitation of 552 mm and consequent river runoff of 181 mm caused this significant exceeding of evapotranspiration over river runoff, while in the western Tien Shan the high mean air temperature increases evapotranspiration under relatively significant precipitation.

	P	*E*	*D*	*R*
H			0.74	0.57
U	0.50	0.40		0.48
C	-0.56	-0.31		-0.70
Io	0.60	0.37	0.83	0.70
T		0.55	-0.85	
P		0.90		0.86
E				0.55
D=P/E'				0.66
W_l		-0.43	0.70	
W_f	0.56	0.68		

Table 4. *Correlation coefficients between the main water resources characteristics in Tien Shan river basins with areas over 5,000 km²: annual long-term mean precipitation (P), evapotranspiration (E), index of moisture (D), river runoff (R) and topographical parameters of elevation (H), slope angle (U), surface flexion (C), index of orientation (I_0), lake (W_l), and forest (W_f) areas.*

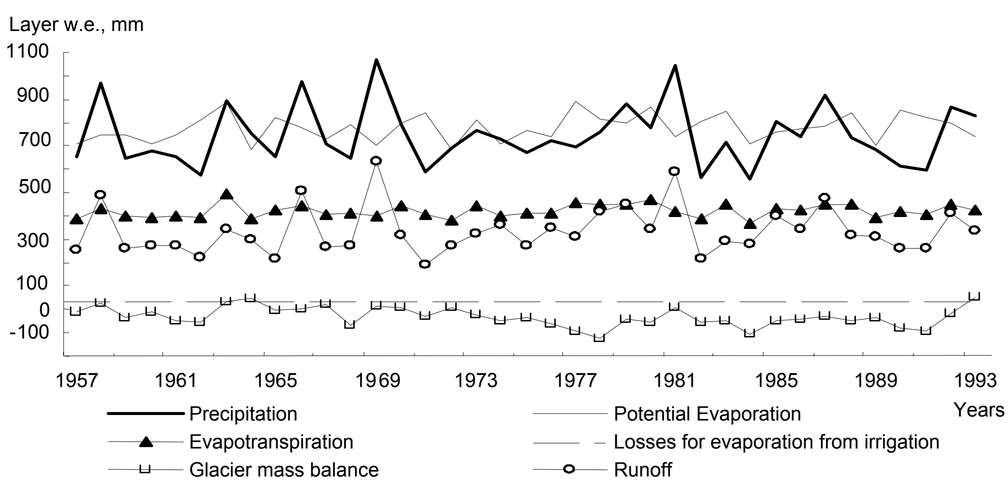

Fig. 6. *An example of simulated and corrected water resources characteristics in the Chon Kemin R. basin (Ch.1)*

The forested area, mean slope angle, and index of orientation in the Tien Shan watersheds were correlated positively with the average precipitation, evapotranspiration, and river runoff (Table 4). Surface flexion was negatively associated with water resources characteristics, so convex surfaces increased precipitation, evapotranspiration, and river

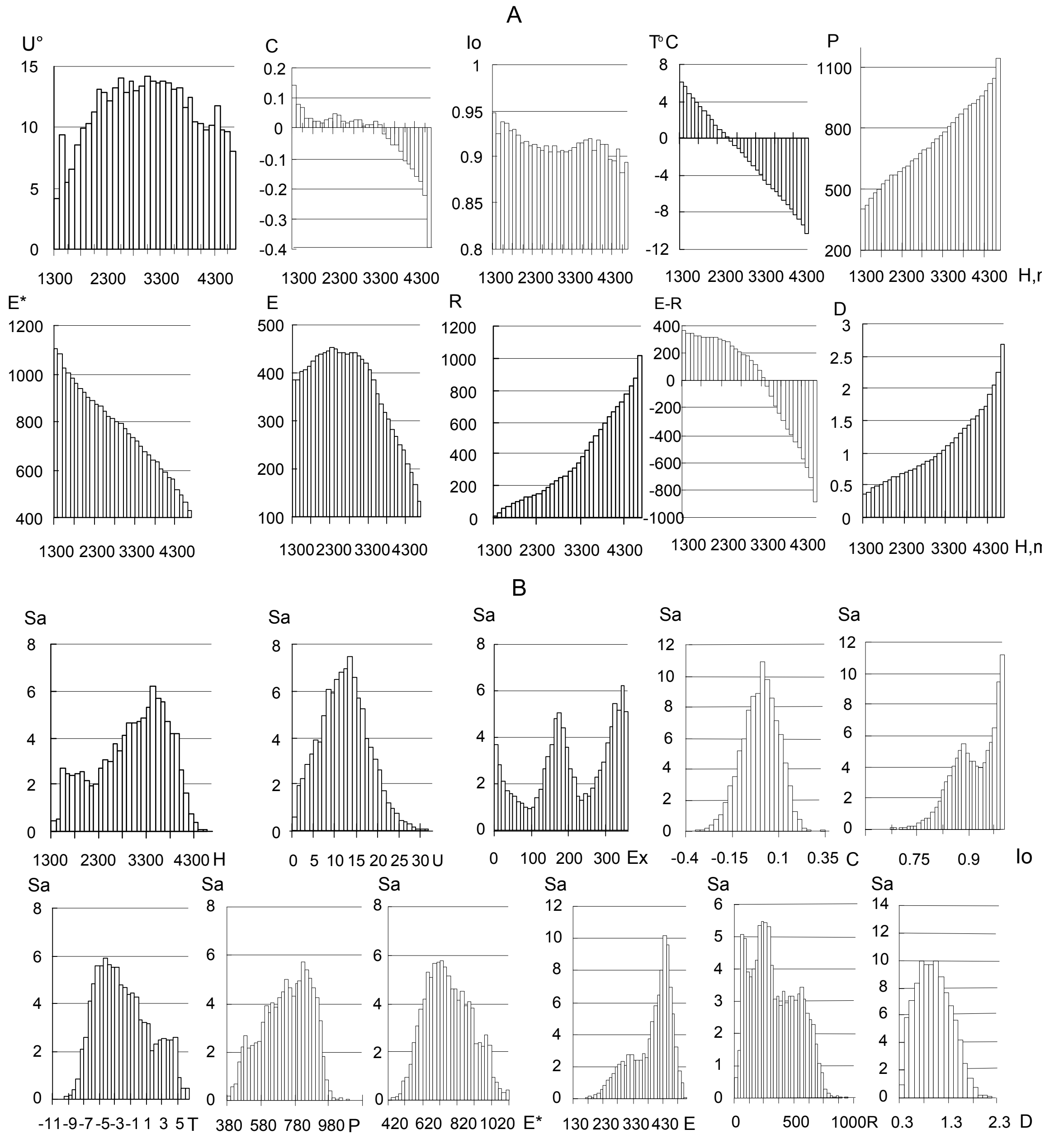

Fig. 7. *Distribution via elevation (A) and areas (B) of mean characteristics obtained from DEM and GIS-based distributed Models of DMMAT, DMAMP, DMAMPE and DMAMET implemented in Chon Kemin River basin (Ch.2). H,m, is elevation; Sa,%, is area share; C km^{-1} is flexion; Io is index of orientation; T°C is annual air temperature; P, mm, is annual precipitation; E*, mm, is potential evaporation; E, mm, is evapotranspiration; R, mm, is river runoff; D is index of moisture.*

runoff. The indexes of moisture and river runoff correlated positively with the average altitude of basin (Table 4).

3.12. Annual distribution of water resources characteristics over the watersheds

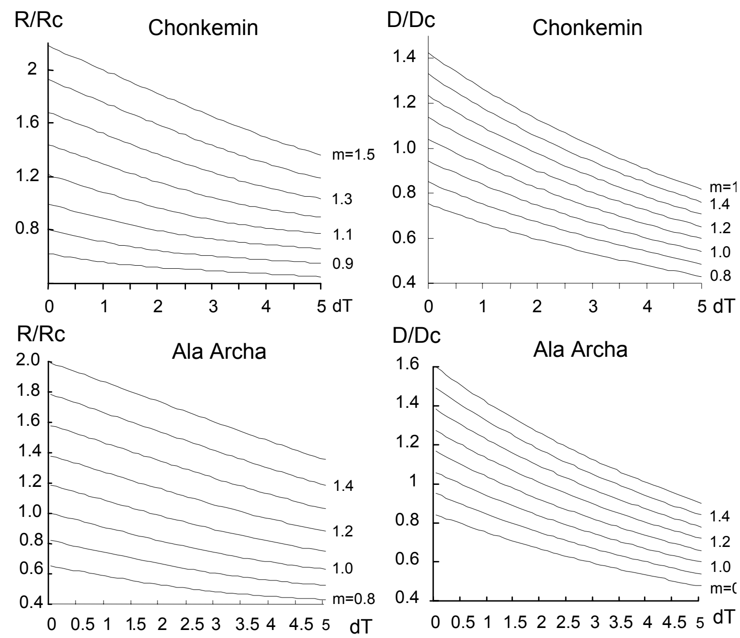

Fig. 8. *Predicted changes in the current river runoff (R/R_c) and index of moisture conditions (D/D_c where $D=P/E^*$) in the Chon Kemin (A) and Ala Archa (B) river basins under the different scenarios of climatic changes ($T = T_c + d$; $P = mP_c$). R and R_c are predicted and current river runoff; T and T_c are predicted and current air temperatures; P and P_c are predicted and current precipitation.*

Changes in water resources characteristics from 1957 to 1995 revealed no significant trend in their variability (Fig. 6). The most variable characteristics were precipitation and potential evaporation, which had similar ranges. The index of moisture in the basins was stable and varied around 1.0 for the alpine Chon Kemin and Ala Archa watersheds (Table 5). This exceeded the other observed means of the large Tien Shan basins (Table 1) where low elevated areas are affected by more extensive evapotranspiration and pointed on precipitation and river runoff deficiency. Intensive use of ground water caused intensive depletion of the aquifers during the 1960s, and beginning of the 1970s that resulted in intensive growth of cumulative corrections (Fig. 5b). The abrupt decrease in the annual precipitation from 1100 mm to 600 mm and the simultaneous increase of potential evaporation up to 800 mm that observed at the beginning of 1970s caused the aquifers consequent depletion (Fig. 6). The mean annual evapotranspiration was higher than river runoff. The mean annual evapotranspiration exceeded river runoff and exceeded the half of the basin average precipitation up to 3700 m (Fig.7). Above 3700 m, river runoff exceeded evapotranspiration where more than half of precipitation runs off into river streams.

3.13. Calculation of mean forecasted water resources characteristics for the different scenarios of climate changes

As was calculated for each knotted points, the two dimensional array of climate change scenarios with stepwise progression of air temperature increased by 1, 2, 3, 4 and 5ºC, and precipitation changed by ±10, 20, 30, 40, 50% relative to the current state. Stated values in the digital models annual mean air temperature and annual precipitation were consequently changed and forecasted values of potential evaporation were computed (Eq. 1). The forecasted evapotranspiration was calculated based on DEM, forecasted precipitation, and the already computed potential evaporation (Eq. 2). The river runoff was forecasted as the difference between annual precipitation and annual evapotranspiration. The forecasted indexes of moisture were calculated as the ratio between forecasted annual precipitation and potential evaporation. The calculated data were averaged for the studied basins and presented as the array of scenarios for possible climate changes (Table 5).

3.14. Possible scenarios of water resources characteristics *(Note: the long-term changes in the glacier- covered areas were not considered in the simulated forecast).*

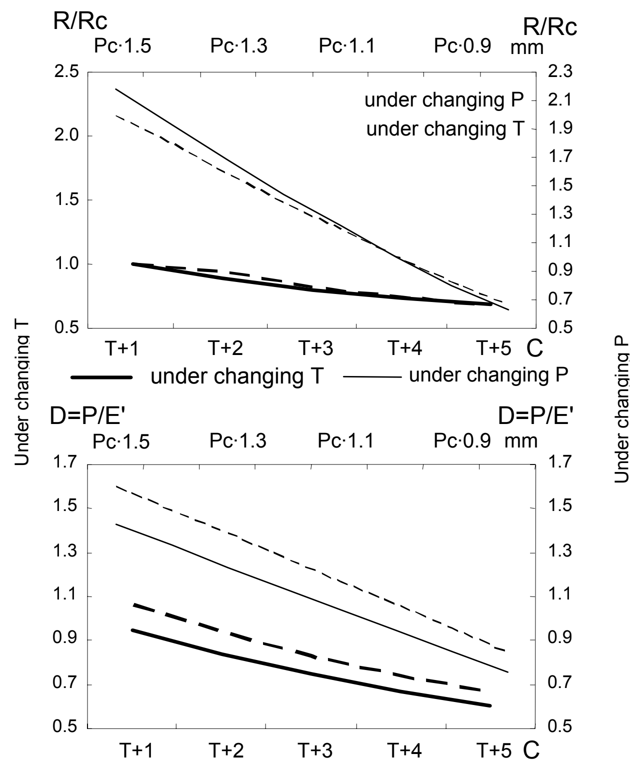

Fig. 9. *Ratio between predicted (R) and current (R_c) runoff and index of moisture conditions (D=P/E*) in the Chon Kemin (solid line) and Ala Archa (dotted line) river basins under the different scenarios of climatic changes (bold lines: $T = T_c + d$ and $P = P_c$; regular lines: $T = T_c$ and $P = m\ P_c$). R and R_c are predicted and current river runoff; T and T_c are predicted and current air temperatures; P and Pc are predicted and current*

The results of employing the Magicc&ScenGen software complex [*IPCC, 2001*] in the Tien Shan, which considered the scenarios of greenhouse gas emission (IS92a and IS92c), revealed that by 2100 warming over the Tien Shan will ranged between 1.8 and 4.4°C in respect of average annual air temperature. Humidification scenarios predict general variations of annual precipitation amounts that range from reduction by 6% to growth by 54% (i.e., an average growth of 24%) [*UNEP, 2003; Januzakov and Rustembekov, 2004*]. This projects an average increase of river runoff by a magnitude of 1.06 times in the Chon Kemin and Ala Archa River basins. The index of moisture would decrease by a magnitude of 0.82 (Fig. 8; Table5).

The river runoff and the index of moisture mainly depended on changes in precipitation while an increase in the air temperature is not so meaningful (Fig. 9). With no variation in precipitation (m=1), the range in forecasted river runoff grows by 29%, i.e., from the 1.0 (i.e., current air temperature) to 0.71 under forecasted air temperature increase by 4.4°C. At the same time, with no variation in air temperature ($T = T_{current}$), boundary forecasted precipitation ranges from reduction by 6% to growth by 54%, and the range in forecasted river runoff changes is 130%, i.e., from R/Rc = 0.94 to 2.24 correspondingly.

River runoff will drop insignificantly by about 7% (0.93) from current rate even if the air temperature rises to the maximum predicted range by 4.4º C, and precipitation would increase on average 1.24 times the current rate (Fig. 8; Table 5). However, an

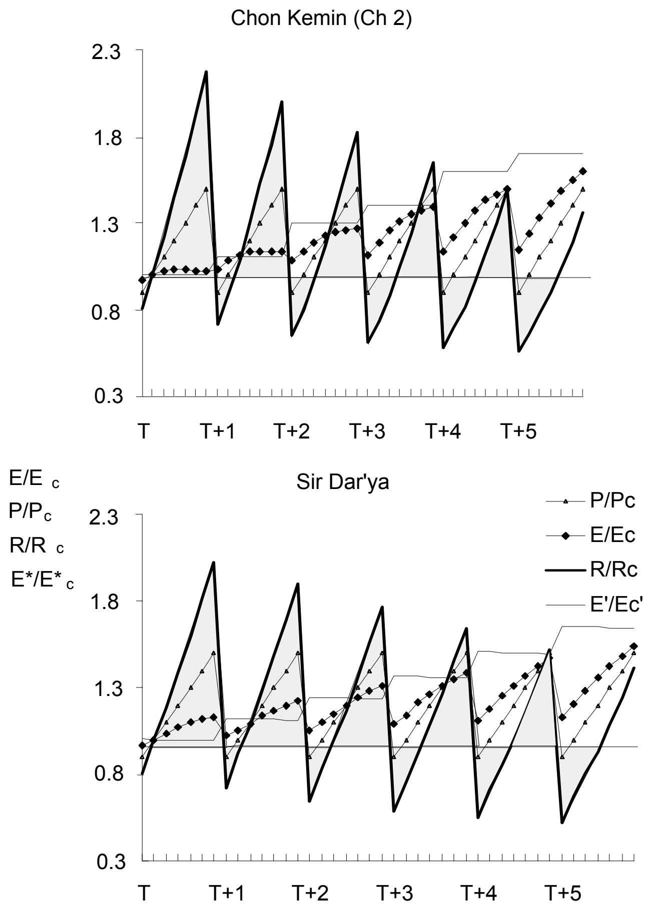

Fig.7. Ratios between predicted by 2001 and current river runoff (R/R_c), evapotranspiration (E/Ec), potential evaporation (E^*/E^*_c) under predicted changes of air temperature (T_c+d; $d=1,2,\ldots5$°C) and precipitation (mP_c, $m=0.9; 1, 1.1, \ldots1.5$) for the Chon Kemin and Sir Dar'ya R. basins.

increase of 1.73 times the current mean river runoff would occur if the maximum predicted range in precipitation were rise to 1.54 times along with an average warming of 3ºC. Provided that boundary conditions would occur (i.e., an increase in air temperature of 4.4ºC with a consequent increase of evapotranspiration at a magnitude of 1.13 times and a decrease in precipitation of 0.94), then Tien Shan's river runoff and its index of moisture would decrease by 0.55 times (Table 5). Under the opposite predicted threshold, conditions with an increase in precipitation of 1.54 times increase and an air temperature increase of 1.8 ^{o}C, the forecasted river runoff would grow about twice (1.8 times). Ratios between the forecasted and current river runoff, precipitation evapotranspiration, and potential evaporation are shown in the Figure 10. The river runoff ratio reached maximum of 2.2 under the current mean air temperature (d=0) and maximum precipitation grew by 56% (m = 1.5). The minimum river runoff ratio is forecasted to be 0.55 if precipitation decreases 10% (m = 0.9) and air temperature increases by 5ºC.

The sum of triangular areas above or below $R/R_c = 1$ was considered to correspond as probability relating to the forecasted river runoff growth or reduction relative to current conditions (Fig. 10). The probability of river runoff growth by 2100 in the Chon Kemin R. basin is 83% and 87% in the Sir Dar'ya R. basins, and the corresponding probability of its reduction is 17-13%.

The rapid change in river runoff indicates a non-linear system response to climate change (Fig. 10) caused by the non-linear response of evapotranspiration, which is a function of air temperature and precipitation. Minimal forecasted values of evapotranspiration ratios ($E/E_{c\ min}$) as well as river runoff ratios ($R/R_{c\ min}$) are related to minimum forecasted mean precipitation $P/P_{c\ min} = 0.9$. Maximum forecasted values of evapotranspiration ratios ($E/E_{c\ max}$) as well as river runoff rations ($R/R_{c\ max}$) are related to maximum predicted mean precipitation $P/P_{c\ max} = 1.5$. The insignificant growth in minimum values of evapotranspiration ratio from 0.97 ($T = T_c$) to 1.15 ($T = T_c+5$) is predicted if the predicted decrease in precipitation occurs ($P/P_c<1$), because the deficit of precipitation would decelerate the evapotranspiration with consequent slowing of the river runoff reduction that would occur with an increase of air temperature. While forecasted changes in maximum values of evapotranspiration ratios will be more notable growing from 1.03 to 1.6 when possible precipitation ratios reach maximum ($P/P_c= 1.5$) and air temperature increase by 5ºC. Under predicted surplus in precipitation, growth of air temperature causes accelerated growth of evapotranspiration and consequent sufficient river runoff decrease (Fig. 10).

3. Conclusion

To model the current river runoff in the Tien Shan, triangulation using Irregular Networks without gaps and interpenetration completely covering the mountain territory was implemented to digitize the annual distribution of air temperature and precipitation. The gradients of annual precipitation in TIN ranged from -102 to 832 mm km^{-1}. Employing just two climatic parameters for air temperature and precipitation is one of the main advantages of this simulation for predicting water resources. The simulation is based on extensive data, which principally distinguishes this simulation from other river runoff simulations.

This GIS model incorporated annual air temperature, precipitation, potential evaporation, evapotranspiration, and river runoff. This model was validated in the Chon Kemin, Ala Archa, Chatkal (Oigaing) and Narin river basins including its low reaches (Sir'Darya River) at the Fergana Valley using the method of transition from larger to smaller geographic units. The discrepancies were approximated through linear functions with multiple parameters of annual precipitation, glacier mass balance, river runoff, and the first-derivative for the current and previous years. The optimization of the measured and simulated annual river runoff values decreased the discrepancy by 2.5 times with 8% of root-mean-square error of measured runoff.

One of the main predictors of the current year's river runoff volume is the volume of river runoff during the previous year, which can be replenished by ground water. For example, at the beginning of 1970s, an observed intensive depletion of aquifers was caused by the abrupt decrease of precipitation and rapid increase of potential evaporation. Therefore, the evapotranspiration rate was higher than surface river runoff, which accounted for more than half of the total precipitation in the Tien Shan river basins.

Apparently, the internal moisture re-evaporation throughout central Asia is significant so, the arid, the semi-arid areas, and even the mountainous regions (up to 3,700 m) provide moisture to the alpine regions that feed back to Tien Shan rivers. This result agrees with our analysis of stable isotope records obtained from the central Asian ice cores [*Aizen et al., 2004a, 2005*], ***which revealed that a considerable amount of accumulated precipitation (more than half) in the high altitudes of central Asian glaciers was re-evaporated from internal moisture sources. Therefore, we propose that central Asia is a self-regulating system, where natural processes maintain the system in a steady state, so an increase of air temperature causes increased internal evapotranspiration with consequent intensifying of re-evaporated moisture precipitated in high mountains that should, as result, suppress the increased air temperature.***

However, the type, the seasonal distribution, and the regime of precipitation and river runoff could change.

The hypothetical climate-change scenarios were modeled as a stepwise progression based on climatic sceneries developed for Kyrgyzstan [*UNEP, 2003*], ***assuming an average increase in air temperature of 3^{o}C and a 1.2 magnitude increase in precipitation by the 2100. This predicts an increase of river runoff by 1.047 times. If we assume the predicted boundary conditions for precipitation decreased by a magnitude of 94% and air temperature increased by 4.4^{o} C, this would cause evapotranspiration to increase 1.13 times and river runoff to decrease by 55%. Under the opposite predicted threshold conditions indicating a 1.54 magnitude increase of precipitation and an air temperature increase on 1.8 ^{o}C, the predicted river runoff would grow by about 1.8. Under invariable precipitation, the range in predicted river runoff changes will be 29% under predicted air temperature increase. Considering invariable air temperature and boundary forecasted precipitation changes, the range in forecasted river runoff changes is 130%, i.e., river runoff increases by more than four times exceeding the changes if precipitation and air temperature do not increase. Thus, change in precipitation, rather than temperature, is the main parameter determining river runoff in the Tien Shan.***

In the frame of predicted possible climate change scenarios [*UNEP, 2003*] ***the probability of river runoff growth amounts to 87% and probability of its decline is 13%. Therefore, by 2100 in the Tien Shan R. basins flooding rather than drought could be expected in six cases out of the seven cases presented here. The maximum river runoff ratio could reach up to 2.2 times greater than current conditions, and the minimum river runoff ratio could possibly be 0.55 greater. The possible sharp change in river runoff indicates the non-linear system response caused mainly by non-linearly response of evapotranspiration to air temperature and precipitation changes. Therefore, a surplus of precipitation accelerates growth of evapotranspiration when the air temperature increases, while a precipitation deficit slows this process when air temperature growth.***

4. Training and Development

During the project several undergraduate and graduate students from the University of Idaho were involved in research and the result of their research was a base for the Senior thesis, Master Diploma and PhD thesis:

1. Arzhan Surazakov, UI PhD student since 2004 (2007 is a projective year for the PhD defence)
2. Daniel Joswiak, UI PhD student since 2005 (2008 is a projective year for the PhD defence)
3. Daniel Joswiak, UI grad student since 2002 (MSc in 2005)
4. Maria Glazirina, UI grad student (2002-2003)
5. Daniel Surgis, UI undergrad since 2005 (2008 is a projective year for the Senior Thesis completion)
6. Michael Clancy, UI undergad since 2002 (BA in 2006)
7. Brian Andesen, UI undergrad since 2001 (BA in 2004)
8. Christina Schwartz, UI undergrad since 2001 (BA in 2004)

All these students have been involved in laboratory or field researches, data processing and interpretation of results. The results of their research were discussed at UI and the Department Geography "Alpine Seminars" and have been included in the curriculum for Geog. 404/504 and Geog. 591 classes. Based on this project the Global Change and Alpine Ecosystems Research/Educational Program has been developed and implemented in College of Science at the University of Idaho (http://www.sci.uidaho.edu/cae/index.html) to recruit more students and intensify the environmental research in the National and International scale.

5. Outreach Activities

Several lectures about the Central Asia environmental changes and concequences have been given to the Moscow Idaho public community during 2003-2006 at the University of Idaho and Idaho High School.

Eight invited lectures were presented at the International Meetings and Universities (please see the ***Scientific Meetings and Invited Lectures*** above).

6. Major Findings

- ***More than half precipitation (up to 87%) in Central Asia has originating from re-evaporated, internal moisture that feed back to the mountain rivers. Only 13% of annual precipitation brought from the North Atlantic.***

- ***There has been a definite trend of the glacier recession over the last 140 years and especially since the middle of the 1970s, which indicates an abrupt climate change effect. The total reduction of the Tien Shan glacier is 14.2% during the last 60 years (1943-2003).***

- ***The main factor controlling the glacier regime is the impact of air temperature that affects the type of precipitation, the duration, and the intensity of snow and ice melt throughout altitudinal belts. The modern increase of air temperature, which is also observed in the Tien Shan's alpine areas, extends the period and intensity of melt and the glacier recession.***

- ***The glaciers and permafrost intensive melt in summer doesn't effect the Tien Shan river water solute concentration.***

- ***Separation of anthropogenic and natural variability of the Tien Shan river water solute revealed increased concentration of*** SO^{2-}, Ca^{2+} ***and*** $Na^{+} + K^{+}$ ***ions since the middle of 1970 in transitional zone at foothills, which occurred simultaneously with intensification of agricultural development in Central Asia.***

- ***The next year volume of river runoff in Central Asia watersheds depend on precipitation, snow or glacier melt amount of the previouse year, which can be replenished by ground water.***

- ***Melt water from alpine permafrost doesn't effect changes in the total river runoff.***

- ***Increase in anuual air temperature by 3^{o}C and 1.2 magnitude increase in precipitation may increase Central Asia river runoff only by 1.047 times.***

- ***An decrease in precipitation by a magnitude 0.94 and icrease of annual air temperature by 4.4oC would increase evapotranspiration by 1.3 times and decrease runoff by 55%.***

- ***Under the opposite predicted threshold conditions indicating a 1.54 magnitude increase of precipitation and an air temperature increase on 1.8^{o}C, the predicted river runoff would grow by about 1.8 times. Under invariable precipitation, the range in predicted river runoff changes will be 29% under predicted air temperature increase. Considering invariable air temperature and boundary forecasted precipitation changes, the range in forecasted river runoff changes is 130%, i.e., river runoff increases by more than four times exceeding the changes if precipitation and air temperature do not increase. Thus, change in precipitation, rather than temperature, is the main parameter determining river runoff in the Tien Shan.***

- ***In the frame of predicted possible climate change scenarios*** [*UNEP, 2003*] ***the probability of river runoff growth amounts to 87% and probability of its decline is 13%. Therefore, by 2100 in the Tien Shan R. basins flooding rather than drought could be expected in six cases out of the seven cases presented here. The maximum river runoff ratio could reach up to 2.2 times greater than current conditions, and the minimum river runoff ratio could possibly be 0.55 greater. The possible sharp change in river runoff indicates the non-linear system response caused mainly by non-linearly response of evapotranspiration to air temperature and precipitation changes. Therefore, a surplus of precipitation accelerates growth of evapotranspiration when the air temperature increases, while a precipitation deficit slows this process when air temperature growth.***

7. Contribution

NSF's broad programs help us to build new science and technology base at the University of Idaho particularly in alpine hydrology, alpine GIS, and hydrological simulations, which give an excellent opportunity for students and researchers to learn and share their experience. The new knowledge will greatly impact to fields of water resources, hydropower, agriculture and melioration systems, water supply and mountain sustainable development. Central Asia has a history of more than 4000 years of irrigation-based agriculture. Today, Central Asia countries, Kazakhstan, Afghanistan, and north-western China have more than 100 million population living in small irrigated oasis's. Thus, storage capacity and seasonal regulation of streamflow in the mountains are vital for the ecological and socio-economic welfare of the downstream users.

The results received from our research will enable better develop and build the mountain infrastructure and avoid the consequences of the natural hazards and loss for people and local communities that will revenue billions of dollars to the national economies.

8. Contributions within Discipline

Our research will improve the hydrological and climate predictive models particularly for Central Asia. Build new understanding of the natural processes in alpine mountains that are the water tower of the World. The findings of this research enable to develop some new principal conceptions for education and public needs, for the hydrological, hydropower and melioration constructions, the road and industrial infrastructure. The knowledge received has an immediate availability for the public and civil engineering communities through the papers published in peer-reviewed journals (please see list publications below). New method of GIS of the alpine regions has been also delivered for many new students through the UI Global Change and Alpine Ecosystems Research/Educational Program and Alpine Seminars.

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