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Analogous simulation of the annual runoff of Heihe River (China, Qilianshan)

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Abstract

Analogous simulation model was developed and used to calculate annual runoff of the Heihe River, located in western China with limited hydrological data available. The analogy was drawn with the Naryn Basin having similar hydrographic and climate characteristics. The runoff and climate characteristics of Keria and Yurungkax river basins in western China were also taken into consideration. Simulated annual runoff is considered as rather satisfactory.

1. Introduction

Glaciers are one of the most important water resources, in particular, in the arid region extending over central Eurasia. It is of importance, therefore, to estimate the changes of annual river runoff from glacierized area, since the river water is of significance for local people to use for irrigation, drinking, and the other daily use. The Heihe River, one of the rivers originating from glaciers in Qinghai, Gansu Provinces, and Inner Mongolia, China, starts to flow from Qilian Mountains, running toward north, and disappears in a lake : a typical inland river. The length is roughly 400 km in total.

The famous Silk Road locates through the basin in the east and west direction. At the same time, a nomadic route in the north and south direction also penetrating through the basin, crossing with the Silk Road. The basin is considered hence the most important area in the long history, because many fights have taken place between nomads and agrarians in the basin in some era, and they are in harmony in other era. The runoff variation of the basin is of great importance for interpreting the historical events, since the people have been dependent on the availability of water even in the historical time.

For estimating the historical variation of the river runoff, however, available data are very limited. As a first trial of the estimation, therefore, we have tried to estimate the runoff changes in the last several decades by introducing the analogous simulation method.

2. Statement of a problem

Various on complexity mathematical models and computer programs (*e.g.*, Borovikova *et al.*, 1972 ; Abbott *et al.*, 1986a, 1986b ; Bergstrom, 1995 ; Beven *et al.*, 1995 ; Vinogradov, 1982 ; Konovalov, 1985 ; Seibert, 1999) use at present for description and calculation runoff process of mountain rivers with undistorted seasonal course. One of the basic conditions for development and application methods of mathematical modeling in hydrology is availability of the long-term climatic information, and also data for determination parameters of a basin, coefficients of empirical equations and dependences used to simulate components of hydrological cycle. After estimating, the volume of information available now for Heihe river basin, we come to the conclusion, that any of the listed above models can not be used because of the absence of long-term data on runoff, which are necessary first of all for calibration and testing a model.

In this situation it is expedient to fit up for Heihe basin an analogous watershed with a similar complex of parameters influencing on formation and a long-term regime of annual runoff. The method of runoff calculation for a basin-analogue should allow its certain even indirect confirmation or testing besides of substantial utilization in Heihe basin.

3. Criteria similarity of river basins

The following criteria were accepted as parameters of similarity between Heihe watershed and a certain basin-analogue.

1. Close enough values of area and average

weighted altitude of both basins.

2. The same major factors of runoff formation, having similar relative contributions to the river feeding.
3. Similar seasonal distribution of monthly averaged air temperature and monthly sums of precipitation at the average weighted altitude of a watershed.
4. Similar seasonal distribution of runoff, which have to be resulted after realization of the above three conditions.

The first stage to determine area of Heihe river basin was bounding this watershed on topographic map. The isoline 1500 m a.s.l was accepted as the low border closing basin area. Geographical coordinates - longitude and latitude were further determined for all points forming closed contour of the watershed. Then boundary of the basin was overlaid on the Earth digital elevation model - GTOPO30, prepared by US Geological Survey (1997). Contour of this basin was finally updated by means of GTOPO30 DEM model where longitude, latitude and elevation above sea level are known for each pixel of raster image and their size corresponds to the map of 1 : 100000 scale. Values of area and average weighted elevation within the boundary of Heihe watershed were estimated by means of appropriate software modules of GIS IDRISI 32 2nd version (Eastmen, 2001). As a result, it was determined that area of Heihe basin at outlet limited by isoline of 1500 m a.s.l. is 9900 km^2, and average weighted elevation for this area equals to 3671 m a.s.l.

4. Determination average values of climate factors

Average weighted altitude is one of the basic geometrical parameters of a mountain river basin, where spatial variability of the main climatic factors of runoff formation (precipitation, air temperature and its humidity, solar radiation, etc.) essentially depending on elevation of a region.

Analysis performed by Denisov (Borovikova *et al.*, 1972) has shown, that for extrapolation data on precipitation x along elevation z the most common form of dependence $x=x(z, t)$ is a nonlinear function :

$$x(z)=x(z_0)[1+k_2(z-z_0)+k_3(z-z_0)^2], \qquad (1)$$

where $x(z)$ and $x(z_0)$ are accordingly sums of precipitation on the elevations z and z_0, k_2 and k_3, empirical coefficients. Following to the method, suggested by Borovikova *et al.* (1972), decomposition of function x (z) at the point z_0 to the Taylor series is used for determination the parameters k_2 and k_3 :

$$x(z)=x(z_0)+x'(z_0)(z-z_0)+\frac{x''(z_0)}{2!}(z-z_0)^2. \qquad (2)$$

Bringing $x(z_0)$ out of parenthesis, we obtain :

$$x(z)=x(z_0)\left[1+\frac{x'(z_0)}{x(z_0)}(z-z_0)+\frac{x''(z_0)}{2x(z_0)}(z-z_0)^2\right]. \qquad (3)$$

Function $x(z_0)$ could be defined by means of analytical expression approximating dependence of precipitation from altitude, which based on long-term average data. In the most common case it is

$$x(z_0)=az_0^2+bz_0+c. \qquad (4)$$

Then

$$x(z)=(az_0^2+bz_0+c)\left[1+\frac{2az_0+b}{az_0^2+bz_0+c}(z-z_0)+\frac{a}{az_0^2+bz_0+c}(z-z)^2\right]. \qquad (5)$$

It follows from this equation, that

$$k_2=\frac{2az_0+b}{az_0^2+bz_0+c}, \qquad (6)$$

and

$$k_3=\frac{a}{az_0^2+bz_0+c}. \qquad (7)$$

In the case of rather homogeneous spatial distribution of precipitation, their average layer $\bar{x}$ for some basin with area F could be obtained by means of the following expression-

$$\bar{x}=\frac{1}{F}\int_{Z\min}^{Z\max} x(z)\frac{dF}{dz}dz. \qquad (8)$$

Substituting $x(z)$ according to Eq. (1) into the expression for $\bar{x}$ we get :

$$\bar{x}=\frac{x(z_0)}{F}\int_{Z\min}^{Z\max}[1+k_2(z-z_0)+k_3(z-z_0)^2]\frac{dF}{dz}dz. \qquad (9)$$

At the integrating procedure in Eq. (9) we will take into consideration that

$$\tilde{z}=\frac{1}{F}\int_{Z\min}^{Z\max} z\frac{dF}{dz}dxz, \qquad (10)$$

is mean weighted elevation for the basin area F bounded by altitudes Z_{min} and Z_{max}, and Eq. (11)-

$$\sigma_z{}^2=\frac{1}{F}\int_{Z\min}^{Z\max}(z-\tilde{z})^2\frac{dF}{dz}dz, \qquad (11)$$

represents variance of altitudes within this area. Ultimately for determination average layer of precipitation for area F within the altitudes Z_{min} and Z_{max} we got equation :

$$\bar{x}=x(z_0)[1+k_2(\tilde{z}-z_0)+k^3(\tilde{z}-z_0)^2]+x(z_0)k_3\sigma_z^2, \qquad (12)$$

where the first term in the right part represents amount of precipitation at the average weighted elevation $\tilde{z}$.

Table 1. Long-term average values of air temperature and annual precipitation by the data of meteorological stations located within 93.0–104.0° E and 36.0–43.0° N.

Mst Title	Lat	Long	Alt, m a.s.l	BegYear (T)	BegYear (P)	T℃ Mean I-XII	T℃ Mean VI-VIII	P I-XII, mm
HaMi	42.82	93.52	738	1951	1951	9.8	25.4	36
Ejin Qi	41.95	101.07	941	1960	1960	8.4	25.1	36
Guaizinhu	41.18	103.27	959		1960			38
Dunhuang	40.15	94.68	1139	1938	1951	9.3	23.5	38
Anxi	40.53	95.77	1171	1939	1951	8.7	23.3	47
Minqin	38.63	103.08	1367	1953	1953	8.0	21.9	111
Jiu Quan	39.77	98.52	1477	1934	1934	7.2	20.5	88
ZhangYe	38.93	100.58	1483	1937	1937	7.0	20.3	128
Abagaqi	39.22	101.68	1510		1960			112
Yumenzhen	40.27	97.03	1526	1953		6.9	20.6	
Wuwei	37.92	102.67	1532		1960			162
Yemajie	41.58	96.88	1963	1958		4.1	18.2	
XiNing	36.62	101.77	2261	1936		6.0	16.4	
Lengh	38.83	93.38	2733	1957		2.7	15.9	
Golmud	36.42	94.90	2808	1956		4.6	16.6	
Gonghe	36.27	100.62	2835	1953	1953	3.6	14.3	322
Delingha	37.37	97.37	2982	1955		3.8	15.6	
Dulansi	37.02	98.77	2985	1957		4.3	15.3	
Wushaoling	37.20	102.87	3045	1951	1951	−0.2	10.1	391
Uulan Caka	36.78	99.08	3088	1956	1956	1.7	13.1	209
Da Qaidam	37.85	95.37	3173	1957		1.4	14.0	
Dulan	36.30	98.10	3191	1940		2.9	13.7	
Gangca	37.33	100.13	3301	1957	1960	0.1	9.8	380
Qilian Tuole	38.82	98.42	3361	1957	1957	−3.0	9.1	288

Note: T- is air temperature, P- is precipitation

It follows from Eq. (12) that if $k_3=0$, mean value of linear function x from z equals to its value at the average weighted elevation of a basin, *i.e.* $\bar{x}=x(\bar{z})$. This important conclusion will be repeatedly used in the further research.

All available data from different open international sources of meteorological information (Guterman (ed.), 1968 ; Kaiser *et al,* 1997 ; Lebedev and Kopanev (eds), 1975 ; WMO/OMM, 1996) were collected for obtaining local dependences of precipitation and air temperature from elevation in Heihe basin. List of meteorological stations, within the mountain area Nanshan including Qilianshan ridge and Heihe river basin is given in Table 1. Location of these stations could be seen on Fig. 1.

This set of meteorological data and altitude of stations above sea level allowed us to get representative dependences both annual sums of precipitation $P_{i-xii}=f(z)$ and average summer air temperature $T_{vi-viii}=f(z)$ from elevation z above sea level. Empirical formulae for these dependences have the following form:

$$P_{i-xii}=0.125z=75.15, \quad (13)$$

for annual sum of precipitation and

$$T_{vi-viii}=29.15-0.0053z, \quad (14)$$

for average summer air temperature. The following dimensions were used in Eqs. (13) and (14) : elevation z, in m a.s.l., precipitation in mm, air temperature in℃. The index of determination or squared coefficient of correlation was 0.85 for $P_{i-xii}=f(z)$, and 0.93 for $T_{vi-viii}=f(z)$.

Since dependence $P_{i-xii}=f(2z)$ for the territory Nanshan within 93.0–104.0°E and 36.0–43.0°N found out linear (*i.e.* $k_3=0$), it is necessary to determine only parameter k_2 in Eq. (1) using the Denisov's method (Borovikova *et al,* 1972). Empirical formulae of Eq. (13) and Eq. (15) were used for this purpose. The following form of Eq. (15) was obtained from common Eq. (6) for k_2 at $a=0$:

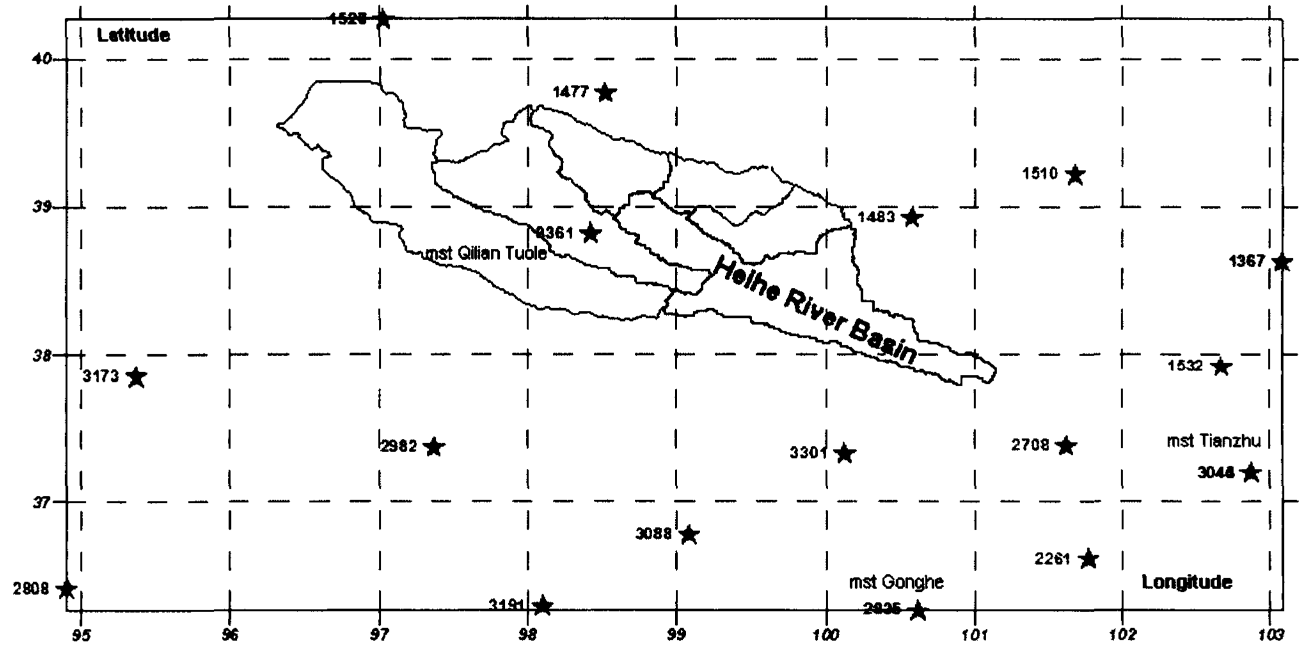

Fig. 1. Sites of meteorological observation (marked by star) within Nanshan region. Near to the mark of meteorological station is its elevation in m a.s.l.

$$k_2 = b/(bz_0 + c). \qquad (15)$$

Here, following to Eq. (13), parameter b for the considered region equals to 0.125, and $c = -75.15$, but z_0 equals to elevation of the meteorological station, which data on precipitation will be extrapolated to the average weighted elevation of Heihe basin. Widespread linear extrapolating formula is used for calculating long-term range of T_{v-viii} values at the average weighted elevation of Heihe river basin :

$$T(\hat{z}, t) = T(z_0, t) - \gamma(\hat{z} - z_0), \qquad (16)$$

where γ is vertical lapse rate of air temperature, and $T(z_0, t)$ is known air temperature at the elevation z_0 where certain meteorological station locates. It follows from Eq. (14), that the parameter γ for calculations of average summer air temperature at the average weighted elevation of Heihe basin equals to 5.3℃ km^{-1}. Thus the considered method of calculation $T_{vi-viii}$ and P_{i-xii} at the average weighted elevation $\underline{z}$ and Eqs. (1), (13), (14) and (16) allowed us to obtain annual sums of precipitation and summer air temperature as mean values for the whole area of Heihe river basin.

Ranges of observation on precipitation and air temperature for 1960-1993 on a network of the meteorological stations located within 93.0-104.0°E and 36.0-43.0°N were used for revealing the features of seasonal course of these elements. Good representation on spatial and temporal variability of climate characteristics for the considered territory can be received from Fig. 2 and 3. Basing on these graphs, we formulated conclusions for understanding conditions of runoff formation in Heihe river basin, and for search of a watershed with a similar hydrological regime.

- Intra-annual distribution of monthly precipitation has a well defined maximum in the summer period (the largest monthly sum is in July) and a minimum in the winter (the smallest monthly sum is in December-January). This feature is typical for all considered meteorological stations.
- The largest values of average monthly air temperature also take place in summer time (June-August) with a maximum in July. Regular decreasing of air temperature is observed in all months of a year depending on the elevation of the region. On Fig. 2 it is well visible that according to falling air temperature at meteorological stations, the height of a set of bars gradually decreases within the marked limits of each month on a time or abscissa axis. Here it is necessary to notice that the described spatial and temporal distribution of air temperature is the common property for many river basins of the Central Asia (Amudarya, Syrdarya, Tarim, Indus, Ganges, Brahmaputra, Huang He and others).

The analysis described above allowed formulating the following characteristic attributes in order to select basin-analogue for Heihe river watershed.

1. The area of a basin located in the Central Asia is around of 10000 km^2.
2. The average weighted elevation of a basin is within 3500-3700 m a.s.l.

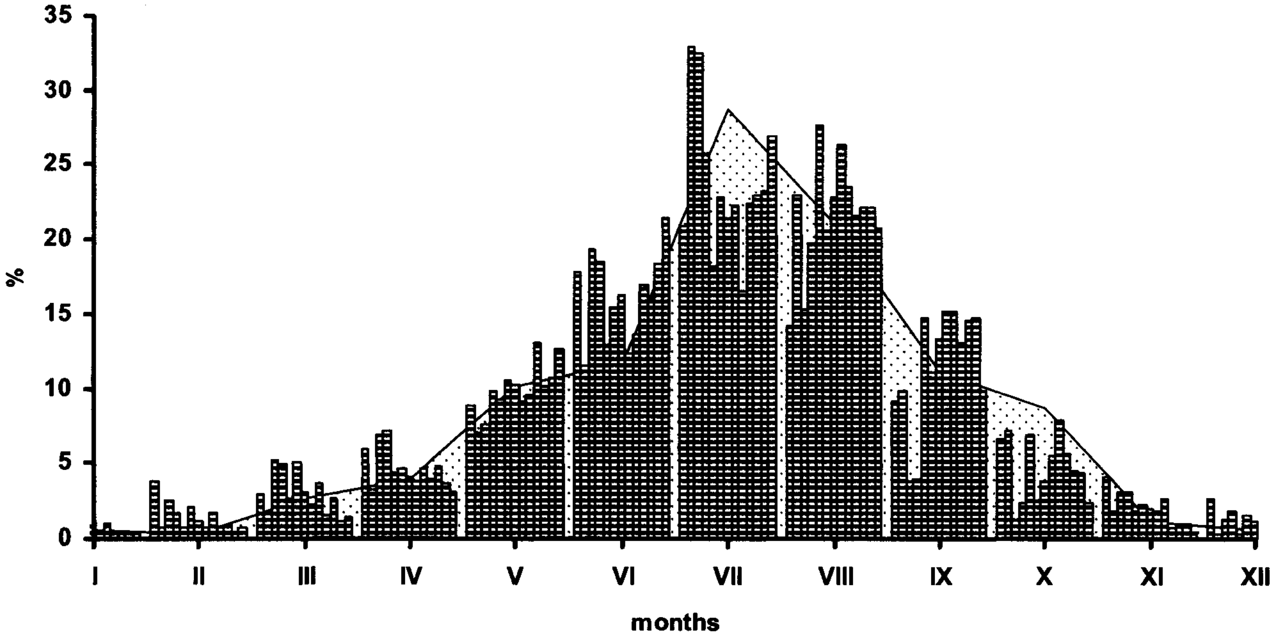

Fig. 2. Intra-annual course of relative monthly precipitation within Nanshan region. Each vertical bar on the graph related to the data at separate meteorological station.

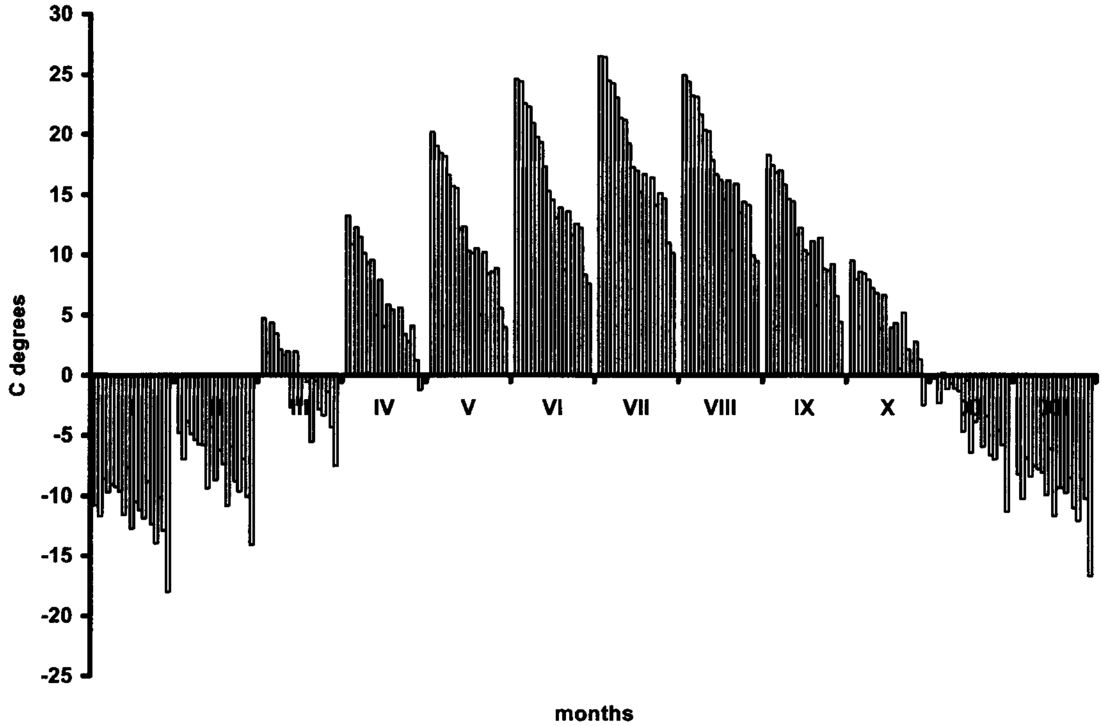

Fig. 3. Intra-annual course of monthly air temperature within Nanshan region. Each vertical bar on the graph related to the data at separate meteorological station.

3. There is clear characteristics of summer maximum and winter minimum of precipitation.
4. Long-term year-round runoff data are available measured at hydrological gorging site.
5. Long-term year-round data of precipitation, temperatures and humidity of air are available measured at meteorological stations, whose number is enough for obtaining regionally representative dependences of the listed climatic characteristics from elevation above sea level and/or other spatial coordinates.
6. There is prevalence of snow or snow-rain type of runoff formation.

Table 2. Some topographical characteristics of Yurungkax and Keria river basins.

Basin	Area, km²	Mean weighted elevation of catchment, m a.s.l	Glaciers area, km²	Mean weighted elevation of glaciers, m a.s.l
Yurungkax	17046	4416	3581	5582
Keria	13249	4417	738	5929

Note: 1. Function of area distribution along altitude for Yurungkax river basin is $y=-0.0196x^4-0.0131x^3+0.1081x^2+0.323x+0.436$.
2. Function of area distribution along altitude for Keria river basin is $y=-0.0439x^4-0.0628x^3+0.1957x^2+0.430x+0.383$.
Here y is integral function of x distribution,, std - is standard deviation.

5. Selection basin-analogue

There are some grounds to assume that conditions of runoff formation for right tributaries of Tarim River and over the territory bounded by coordinates 93.0–104.0°E and 36.0–43.0°N, may have common features because they located close enough to each other. This assumption proves to be true that on a map of distribution the annual sum of precipitation for China territory (http://www.lib.utexas.edu/maps/middle_east_and_asia/china_precip.jpg) and for the Asian continent (GPCC, Offenbach, Germany Wetter Dienst) both areas are inside the same zone interval of precipitation scale.

From the number of right tributaries of Tarim, the most various set of the hydrometeorological information is available for Keria and Yurungkax river basins. Geometrical parameters of these basins are given in Table 2. All area and altitudinal characteristics in Table 2 were obtained by reconnaissance for the contours of watersheds and glaciers on topographical maps, definitions of geographical coordinates of these contours and utilization of the proper software modules of GIS IDRISI 32, v. 2 for calculation of the required parameters.

Analysis of the intra-annual distributions of climatic factors of runoff in Yurungkax and Keria basins showed that in both basins maximum of monthly sum of precipitation is in June, but not in July as in Nanshan area. Nevertheless, it is possible to assume, that distribution of runoff in Nanshan area and Yurungkax and Keria basins can have similar features. However neither Yurungkax, nor Keria can be entirely used for decision of the given problem, if we will take into account all criteria accepted for search analogue-watershed. There is rather noticeable difference of geometrical characteristics and insufficient number of meteorological stations for getting dependences from elevation z above sea level as for the annual sums of precipitation $P_{i-xii}=f(z)$, and average summer air temperature $T_{vi-viii}=f(z)$.

Essentially more acceptable results were received after performing analysis of intra-annual distributions of runoff and its climatic factors in the other watershed of Central Asia—Naryn river basin.

6. Naryn river basin as analogue for calculation of Heihe river annual runoff

Central Tien Shan mountain area is located upstream of Naryn river basin, and it relates to the rivers of snow-glacial type of runoff formation (Shul'ts, 1965). The considered region includes Bolshoi Naryn and Malyi Naryn watersheds. Number of parameters for estimating topographical similarity of Naryn and Heihe basins is given in Table 3. The sources of hydrographic and glaciological data for Naryn river basin are given in USSR, Main Administration on Hydrometeorology (1967; 1974) and Vinogradov and Kotlyakov (1973-1977). Figures 4a, 4b and 5 present average long-term intra-annual distributions for monthly sums of precipitation, average monthly temperatures of air and Naryn river runoff, respectively. Quantitative similarity estimations of topographical parameters for Heihe and other basins are presented in Table 4.

Considering data in Table 4, we see that closeness of topographical parameters between Heihe and Naryn basins is very good and this is a ground to conclude that both rivers have identical type of feeding since the size of the basins and their average weighted elevations essentially influence to the runoff regime as Shul'ts (1965) has shown. One more confirmation of analogousness between Naryn (at gp Naryn) and Heihe basins on intra-annual distribution of the runoff and its climatic factors follows from comparison of Figs. 2, 3, 4a and 4b.

Maximum of monthly sum of precipitation is observed in July for Naryn basin, and their seasonal minimum in December-February. Similarity of temporal course of average monthly air temperature could be noted also both at the average weighted altitude, and in all range of elevations for Naryn and Heihe basins. Thus, we concluded the analogousness of topographical parameters for Naryn and Heihe river basins, intra-annual distribution of their runoff and its basic climatic factors. This conclusion is a necessary

Table 3. Some characteristics of Naryn and Heihe river basins.

Basin	Area, F_{bas}, km^2	Mean weighted elevation, m a.s.l	Glaciers area, km^2	Mean weighted elevation of glaciers, m a.s.l
Naryn (gp Naryn)	10500	3570	716	4208
Heihe (above 1500 m a.s.l.)	9900	3671	64	4556

Note: 1. Function of area distribution along altitude for Naryn river basin is $y=-0.0064x^4-0.0283x^3+0.0395x^2+0.359x+0.477$.
2. Function of area distribution along altitude for Heihe river basin is $y=-0.0058x^4-0.0295x^3+0.0331x^2+0.365x+0.485$.
Here y is integral function of x distribution, , std - is standard deviation.

Table 4. Relative differences (in%) between parameters of Heihe and other basins.

Basin	Area	Mean weighted elevation	Mean module of relative difference between coefficients in F (z) equations (see Tables 2–3)
Naryn	6.1	2.8	7.4
Yurungkax	−72.2	−20.3	108.4
Keria	−33.8	−20.3	260.6

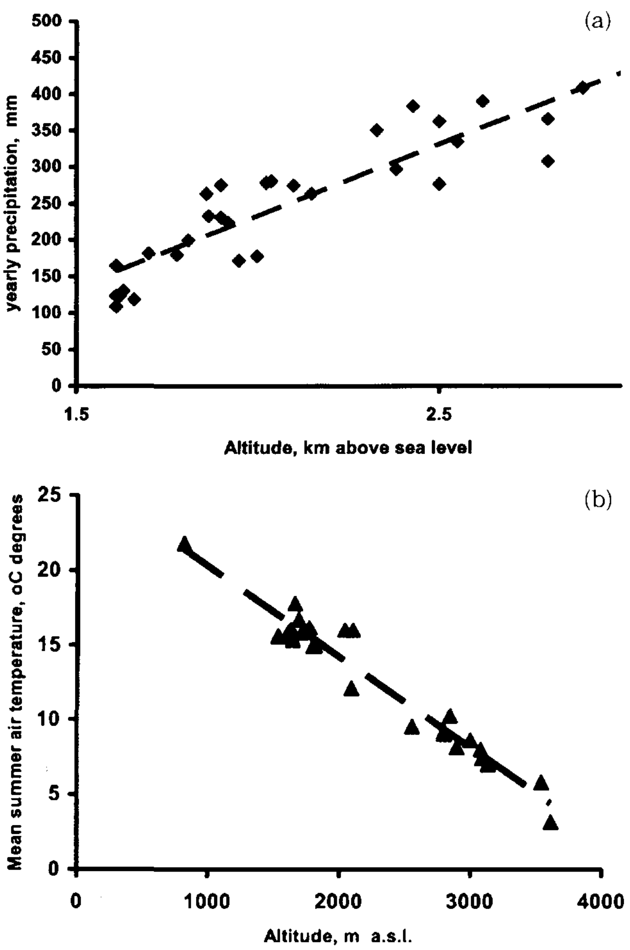

Fig. 4. (a) Dependence of yearly precipitation and (b) mean summer air temperature from elevation. By data of meteorological stations located within Naryn river basin and adjacent territory (USSR, Main Administration on Hydrometeorology, 1967, 1974; 1966,1968).

methodical substantiation for elaborating method to calculate long-term series of Naryn river annual runoff, which should provide an adequate quality of runoff simulation in the Heihe river basin. Glacier runoff has different relative contribution in feeding Naryn and Heihe rivers. In the Heihe basin it could be considered as neglible but not in the Naryn and we will bear it in mind.

7. Calculation annual runoff of Naryn river basin on equation of water balance

List of meteorological stations for Naryn basin and adjoining territory includes 51 points (USSR, Main Administration on Hydrometeorology, 1966, 1968). The empirical dependences (Fig. 5) and equations below $T_{vi-viii}=f(z)$ and $P_{i\text{-}xiii}=f(z)$ were received by these materials.

$$T_{vi-viii}=26.37-0.0061z, \tag{17}$$
$$P_{i-xii}=0.196z-158.5. \tag{18}$$

Here z is given in m a.s.l., $T_{vi-viii}$, in℃, P_{i-xii}, in mm. Taking into account these formula and Eqs. (1), (6) and (7), we obtain empirical Eqs. (19) and (20) for calcula tion of the average air temperature in summer season:

$$T_{vi-viii}(\hat{z},t)=T_{vi-viii}(z_0,t)-0.0061(\hat{z}-z_0), \tag{19}$$

and annual sum of precipitation on the average weighted elevation of Naryn basin :

$$P_{i-xii}(\hat{z},t)=P_{i-xii}(z_0,t)[1+0.503(\hat{z}-z_0)]. \tag{20}$$

Empirical parameter $k_2=0.503$ in Eq. (29) was determined, provided that elevations $\hat{z}$ and z_0 expressed in km, and basic point of observation $P_{i-xii}(z0,t)$ is mete-

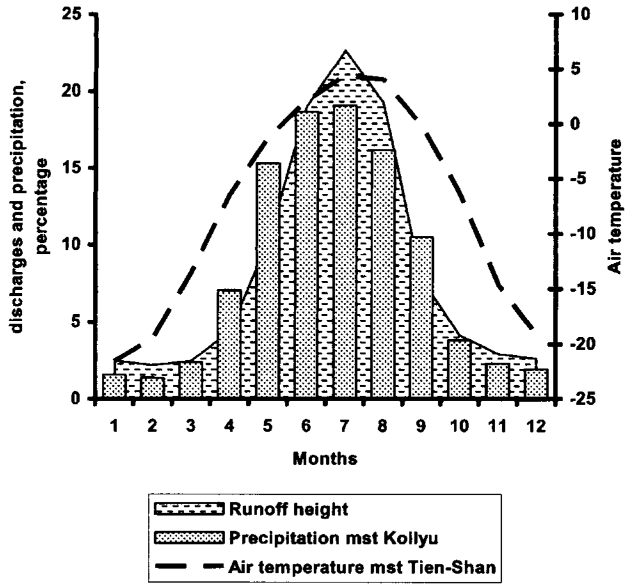

Fig. 5. Intra-annual distribution of monthly values of runoff and its climatic factors in Naryn river basin (averaged for 1952-988) by data gorging site Naryn, meteorological stations Tienshan and Koilyu (Bodo, 2000; USSR, Main Administration on Hydrometeorology, 1967, 1974; 1966, 1968).

orological station Koilyu for spatial and temporal extrapolation of annual sum of precipitation. This meteorological station locates within Naryn basin and its data almost do not deviate from the received relationship $P_{i-xii}=f(z)$. After substituting the average weighted elevation of Naryn basin (3.57 km) and the altitude of meteorological stations Koilyu (2.80 km) and Tien Shan (3.614 km) into Eq. (19) and Eq. (29), we got final formulas to calculate average value of meteorological variables for Naryn basin at $z=\tilde{z}$. Namely, air temperature of summer :

$$T_{vi-viii}(\tilde{z},t)=T_{vi-viii}(z_0,t)+0.27, \quad (21)$$

and annual sum of precipitation :

$$P_{i-xii}(\tilde{z},t)=P_{i-xii}(z_0,t)1.39. \quad (22)$$

Thus, based on the measured annual values of precipitation and runoff, we determine the coefficient of the annual runoff for Naryn (gp Naryn) basin, according to the well-known equation of water balance :

$$RC=R/[P-(E\pm W)], \quad (23)$$

where RC is a coefficient of annual runoff, R is runoff, E is evapotranspiration, W is dynamic storage of water in a basin.

Values RC, calculated by simplified version of Eq. (23), *i.e.* $RC=R/P$, are quite realistic for the given basin and meet well to characteristic values of this index for the rivers of Central Asia, which have been revealed by Shul'ts (1965). It is around 0.6 at the mean weighted altitude 3.5 km a.s.l.

For determining temporal variability of coefficient RC, let us present it as a stochastic function of some climatic factors of runoff :

$$RC=f(P,T,H). \quad (24)$$

Here P, T, and H are values of precipitation, temperature and humidity of air by data of meteorological observations for characteristic intervals of time. Undoubtedly the list of arguments in the right part of Eq. (24) can be expanded. As one may see, Eq. (24) presents general form of mathematical model, described temporal variability coefficient of an annual runoff. Concrete form of this model is multifactor equation of regression. All arguments of Eq. (24) should be extrapolated to the average weighted elevation of Naryn basin taking into account the further application of this equation in Heihe basin.

During the optimization of the structure of model of Eq. (24), it was revealed that the pair dependence $RC=f(P)$ is nonlinear. Finally, the following practical formula was received for calculation of long-term variability of annual runoff coefficient in Naryn river basin :

$$RC=0.891\Omega^2-2.443\Omega+2.148\theta, \quad (25)$$

where Ω is a relation of annual sum of precipitation at the $\tilde{z}$, average weighted elevation of Naryn in *i-th* year to their average long-term norm, θ is relation of average summer temperature in *i-th* year to the average long-term norm $T_{vi\ \ viii}(\tilde{z})$ at the average weighted elevation of Naryn. The coefficient of determination of Eq. (25) equals to 0.72. Before normalization, values of air temperature at the average weighted elevation of Naryn were transformed from Celsius scale to the Kelvin scale in order to avoid operations with numbers of different sign or equaled to zero. Numerical presentation model of Eq. (24) as function of normalized arguments is necessary, in relation to forthcoming use of Eq. (25) in Heihe basin with other ranges of precipitation and air temperatures at the average weighted elevation.

We got one more empirical Eq. (26) after including water vapor pressure u to the structure of the model of Eq. (24). In this case the coefficient of determination was 0.77.

$$RC=0.988\Omega^2-2.619\Omega+2.408\theta-0.33u. \quad (26)$$

Thus, expansion of the structure of model of Eq. (24) allows more precisely describing long-term variability of coefficient RC. However, Eq. (26) does not intend for application in Heihe river basin, because of the absence of long-term data on water vapor pressure.

Let us denote measured annual layer of Naryn river runoff as R_1 and calculated one by Eq. (25) as R_2. Series of R_1 and R_2 are related to the 1952-1985 time interval and these data were used to get distribution of statistical probabilities for both variables. Further we calculated relative deviations D (in %) of simulated values R_2 from the measured ones.

The equation

$D=100(R_1-R_2)/R_1$.

was applied for these calculations. Analysis of D modules showed that their averaged absolute value (*i.e.*, mod $\overline{D}$) is 5.5% for years whose probability of runoff deviates from long-term average value no more than 25%.

Value of $\overline{D}$ for low and high water years equals to 18.1%. The abnormal on water flow years are related to the cases, when integral function of distribution of runoff is in the limits from $P(X\pm0.674\ \sigma x)$ till $P(X\pm 2\ \sigma x)$. Here X is mean value of the range, σ_x is standard deviation of the variable x.

Annual runoff of Naryn river, calculated by means of empirical Eq. (25) and equation of water balance, should be considered as satisfactory, taking into account not so high coefficient determination of the Eq. (25) and essential enough errors of measured water discharges and precipitation in high-mountainous basins. It is necessary to add some new independent variables in model of Eq. (24) or to describe spatial variability of climatic factors of runoff formation by other methods and make better the convergence between time series $R_1(t)$ and $R_2(t)$,. Once more opportunity to improve results of simulation Naryn river runoff is the estimation of glaciers runoff in Eq. (23) but in this case we refused to do it in order to elaborate slightly simplified solution for Heihe basin where relative glaciers area is only 0.7%.

8. Modeling annual runoff of Heihe river by means of basin-analogue

Selection of the meteorological station, whose data on precipitation and/or temperature of air will be extrapolated on the average weighted elevation of a basin and substituted in Eq. (25) is undoubtedly crucial stage of application of the method of water balance and the empirical Eq. (25) in Heihe basin. High-mountainous meteorological stations having longest ranges of climatic observations within Nanshan territory were preliminary selected for decision of this problem.

Data on precipitation and air temperature at these stations were extrapolated to the average weighted elevation of Heihe river basin and norm and standard deviation values were received for each time series. Extrapolations were performed by means of the following equations :

$$T_{vi-viii}(\tilde{z}, t)=T_{vi-viii}(z_0, t)+0.27, \quad (27)$$

for average summer air temperature when data of Qilian meteorological point, served as $T_{vi-viii}(z_0, t)$ and

$$P_{i-xii}(\tilde{z}, t)=P_{i-xii}(z_0, t)1.39, \quad (28)$$

for annual sum of precipitation when Gonghe used as basic meteorological station, i.e., $P_{i-xii}(z_0, t)$.

As well as in Naryn river basin, the regional dependences of Eq. (13) for $P_{i-xii}=f(z)$ and Eq. (14) for $T_{vi-viii}=f(z)$, and also Eqs. (15) and (16) were used for definition empirical coefficients in Eqs. (27) and (28). Values of $T_{vi\ \ viii}(\tilde{z}, t)$ and $P_{i-xii}(\tilde{z}, t)$ were transformed further, in the same way as it was made for Naryn. Finally, long-term series coefficients of annual runoff in Heihe basin RC_2 was calculated by Eq. (25). Substantiated using this equation for Heihe river basin is the important result obtained by means of proven similarity of the watersheds topography and climate factors for runoff formation between Naryn and Heihe river basins.

Layers of annual runoff during of 1957-1993 were computed after multiplication of the annual sum of precipitation at the average weighted elevation of Heihe watershed on the coefficient of runoff. Long-term serie of Heihe river annual runoff, computed on the basis of equation of water balance, is the main result of the present research.

Certain indirect methods were used to estimate quality of calculated long-term serie, because of absence of sufficient sample of direct measurements of runoff. Particularly Fig. 6 illustrates temporal fluctuations of an annual runoff of Yurungkax and Heihe rivers during 1957-1990. It is established earlier, that conditions of runoff formation in these two river basins have some similar properties. Analysis of temporal changes of the annual runoff of both rivers allows concluding on synchronism of low and high water years in most cases for the compared watersheds. This conclusion confirms the acceptable quality of simulated annual runoff of Heihe river.

One more way to test results of calculated annual runoff for Heihe basin is independent determination of annual evapotranspiration for its area and solving equation of water balance. Empirical Eq. (29), suggested by Romanenko (1961), was applied for calculating potential evaporation E.

$$E=0.0018(25+T)^2(100-H_m). \quad (29)$$

Here T is air temperature in℃, Hm is relative humidity of air in%. Analysis and control various methods of calculation E have shown (Xu and Singh, 1998) that results obtained by Romanenko's formula are rather close to the data of evaporimeter. It is obvious, that the values of air temperature and relative humidity should be determined at the average weighted elevation for Heihe basin in order to get mean layer of evaporation for this watershed.

Empirical Eq. (30) was used for calculation of air temperature T_y averaged for year at the elevation 3671 m a.s.l. :

$$T_y=9.3-0.9\times10^{-6}z^2+0.0004\ z, \quad (30)$$

where z is elevation of region in m a.s.l.

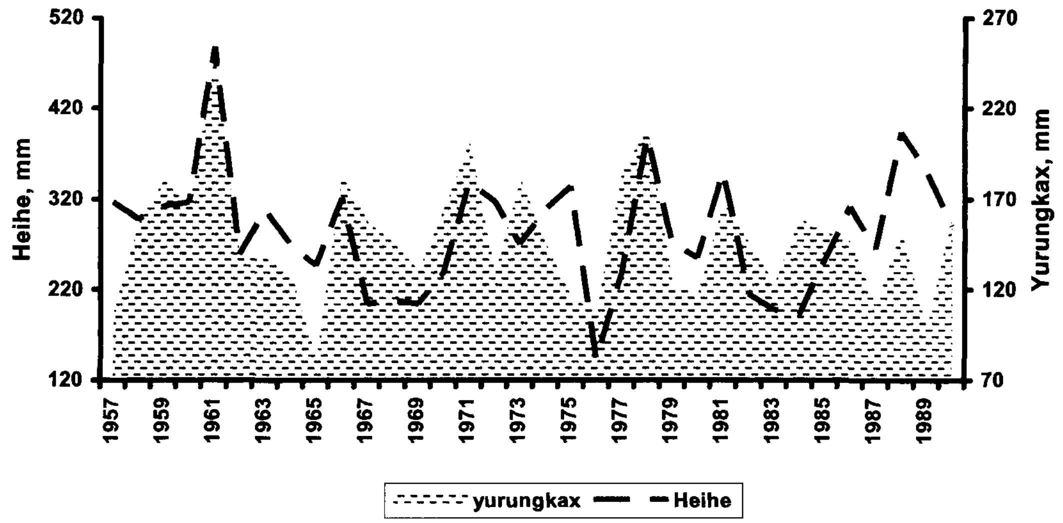

Fig. 6. Temporal course of measured and computed yearly layer of runoff. Yurungkax and Heihe rivers.

Spatial variability of average annual relative humidity of air $Hm_{(i-xii)}$ was studied in order to determine this meteorological element on the elevation $\bar{z}=3671$ m. The region under research includes plain territory of China and bounded by mountain ranges: Nanshan, Kunlun, Tien Shan, Pamir and Hindu Kush. Data of observation (Titov, 1976; Pertziger, 1996; Kaiser *et al*, 1997) basically for 25 to 30 years interval were processed for determining parameters of multiple linear regression of Eq. (31):

$$Hm_{(i-xii)}=47.7+0.175\lambda-0.754\varphi-0.0038z. \quad (31)$$

Here λ and φ are longitude and latitude in degrees, and z is elevation in m a.s.l. Complex coefficient of correlation for Eq. (31) equals 0.73, and average standard error of calculation was 7.1%. After substitution in Eq. (31) mean weighted elevation and geographical coordinates of Heihe basin, it was found that average long-term relative humidity equals to 52%.

Values T_y and $Hm_{(i-xii)}$, received by Eqs. (30) and (31), were used in Eq. (29) for estimating potential annual layer of evaporation E in Heihe basin. Ultimately E was determined as 572 mm. The searched for evapotranspiration ET presents production of the computed value E on the coefficient describing soil moisture K_{sm} that is

$$ET=K_{sm}\,E. \quad (32)$$

We accepted $K_{sm}=0.4$ as approximate estimation, based on measured evaporation in Yurungkax river basin (Ujihashi and Kodera, 2000).

As a result of application of the Romanenko's method and calculations by Eqs. (30) and (32), it was revealed that the average long-term value of evapotranspiration in Heihe basin was up to 229 mm. Hence, solving equation of water balance, we received, that the difference between input (precipitation) and output (runoff+evapotranspiration) parts of this equation equals to 6% only. This distinction becomes undoubtedly even less if to add runoff from melting ice and firn on glaciers area in Heihe basin to the input part of water balance. Thus, almost ideal convergence between input and output parts of the equation of water balance is an additional confirmation of representatively simulated long-term series of annual runoff in Heihe river basin.

9. Conclusion

1. Method to determine components of water balance equation in the Heihe river basin was elaborated and realized for simulating a temporal range of annual runoff in this watershed. The following stages were fulfilled in order to get acceptable results.

- Revealing characteristic features of intra-annual distribution of precipitation and air temperature for Heihe river basin by data of meteorological stations located within of 93.0-104.0°E and 36.0-43.0°N.
- Determination the following morphometry parameters of the Heihe river watershed: area of the basin, its average weighted altitude, function of the basin area distribution in relation with elevation above sea level, glaciers area and its average weighted altitude.
- Definition of the criteria for river basins similarity on conditions of runoff formation and its intra-annual distribution.
- Analysis of mean weighted elevation of a watershed as characteristic level for determining values of precipitation, air temperature or another meteorological variable, which equaled to their average meaning for the whole given area of a river basin. Thus calculating climate factors at the mean weighted elevation of a watershed allows application of water balance method for simulat-

ing annual runoff both for Heihe and its analogy river basins.

- Revealing basin-analogy for modeling long-term range of annual runoff of Heihe river. Naryn river basin was adopted as basin-analogy for Heihe watershed.
- Preparation digital archive of long-term climate observations for the following areas : China territory within 93.0–104.0°E and 36.0–43.0°N, Yurungkax and Keria river basins (right tributaries of Tarim river) and Naryn basin (right origin of Syrdarya river). This archive includes also runoff data for the listed watersheds. Empirical formulae were obtained for calculations annual sum of precipitation and average summer air temperature at the mean weighted elevation of Heihe river and its basin-analogy.

2. Multiple regression equation was obtained for computing annual runoff coefficient related to the Naryn river. Comparison of calculated and measured long-term ranges of Naryn river runoff and their statistical parameters demonstrates a rather acceptable quality of the simulation results based on water balance equation.

3. Long-term range of Heihe river annual runoff for 1957–1993 was simulated as the results of applying water balance method and equation for calculating annual runoff coefficient, obtained by means of the basin-analogy. Independent estimations of simulation quality allow considering this temporal range as rather representative and corresponded to climate conditions in the considered region.

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