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«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ
«ХАЛЫҚ» ЖҚ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ
КАЗАХСТАН»
ЧФ «Халық»

NEWS

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NAS RK is pleased to announce that News of NAS RK. Series of geology and technical sciences scientific journal has been accepted for indexing in the Emerging Sources Citation Index, a new edition of Web of Science. Content in this index is under consideration by Clarivate Analytics to be accepted in the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index. The quality and depth of content Web of Science offers to researchers, authors, publishers, and institutions sets it apart from other research databases. The inclusion of News of NAS RK. Series of geology and technical sciences in the Emerging Sources Citation Index demonstrates our dedication to providing the most relevant and influential content of geology and engineering sciences to our community.

Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

ЧФ «ХАЛЫҚ»

В 2016 году для развития и улучшения качества жизни казахстанцев был создан частный Благотворительный фонд «Халык». За годы своей деятельности на реализацию благотворительных проектов в областях образования и науки, социальной защиты, культуры, здравоохранения и спорта, Фонд выделил более 45 миллиардов тенге.

Особое внимание Благотворительный фонд «Халык» уделяет образовательным программам, считая это направление одним из ключевых в своей деятельности. Оказывая поддержку отечественному образованию, Фонд вносит свой посильный вклад в развитие качественного образования в Казахстане. Тем самым способствуя росту числа людей, способных менять жизнь в стране к лучшему – профессионалов в различных сферах, потенциальных лидеров и «великих умов». Одной из значимых инициатив фонда «Халык» в образовательной сфере стал проект Ozgeris powered by Halyk Fund – первый в стране бизнес-инкубатор для учащихся 9-11 классов, который помогает развивать необходимые в современном мире предпринимательские навыки. Так, на содействие малому бизнесу школьников было выделено более 200 грантов. Для поддержки талантливых и мотивированных детей Фонд неоднократно выделял гранты на обучение в Международной школе «Мирас» и в Astana IT University, а также помог казахстанским школьникам принять участие в престижном конкурсе «USTEM Robotics» в США. Авторские работы в рамках проекта «Тәлімгер», которому Фонд оказал поддержку, легли в основу учебной программы, учебников и учебно-методических книг по предмету «Основы предпринимательства и бизнеса», преподаваемого в 10-11 классах казахстанских школ и колледжей.

Помимо помощи школьникам, учащимся колледжей и студентам Фонд считает важным внести свой вклад в повышение квалификации педагогов, совершенствование их знаний и навыков, поскольку именно они являются проводниками знаний будущих поколений казахстанцев. При поддержке Фонда «Халык» в южной столице был организован ежегодный городской конкурс педагогов «Almaty Digital Ustaz.

Важной инициативой стал реализуемый проект по обучению основам финансовой грамотности преподавателей из восьми областей Казахстана, что должно оказать существенное влияние на воспитание финансовой грамотности и предпринимательского мышления у нового поколения граждан страны.

Необходимую помощь Фонд «Халык» оказывает и тем, кто особенно остро в ней нуждается. В рамках социальной защиты населения активно проводится работа по поддержке детей, оставшихся без родителей, детей и взрослых из социально уязвимых слоев населения, людей с ограниченными возможностями, а также обеспечению нуждающихся социальным жильем, строительству социально важных объектов, таких как детские сады, детские площадки и физкультурно-оздоровительные комплексы.

В копилку добрых дел Фонда «Халык» можно добавить оказание помощи детскому спорту, куда относится поддержка в развитии детского футбола и карате в нашей стране. Жизненно важную помощь Благотворительный фонд «Халык» оказал нашим соотечественникам во время недавней пандемии COVID-19. Тогда, в разгар тяжелой борьбы с коронавирусной инфекцией Фонд выделил свыше 11 миллиардов тенге на приобретение необходимого медицинского оборудования и дорогостоящих медицинских препаратов, автомобилей скорой медицинской помощи и средств защиты, адресную материальную помощь социально уязвимым слоям населения и денежные выплаты медицинским работникам.

В 2023 году наряду с другими проектами, нацеленными на повышение благосостояния казахстанских граждан Фонд решил уделить особое внимание науке, поскольку она является частью общественной культуры, а уровень ее развития определяет уровень развития государства.

Поддержка Фондом выпуска журналов Национальной Академии наук Республики Казахстан, которые входят в международные фонды Scopus и Wos и в которых публикуются статьи отечественных ученых, докторантов и магистрантов, а также научных сотрудников высших учебных заведений и научно-исследовательских институтов нашей страны является не менее значимым вкладом Фонда в развитие казахстанского общества.

С уважением,
Благотворительный Фонд «Халык»!

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LONG TERM FORECAST OF THE MONTHLY FLOW HYDROGRAPH OF YERTIS RIVER (VILLAGE BORAN) BASED ON COMBINED STATISTICAL MODELING OF THE RIVER FLOW AND PRECIPITATION

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Abstract. The article provides an attempt to make scenario forecasts of the Yertis river flow (v. Boran) based on combined statistical modeling of the river flow and atmospheric precipitation. Forecasting by the canonical expansion method makes it possible to forecast not only the annual runoff, but also its distribution within the year by the monthly time intervals, as well as the possibility of making a forecast with any time period from one year to several years, depending on the period time of meteorological forecasts, taking into account possible climate changes. To check the quality of the modeling, the obtained simulated data of mean precipitation and runoff, coefficients of variation and asymmetry, auto and cross-correlation were compared with the actual data. Results of checking statistical modeling for the hydrological station of the Ertis River – p. Boran showed that the deviation of modeled data from actual data on annual and vegetation runoff in high-water years is 20–23 %, in average-water years it is 3–4 %, and in low-water years – 29–33 %. Consequently, the canonical expansion method can be used to assess changes in river runoff under conditions of current climate change, as well as for the future prospective. According to the estimates obtained on the river.

Ertis – s. Boran in general is expected to increase annual flow by up to 10% of normal flow.

Keywords: monthly flow, flow hydrograph, precipitation, temperature, statistical modeling, canonical expansion, long-term forecast of the river runoff, climatic scenarios

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ӨЗЕН АҒЫНДЫСЫ МЕН ЖАУЫН-ШАШЫННЫҢ АЙЛЫҚ МӘНДЕРІН БІРЛЕСТІРІП, СТАТИСТИКАЛЫҚ МОДЕЛЬДЕУ АРҚЫЛЫ ЕРТІС (БОРАН А.) ӨЗЕНІНІҢ ГИДРОГРАФЫН ҰЗАҚ МЕРЗІМГЕ БОЛЖАУ

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Аннотация. Мақалада Ертіс өзені-Боран а. гидрологиялық бекеті мысалында айлық ағынды мен жауын-шашын мәндерін канондық жіктеу әдісі арқылы бірлестіре статистикалық модельдеу мүмкіншілігі көрсетілген. Канондық жіктеу әдісін қолдана отырып болжау тек жылдық ағынды ғана емес, сонымен бірге оның жыл ішінде таралуын болжауға, сондай-ақ бір жылдан бірнеше жылға дейінгі кез келген уақытқа метеорологиялық болжамдардың орындалу мерзіміне байланысты климаттық өзгерістерді ескере отырып болжам жасау мүмкіндігін береді. Модельденген қатардың сапасын тексеру мақсатында бақыланған және модельденген мәндердің, яғни орташа мәндері, ассиметрия және вариация, авто және өзара корреляция коэффициенттері салыстырылды. Ертіс өзені - Боран а. гидрологиялық станциясы бойынша статистикалық модельдеуді тексеру нәтижелері сәйкес жылдық және вегетация кезеңінде модельденген мәліметтер бақыланған мәліметтерден ауытқуы суы мол жылдары 20–23 %, орташа сулы

жылдары 3–4 %, ал суы аз жылдарда 29–33 % құраған. Яғни, канондық жіктеу әдісін өзен ағындысын климаттың өзгеруінің әртүрлі сценарийлері негізінде ұзақ мерзімді болжау үшін қолданылды. Жалпы алынған болжамдарға сәйкес Ертіс өзені – Боран а. бойынша жылдық ағындының 10% дейін өсуі күтілуде.

Түйін сөздер: айлық ағынды, ағынды гидрографы, жауын-шашын, температура, статистикалық модельдеу, канондық жіктеу, өзен ағындысының ұзақ мерзімді болжамы, климаттық сценарийлер.

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ДОЛГОСРОЧНЫЙ ПРОГНОЗ ГИДРОГРАФА МЕСЯЧНОГО СТОКА Р.ЕРТИС (С. БОРАН) НА ОСНОВЕ СОВМЕСТНОГО СТАТИСТИЧЕСКОГО МОДЕЛИРОВАНИЯ СТОКА И ОСАДКОВ

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Аннотация. В статье показана возможность совместного моделирования значений месячного стока и атмосферных осадков с методом канонического разложения на примере гидрологического поста р. Ертис – с. Боран. Прогнозирование методом канонического разложения дает возможность составления прогноза не только годового стока, но и его распределения внутри года по месячным интервалам времени, а также возможность составления прогноза любой заблаговременности – от одного года до нескольких лет, в зависимости от заблаговременности метеорологических прогнозов с учетом возможных изменений климата. Для проверки качества моделирования, полученные данные средних значений осадков и стока, коэффициенты вариации и асимметрии, авто и взаимная корреляция сравнивались с фактическими данными. Результаты проверки статистического моделирования по гидрологическому посту реки Ертис – с. Боран показали, что отклонение смоделированных данных от фактических по годовому и вегетационному стоку в многоводные годы составляет 20–23 %, в средневодные годы составляет 3–4 %, а в маловодные годы – 29–33 %. Следовательно, метод канонического разложения был использован для прогнозирования стока реки на долгосрочную перспективу на основе различных сценариев изменения климата. Согласно полученным оценкам на р. Ертис - с. Боран в целом ожидается увеличение годового стока до 10 % от нормы стока.

Ключевые слова: месячный сток, гидрограф стока, осадки, температура, статистическое моделирование, каноническое разложение, долгосрочный прогноз речного стока, климатические сценарии.

Introduction

Yertis river basin is a strategically important water basin for the economic development of Kazakhstan, which is sharing its waters with the People's Republic of China and the Russian Federation. In modern conditions of regional climate changes, as well as dependence from the water policy of neighboring countries and possible increase in water demand, it is more necessary than ever to assess the future condition of renewable water resources of the Yertis transboundary basin. In the current cycle of water availability (from 1974 to 2015), the total natural resources of river runoff of the Yertis river basin make 36.1 km^3, of which the local resources are 26.8 km^3, inflow from China is 10.6 km^3, outflow to China (rivers Kaba and Belozek) is 1.36 km^3. In addition, the lower reaches of the river Yertis are located on the territory of the Russian Federation, and the outflow from the Republic of Kazakhstan to Russia in natural conditions makes 30.5 km^3. The total factual resources of the river runoff of the Yertis river basin make 29.4 km^3, of which the local resources are 26.5 km^3, the inflow from the PRC is 8.32 km^3, the outflow to the PRC (rivers Kaba and Belozek) is 1.36 km^3, outflow to the Russian Federation is 23.7 km^3 (Alimkulov **et.al., 2019)**.

To substantiate the measures for guaranteed water supply to the population of the country and to the sectors of the economy, it is necessary, first of all, to get prognostic estimates of water resources for the future prospective of several decades. Until now, the methods of such assessments have been based on the results of statistical analysis of the data of long-term observations of the characteristics of river runoff under the assumption of stationarity of their long-term changes. In connection with the ongoing and expected climatic changes, it is required to develop the new approaches for the assessment of water resources in the future (Wood et.al., 2004; Leonov, 2010). More or less those requirements are met by the method of predictive estimates of river runoff resources based on the forecast of meteorological characteristics using the models of the general circulation of the atmosphere and ocean. Prospective changes in water resources are assessed by the prognostic dependences of the river runoff from the climatic characteristics (forecasted values of precipitation and air temperature). Most of the scientists accept and use these models (Climate Change, 2014: General Report, 2014; Davletgaliyev et.al., 2017; Riahi et.al., 2011).

The use of models of the general circulation of the atmosphere and ocean for prognosis river flow scenarios at the same time face a number of unaccounted features of the modeling itself. The affirmation that climate warming is due to the anthropogenic factors has also different opinions (Leonov, 2010; Kauppinen, et.al., 2014; Zharkova et.al., 2015; Yusuke et.al., 2019). Unfortunately, the current level of the development of science does not yet allow us to develop a reliable forecast of river runoff, we can only talk about possible "scenarios" or "scenario forecast". There is no doubt that models of the general circulation of the atmosphere and ocean will develop, and the use of method for predicting changes of the river water resources in the long term based on ensemble averaging together with other accepted approaches (statistical modeling, HBV modeling, etc.) is the main from methods of forecasting of the river flow.

In the modern world, among the variety of forecasting methods, the important value has hydrological data modeling. Modeling is a mathematical tool that allows us to investigate the processes occurring in the natural environment. There are two types of hydrological models: models based on statistical data, they study the data using mathematical and statistical tools, indicators are provided into the input; the behavior of the system, dependencies, laws describing the phenomenon under the study are obtained at the output. The second type of models is built on the basis of laws already known to science, at first the model can be developed on the arbitrary set of data, and then it can study the real processes. These models can be used for forecasting, setting possible values of the parameters at the input, and obtaining the system response at the output. The first type of models is referred to stochastic modeling; the second is to deterministic one (Kuzin et.al., 2014; Davletgaliyev et.al., 2020).

In this work, the long-term forecast of river runoff was carried out using a statistical model with the canonical expansion method, which is a universal system for analyzing of the casual processes. The task was to assess the possibility of its application for long-term forecasting of hydrological characteristics. Forecasting by the canonical expansion method makes it possible to forecast not only the annual runoff, but also its distribution within the year by the monthly time intervals, as well as the possibility of making a forecast with any time period from one year to several years, depending on the period time of meteorological forecasts, taking into account possible climate changes.

Research object

The river Yertis is the largest river in Kazakhstan, which flows through the territory of three independent countries — the People's Republic of China (618 km), the Republic of Kazakhstan (1698 km) and the Russian Federation (1964 km). The catchment area of the river is 1643 thousand km² (Surface water resources of the USSR, 1969).

The sources of Yertis are located on the border of Mongolia and China, on the eastern slopes of the Mongolian Altai ridge. From China, with the name of Kara Yertis, it enters Kazakhstan, passes through the Zhaisan depression and flows into the Buktyrma reservoir. Many rivers from the Rudnyi Altai, Tarbagatai and Sauyr ridges flow into the Buktyrma reservoir (formerly Lake Zhaisan). Having significantly increased its water content, Yertis flows out to the northwest through the Buktyrminskaya hydroelectric power station to the Ust-Kamenogorsk reservoir located behind it. After passing through the Ust-Kamengorsk hydroelectric power station, Yertis enters the Shulbinskoye reservoir. Downstream is the Semey town. In this section, Yertis receives the flow of its largest right-bank tributaries - rivers Buktyrma, Oba and Ulbi (Surface water resources of the USSR, 1969).

The structure of the hydrographic net of the Upper Yertis basin, belonging to the East Kazakhstan region, is conditioned by the complex relief, latitudinal and vertical zoning, and various climatic conditions. The features of the relief of the territory of Yertis basin are determined by the inclusion of the large orographic units in its composition: Rudnyi and Ontustik mountains of Altai, Sauyr-Tarbagatai, Shyngyztau, Kalba ridge, as well as the hummocky terrain region of the Kazakh folding country and the lowland of Priyertissie (Surface water resources of the USSR, 1969).

Geographical research in the area under consideration was carried out as early as the 18th century. By the end of the 19th century, in connection with the colonization of areas adjacent to the construction sites of the Siberian Railway, it became necessary to systematically study this area. In particular, it was connected with the search of water supply sources. The conducted expeditionary studies were of hydrographic nature and were accompanied only by episodic measurements of water discharge.

The first gauging station in the Upper Yertis basin was opened on Yertis river on October 29, 1899 near the city of Ust-Kamenogorsk and it is still in operation. In 1909, on the river Kaldzhir near the village Chernyayevka, another gauging station was opened, which was functioning until October 2005. The main number of the gauging stations was organized in the 30s of the XX century. Currently, about 30 gauging stations are considered active. The rest of them were closed at various times. The observations of the considered cross-section of Yertis river - v. Boran have been conducted since 1938.

The water resources of Yertis river are of great importance for the economy and health of the population of the large industrial region of Kazakhstan, which includes three regions: East Kazakhstan, Pavlodar and Karaganda, with a total area of more than 836 thousand km^2. The river provides water to the population and economy not only within its basin, but also through the K. Satpayev Canal (KSC), the inter-basin transfer of a part of the flow to the vast territory of low-water Central Kazakhstan is carried out (Basin plan for integrated water resources management and water conservation for the Irtysh river basin of the Republic of Kazakhstan, 2006; BI activity report for 2015, 2016).

The use of river flow of the Yertis basin dates back to the mid-1950s in the upper part of the basin in the territory of PRC, but until the 1990s, water management activities in the basin did not significantly affect the river flow. Serious measures for the development of water resources originate from the second half of the 1990s in order to provide water to the region of an oil field near the Chinese city of Karamai (Basin plan for integrated water resources management and water conservation for the Irtysh river basin of the Republic of Kazakhstan, 2006; BI activity report for 2015, 2016). For the statistical modeling on the basis of the canonical decomposition of runoff and precipitation, the reconstruction of the series of natural annual runoff of Yertis river – v. Boran by the method of hydrological analogy was carried out (the chosen calculation period was 1960–2015) (Determination of the main calculated hydrological characteristics, 2004).

Research methods

A number of works (Pugachev, 1962; Busalayev et.al. 1973; Davletgaliyev, 1991; Frolov et.al. 2014; Davletgaliyev et.al., 2019) were devoted to the issue of modeling hydrographs of monthly runoff, including their group modeling. The advantages and disadvantages of those methods were discussed in (Davletgaliyev, 1991). However, those works did not consider the possibility of their application for the combined modeling of monthly runoff and runoff-forming factors. Close to the idea of this work, the studies were carried out in the work (Davletgaliyev et.al., 2019), where runoff factors are taken into account on the basis of physical and mathematical model of runoff formation, developed at Water Problems Institute of the Russian Academy of Sciences. However, the advance time of such forecasts is limited (Kuzin et.al., 2014) and does not take into account possible changes in runoff-forming factors as a result of global climate change.

By solving a number of water management and hydrological tasks, there is a need for combined statistical modeling of not only runoff values, but also runoff-forming factors, in particular precipitation and air temperatures. Such a task may arise by predicting river runoff taking into account possible climate changes.

Obtaining a set of realizations of flow hydrographs and flow-forming factors can be considered as a task of modeling casual vectors and processes specified in a finite time interval. Modeling can be performed by the method of conditional distributions, for which the multivariate distributions of the process must be known. The question of choosing multivariate probability distributions has not been finally resolved. Therefore, from a practical point of view, the methods of obtaining possible realizations of a casual process within the frames of the correlation theory turn out to be more acceptable than within the frames of multivariate distributions. In this case, the task of modeling processes other than normal is reduced to modeling normal processes with a subsequent transition to the original distribution law. Normal processes are uniquely specified by the matrix of correlation moments and, therefore, their modeling within the frames of the correlation theory is equivalent to modeling by specified multidimensional distributions. From this point of view, the canonical decomposition could be the best method for statistical modeling of the runoff process. It allows characterizing a casual process by the set of independent casual values and non-casual functions. The method is optimal in the class of linear transformations. In fact, here we have decomposition by natural orthogonal components (main components method) (Kuzin et.al., 2014; Pugachev, 1962; Busalayev et.al., 1973; Davletgaliyev, 1991; Frolov et.al., 2014; Davletgaliyev et.al., 2019).

An important advantage of the canonical expansion method is the possibility of its generalization for modeling of interconnected hydrometeorological series simultaneously in several sections (Davletgaliyev et.al., 2020; Pugachev, 1962). The modeling task is reduced to modeling random vector functions.

The canonical expansion of random vector functions is obtained by a natural way by generalizing the formulas of the one-dimensional case. For this, as shown in (Pugachev, 1962), it is enough in the corresponding relations to replace the argument t by the set of arguments t and enter the number of the components of the random vector function. Then the expansion of the random vector function is given by the following formula:

$$Q_\ell(t_\nu) = m_Q(t_\nu) + \sum_{i=1}^{N}\sum_{\nu=1}^{M} \varphi_{\nu\ell}^{(i)}(t_\nu)V_\nu, \qquad (i, \ell = 1,\ldots,N) \tag{1}$$

where

$$\varphi_{\nu\ell}^{(i)}(t_\nu)=\frac{1}{D_\nu^{(i)}}\left[K_{i\ell}(t_\nu t_\mu)-\sum_{k=1}^{i-1}\sum_{m=1}^{M}D_m^{(k)}\varphi_{mi}^{(k)}(t_\nu)\varphi_{mi}^{(k)}(t_\mu)-\sum_{m=1}^{\nu-1}D_m^{(i)}\varphi_{mi}^{(i)}(t_\nu)\varphi_{m\ell}^{(i)}(t_\mu)\right] \quad (2)$$

- auto- and cross-correlation functions;

$$D_\nu^{(i)}=K_{ii}(t_\nu t_\nu)-\sum_{k=1}^{i-1}\sum_{m=1}^{M}D_m^{(k)}\left[\varphi_{mi}^{(k)}(t_\nu)\right]^2-\sum_{m=1}^{M}D_m^{(i)}\left[\varphi_{mi}^{(i)}(t_\nu)\right]^2 \quad (3)$$

- dispersion of random coefficients V;

$K_{ii}(t_\nu t_\mu)$ – correlation and cross-correlation functions of vector random function $Q_l(t)$, *M*- number of calculated intervals a year (months, decades).

Here:

ν = 1,2,……..M;

$\mu > \nu$; $\mu = \nu+1,\ \nu+2,\ \ldots M$ (with $\ell = i$);

μ=1,2,…..*M*; l= i+1, *i*+ 2,…. *N* (with $\ell > i$).

Writing expression (1) for centered functions, multiplying both sides of the resulting equation by V and performing the mathematical expectation operation, and also taking into account the properties of random correlated coefficients, we obtain coordinate functions of the first component Q_1(t) and its cross-coordinated function with other components. Further, taking into account the difference between the canonical expansion of the components Q_2(t), Q_3(t), ... Q_N(t) from Q_1(t), we determine the canonical expansion of the second component Q_2(t) and obtain a formula for the correlation functions Q_3(t) and its cross-correlation function with the other components Q_3(t),…., Q_N(t). This formula determines the auto- and cross-coordinate functions of the component Q_2(t). Continuing this process, we construct in turn the canonical expansion of all components of the random vector function $Q_\ell(t)$.

If we consider the monthly amount of precipitation as the main flow-forming factors, then the canonical expansion formula (1) for two random functions in relation to this task can be written in the form

$$Q\ (t)=m_Q(t)+\sum_{\nu=1}^{M}\varphi_{\nu1}^{(1)}(t)V_\nu^{(1)} \quad (4)$$

$$P(t)=m_p(t)+\sum_{\nu=1}^{M}\varphi_{\nu2}^{(1)}(t)V_\nu^{(1)}+\sum_{\nu=1}^{M}\varphi_{\nu2}^{(2)}(t)V_\nu^{(2)}, \quad (5)$$

where m_Q(t), m_p(t), is mathematical expected value of components Q(t), P(t);

$V_\nu^{(1)}$, $V_\nu^{(2)}$ - uncorrelated random values which mathematical expectations are equal to zero; $\varphi_{\nu2}^{(1)}(t)$ – the mutual coordinate function Q(t) with the component P(t); $\varphi_{\nu3}^{(2)}(t)$ – same with the component P(t). Here Q(t) means flow, P(t) – atmospheric precipitation.

Coordinate functions $\varphi_{\nu3}^{(1)}(t)$, $\varphi_{\nu3}^{(2)}(t)$ and variances of random variables are calculated by the formulas given in (Davletgaliyev S.K., 1991), where the possibility of the canonical expansion method for group modeling of runoff hydrographs is considered.

Functions $\varphi_{\nu 1}^{(1)}$, $\varphi_{\nu 2}^{(1)}$, $\varphi_{\nu 2}^{(2)}$ are determined from (2) by i = 1, $\ell = 1$; i = 1, $\ell = 2$; and i = 2, $\ell = 2$.

Statistical modeling of monthly runoff and precipitation was performed according to the formula (4). It follows from it that first is constructed a canonical expansion of the flow of the first component Q(t), as in the case of a one-dimensional expansion, then by the values $\varphi_{\nu 2}^{(1)}(t)$, $\varphi_{\nu 2}^{(2)}(t)$ – is canonical expansion of the second component P(t). Modeling can be performed in the same way as in the case of group modeling of monthly runoff by the canonical expansion method. The algorithm for combined modeling of runoff, precipitation and air temperatures is detailed in (Davletgaliyev, 1991).

Results and discussion

Let us consider the possibility of making a forecast of the hydrograph of the monthly runoff of Yertis river on the basis of the modeled series of runoff and runoff-forming factors. To test the model, we used the monthly mean values of river runoff and monthly values of atmospheric precipitation as a runoff-forming factor observed at meteorological stations located near the hydrological gauging stations under consideration. The length of the modeled series is 500 years, which is considered sufficient for rivers with the coefficients of correlation no more than 0.50–0.60. In all cases, the distribution law of monthly runoff and precipitation was chosen according to Pearson's criterion χ^2. The quality of the model, as noted above, is assessed by the degree of correspondence between the parameters of the original and modeled series. This requirement is met in all cases.

In this task, the average monthly water discharge of Yertis river – v. Boran and data of atmospheric precipitation at meteorological stations (MS) Kurshim and Zaisan for the period 1960–2015 was used as the initial data. Comparison of the statistical parameters of average monthly water discharge and atmospheric precipitation for the observed and modeled series of the river Yertis - v. Boran and MS Kurshim and Zaisan are shown in Table 1. The last column of the table shows the characteristics of the annual values of runoff and precipitation, obtained from the observed and simulated monthly values of runoff and precipitation.

Table 1 - Statistical parameters of average monthly stream flow and precipitation for the observed (1st line) and modeled (2nd line) series (n = 500) river Yertis - v. Boran and MS Kurshim and Zaisan

Charac-teristic	Months												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
stream flow													
Q, m^3/s	63.1	60.8	68.9	230.3	726.8	1121.8	695.6	428.5	271.1	191.7	115.5	72.4	337.2
	63.8	61.1	69.8	233.9	726.4	1119.5	692.5	423.2	264.1	184.8	111.2	69.5	337.5
Cv	0.17	0.13	0.23	0.29	0.27	0.32	0.34	0.25	0.38	0.61	0.62	0.31	0.22
	0.17	0.13	0.23	0.31	0.29	0.33	0.34	0.22	0.35	0.57	0.58	0.28	0.21
Cs/Cv	1	5	2	4	1	1	1	6	6	5	5	5	2
	2	8	3	4	1	1	1	5	5	4	4	5	2
R	0.06	0.17	0.22	-0.03	-0.22	0.07	-0.01	-0.02	0.06	-0.02	-0.03	0.11	-0.06
	0.08	0.20	0.23	-0.11	-0.27	0.09	-0.02	-0.08	0.01	-0.08	-0.11	0.09	-0.01

Precipitation													
X, mm	15,6	12,9	15,2	24,4	34,6	28,2	36,5	22,1	23,1	29,9	27,3	21,1	290
	14,6	12,2	14,7	24,3	35,5	28,2	37,4	21,7	23,0	30,1	27,0	19,8	289
Cv	0.66	0.55	0.68	0.58	0.61	0.57	0.54	0.59	0.62	0.50	0.43	0.53	0.20
	0.67	0.56	0.69	0.56	0.62	0.57	0.51	0.61	0.61	0.49	0.43	0.56	0.20
Cs/Cv	2	3	3	2	1	2	1	1	2	1	1	1	1
	2	4	2	2	1	2	1	1	2	1	1	1	1
R	0.12	0.03	-0.03	0.03	-0.16	-0.12	-0.07	0.06	-0.02	0.08	0.02	0.10	-0.09
	0.08	0.02	-0.03	0.01	-0.12	-0.16	-0.05	0.01	-0.05	0.09	0.08	0.06	-0.09

This table shows a good agreement between the mean and the coefficients of variation of monthly runoff and precipitation values by the duration of the modeled series n=500 years. The discrepancy between the observed and modeled values of the asymmetry coefficients of the first-order autocorrelation lies within the accuracy of calculating of these parameters. The canonical expansion model also reproduces well the correlation and cross-correlation matrix of the initial and simulated data. Comparison of the observed and modeled data of the cross-correlation matrix of runoff and precipitation showed good results (Table 2). Comparison of observed and modeled data of the cross-correlation matrix of runoff and precipitation also showed good results as in the Ile river basin (Davletgaliyev et.al., 2019).

Table 2 - Cross-correlation matrix of average monthly water discharges and monthly precipitation for the observed (1st line) and modeled (2nd line) series (n = 500)

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
I	0.15	-0.06	-0.15	0.21	0.46	0.16	0.43	-0.11	-0.01	0.03	-0.04	-0.08
	0.14	-0.04	-0.20	0.23	0.42	0.11	0.28	-0.09	-0.10	0.00	-0.03	0.00
II	-0.19	0.02	-0.34	-0.90	0.92	0.81	0.50	0.13	0.31	0.48	0.17	-0.33
	-0.27	0.04	-0.21	-0.74	0.98	0.54	0.61	0.23	-0.15	0.56	0.21	-0.08
III	0.05	-0.07	-0.08	-0.05	-0.14	-0.11	-0.15	-0.14	-0.09	-0.44	-0.14	-0.04
	0.03	-0.06	-0.07	0.03	-0.12	-0.13	0.04	-0.12	0.01	-0.34	-0.14	-0.01
IV	0.01	-0.01	0.01	0.05	-0.04	-0.04	-0.04	0.02	0.00	-0.02	0.00	-0.01
	0.01	-0.01	0.01	0.04	-0.02	-0.02	-0.02	0.01	-0.01	-0.01	0.01	0.01
V	0.01	0.00	0.00	0.00	0.01	0.00	-0.01	0.00	-0.03	0.01	0.00	0.01
	0.01	0.00	-0.01	0.00	0.01	0.00	0.00	0.00	-0.03	0.01	-0.01	0.01
VI	0.01	0.01	0.01	0.01	0.03	0.01	0.01	0.01	0.00	-0.01	0.01	0.00
	0.01	0.01	0,01	0,01	0,03	0,01	0,01	0,01	0,00	-0,01	0,01	0,00
VII	0.01	0.01	0.01	-0.02	0.03	-0.01	0.02	0.03	-0.01	0.01	0.00	0.02
	0.00	0.01	0.01	-0.02	0.04	0.00	0.02	0.03	0.01	0.02	0.00	0.02
VIII	0.05	0.01	0.03	-0.06	-0.01	0.00	0.10	0.08	-0.06	0.04	-0.03	0.01
	0.05	0.01	0.03	-0.05	-0.03	0.00	0.07	0.07	-0.06	0.04	-0.04	0.01
IX	0.05	0.00	0.07	0.06	-0.03	-0.04	0.01	0.03	-0.07	-0.12	0.00	0.04
	0.04	0.02	0.05	0.05	-0.08	-0.03	0.03	0.01	-0.03	-0.11	-0.01	0.01
X	0.02	0.04	-0.07	0.13	-0.05	0.05	-0.20	0.01	0.13	0.10	0.07	0.07
	0.03	0.02	-0.03	0.05	-0.02	0.03	-0.10	0.01	0.04	0.04	0.03	0.04
XI	0.04	-0.06	-0.02	-0.23	0.56	0.37	0.44	0.42	-0.68	0.10	0.15	0.37
	-0.09	-0.15	0.04	-0.21	0.18	0.08	0.40	0.16	-0.21	-0.01	0.08	0.01
XII	0.29	-0.08	0.29	0.16	0.11	-0.40	-0.32	-0.21	0.04	0.03	0.06	0.25
	0.18	-0.03	0.03	0.06	0.12	-0.08	-0.05	-0.12	-0.04	0.22	0.06	0,24

Also, to check the simulation results, the obtained simulated data was compared with the actual data for the different by water content years and the solution of the problem was verified using the example of data for 1969 (high-water year), 1982 (low-water year) and 1985 (average water year) (Table 3). For this purpose, the following parameters were selected from the actual observation data for those years: average annual precipitation, average precipitation for the vegetative period, annual runoff, runoff for the vegetative period. From the variety of simulated precipitation data, using the analogy method, we select approximate values by the ordinal number of realization and, using these numbers, we determine the corresponding to them hydrograph of the monthly runoff. As noted above, in the simulated series the values of runoff factors corresponding to their actual or modeled values can be represented by several realizations and the averaged value of the monthly runoff hydrograph should be taken as the simulated values.

Table 3 - Table of verification data Yertis river - v. Boran

	No. of the corresponding simulated hydrograph	Year	Annual precipitation, Mm	Precipitation for the vegetative period, mm	Annual runoff, m^3/s	Runoff for the vegetative period m^3/s
1		2	3	4	5	6
High-water year	№ 19, 28, 308, 343, 382, 449	1969	398 397	245 196	496 383	805 640
Deviation, %			0.20	20	23	21
Average water year	№ 85, 151, 220, 325, 341, 378, 472	1985	280 281	160 173	339 350	591 613
Deviation, %			0.20	8	4	4
Low-water year	№ 73, 89, 205, 256, 352, 376, 446	1982	215 213	116 107	195 252	328 436
Deviation, %			0.80	8	29	33

Note: the numerator is the actual data, the denominator is the simulated value

As for the year 1969, based on actual runoff and precipitation data, six hydrographs of monthly runoff were selected with the corresponding number of the modeled series 19, 28, 308, 343, 382 and 449. The deviation of the simulated annual runoff from the actual data is 23 %, and the runoff for the vegetative period is less than the simulated runoff by 21 %. The difference between the simulated and actual data (annual and vegetation flow) in the average water year (1985) does not exceed 5%, and in the dry year (1982) this indicator for the vegetation year is 33 %. To illustrate the simulation results, Figure 1 shows a comparison graph between simulated and measured runoff hydrographs.

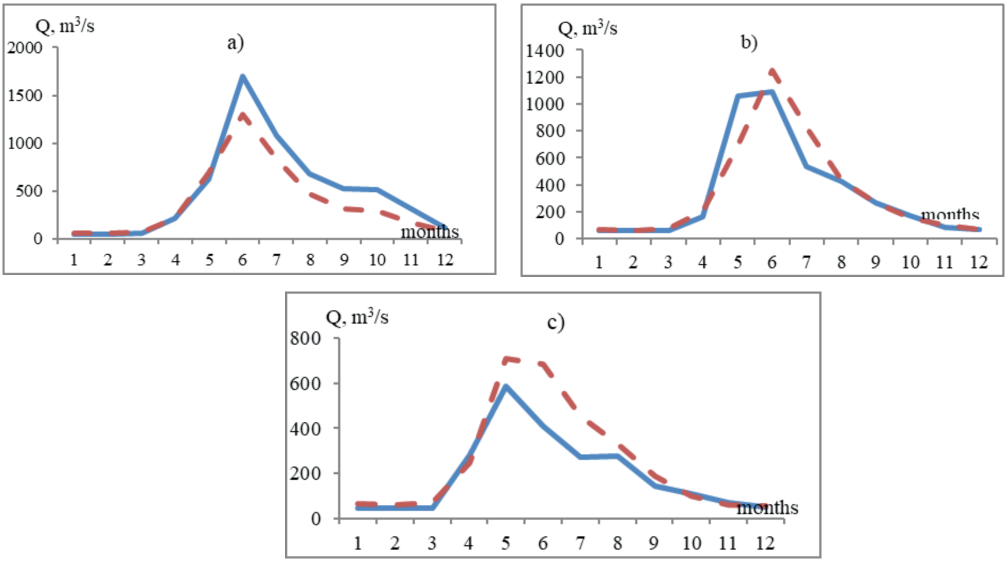


Figure 1 - Hydrographs of the monthly runoff of the river Yertis - v. Boran: a) - high-water year (1969); b) - average year (1985); c) - dry year (1982) - observed data; --- simulated data

Thus, the runoff and precipitation series modeled by the canonical expansion method have parameters close to the parameters of the actual data, and keeps the auto — and mutual-correlation matrix which are in the original series. Consequently, the canonical expansion method can be used to assess changes in river runoff under conditions of current climate change, as well as for the future prospective.

The modeled values of runoff-forming factors can be used to produce scenario forecasts of runoff hydrographs based on forecast data of meteorological factors. The advance time of such forecasts can be several decades of years, depending on the advance time of meteorological forecasts, produced taking into account possible climate changes.

For the forecast of the river flow in the long term based on various climate change scenarios, as input parameters were used the precipitation values, which were modeled for the future prospective using the global climate models according to the fifth IPCC report. Despite the skeptical assertion that the models of the general circulation of the atmosphere and ocean contain simplified calculation schemes for forecasting, it should be borne in mind that the leading scientific centers of world hydrometeorology are constantly improving the developed models; therefore this approach is one of the most promising. CMIP5 is based on calculations of the climate of the 20th century by specified in accordance with the observed concentrations of greenhouse gases and aerosols, as well as scenario calculations of the climate of the 21st century, taking into account a new group of scenarios of anthropogenic emissions — the so-called Representative Concentration Pathways (RCP). For the Fifth IPCC Report, the scientific community identified a set of four new scenarios, these four RCP include one emission reduction scenario that assumes a very low level of impact (RCP2.6); two stabilization scenarios (RCP4.5 and RCP6.0) and one scenario with very high levels of greenhouse gas emissions (RCP8.5) Their detailed description can be found in works (Climate Change, 2014: General Report, 2014; Riahi et.al., 2011).

The input meteorological data were used for three periods: 2030, 2040, 2050 for two scenarios RCP 4.5 and RCP 8.5. Period of 1981–2000 was taken as the base period. Using the simulated forecasted precipitation values obtained by the canonical expansion method, there were selected those values that are closest to the values obtained by the climate model for 2030, 2040, 2050 under two scenarios RCP 4.5 and RCP 8.5. The expected precipitation values in the simulated series can correspond to several realizations; from several obtained sample values was made averaging, i.e. forecasted precipitation values for the certain year are obtained (2030, 2040, 2050).

By the numbers of the predicted precipitation values obtained above were found the numbers of the corresponding runoff hydrographs. In this case, the forecast data can be presented in the form of a set of hydrographs, which are subject to averaging. The values of the averaged hydrograph are taken as scenario values of the future condition of the monthly river flow. Scenario forecast values of monthly runoff, as well as its changes from the base runoff of the Yertis river - v. Boran are provided in Table 4.

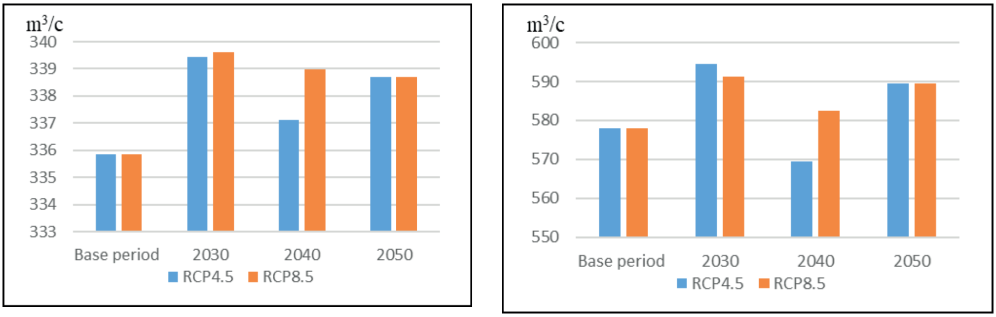
Table 4 - Change in monthly flow of the river Yertis - v. Boran by the various climatic scenarios for the future til 2030-2050.

	Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Base period (1960-2015)		62.7	60.6	69.5	220.4	719.8	1125	711.3	422.9	267.9	186.9	111.8	70.9
RCP4.5	2030	68.5	64.4	73.7	275.1	798.3	1132	728.4	407.6	224.6	145.0	88.6	66.1
	2040	63.2	59.4	64.7	234.5	710.7	1055	683.2	456.2	277.8	223.1	137.4	80.2
	2050	69.6	64.7	70.3	252.4	702.0	1102	817.6	435.2	227.9	162.1	100.7	59.8
RCP8.5	2030	70.5	64.4	73.8	275.0	929.2	1105	590.1	411.9	236.5	155.4	93.4	70.2
	2040	70.8	67.3	82.9	277.8	797.1	1093	675.5	408.6	242.9	164.5	101.4	85.9
	2050	69.6	64.7	70.3	252.4	702.0	1102	817.6	435.2	227.9	162.1	100.7	59.8
%*	2030	9.2	6.3	6.1	24.8	10.9	0.7	2.4	-3.6	-16.2	-22.4	-20.7	-6.7
	2040	0.8	-2.1	-6.9	6.4	-1.3	-6.3	-3.9	7.9	3.7	19.4	22.9	13.1
	2050	10.9	6.7	1.2	14.5	-2.5	-2.1	14.9	2.9	-14.9	-13.3	-9.9	-15.6
%*	2030	12.4	6.2	6.2	24.8	29.1	-1.8	-17.0	-2.6	-11.7	-16.9	-16.5	-1.0
	2040	12.9	11.0	19.3	26.1	10.7	-2.9	-5.0	-3.4	-9.3	-12.0	-9.3	21.2
	2050	10.9	6.7	1.2	14.5	-2.5	-2.1	14.9	2.9	-14.9	-13.3	-9.9	-15.6

* Changes in monthly flow from the base period (1974-2015), %

Analysis of the results obtained using climatic scenarios shows that under both scenarios, by 2030 and by 2050, an increase in runoff of the river Yertis – v. Boran is to be expected mainly from January to May from 1 % to 29 %, and the decrease in runoff mainly in the second half of the year up to to 23 %. The largest increase is expected up to 29 % in May by 2030 under the RCP 8.5 climate scenario, and the smallest decrease by 23 % in October by 2030 under the RCP 4.5 scenario.

Figure 3 shows changes in the annual and vegetative season runoff of the river Yertis - v. Boran from the base period (Figure 2).



a b

Figure 2 - Change in the annual (a) and vegetative season (b) runoff of the river Yertis - v. Boran by the various climatic scenarios for the future until 2030-2050.

According to the obtained estimates, for the river Yertis - v. Boran as a whole is expected insignificant increase of the annual runoff from the norm (335.9 m^3/s) in all forecasted years up to 2 % and will be in the range of 337.1–339.6 m^3/s. In the vegetative season the runoff under the RCP 8.5 scenario is expected to increase up to 3 % from the base period, but under the RCP 4.5 scenario in 2040 a slight decrease in runoff up to 2 % is expected.

Conclusion

The results of statistical modeling showed that the series of runoff and precipitation modeled by the canonical expansion methods have parameters close to the parameters of the observed parameters. Results of verification data for the section of the river Yertis - v. Boran showed that the deviation of the simulated data from the observed data for the annual and vegetative season runoff in high-water years is 20–23 %, in middle-water years is 3–4 %, and in low-water years is 29–33 %. Thus, the runoff and precipitation series modeled by the canonical expansion method have parameters close to the parameters of the actual data, and retains the auto – and cross-correlation matrix inherent to the original series. Consequently, the canonical expansion method was used to predict the river flow for the long term prospective based on various scenarios of climate change. In general, as for the section of the river Yertis – v. Boran, it is expected the slight increase in the annual runoff, and the analysis of the obtained results of assessed possible changes in the intra-annual runoff distribution shows an increase in runoff during the flood period up to 30 % under the climate scenario RCP 8.5, and a decrease in runoff mainly in the second half of the year up to 25 % under the scenario RCP 4.5.

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