Methods of mathematical modelling for calculating flow characteristics of ungauged rivers in engineering design tasks (by the example of the Khemchik River, Tyva Republic, Russia)

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Abstract. In this study, we assess the results of the application of the deterministic hydrological model Hydrograph for calculating the maximum discharge of various recurrence frequencies at the ungauged mountain catchment of the Khemchik River – Khemchik village (the Tyva Republic, Russia, area 1750 km²). We have assessed the parameters of the model for three main landscapes of the study area. Based on streamflow modelling at two gauged catchments, we have verified the parameters and algorithms of the hydrological model and the results of modelling are satisfactory. The simulations of streamflow with daily time step for the Khemchik River – Khemchik village was conducted for the period between 1966 and 2012 using meteorological observational data from the Teeli meteorological station. Based on the simulated maximum discharge series, we have constructed the frequency distribution curves and compared with the data on calculations according to the standard methodology of frequency analysis provided in SP 33-101-2003. The modelling-based maximum instantaneous discharges for the frequency interval between 99 and 0.7% are 1.3-5 times higher than the values estimated by the standard methodology. The Ministry of Emergency Situations of the Tyva Republic indirectly confirms the plausibility of model calculations, evidencing the regular flooding of the Khemchik village, which is not predicted by the values obtained with the standard methods.

1. Introduction
One of the key practical issues of hydrology is the assessment of the maximum water discharges. In Russia, the guidelines SP 33-101-2003 [1], describing statistical approaches to flood-frequency analysis, are mandatory for application in engineering design. In some cases, the surveyors may face the problem of the validity of hydrological characteristics calculations based on flood-frequency analysis. They do not guarantee to obtain values with sufficient accuracy in the mountainous and poorly-studied regions [2]. This is due to the complex distribution of meteorological elements in dissected relief conditions, a sparse hydrometeorological network, the specific factors of flow formation (for example, glaciers), climate change, and a non-linear hydrological regime.
Underestimation of the risks associated with hydrological phenomena causes significant damage to the population and the economy of the regions [3].

In the Republic of Tyva (Russia), the floods regularly lead to emergencies, such as the flooding of households, destruction of bridge crossings across mountain rivers and disruption of connectivity of remote areas with regional centers. In 2014, the flood damage amounted to more than 767 million rubles [4], and the damage caused to the transport infrastructure was even greater [5].

The limited possibilities of using flood frequency analysis pose the task of developing additional approaches to obtain flow characteristics [6], such as the methods of mathematical distributed modelling of hydrological processes.

Many studies on the possibilities of hydrological modelling in the tasks of streamflow characteristics assessment are carried out in European countries, for example [7, 8, 9]. The need to develop new methods of calculation under climate change conditions and anthropogenic impact is recognized [10]; the work of scientific groups is coordinated at the level of state and interstate structures [11]. In many countries, regulatory documents contain recommendations on the use of hydrological models for engineering calculations, for example [12]. In Russia, engineering design specialists also note that hydrological models can be used as an alternative to probabilistic methods for calculating the maximum flow characteristics [13], but systematic development is not conducted.

The aim of this study is to assess the maximum discharge values of different recurrence frequency at the ungauged catchment of the Khemchik River (Khemchik village, Tyva Republic) with the catchment area of 1750 km² using distributed hydrological modelling. The relevance of the research is due to the regular flooding of settlements in the valley of the Khemchik River basin and the need for engineering solutions to prevent dangerous hydrological phenomena.

2. Objects, methods and data

The Khemchik River basin, a left tributary of the Yenisei River, originates at the Eastern slopes of the Shapshal ridge with an elevation of more than 3600 m. The streamflow of the Khemchik River is sourced from rain and snow with a significant underground contribution. Summer-autumn peaks formed by rains can be two-five times higher than the spring snow floods. The climate is dry with snow-poor winters. The steady transition of temperature through zero occurs in late March–early April, and in the mountains above 3000 m – only in June.

The object of study is the ungauged upstream catchment of the Khemchik River basin in the Khemchik village with an area of 1750 km². The maximum and the average elevation of the catchment area is 2240 m and 3606 m, respectively. There are small glaciers found within the catchment area with a total area of 9.1 km², which provide additional flow in the summer (figure 1).

The distributed hydrological Hydrograph model [14] was used to simulate runoff formation processes. The model contains algorithms describing the dynamics of heat and moisture in the soil profile depending on their physical properties [14]. The model is robust in the sense of input meteorological information. It requires data on air temperature, humidity and precipitation allowing for calculations in poorly monitored basins. Previously, the Hydrograph model was used to calculate the maximum flow characteristics of rivers in mountain conditions, for example [15, 16].

Within the study basins, runoff formation complexes (RFC) similar to hydrological response units (HRU) are delineated. The schematization of soil and vegetation cover and estimation of model parameters are performed for these RFC’s. The basin areas of the studied catchments are covered with a regular hexagonal grid, the nodes of which are representative points (RP). Meteorological information is interpolated to these RP’s from the stations.

A common feature of previous modelling studies using the Hydrograph model [6, 17] was the availability of special observational data, which allowed the more confident estimation of the parameters of the Hydrograph model and the verification of the calculation results. Long-term (more than 40 years) data from the Kolyma water balance station [17], as well as field data from the high-altitude Suntar-Hayata station [6], were used to assess the parameters in the mountainous conditions of the Northeast of Russia. When modelling streamflow at the watersheds of the Baikal-Amur Railway...
zone [18], the parameter assessment was based on the data from the special observations of experimental hydrological site Mogot of State Hydrological Institute. The data on field studies, including a set of hydrometeorological observations, landscape descriptions, assessment of water-physical properties of soils [19], conducted during the complex expeditions of the Faculty of Geography of St. Petersburg State University in the Altai-Sayan region in 2010-2013, were used for model calculations in the mountains of Western Sayan [20].

The authors of the study could not find any special observations data on the Khemchik River basin. Therefore, the model parameters were evaluated based on expert assessment, reference data, the results of studies under similar conditions, and general ideas about the water balance of the studied catchment area, and their verification was carried out using data on daily water discharges at two hydrological gauges.

All the diversity of landscapes and soils was summarized in three RFC based on the cartographic information and satellite images “World Imagery” of ArcGIS (figure 1). Rocky talus and tundra in the upper part of the catchment are located on average above 2000 m. Coniferous forests are found in the range from 1300 to 2000 m, steppe occupies the river valleys at the elevation of 1300 m and below. Within the catchment of the Khemchik River rocky talus occupy 36 % of the area, coniferous forests is 48 % and steppes – 16% (figure 1).

Parameterization of selected RFCs is schematic; it was based on several assumptions. Within the steppe RFC, the flow coefficient is less than 0.1; river streamflow is formed only during snowmelt when the soil is frozen. During the summer, all precipitation is expended for evaporation.

The majority of precipitation in the zone of rocky talus RFC is contributing to river streamflow, mainly its underground component. The flow coefficient is approximately 0.7-0.8. Forest RFC is an intermediate landscape; its contribution to the formation of streamflow is two times less than at rocky
talus landscape. At the same time, the amount of precipitation in the forest zone can be two-three times higher than in the steppe [21, 22]. The runoff coefficient in the forest is 0.50.

The input information for the simulation was daily data on air temperature, humidity and precipitation at meteorological stations. Meteorological elements were interpolated from ground stations into RPs, accounting for change with elevation via a gradient.

3. Results of the maximum water discharge calculation

Daily simulation of streamflow hydrographs in two watersheds of different scales was carried out to verify the proposed conceptual scheme of runoff formation processes (the Tapsy River basin – Kara-Khol’, 302 km²; the Khemchik River basin – Iyme, 25500 km²) from 1975 to 1993. For the Tapsy River, we have obtained the following distribution of annual water balance: precipitation 430 mm, the calculated and observed flow 180 and 200 mm and the evaporation 250 mm. The same values for the Khemchik River are: precipitation 390 mm, the calculated and observed flow 120 and 130 mm and evaporation 270 mm. The median efficiency coefficient of Nash-Sutcliffe (NSE) is 0.30 and 0.60 for the Tapsy and Khemchik River basins, respectively. Figure 2 shows the examples of the simulated and observed hydrographs of the Tapsy and Khemchik Rivers.

![Simulated and Observed Hydrographs](image)

**Figure 2.** The examples of simulated and observed hydrographs a) the Tapsy river– Kara-Khol’; b) the Khemchik river – Iyme.

The results of the annual water balance modelling allow us to evaluate the proposed design scheme as satisfactory. However, in the formal assessment of the calculated daily hydrographs based on the NSE criterion, the simulation results for the Tapsy River basin should be considered unsatisfactory. The low NSE values are due to the unrepresentative input precipitation data from the Teeli meteorological station, which is located at a considerable distance from the catchment beyond the mountain range. In this case, the input meteorological data can be considered as a stochastic
component, and the evaluation of the simulation results is based on the comparison of empirical and calculated curves of the maximum water discharge repeatability, which have a satisfactory coincidence for the Tapsy River basin (figure 3).

Streamflow modelling for the ungauged Khemchik River basin – Khemchik was conducted using the Teeli meteorological observations from 1966 to 2012. The average precipitation for this period was 470 mm; evaporation and streamflow – 240 and 230 mm, respectively.

The probabilistic curve of the maximum water discharge was constructed based on the simulation results. The dependences of the observed values of the maximum instantaneous and daily discharges at the studied sites are used for the transition from simulated daily discharge to instant ones.

![Figure 3. The curves of repeatability of observed and simulated series of maximum flow discharges, the Tapsy river–Kara-Khol’ (1979-1993 observed and 1966-2012 simulated).](image)

In addition, the calculation of the maximum discharge characteristics of the Khemchik River – Khemchik was carried out based on flood frequency analysis at an analogous basin [1]. The Elegest River (catchment area 1850 km²) is the only catchment with a sufficient length of series of streamflow observations (since 1969), which can be used as an analogue for the flow characteristics calculation of the Khemchik River according to the recommendations provided by Russian standard methods SP [1].

Figure 4 presents the comparison of the frequency curves of the maximum instantaneous discharges obtained by the Hydrograph model and the standard method SP [1]. The simulated maximum discharges for the frequency interval from 99 to 0.7% are 1.3-5 times higher than the values obtained by the standard method SP. The runoff formation conditions are significantly different at the Khemchik and Elegest Rivers despite their satisfying the rivers-analogues requirements [1]. For example, the average and the maximum elevation of the Elegest River catchment is lower by almost 1000 m than in the Khemchik River basin. In addition, the distinctive feature of the Khemchik River is the presence of glaciers, untypical of the catchment of the Elegest River.

4. Conclusions

The study presents the possibility of using the distributed hydrological Hydrograph model for the assessment of maximum discharge frequency curve using the example of ungauged mountain catchment of the Khemchik River – Khemchik village (the area 1750 km², the Republic of Tyva). We have constructed the frequency curve based on the simulated maximum water discharge and compared the simulated values with those obtained by flood frequency analysis [1] using an analogous basin. The maximum discharges in the frequency interval from 99 to 0.7 % obtained by standard methods [1]
are 1.3-5 times underestimated compared to modelling results. The evidence of the Ministry of emergencies of the Tyva Republic of regular flooding at the Khemchik village indirectly confirms a higher likelihood of the calculations based on the use of the Hydrograph model, which is not predicted at the discharge values obtained by the method [1].

![Figure 4](image_url)  
**Figure 4.** The frequency curves of the maximum instant discharges calculated by the Hydrograph model and the standard method SP [1].

The problem of choosing analogous rivers is also typical of other Russian regions. In the study [2], the authors showed on the example of calculations at small catchments of East Siberia and the Far East that the choice of the analogous rivers based on recent data of observations was strongly limited. The calculated hydrological characteristics may differ significantly when using several analogous rivers that meet the requirements of standard method SP 33-101-2003 [1]. This rather applies to mountain rivers to a greater extent.

In addition to the current study, there have been several studies published upon the application of mathematical modelling methods for assessing hydrological characteristics. In [15, 16], the authors used the Hydrograph model to calculate the instant water discharges of catastrophic floods at the Tuapse River and unexplored Tsemes river (the Black sea coast of the Caucasus of Russia). Calculated on the basis of modelling, the maximum water discharges of two catastrophic floods in 2002 and 2012 at the Tsemes River had the same 1% water discharge of frequency as that calculated by SP 33-101-2003 [1], and model water discharge of the flood in 1988 is almost two times higher than the values in 2002 and 2012. This means that the value of 1% flood estimated by standard methods was observed at least three times during 25 years. The results presented in [15, 16] suggest that the flood frequency analysis significantly underestimate the recurrence of floods.

Those examples and the results of the current study show that the use of mathematical modelling methods can serve as a useful addition to solving practical problems in poorly studied regions.

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**References**

[1] _SP 33-101-2003 Determination of Basic Design Hydrological Characteristics_ 2004 (Moscow: Gosstroy of Russia) p 73
[2] Makarieva O M, Beldiman I N, Lebedeva L S, Vinogradova T A and Nesterova N V 2017 On the question of the validity of the recommendation SP 33-101-2003 for calculations of the characteristics of the maximum flow of small rivers in the zone of permafrost Engineering Surveys 6-7 50–63

[3] Razumov V V, Razumova N V and Pchelkin V I 2015 Scales and danger of flooding in the Siberian region of Russia The Science. Innovation. Technology 4 103-44

[4] The official site of the IA Tyva-Onl “In Tyva, the Total Damage from the Flood Amounted to More Than 767 Million Rubles” 2014 (in Russian) Income accessed online on 18th July 2018 via https://www.Tyvaonline.ru/2014/06/16/v-tuves-obshiy-uscherb-ot-pavodka-sostavil-bolee-767-millionov-rubley.html

[5] The official portal of the Republic of Tyva "In Tyva, the Consequences of Severe Flooding and Flooding That Happened in the Summer Are Eliminated" 2014 (in Russian) Income accessed online on 18th July 2018 via http://gov.Tyva.ru/press_center/news/activity/11161/

[6] Makarieva O M, Nesterova N V, Lebedeva L S and Vinogradova T A 2019 Modelling of the flow formation of rivers of the high-altitude cryolithozone of Eastern Siberia (using the example of the Suntar-Khayat ridge) Geography and Natural Resources 1 178-86

[7] Brocca L, Melone F and Moramarco T 2011 Distributed rainfall–runoff modelling for flood frequency estimation and flood forecasting Hydrological Processes 25(18) 280-13

[8] Rogger M, Kohl B, Pirkl H, Komma J, Kirnbauer R, Merz R and Blöschl G 2012 Runoff models and flood frequency statistics for design flood estimation in Austria – Do they tell a consistent story? Journal of Hydrology 456-457 30-43

[9] Viviroli D, Mittelbach H, Gurtz J and Weingartner R 2009 Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results Journal of Hydrology 377(1-2) 208-25

[10] Maghsoud F F, Moradi H, Massah Bavani A R, Panahi M, Berndtsson R and Hashemi H 2019 Climate Change Impact on Flood Frequency and Source Area in Northern Iran under CMIP5 Scenarios Water 2(11) 273

[11] Madsen H, Lawrence D, Lang M, Martinkova M and Kjeldsen TR 2013 A Review of Applied Methods in Europe for Flood-Frequency Analysis in a Changing Environment NERC/Centre for Ecology & Hydrology (ESSEM COST Action ES0901) p 180

[12] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M and Testoni I 2019 Australian Rainfall and Runoff: A Guide to Flood Estimation, Commonwealth of Australia Income accessed online on 9th May 2019 via http://arr.ga.gov.au/arr-guideline

[13] Zhirkевич A N and Asarin A E 2010 Probable maximum flood (PMF): basic information and problems of its calculation method application in Russia Hydraulic Engineering 4 30-6

[14] Vinogradov Yu B 1988 Mathematical Modelling of Runoff Formation Processes (Experience of Critical Analysis) (Leningrad: Gidrometeoizdat) p 312

[15] Makarieva O M, Vinogradova T A, Nesterova N V, Vinogradov A Yu, Beldiman I N and Kolupaeva A D 2018 Simulation of catastrophic floods in the Tsupae River basin Georisk XII 3 78-89

[16] Makarieva O M, Nesterova N V, Vinogradova T A, Beldiman I N and Kolupaeva A D 2019 Calculation of the characteristics of catastrophic floods of the unexplored Tsemes river (Novorossiysk, the Black Sea coast of Russia) based on the Hydrograph hydrological model Bulletin of St. Petersburg State University. Earth Sciences 1 24-43

[17] Makarieva O, Nesterova N, Lebedeva L and Sushansky S 2018 Water balance and hydrology research in a mountainous permafrost watershed in upland streams of the Kolyma River, Russia: a database from the Kolyma Water-Balance Station, 1948–1997 Earth System Science Data 10 689-710

[18] Vasilenko N G 2013 Hydrology of Rivers of the BAM Zone: Expeditionary Research (Saint Petersburg: Nestor-Istoriya)
[19] Vinogradova T A, Pryakhina G V and Mosolova G I 2014 Methodological foundations of field hydrology and the organization of complex expeditionary works in mountainous watersheds *Bulletin of St. Petersburg State University. Earth Sciences* 7(4) 189-96

[20] Pryakhina G V, Zelepukina E S, Zhuravlev S A, Osipova T N, Amburtseva N I, and Vinogradova T A 2017 Estimation of run-off from the small mountain drainage basins using the model of run-off formation *Moscow University Bulletin, Geography* 5 29-37

[21] Kamanin L G and Likhanov B N 1964 *Natural Conditions and Natural Resources of the USSR. Central Siberia* (Moscow: Science) p 480

[22] Minderlein S and Menzel L 2014 A semi-arid mountainous steppe and shrubland site in Northern Mongolia *Environmental Earth Sciences* 73(2) 593–609