DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

Proceedings
of the 7th International Conference

Chengdu, China, 23–27 September 2024

Edited by
S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva

Geomarketing LLC
Moscow
2024

СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

Труды
7-й Международной конференции

Чэнду, Китай, 23–27 сентября 2024 г.

Ответственные редакторы
С.С. Черноморец, К. Ху, К.С. Висхаджиева

ООО «Геомаркетинг»
Москва
2024

泥石流：
灾害、风险、预测、防治

會議記錄
第七届国际会议

中国成都, 2024年9月23日至27日

編輯者
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Geomarketing LLC
莫斯科
2024

УДК 551.311.8
ББК 26.823
С29

Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 7th International Conference (Chengdu, China). – Ed. by S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva. – Moscow: Geomarketing LLC. 622 p.

Селевые потоки: катастрофы, риск, прогноз, защита. Труды 7-й Международной конференции (Чэнду, Китай). – Отв. ред. С.С. Черноморец, К. Ху, К.С. Висхаджиева. – Москва: ООО «Геомаркетинг», 2024. 622 с.

泥石流：灾害、风险、预测、防治. 會議記錄 第七届国际会议. 中国成都. 編輯者 S.S. Chernomorets, K. Hu, K.S. Viskhadzhieva. – 莫斯科: Geomarketing LLC. 622 p.

ISBN 978-5-6050369-6-8

Ответственные редакторы: С.С. Черноморец (МГУ имени М.В. Ломоносова), К. Ху (Институт горных опасностей и окружающей среды Китайской академии наук), К.С. Висхаджиева (МГУ имени М.В. Ломоносова).

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

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MODIS imagery-based water content forecasting methodology for the Kyzylsu River

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Abstract. The article investigates the possibility of using snow cover satellite data for short-term hydrological forecasting for the Kyzylsu River with high-altitude catchment. The research aimed to elaborate a methodology for forecasting mean 10-day (decadal) river discharge (MDD) of the Kyzylsu River based on MODSNOW-processed MODIS satellite imagery. The objectives of the study were to calculate the snow cover index (SCI) for high-altitude zones in 200 m increments for selected river basins, and to analyze the closeness of dependency between the corresponding SCIs and MDDs. The research resulted in equations applicable for producing operational river water content forecasts. Timely and reliable information on expected river water content during the forthcoming 10-day period allows decision makers (water management and hydropower agencies, emergency authorities) plan water supply for various economic sectors, as well as take measures to prevent hazardous hydrological phenomena on the rivers of Central Asia. The main advantage of the applied method is the possibility of obtaining high-quality and reliable forecasts of high-mountain river runoff based on MODIS satellite imagery processed in the MODSNOW application. The forecasting for the Kyzylsu River is extremely important for preventing hazardous hydrological events like floods, hydrological droughts and mud floods.

Key words: *water discharge, snow cover, hydrological forecasting, space imagery, Central Asia*

Cite this article: Niyazov J.B., Kalashnikova O.Yu. MODIS imagery-based water content forecasting methodology for the Kyzylsu River. In: Chernomorets S.S., Hu K., Viskhadzhieva K.S. (eds.) Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 7th International Conference (Chengdu, China). Moscow: Geomarketing LLC, 2024, p. 359–366.

Методика прогнозирования водности реки Кызылсу на основе снимков MODIS

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Аннотация. В статье рассматривается возможность использования спутниковых данных о снежном покрове для краткосрочного гидрологического прогноза для реки Кызылсу с высокогорным водосбором. Цель исследования – разработать методику прогноза среднего 10-дневного (декадного) речного стока (СРС) р. Кызылсу на основе спутниковых снимков MODSNOW, обработанных спутником MODIS. Задачи исследования заключались в расчете индекса снежного покрова (ИСП) для высотных поясов с шагом 200 м для выбранных речных бассейнов и анализе тесноты зависимости между соответствующими ИСП и БДР. В результате исследований

были получены уравнения, применимые для составления оперативных прогнозов водности рек. Своевременная и достоверная информация об ожидаемой водности рек на предстоящий 10-дневный период позволяет лицам, принимающим решения (водохозяйственным и гидроэнергетическим ведомствам, органам МЧС), планировать водоснабжение различных отраслей экономики, а также принимать меры по предотвращению опасных гидрологических явлений на реках Центральной Азии. Основным преимуществом применяемого метода является возможность получения качественных и достоверных прогнозов стока высокогорных рек на основе спутниковых снимков MODIS, обработанных в приложении MODSNOW. Прогноз для реки Кызылсу чрезвычайно важен для предотвращения опасных гидрологических явлений, таких как наводнения, гидрологические засухи и селевые паводки.

Ключевые слова: *сток воды, снежный покров, гидрологический прогноз, космические снимки, Центральная Азия*

Ссылка для цитирования: Ниязов Дж.Б., Калашникова О.Ю. Методика прогнозирования водности реки Кызылсу на основе снимков MODIS. В сб.: Селевые потоки: катастрофы, риск, прогноз, защита. Труды 7-й Международной конференции (Чэнду, Китай). – Отв. ред. С.С. Черноморец, К. Ху, К.С. Висхаджиева. – М.: ООО «Геомаркетинг», 2024, с. 359–366.

Introduction

For the first time, satellite information about snow cover contained in satellite images was applied for hydrological forecasting in 1977 in the Martinek-Rango SRM (Snowmelt Runoff Model) [*Rango, 1977*]. However, the 1.1 km spatial resolution of the AVHRR (NOAA) imagery allowed using snow cover data only for watersheds with significant areas; in addition, satellite images could be used only in case of clouds not distorting the snow cover picture. For long-term forecasting of Central Asian river runoff, snow cover data of AVHRR imagery were processed using the ERDAS Software with 10-day interpolation [*Pertzinger, 2002; Baumgartner, 2000*].

The algorithms for calculating snow cover area allow for the removal of cloud cover from MODIS images making it possible to obtain daily data on snow cover dynamics. Using satellite information about snow cover contained in MODIS images for operational hydrological forecasting in Central Asian countries became possible thanks to the MODSNOW-Tool application [*Gafurov, 2009*]. It allows automatically downloading images from the Internet, removing cloud noise and calculating snow cover area for various river basins [*Gafurov, 2016*]. As studies have shown, the 500 m spatial resolution of MODIS imagery permits using this information for a wider range of catchments – from 1,000 km^2 or more.

The river water content forecasting methods based on MODIS imagery were successfully applied for producing vegetation season and monthly forecasts for the rivers in the Naryn Basin [*Kalashnikov, 2015; 2017; 2020*], as well as for forecasts for vegetation season months for the Pamir-Alai rivers [*Niyazov, 2020*]. When designing the river discharge forecasting methodologies for vegetation months for the Tien Shan and Pamir-Alai rivers, the method accommodating the duration of snow cover accumulation based on MODIS imagery was applied [*Gafurov, 2018; 2019*]. H. Apel conducted a significant amount of work on MODIS-based statistical modeling for the Central Asian region [*Apel, 2018*]; he demonstrated the efficiency of using snow cover information in these images to forecast seasonal river runoff. The efforts of the academic community in recent years have focused on the prevention of hydrological droughts in the Central Asian region important for integrated water resources management [*Gerlitz et al., 2020*].

The Kyzylsu River is the main tributary of the Vakhsh River and is formed in the mountains of Kyrgyzstan. The Vakhsh cascade of hydroelectric power stations operates on the Vakhsh River in Tajikistan. Nurek hydroelectric power station is the largest power plant in Tajikistan, and the most powerful hydroelectric power station in Central Asia.

The 300 m high Nurek hydroelectric power station dam is one of the highest in the world. An artificial Nurek reservoir with a volume of 10.5 km^3, which has great hydro-energy and water-economic importance for Tajikistan and for the countries located downstream in the Amudarya River basin (Uzbekistan and Turkmenistan). However, the pressure on the river system is constantly increasing, which is a cause of concern for downstream countries.

Water content forecasting for the Kyzylsu River is important both for water resource planning and preventing hydrological hazards associated with expected low-water (hydrological drought) or high-water (flood) periods.

The authors of the article possess the experience of successfully applying MODIS satellite imagery data for long-term hydrological forecasting (flood period and its months) for the river catchment of the Kyzylsu. Using the forecasting equations for 10-day (decadal) intervals makes this approach innovative. The study used the snow cover information contained in MODIS satellite imagery processed in MODSNOW to determine the spatial characteristics of seasonal snow cover reserves in the high-altitude Kyzylsu. The research aimed to analyze the correlation dependencies between mean 10-day river discharge and snow cover area in high-altitude zones in 200 m increments. The analysis led to elaborating prognostic equations of applied significance for executing timely and high-quality decadal river water content forecasts.

The article includes the review of the main characteristics of the studied object. It likewise presents the formulas for calculating the snow cover index, main equation parameters and quality criteria for the proposed short-term hydrological forecasting methodology. The article also presents the advantages of the newly developed methodology for operational short-term hydrological forecasting.

The article's Conclusions Section describes the main research findings and further research prospects.

Materials and methods

The Kyzylsu River basin is distinguished by the presence of powerful Glaciers on the Zaalay Range, which to a significant extent has elevations of 6000 meters, and the maximum individual heights are about 6500 meters or more (Lenin (Abu Ali ibn Sino – in present) peak is 7134 m), most of the rivers (about 23) flow from its northern slope with length 1251 km. The rivers flowing from the southern slope of the Alai Range with a height of no more than 4000 meters (about 15 rivers) are less water-bearing and have a length of 451 km. Noteworthy is the high regulation of the flow of the Kyzylsu River, associated with the distribution of coarse material in the Alai Valley [*Shults, 1965*].

The Kyzylsu River, which are glacier-snow fed have a tight flow regulation (the base flow is 60–70% of the annual), due to the peculiarities of the geological structure in the river basin. The melted snow and glacier feeding are for 15–22% in a percentage ratio, but air temperature has the greatest influence on runoff [*Niyazov, 2022; Podrezova et al, 2022*]. The location of the basins in Central Asia is shown in Fig. 1. Main characteristics of the basins up to the observation points are given in Table 1.

High water is observed on the Kyzylsu from April to September. River belongs to the glacial- snow nourishment type with peak floods and maximum water discharge in July-August. The Kyzylsu River runoff hydrographs differ greatly from year to year and can be either saw tooth or, to a lesser extent, change during the flood period, forming a ridge of long constant duration due to the glaciers melting. During high-water period, the main sources of river nourishment are meltwater from glacial meltwater, seasonal snowmelt, ground- and to a lesser extent rainwater. Due to this, the hydrological forecasting practice has been taking into account the snow reserves accumulated during the cold season. The information on the snow cover depth and water content is collected via a network of observation stations of national hydrometeorological services. Yet, the point nature of the information and the widely spaced grid of the observation network do not allow assessing the situation with snow reserves in the mountains reliably. The study team used the snow cover information in MODIS satellite imagery providing for spatial characterization of its distribution in high-altitude zones. MODIS snow cover data underwent processing using the MODSNOW software.

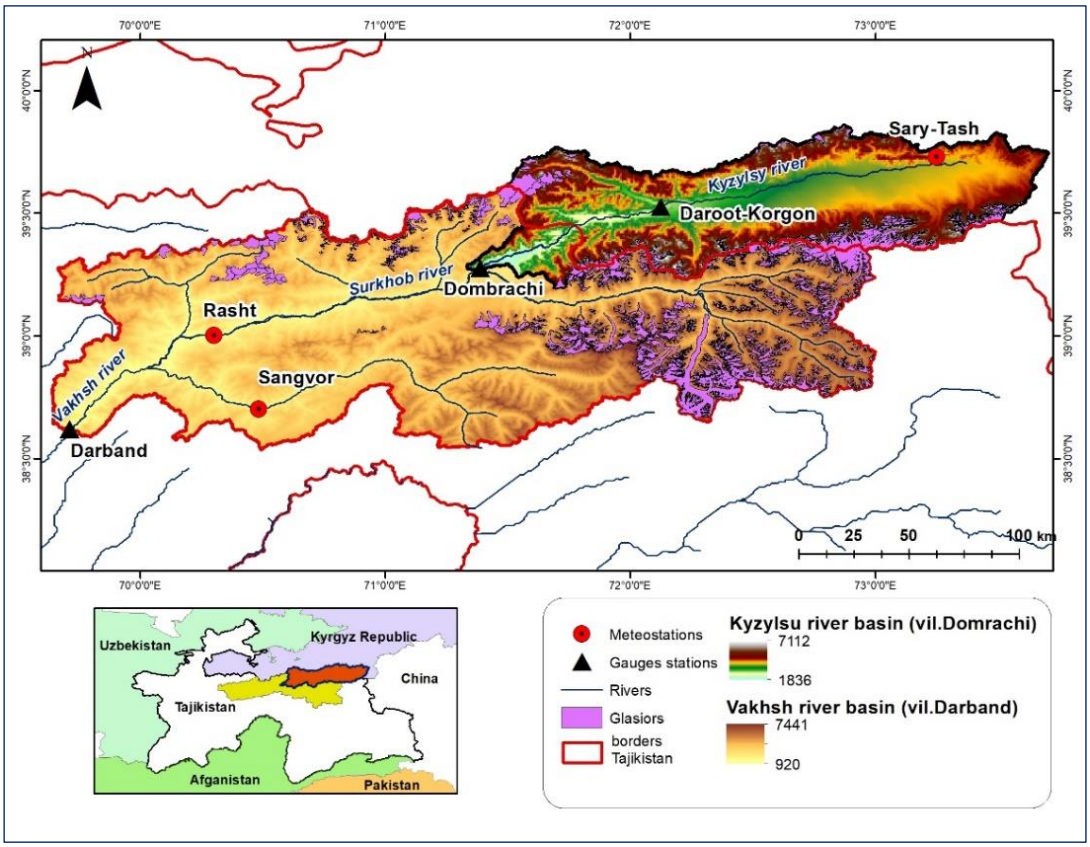

Fig. 1. Geographic location of the Kyzylsu River Basins on the territory of Tajikistan and the countries of Central Asia and observation networks of meteorological and hydrological parameters the Dombrachy and Sary-Tash hydroposts (compiled by the authors)

Table 1. Basic information about the Kyzylsu river basin*

Name of the gauging station	Catchment area in km^2	Mean catch-ment elevation, m a.s.l.	Glacier area			Mean annual water discharge, m^3/s
			1940–1970s, km^2	*2013–2016, km^2	Percen-tage of the basin area*	
Kyzyl-Suu River – Dombrachi	8470	3540	640,3	578,4	6,8	76,2

*Glacier area according to Landsat images for 2013–2016. Compiled by the author.

To develop a methodology for 10-day river water content forecasting, snow cover data calculated for high-altitude zones with 200 m increments were used. Calculations of the snow cover area (SCA) as a percentage of basin area were carried out for each day in the series.

Snow cover duration (or the number of days with snow cover) also affects the formation of river runoff. In this regard, the snow cover index (SCI) was also applied calculated based on the following formula [*Gafurov et al., 2018*]:

$$SCI_t = \sum_{n=1}^{n=365/366} SCA_i,$$

where *SCA* represents snow cover area as a percentage of basin area for *i*-day (in our case for each day); *SCI* – snow cover index, duration of snow cover accumulation during forecast time (*t*); and *n* is the number of days with snow cover for hydrological year.

The linear regression method [*Podrezov, 2019*] was used to analyze the dependence between MDD and SCI.

Research results

The snow cover area as a percentage of the total basin area for high-altitude zones with 200 m increments was calculated for every day during 2000–2019 for the Kyzylsu River Basins (Fig. 2.).

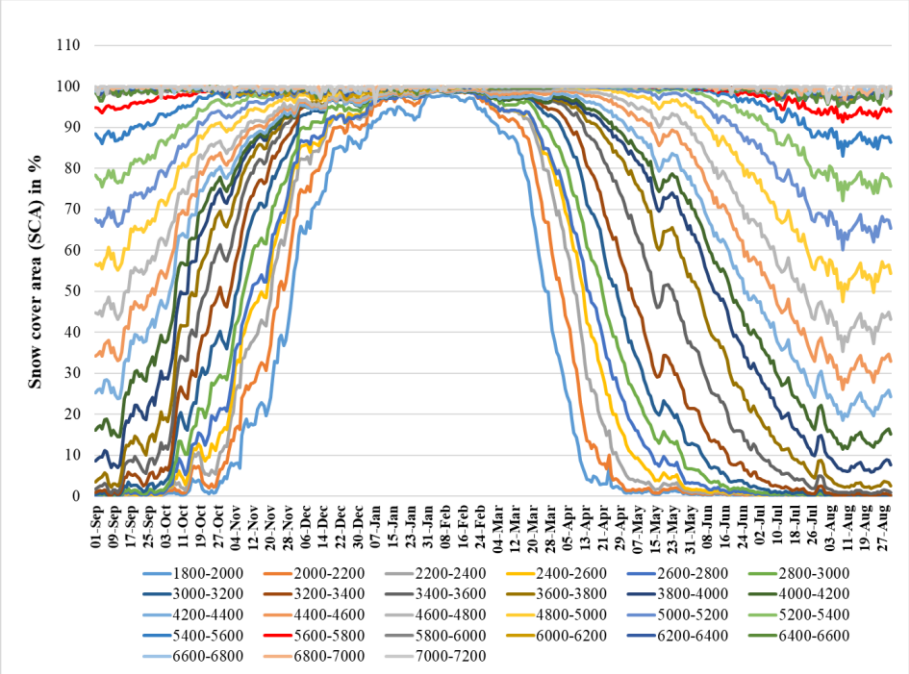

Fig. 2. Snow cover area as a percentage of total river basin area (Kyzylsu River, high-altitude zones in 200 m increments) (compiled by the authors)

According to formula (1), SCI was calculated from September 1 up to the forecasted 10-day interval. For instance, to forecast the situation during the first 10-day interval of May, SCI was calculated from September 1 until April 30; and to forecast the situation during the second 10-day interval of May – from September 1 until May 10, and so forth.

Further, the linear dependency correlation ratios between mean 10-day water discharge and SCI for high-altitude zones with 200 m increments for the Kyzylsu were calculated. The highest correlation ratios corresponded to the discharge with zone elevation 2800–3000 m. The calculation results are shown in Fig. 3.

The analysis of calculation results of the correlation ratios between mean 10-day water discharge and SCI for various altitude ranges allowed identifying the most effective linear relations and elaborating the corresponding equations. Table 2 shows the obtained equations of linear dependence between mean 10-day water discharge of the Kyzylsu River with SCI and discharge of previous decade, correlation ratios (R) calculated for the observation period from 2000 to 2017. An example of the analysis of simulated and observed water flow for the August first decade is shown in Fig. 4. In most calculations, the value of the correlation coefficient R was greater than 0.6, which allows the equations to be used for forecasts over decades.

Discussion

The lack of information on the conditions of snow accumulation in the discharge formation zones of Central Asian rivers with high-altitude catchments can be replenished by satellite sensing data. MODIS imagery processed using the MODSNOW software provide information on the daily snow cover dynamics, and can be applied for designing short-term hydrological forecasting methods. The method developed for the Kyzylsu River based on the snow cover data of MODIS images and previous decade can be used for making 10-day

forecasts. In most calculations, the value of the correlation coefficient R was above 0.6, into the category of "good" and "satisfactory", which allows the use of equations for forecasting over decades.

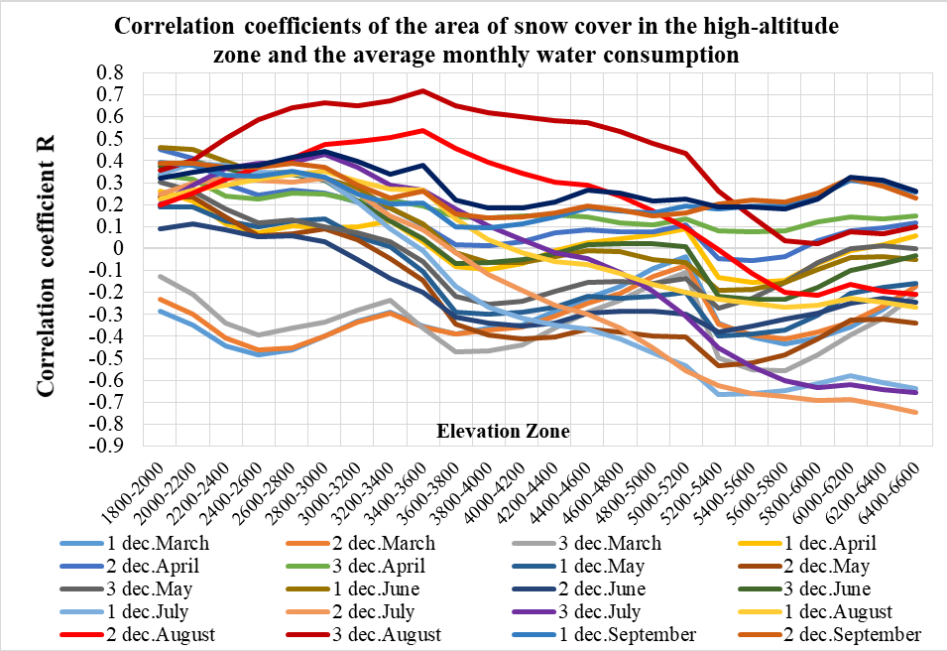

Fig. 3. SCI and mean decadal discharge correlation ratios (R) Kyzylsu – Dombrachi River Basin, high-altitude zones in 200 m increments (compiled by the authors)

Table 2. Linear dependency equations for mean monthly water discharge and SCI by high-altitude zone 2800–3000 m increments

Ten-day interval	Equation	R
1rd 10-days (April)	1.19Q 3 dec. March+29.8*SCI zone 2800–3000 –20.2	0.81
2rd 10-days (April)	0.98Q 1 dec. April+19*SCI zone 2800–3000 –3.4	0.77
3rd 10-days (April)	1.24Q 2 dec. April–0.23*SCI zone 2800–3000 –4.52	0.78
1nd 10-days (May)	0.86Q 3 dec. April–15.8*SCI zone 2800–3000 +28.5	0.67
2nd 10-days (May)	0.66Q 1 dec. May–0.09*SCI zone 2800–3000 +40.4	0.67
3rd 10-days (May)	0.64Q 2 dec. May+5.11*SCI zone 2800–3000 +27.8	0.42
1st 10-days (June)	1.14Q 3 dec. May+49.4*SCI zone 2800–3000 –30.7	0.82
2nd 10-days (June)	1.02Q 1 dec. June–52.8*SCI zone 2800–3000 +61.1	0.66
3rd 10-days (June)	0.72Q 2 dec. June+63.1*SCI zone 2800–3000 –8.18	0.66
1st 10-day (July)	0.68Q 3 dec. June+26.3*SCI zone 2800–3000 +28.7	0.49
2nd 10-days (July)	0.86Q 1 dec. July+19.5*SCI zone 2800–3000 +7.15	0.65
3rd 10-days (July)	0.70Q 2 dec. July+32.4*SCI zone 2800–3000 +23.4	0.82
1st 10-days (Aug)	0.41Q 3 dec. July+28.3*SCI zone 2800–3000 +73.5	0.30
2nd 10-days (Aug)	1.05Q 1 dec. August +40.8*SCI zone 2800–3000 –45	0.83
3rd 10-days (Aug)	0.32Q 2 dec. August +72.8*SCI zone 2800–3000 +36.2	0.60
1st 10-days (Sept)	0.72Q 3 dec. August–25.6*SCI zone 2800–3000 +40	0.74
2nd 10-days (Sept)	0.96Q 1 dec. September+11.7*SCI zone 2800–3000 –20.2	0.91
3rd 10-days (Sept)	0.76Q 2 dec. September+21.9*SCI zone 2800–3000 –8.97	0.77

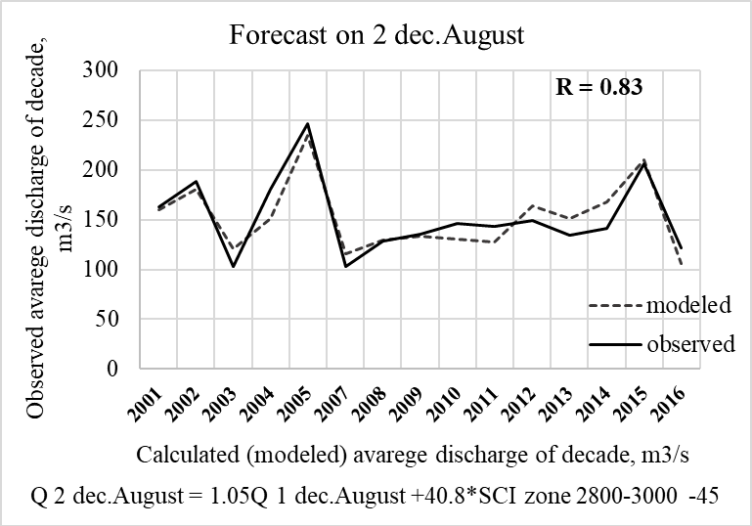

Fig. 4. Simulated and observed water discharge for the first August decade (compiled by the authors)

The limitations of using MODIS imagery for developing river runoff forecasting methods are predetermined by image resolution. The snow cover on MODIS images has the spatial resolution of 500 m and, thus their use for watersheds smaller than 1,000 km^2 is considered inappropriate.

Conclusions

The main advantage of the applied method is the possibility of obtaining high-quality and reliable forecasts of high-mountain river runoff based on MODIS satellite imagery processed in the MODSNOW application. This is particularly important for the catchments where no land-based snow cover observations are carried out currently and/or for the river basins not sufficiently covered by observations;

Water content forecasting for the Kyzylsu River is extremely important for preventing hazardous hydrological events like floods, hydrological droughts and mud floods;

The analysis of the correlations between SCI calculated for high-altitude zones with 200 m increments and the mean water discharge pointed to their close dependence over the months when melt snow and glacial runoff play a decisive role in the formation of river runoff;

Future studies will be conducted for other mountain river basins in Central Asia to elaborate MODIS-based methods for short-term hydrological forecasting for operational application by national hydro meteorological agencies.

Acknowledgements

This research effort was supported by the Central Asian Water (CAWa) Project (www.cawa-project.net; Grant AA7090002) funded by the German Federal Ministry of Foreign Affairs under the 343rd German Water Initiative for Central Asia (“Berlin Process”).

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