Application of the Snowmelt Runoff model in the Kuban river basin using MODIS satellite images

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Abstract
This paper analyses an opportunity to integrate remote sensing data in a forecasting scheme of river inflow to the Krasnodar reservoir. MODIS MOD10A2 eight-day composite snow cover data was selected as the basic remote sensing information. Based on these data, a database which consists of maximal snow extent maps covering the Kuban river basin over the period from March 2000 to the present, along with the technique of operative monitoring of the maximal snow covered area for the main basins of the rivers flowing into the Krasnodar reservoir were developed. It was revealed that the snow cover distribution data could be useful in the prediction of flooding in the basin. In addition, the Snowmelt Runoff model, application of which is based on snow cover remote sensing data as the input information, was tested as a short-term forecasting model. The obtained results enable us to conclude that the model can be used for short-term runoff forecasts in the mountain and foothill areas of the Krasnodar reservoir basin.

Keywords: Kuban river basin, Snowmelt Runoff model, MODIS snow data

1. Introduction
From the 20 to 21 June 2002 a raging flood formed in the Kuban river basin due to a combination of heavy rainfall and snow which had not melted during the preceding, abnormally cold, spring. The flood has no analogue in the observed record in terms of maximum discharge, rise of water level and/or damage caused to the population and environment. As a result of this catastrophic flood, more than 100 people died, more than 210 settlements (total population around 230,000 people) were affected and an area of more than 1100 km² was flooded (Lourie et al. 2005, p 353). In 2006 the Government of the Russian Federation announced a tender for implementation of the scientific project ‘Investigation of modern conditions and scientific justification of new methods and tools for providing stable functioning of a multipurpose water-resources scheme of the Kuban river as well as decreasing of risks of water deleterious effects in the basin’. The results presented in this paper emanate from the above-mentioned project and are specifically related to the sub-project entitled ‘Development of forecasting schemes of river inflow to the Krasnodar reservoir’.

The intent and purpose of this study is to work out schemes of short-term forecasting of water inflow into the Krasnodar reservoir based on remote sensing information.

2. Study area: Kuban river basin and Krasnodar reservoir
The Kuban river basin, which flows into the Sea of Azov, is located in the south of European Russia, in the southern part of the Azovo-Kubanskaya plain and the western part of the Northern slope of the major Caucasus mountains (see figure 1). The drainage boundary of the river in the south passes through the Greater Caucasus Mountain range, in the east—on the Lateral Ridge and in the north—on spurs of the Stavropolskoye plateau. The area of the drainage basin is 57 900 km² and the length of the Kuban river is 870 km. The flat part of the basin has heights of up to 200 m and makes up 52% of the entire area of the watershed. Foothills with highlands, with heights from 200 to 5500 m, make up the remaining 48%
Figure 1. Map of the Kuban river basin.

Table 1. Main characteristics of the database of MODIS satellite images created for the Kuban river basin.

| Name of original snow product MODIS       | MOD10A2 8 day       |
|------------------------------------------|---------------------|
| Time period                              | 24-02-2000–present  |
| Repeat period                            | 8 days              |
| Spatial resolution                       | 450 m               |
| Number of images                         | 430 (at the moment) |
| Spatial covering                         | Lat: 43–46° N       |
|                                          | Lon: 37.2–42.7° E   |

(Lourie et al 2005, p 143), and this is where the majority of the runoff originates. The Kuban river basin is a unique area of Russia in terms of its geopolitical location and environment. It is the most southerly region of the country with a warm climate, lots of sunny days, fertile soils, a unique combination of steppes and woods, mountain landscapes and sea beaches, with extensive opportunities for development of agricultural, transport, tourism and recreational complexes.

The Krasnodar reservoir which controls more than 95% of the basin runoff is the most radical regulator of the Kuban river flood runoff. It is the largest reservoir of Northern Caucasus located at a distance 242 km from the Kuban river mouth and was put in operation at full capacity in 1975. The basic purpose of the reservoir is to regulate runoff so as to:

- provide rice irrigating systems along the Lower Kuban river with water;
- accumulate some volume of flood water for flood protection for the densely populated regions of the lower basin of the Kuban river;
- improve navigation conditions.

3. Creating a database of MODIS satellite images

Choosing the most suitable remote sensing data, with regard to adaptation in forecasting schemes, from the wide range of those existing at present was the first stage of our research work. Our prime interest was remote sensing data on the distribution and properties of snow cover. The main requirements to remote sensing information necessary for our research work were:

- easy and, if possible free, access to the information through the internet;
- high-resolution considering the Kuban river basin size;
- ability to regularly update the database being formed, it is desirable that the remote sensing information would come from active satellites.

Taking these criteria into consideration a comparative analysis of snow cover remote sensing databases easily available through the internet was performed. Based on this analysis it was decided to use MODIS snow products as the input information. Finally, the MOD10A2 snow cover database was created on the basis of satellite images of the moderate-resolution imaging spectroradiometer MODIS, a 36-channel visible to thermal-infrared sensor.

The satellite snow survey MOD10A2 is remote sensing information on the distribution of the snow covered area over eight-day periods (Hall et al 2002). The database, at present, includes 430 processed satellite images, with a spatial resolution of about 450 m completely covering the Kuban river basin from 2000 (i.e. from the moment of launching the sensor as a part of the Earth Observing System (EOS)) to the present. The main characteristics of the created database of MODIS satellite images are introduced in table 1.

In addition, a technique for operative monitoring of the maximal snow covered area for the main basins of the rivers flowing into the Krasnodar reservoir was developed. The technique includes a set of programs allowing the uploading and processing of MODIS satellite images, as well as the ability to calculate the snow covered area based on satellite images for any sub-basin of the Krasnodar reservoir basin. Using the prepared database, the calculations of maximum snow cover dynamics for various areas of the Kuban river basin over the period of 2000–2008 were implemented. Figure 2 shows the evolution of the spatial distribution of the maximal snow covered area over the Kuban river basin, calculated on
the basis of the database of satellite images MOD10A2, for the period of snow accumulation and ablation of 2005–2006.

Following the creation of the database further analysis was performed to investigate:

- the possibility of flood prediction based on the distribution of the maximal snow extent over the investigated area;
- an opportunity to use the relationship between maximum snow cover extent and river runoff in the mountain and foothill areas of the Kuban river basin in a forecasting scheme of river inflow to the Krasnodar reservoir basin.

It was revealed, that the snow cover distribution data could be indirectly useful in the prediction of flooding. For instance, during the second decade of June 2002, the period prior to the catastrophic flood in the Kuban river basin, the snow cover extent over the mountain and foothill parts of the basin was 10–70% greater than typically experienced during the other years (see table 2). Moreover, at the end of June 2002 (i.e. after the flood) the snow cover extent returned to a level similar to that experienced in other years. This suggests a direct relationship between melted water, which was washed down from the snow covered foothill areas with heavy rainfall, and catastrophic flooding in the Kuban river.

Unfortunately, any attempt to find a correlation between the maximum snow cover area, calculated on the basis of MODIS satellite images, and the river inflow to the Krasnodar reservoir failed, leading us to conclude that the use of satellite information alone is insufficient as a forecasting method of river inflow to the Krasnodar reservoir.

Table 2. Snow covered area over the Krasnodar reservoir basin and its several mountain and foothill subcatchments before the third decade of June (the period of the catastrophic flood in 2002).

| Basin                  | Basin area (km²) | Mean elevation (m) | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | Mean |
|------------------------|------------------|--------------------|------|------|------|------|------|------|------|------|------|
| Krasnodar reservoir    | 45041            | 791                | 2    | 3    | 8    | 2    | 5    | 3    | 4    | 1    | 3    |
| r. Maruha              | 306              | 2159               | 9    | 8    | 19   | 6    | 11   | 10   | 13   | 8    | 10   |
| r. Bolshoy Zelencuk    | 768              | 2014               | 13   | 10   | 25   | 6    | 16   | 11   | 17   | 7    | 13   |
| r. Malaya Laba         | 1106             | 1946               | 11   | 13   | 30   | 4    | 14   | 14   | 15   | 9    | 14   |
| r. Bolshaya Laba       | 1182             | 1956               | 6    | 10   | 31   | 6    | 13   | 21   | 9    | 3    | 12   |
| r. Kuban–St. Kosta     | 3784             | 2222               | 20   | 8    | 33   | 13   | 18   | 18   | 17   | 6    | 17   |
| Hetagurova             |                  |                    |      |      |      |      |      |      |      |      |      |
| r. Akasaut             | 547              | 2369               | 20   | 12   | 37   | 14   | 22   | 24   | 19   | 6    | 19   |
| r. Teberda             | 498              | 2509               | 52   | 21   | 59   | 33   | 37   | 43   | 41   | 19   | 38   |

Figure 2. Evolution of maximal snow extent over the Kuban river basin during the season of snow accumulation and ablation of 2005–2006.
The obtained results suggest that the SRM can simulate with success both diurnal water discharge and snow water equivalent in the mountainous study area. Efficiency of the application of the model, which was applied in several of the Krasnodar reservoir basin’s subcatchments, was evaluated by using the developed set of programs and the database of MODIS MOD10A2 snow product data have a good potential for monitoring the maximal snow covered area in non-snow dominated, southern regions of Russia since a comparative analysis of several databases selected according to the set requirements and done with the help of forecasting of river inflow to the Krasnodar reservoir. The only disadvantage of using the SRM for long-term forecasting is that MODIS data are not available prior to 2000, making it difficult to evaluate the accuracy of long-term forecasts.

As an example of the adaptation of the SMR in the forecasting scheme of snowmelt inflow for the mountainous part of the Krasnodar reservoir basin, its application in the Laba river basin is briefly reviewed below.

Initial data for the model application were:

• daily air temperature and precipitation data for the period of 2000–2002 at two weather stations;
• daily discharge data of r. Laba–Doguzhiev discharge gauging station required for the model calibration over the period of 2000–2002;
• data on maximum snow covered area dynamics for the period 2000–2002.

At the initial stage, the watershed of the Laba river was delineated into three elevation zones by using the digital elevation model GTOPO30: from 40 to 500 m, from 501 to 1500 m, from 1501 m and above up to a watershed. Then, by using the developed set of programs and the database of MOD10A2 satellite images, the maximum snow covered area for each elevation zone during the period of 2000–2002 was calculated (see figure 3).

The information relating to the dynamics of snow cover distribution were used as input data for the adaptation of the SRM. In figure 4, the result of the model’s application for the Laba river basin during the period of the catastrophic June 2002 flood is shown.

5. Conclusions

This paper presents the development of methods to forecast river inflow to the Krasnodar reservoir. The main feature of this study, which is at the initial stage, is the application of remote sensing data in forecasting schemes. Summarizing the implemented investigations along with the obtained results, the following conclusions can be drawn:

• MODIS MOD10A2 snow product data have a good potential for monitoring the maximal snow covered area in non-snow dominated, southern regions of Russia since a comparative analysis of several databases selected according to the set requirements and done with the help of
snow survey data showed that the data could be classified as the most reasonable for the Kuban river basin.

- MOD10A2 data can be useful in the prediction of flooding for the Kuban river basin.
- It is insufficient to use remote sensing data on snow cover extent alone in forecasting methods because any attempts to find correlation between the maximal snow cover extent, obtained from MODIS satellite images, and river inflow to the Krasnodar reservoir failed.
- Snowmelt Runoff model together with the MOD10A2 data could be used to provide reasonable short-term (1–7 days in advance) runoff forecasts in the mountain and foothill areas of the Krasnodar reservoir. The efficiency of the model’s applications to several mountainous subcatchments of the basin showed that the model performed well on sub-basins with differing characteristics.

The next step of this study is the development of a long-term forecasting method.

References

Hall D K, Riggs G A, Salomonson V V, DiGiromamo N and Bayr K J 2002 MODIS Snow-Cover Products Remote Sens. Environ. 83 181–94
Lourie P, Panov V and Tkachenko Yu 2005 Kuban River: Hydrography and Flow Regime ed A Pogorelov and Yu Fedorov (St Petersburg: Gidrometoizdat) p 498
Martinec J, Rango A and Major E 1983 The Snowmelt-Runoff Model (SRM) User’s Manual NASA Ref. Publ. 1100 Washington, DC
Martinec J, Rango A and Roberts R 1994 The Snowmelt Runoff Model (SRM) User’s Manual ed M F Baumgartner Geographica Bernensia, p 29 Department of Geography, Univ. of Berne, Berne, Switzerland
WMO 1986 Intercomparison of Models of Snowmelt Runoff Operational Hydrology Report vol 23 (Geneva: World Meteorological Organization)
WMO 1992 Simulated real-time intercomparison of hydrological models Operational Hydrology Report vol 38 (Geneva: World Meteorological Organization)