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Geophysics

Utilization of a Rainfall-Runoff Hydrological Model in Studies on the Impact of Land Use Changes: Case Study from Georgia

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ABSTRACT. Land use and climate change along with anthropogenic impacts have significant effects on hydrological processes in river basins. Therefore, increased attention in hydrological modelling is being paid to the assessment of the impact of these factors on runoff characteristics. This contribution deals with an analysis of the runoff characteristics in the Bolnisistskali River basin with the current land use. The results of the analysis were compared with a scenario consisting of a change in the land use. The scenario is geared towards the land use for agricultural purposes and cattle breeding. The rainfall-runoff model with spatially distributed parameters was used for the research and comparison analyses. From the results of the modelling, it is obvious that the current state of the land use in terms of the runoff conditions from the basin is perceived more positively than a scenario based on delimitation criteria. *©2017 Bull. Georg. Bull. Acad. Sci.*

Key words: the model, River basin, land use change, scenario

The problem of environmental protection belongs to one of the most significant topics which society is currently dealing with. Land use and climate changes affect water regime, rainfall events, sea levels, and all the elements of the hydrological cycle. At present flood frequency and intensity according to the growth of the amount of extreme floods and rainfall are increasing. Flood protection is an elemental activity which can also affect the environment.

In recent years, the impacts of climate and also land use changes, particularly with regard to the formation of runoff, are among the most important elements influencing flood regimes [1]. Land use and climate change directly affect key aspects of hydrological processes such as evapotranspiration [2], interception [3], and runoff.

At present flood frequency and intensity are significantly increased due to modern climate change. There are several studies that focus on the environmental impacts of climate change adaptation on land use and water quality [4].

The modern climate change affects the water regime, rainfall events, sea levels, and all the elements of the hydrological cycle. In the future, the incidence of floods linked to changes in the frequency and intensity of precipitation will have an upward trend, mainly due to long-term climate change. Flood protection is among the significant activities that can greatly affect the environment. Construction measures are usually used to regulate water or as prevention and protection measures against floods. These measures have many advantages, but in some cases they also cause environmental problems. However, there are also environmentally friendly solutions in the form of green measures that do not require or require only minimal structural interventions to the environment. In the past people built dams to protect their dwellings and adjacent lands, but also "cut" parts from sites near rivers (so-called “inundation areas”). Therefore, due to human activities and climate change, flood risks are still increasing.

Hydrological models are widely used in the resolution of many practical and urgent issues that arise during the planning, design, operation and management of water resource systems [5] as well as in the quantification of the impacts of land use and climate change on the hydrological cycle [6]. In the last decades of the 20th century, many experiments were conducted in the hydrological science to develop new hydrological analyses and modelling tools, including the massive development of complex hydrological models for simulating runoff formation and erosion processes. Some of these models, which belong to a group of spatially distributed models, take into account the effect of different land use types in the simulation of runoff from a river basin along with individual hydrological processes. The best practices in the field include WetSpa [7-10], SWAT [11] and MIKE SHE [12] models.

In this paper, we focused on the development of a land use change scenario and runoff simulation for estimating potential changes under the changed land use conditions in the Bolnisistskali catchment. The runoff change in the land use scenario was compared to the current state. Emphasis was put on a comparison of the changes in the depth of the runoff and its related components, changes in the spatial distribution of runoff in the basin, and changes in selected components of the water balance.

Description of the Study Area

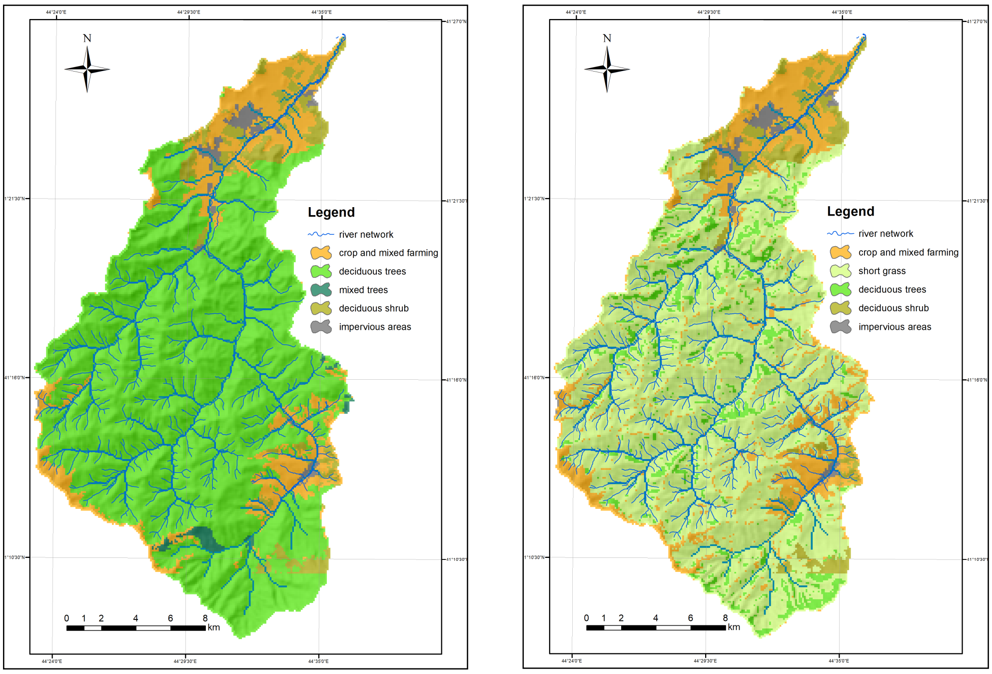
The climate of Georgia is characterized by great diversity. Almost all types of climate regimes are represented here, with the exception of deserts, savannas and tropical forests. The Likhi range, which passes through the centre of the country, divides the territory into two regions with dramatically differing climates, i.e., humid subtropical in western Georgia and mainly dry subtropical in eastern Georgia. Georgia has great potential in hydropower, which covers its needs for domestic as well as industrial use of energy. In addition, the surplus energy may be exported to neighbouring countries and can contribute to economic development in the country [13].

The Bolnisistskali River basin with the Samtsverisi final profile, an area of 360 sq.km, and an altitude ranging from 450 to 2540 m a.s.l. was selected as study area for the rainfall-runoff modelling. The catchment is situated in south-eastern Georgia in the Kvemo Kartli region.

Deciduous forests predominate in the land use (Fig. 1a). The cropland is situated in the northern part of the catchment. The soil types are mainly characterized by sandy-clay loam and loam soils.

Methodology

The main aim of the article is to estimate the effect of changes in the land use on the runoff processes in the Bolnisistskali River basin. We simulated



a) b)

Fig. 1. a) Map of the current land use; b) Map of the land use change scenario.

Table 1. Comparison of the land use elements between the land use change scenario and the current state

Land use type	Current state [%]	Scenario [%]	Increase/ decrease [%]
cropland	14	18	+ 4
short grass	-	64	+ 64
deciduous trees	73	6	- 67
mixed trees	1	-	- 1
deciduous shrub	10	10	0
impervious areas	2	2	0

runoff in daily steps for the period 1971 – 1985. In order to express the changes in the land use, a scenario was created (Fig. 1b). Therefore, the land use scenario was also used to test the ability of the model to simulate the changes in the land use.

An analysis of the land use in a territory involves the calculation of the individual areas of the land use. We are therefore talking about the percentage of each type of land use utilized in the catchment. As part of this work, we have been working with the current land use and a land use change scenario. The land use scenario was created on the basis of the combination of the slope characteristics and land use classes. Zones with slopes of less than 12% and covered with grass were changed to cropland. Areas with a declination (12-20%) covered with cropland were changed to grasses. Areas with over 20% slopes, cropland, and grasses were changed to deciduous trees.

The percentages of the individual land use elements and their increases or decreases between the current state and the land use change scenario are shown in Table 1.

The percentages of the various land use types are expressed in relation to the total area of the selected river basin. On the basis of the delimitation criteria, the forested areas (- 67 %) in the scenario were mostly replaced by short grass (+ 64 %).

To simulate the flow from the basin, the physically-based WetSpa rainfall-runoff model was used. The model uses geospatially referenced data as the input for deriving the model parameters, which include most data types supported by ArcGIS, such as shape files, grids, and ASCII files. Digital maps of the topography, land use (Fig. 1a), and soil types (Fig. 2) are the 3 base maps used in the model, while other digital data are optional, depending upon the data availability, the purpose, and the accuracy requirements of the project [14]. The following meteorological data were used in the model: daily precipitation totals from spot measurements at 2 stations and the average daily values for the air temperature at 4 climatological stations. The flow data consisted of the average daily flows at the Bolnisistskali – Samtsverisi profile. The input data (spatial and hydrometeorological) was provided by the National Environmental Agency (NEA, Tbilisi). We used the data from the period between 1971 and 1985.

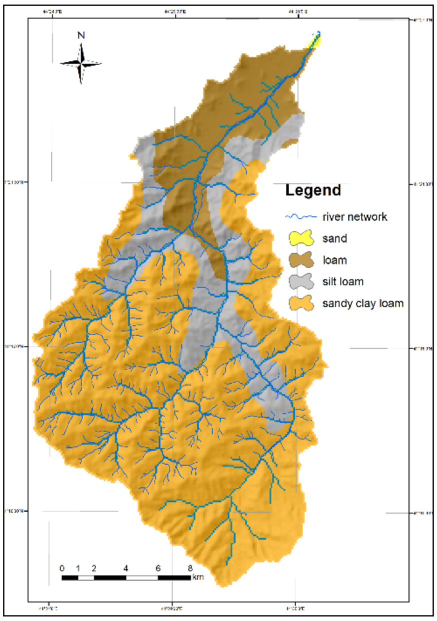


Fig. 2. Map of soil types in the Bolnisistskali River basin.

The calibration of the model requires the identification of a set of parameters that will provide the best possible agreement between the measured and simulated parameters of the hydrological model in accordance with the selected criteria. Various agreement criteria were used during the calibration of the model for expressing any differences between the observed and modelled data. The calibration period was from 1971–1985. Twelve parameters for which a range of admissible values were set optimized. The Nash–Sutcliffe (NS) coefficient was chosen as the dominant criterion in this work. In this case the NS coefficient value was 0.65, which represents a comparatively good degree of accuracy in the calibration of the global parameters. It is essential in rainfall-runoff modelling to take into account various sources of uncertainties that influence the quality of the simulated runoff from a catchment [15].

Results

The differences between the simulated and measured daily flows are shown in the hydrograph of the selected time period (1976) from the calibrated period (Fig. 3). The picture shows the inaccuracy in the runoff simulation with the WetSpa rainfall – runoff model. In the case of the simulated daily flows, the model understands them but has a problem with a sufficient capture of the hydrograph peaks. The runoff changes were evaluated by comparing the simulated average daily flows and their statistical characteristics for the current state and the land use change scenario. We also focused on an evaluation of individual components of the runoff that forms the surface, groundwater, interflow, and total discharge (Table 2).

In the selected period, it can be observed that the outflow for the land use change scenario is lower, but the total runoff from the basin in the scenario is higher by about 1,100 m^3. That confirms the assumption of an increase in the outflow from the area in the case of massive deforestation. The values of the components of the water balance about 9,500 m^3 for the current land use.

The created scenario was also used to analyse the ability of the Wetspa model to simulate changes in land use. The WetSpa model demonstrated sufficient ability to simulate runoff under changing land use conditions.

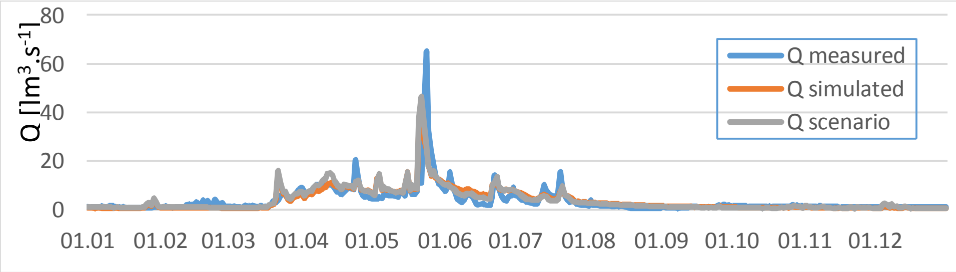


Fig. 3. Comparison of the mean daily runoff between the scenario and the current state.

Table 2. Comparison of the long-term mean monthly runoff in the Bolnisistskali River basin between the land use scenario and the current state

Catch-ment	period/sce-nario [mm]	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Bolnisistskali	measured Q	0.16	0.20	0.48	0.99	1.06	0.83	0.37	0.17	0.21	0.21	0.20	0.18
	simulated Q	0.13	0.25	0.61	1.01	1.08	0.69	0.38	0.20	0.19	0.14	0.16	0.12
	scenario Q	0.17	0.34	0.80	1.14	1.15	0.70	0.38	0.20	0.23	0.17	0.21	0.16

From the results obtained, it is clear that the rainfall - runoff model fairly well simulates the daily flows from the river basin compared to the measured values (the model slightly underestimates them). In reality, however, the mo del fails to take into account the benefits of various land use measures and is very sensitive to the quality of the input data that affects the simulation results.

Conclusions

In the article, the research and analysis of the impact of land use changes on runoff in the selected basin are carried out. For the purposes of this task, a land use scenario was created on the basis of the delimitation criteria, where the extreme land use changes were made. As a result, approximately 90% of the deciduous trees were removed from this scenario and replaced by short grass.

The use of water on forested land is generally greater than that of other land-use types, which leads to reduced flows from river basins; this is mainly caused by higher evapotranspiration. Although forests have obvious effects on flood events for small-scale catchments, the effects of forests on floods are likely to be minimal for large-scale catchments.

The results of the simulation are highly dependent on the availability of the input data, the parameterization of the land use and different types of vegetation in the model, and the schematization of the simulated processes; therefore, they need to be interpreted with a sufficient degree of caution and confronted with other results from the literature and experimental measurements. The results could be used in integrated river basin management, especially in the organization of the river basin management process and the assessment of the impacts of the changes in utilization of river basins on runoff and the size of erosion-accumulation processes. Based on the findings, it can be concluded that the WetSpa rainfall-runoff model with spatially distributed parameters can be used as a useful tool for land-use planning in a river basin. However, it should be noted that the reliability of the model is limited.

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გეოფიზიკა

ნალექი-ჩამონადენის ჰიდროლოგიური მოდელის გამოყენება მიწათსარგებლობის ცვლილებების გავლენის შესახებ კვლევებში: კონკრეტული მაგალითის შესწავლა საქართველოში

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** სლოვაკეთის ტექნიკური უნივერსიტეტი, სამოქალაქო საინჟინრო ფაკულტეტის მიწისა და წყლის რესურსების მართვის დეპარტამენტი, ბრატისლავა, სლოვაკეთი*
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(წარმოდგენილია აკადემიის წევრის თ. ჭელიძის მიერ)

მიწის გამოყენება და კლიმატის ცვლილება ანთროპოგენურ ზემოქმედებებთან ერთად მნიშვნელოვან გავლენას ახდენს მდინარის აუზებში მიმდინარე ჰიდროლოგიურ პროცესებზე. აქედან გამომდინარე, ჰიდროლოგიურ მოდელირებას ეთმობა გაზრდილი ყურადღება იმისთვის, რომ შეფასდეს ამ ფაქტორების გავლენა ჩამონადენის მახასიათებლებზე. სტატიაში განხილულია ბოლნისის წყლის აუზში ჩამონადენის ანალიზი, რომელიც კავშირშია მიწის ნაკვეთების გამოყენების არსებულ პრაქტიკასთან. ანალიზის შედეგები შედარებულია სცენარს, რომელიც შეიცავს მიწათსარგებლობის ცვლილებას და ასევე გათვალისწინებულია სასოფლო-სამეურნეო მიწათსარგებლობა და მეცხოველეობა. ნალექისა და ჩამონადენის მოდელი სივრცულად განაწილებული პარამეტრებით გამოყენებულია კვლევისათვის და შედარებითი ანალიზისთვის. მოდელირების შედეგების მიხედვით, აშკარაა, რომ მიწის გამოყენების არსებული მდგომარეობა აუზის ჩამონადენის სახით უფრო ზუსტია ვიდრე სცენარი, რომელიც ეფუძნება საზღვრების შეცვლის კრიტერიუმებს.

REFERENCES

1. Hlavčová K., Szolgay J., Kohnová S., Kostka Z. (2007) Use of Distributed Rainfall-runoff Models for Estimation of the Land-use Impact on Runoff Regime in Basins (Využitie zrážkovo-odtokových modelov s priestorovo rozčlenenými parametrami pri odhade vplyvu využívania územia na odtokové procesy. *Životné Prostredie*, **41**, 4: 206 -211 (in Slovak).
2. Vitková J., Skalová J., Brezianska K. (2015) Possible impact of climate change on actual evapotranspiration at Zahorska lowland, Slovakia. In: International Multidisciplinary Scientific GeoConference SGEM: *Conference Proceedings*, vol. 1. Hydrology and Water Resources. - Sofia : STEF92 Technology Ltd., 2015, pp. 523-530. ISBN 978-619-7105-36-0.
3. Bartík M., Jančo M., Střelcová K., Škvareninová J., Škvarenina J., Mikloš M., Vido J., Dagsson Waldhauserová P. (2016) Rainfall interception in a disturbed montane spruce (Picea abies) stand in the West Tatra Mountains. *Biologia*, **71**(9): 1002-1008.
4. Minďaš J., Škvareninová J. (2016) Biodiversity and climate change: consequences for upper tree line in Slovakia. *Forestry Journal*, **62**(3): 181-185.
5. Lin K., Guo S., Zhang W., Liu P. (2007) A new baseflow separation method based on analytical solutions of the Horton infiltration capacity curve. *Hydrological Processes*, **21**, 13: 1719 - 1736.
6. Lin K., Zhang Q., Chen X. (2010) An evaluation of impacts of DEM resolution and parameter correlation on TOPMODEL modeling uncertainty. *Journal of Hydrology*, **394**, 3-4: 370 - 383.
7. Rončák P., Hlavčová K., Látková T. (2016) Estimation of the effect of changes in forest associations on runoff processes in basins: case study in the Hron and Topla river basins. *Slovak Journal of Civil Engineering*. **24**, 3 1-7, ISSN 1210-3896, doi:10.1515/sjce-2016-0011.
8. Rončák P., Lisovszki E., Szolgay J., Hlavčová K., Kohnová S., Csoma R., & Poórová J. (2017) The potential for land use change to reduce flood risk in mid-sized catchments in the Myjava region of Slovakia. *Contributions to Geophysics and Geodesy*, **47**(2): 95-112.
9. Valent P., Maliariková M., Rončák P., Hlavčová K., Karabová B. (2015) Analysis of land use changes in the Myjava River basin utilizing historical maps (Analýza zmeny spôsobu využitia územia z historických máp na povodí Myjavy). *Acta Hydrologica Slovaca*, 16, *thematic issue* 1: 152-160 (in Slovak).
10. Valent P., Rončák P., Maliariková M., Behan Š. (2016) Utilization of historical maps in the land use change impacts studies: a case study from Myjava River basin. *Slovak Journal of Civil Engineering*, **24**, 4: 15-26.
11. Arnold J. G., Srinivasan R., Muttiah R. S., Williams J. R. (1998) Large area hydrologic modeling and assessment, part I: Model development, *Journal of the American Water Resources Association*, **34**(1): 73-89.
12. DHI (Danish Hydraulic Institute) (1999) MIKE SHE water movement: user manual, Hørsholm, Denmark.
13. Ministry of the Environment and Natural Resources Protection of Georgia (2015) Georgia’s Third National Communication to the United Nations Framework Convention on Climate Change, 266 pp. Tbilisi.
14. Wang Z., Batellan O., De Smedt F. (1996) A distributed model for water and energy transfer between soil, plants and atmosphere (Wetspa), *Phys. Chem. Earth*, 21: 189-193.
15. Valent P., Danko M., Miklánek P. (2014) Sensitivity analysis of a rainfall-runoff model (Analýyza citlivosti zrážkovo-odtokového modelu). *Acta Hydrologica Slovaca*, **15**, 2: 267 - 280 (in Slovak).

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