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APPLICATION OF POLISH EXPERIENCE IN THE IMPLEMENTATION OF THE FLOOD DIRECTIVE IN GEORGIA – HYDROLOGICAL CALCULATIONS

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Abstract. This paper present an example of the implementation of hydrological calculation methods for delineation of flood risk zones in the conditions prevailing in Georgia. The results, described in the present paper, were obtained in the project "Study of hydraulic modelling against floods – 2nd stage – support to the competence and readiness of Georgian institutions" which was organized and implemented by Polish Center for International Aid (PCPM), and co-funded by the Ministry of Foreign Affairs of the Republic of Poland. The results related to the catchments of the Lopota, the Intsoba, the Chelti, the Avaniskhevi, the Shromiskhevi in Kakheti and the Aragvi. All the catchments named above are hydrologically ungauged, therefore, a rainfall-runoff hydrological model was required for generating hypothetical hydrographs. Based on the peak daily total

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rainfall for the multi-annual period 1966–2014, quantiles of rainfall with a specified exceedance probability were calculated. A rainfall hyetogram was found using the beta distribution function. Effective rainfall was calculated by the SCS-CN method. Details of the land profile, cover and soil conditions were obtained from the numerical land model as well as maps, generated as part of the project named above. The effective rainfall was transformed into runoff using a simple SCS-UH model, based on the synthetic unit hydrograph. Studies indicated that total daily uniform rainfalls were random and could be described using the Fisher-Tippett distribution type III min. The results obtained by modeling were boundary conditions in the hydraulic model of transformation of the flood wave in rivers.

Key words: flood risk zones, hydrological model, peak rainfall, SCS method, Kakheti region

INTRODUCTION

Statistics on floods in Europe and anywhere in the world are alarming. In Europe alone, in the 20th century, floods killed 9500 people, left injured 10 million, and caused losses estimated at some 70 billion Euro. Selected characteristics of the floods which occurred in small and medium-size catchments in several regions of Europe in the years 1946–2007 have been reported by Gaume et al. [2009]. Over the years, major floods have become more common. In all probability, it is not so only because of the growing population but, first of all, because the areas which are exposed to the flood risk have been taken over for housing and for industrial purposes. Moreover, the analyses of available data indicate that, also in the near future, countries in Europe may be affected by flood again, and more than once. Owing to climatic changes, rainfall intensity has increased, resulting in higher sea levels. In addition, the infiltration of rainwater is limited due to mismanagement of river basins and the development of housing projects in areas exposed to the risk of flood, as mentioned above. Furthermore, the coastline is becoming more and more exposed and has already been eroded in many regions [Wałęga and Cupak 2010].

As regards protection from floods, the provisions of the so-called Flood Directive [Dyrektywa… 2007/60/WE] apply in European countries. Essentially, the Flood Directive is intended to diminish the risk and control the consequences of floods in the member countries of the European Union. The objectives include the appropriate control of the risk floods pose to human health, environment, economy, and cultural heritage. Hydrological information in the form of peak flows with a specified exceedance probability as well as freshet waves predicted for various hydrological scenarios are extremely important in flood risk analysis and control of its consequences. This information is the input value for the hydraulic models of flood wave transformation in river beds and valleys. Accuracy and correctness of the calculations are largely dependent on the quality of the hydrological data.

Forecasting floods based on mathematical modeling allows experts to convert information on the past-to-present rainfall into a river flow forecast (discharge, stage, and inundated area for a future time horizon). It helps to reduce flood damage by permitting the public to act before the flood level increases to a critical height. Prognosis of the size of maximum discharge and discharge hydrographs can be created using a rainfall-runoff model [Wałęga et al. 2011]. Values of the model's parameters are estimated using registered rainfall-runoff episodes. In many parts of the world, rainfall and runoff data are seldom adequate enough to determine a unit hydrograph of a catchment or a watershed. In the absence of rainfall-runoff data, unit hydrographs can be derived by synthetic means [Limantara 2009, Wałęga and Cupak 2012, Wałęga et al. 2012, Więzik 2014, Gądek and Bodziony 2015, Gądek and Tokarczyk 2015]. A synthetic unit hydrograph is a unit hydrograph derived following an established formula, without the need for the rainfall-runoff data analysis [Ponce 1989]. The peak discharges of stream flow from rainfall may be obtained from design storm hydrographs developed from unit hydrographs generated from established methods [Salami et al. 2009]. Parameters of the methods mentioned above are estimated on regional regression equations basis [Straub et al. 2000, Belete 2009, Butler and Davies 2011, Wałęga 2012].

The territory where Georgia is situated is strongly exposed to extreme hydrometeorological phenomena. The percentage distribution of hydrometeorological extreme events in the period 1995–2012 over the territory of Georgia was 31% flood and flash flood, 29.8% hail, 23.9% avalanche, 11.8% strong wind, and 3.5% drought. The flood or flash flood events in Georgia affect river shoreline or land erosion processes, change the flood path, cause flooding of arable lands, and flood urban and populated areas. Human loss and damage caused by floods are huge in Georgia. In June 2014, Georgia signed an Association Agreement with the European Union that set out requirements for the country modernization including meeting the provisions of the Flood Directive. The National Environmental Agency in Tbilisi, a public institution responsible for flood analysis in Georgia, has started seeking external experts like Polish Center for International Aid (PCPM) or United Nations Development Programme (UNDP), to transfer knowledge to their specialists concerning professional analysis of flood and designing flood hazard maps.

This paper is intended to provide a methodology of hydrological calculations for the purpose of delineation of flood risk zones in selected catchments in the territory of Georgia, carried out by Polish specialists in cooperation with those in Georgia. The present results were obtained as part of the project "Study of hydraulic modelling against floods – 2nd stage – support to the competence and readiness of Georgian institutions" executed by the Polish Center for International Aid (PCPM) in 2016–2017, and co-financed by Polish Development Cooperation Program of Ministry of Foreign Affairs of the Republic of Poland.

GEOGRAPHIC CHARACTERISTICS OF GEORGIA AND ANALYZED CATCHMENTS

The mountainous relief determines the diversity of Georgia's physical geography. The Likhi (Surami) sub-meridian ridge connects the Greater Caucasus and Lesser Caucasus ranges. Despite its relatively low altitude (the absolute elevation varies between 900–2471 m a.s.l.), the ridge divides the country in climatological terms. Western Georgia descends with slopes of the Great Caucasus, Likhi and Meskheti ranges to the Black Sea like a gigantic amphitheater and forms Kolkhida Lowland triangle in the lower part of the River Rioni. Central part of the Eastern Georgia comprises the valley of the Mtkvari

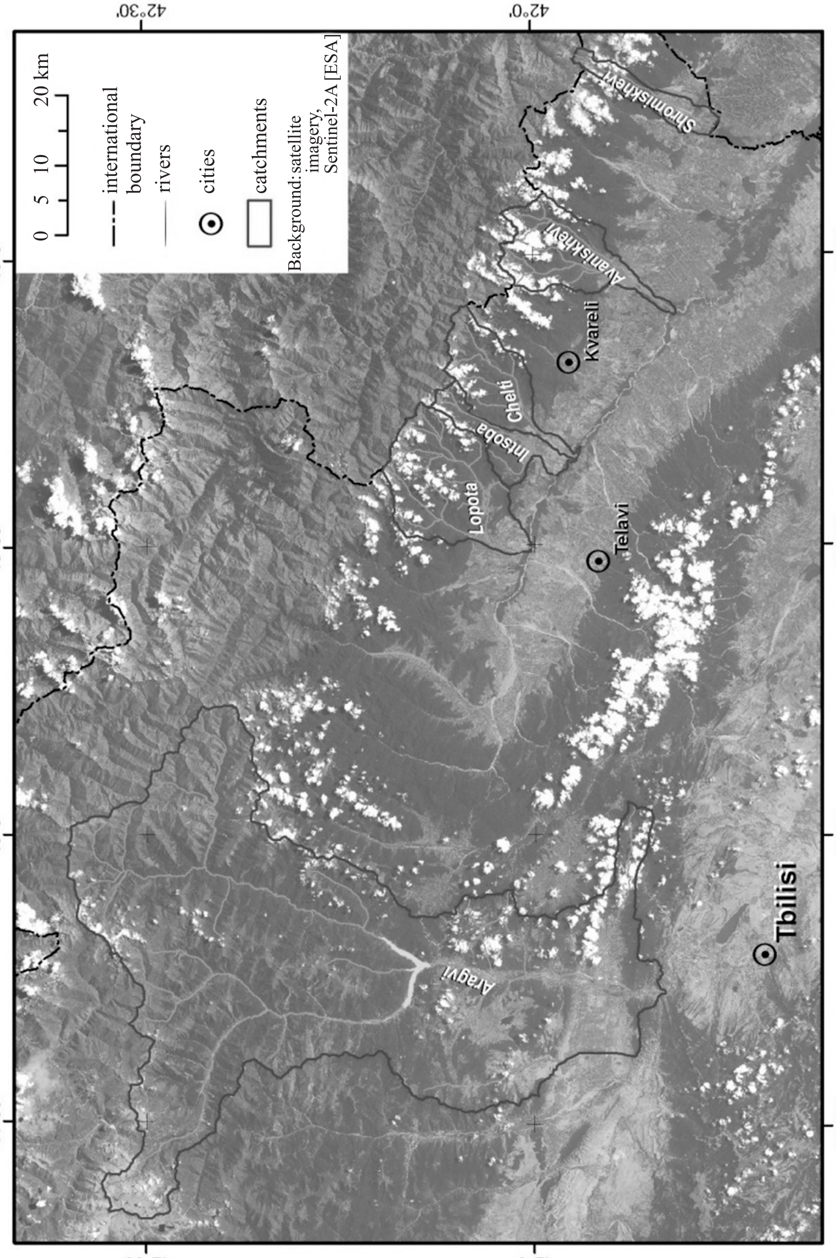


Fig. 1. Catchments covered by the project
Ryc. 1. Zlewnie analizowane w projekcie

(Kura) river, descending uniformly from Likhi Range eastwards. From the north, southern slopes of the Great Caucasus descend into this valley.

The geographical location of Georgia between the Black Sea and the arid regions towards the East, among the Greater and Lesser Caucasus, determines its relief peculiarities and great variety of natural forms. The climate of Georgia is particularly diverse, from perennial snow and glaciers of the Greater Caucasus to a humid subtropical climate of the Black Sea and steppe continental climate of the eastern Georgia. All world climatic zones meet in Georgia except for tropical, arid deserts and savannas.

Annual runoff within Georgia territory is 56.9 km^3, the amount of transported water is 9.4 km^3, and thus total amount of annual runoff is 66.3 km^3. Distribution of surface water in Georgia is irregular: total runoff of the rivers of the western Georgia (Black Sea Catchment) amounts to 49.7 km^3 – 75%, of the rivers in the eastern Georgia (Caspian Sea Catchment) 16.1 km^3 – 25%.

The project included five rivers in Kakheti region and the Aragvi river. The catchments are presented in Figure 1.

ANALYZED CATCHMENTS

The Aragvi catchment is located north of Tbilisi. Kakheti region located in the eastern Georgia comprises the following rivers: the Lopota, the Intsoba, the Chelti, the Avaniskhevi, and the Shromiskhevi. All six rivers are fed by snow, rain and ground waters, and the Aragvi is also a glacier-fed river.

The statistics concerning rivers and their catchments are presented in the Table 1. Length of the river, area of its catchment, density of river network and mean slope of the river were calculated based on a topographic map in a scale 1:25 000 and GIS analysis. Mean slope and altitude of the catchment were calculated using Digital Elevation Model (DEM) in GIS software. Table 2 shows statistics concerning the altitude of the river's spring and mouth from the topographic map as well as the altitude of the highest and the lowest point in each catchment obtained from DEM.

Table 1. Characteristics for the rivers and their catchments, part 1
Tabela 1. Charakterystyki rzek i ich zlewni, część 1

River Rzeka	Length of the river Długość rzeki km	Area of the catchment Powierzchnia zlewni km^2	Density of the river network Gęstość sieci rzecznej km · km^{-2}	Mean slope of the river Średni spadek rzeki, °	Mean slope of the catchment Średni spadek zlewni, °	Mean altitude of the catchment Średnia wysokość zlewni, m a.s.l. – n.p.m.
Lopota	32	275	1.13	7.1	25	1330
Intsoba	23	89	0.96	8.4	17	1002
Chelti	30	149	0.97	6.9	24	1369
Avaniskhevi	31	181	1.31	6.1	24	1223
Shromiskhevi	24	69	0.94	9.1	15	976
Aragvi	108	2726	–	2.2	22	1607

Table 2. Statistics for the rivers and their catchments, part 2
Tabela 2. Charakterystyki rzek i ich zlewni, część 2

River Rzeka	Altitude of the river's spring Rzędna źródeł rzeki m a.s.l. – n.p.m.	Altitude of the river's mouth Rzędna ujścia rzeki m a.s.l. – n.p.m.	The highest point in the catchment Rzędna najwyższego punktu w zlewni, m a.s.l. – n.p.m.	The lowest point in the catchment Rzędna najniższego punktu w zlewni, m a.s.l. – n.p.m.
Lopota	2915	375	3086	359
Intsoba	2510	331	2872	321
Chelti	2590	318	3089	313
Avaniskhevi	2350	240	2721	239
Shromiskhevi	2713	251	3044	251
Aragvi	3130	450	3842	445

The Aragvi is 108 km long and its catchment covers an area of 2726 square kilometers. The river has two main tributaries: the Tetri Aragvi (White Aragvi) with headwaters located at about 3130 m a.s.l. and the Shavi Aragvi (Black Aragvi) with headwaters at about 3200 m a.s.l. These two rivers are joined in the Zhinvali Reservoir by the Pshav Aragvi which itself is fed by the Khevsur Aragvi. Zhinvali Dam was built in the years 1974–1985 to create the Zhinvali Reservoir with an area of 1123 ha. The Aragvi flows down from the southern slopes of the Great Caucasus and merges with the Mtkvari river near the town of Mtskheta at the altitude of 450 m a.s.l. The Aragvi has a relatively small mean slope of 2.2°.

Land cover of a greater part of the catchment (79%) consists of deciduous forest (beech, oak, hornbeam and birch) that grows on the slopes of the mountains, and meadows and pastures that cover the mountain ridges and the highest parts of the slopes (Fig. 2). The terrain lying lower and being more flat is used as arable land. Build-up areas are located mainly in the valley of the Aragvi below the Zhinvali Reservoir and in the valleys of the Narekvavi, the Tezami, the Abanoskhevi, the Dushetiskhevi as well as along the Georgian Military Road. The soils in a greater part of the catchment are eutric cambisols and they cover the area below the Zhinvali Dam and the Aragvi and the Pshav Aragvi valleys up to the altitude of 1600–1700 m a.s.l. Above them, there are dystric cambisols and the highest parts of the mountain ranges are covered by cambisols and cryosols.

The springs of the Lopota, the Intsoba, the Chelti, the Avaniskhevi and the Shromiskhevi are located on the southern slopes of the Caucasus at the altitudes between 2350 and 2915 m a.s.l. and the rivers generally flow in south-western direction feeding the Alazani river. As the only river described here, the Shromiskhevi flows out of a small lake located just outside the border with Russia and then down into the Alazani in Azerbaijan (in the vicinity of the state border its name is changed). Modelling has been conducted only for the part of the river catchment located in Georgia and the point closing the catchment is located near the border of the country.

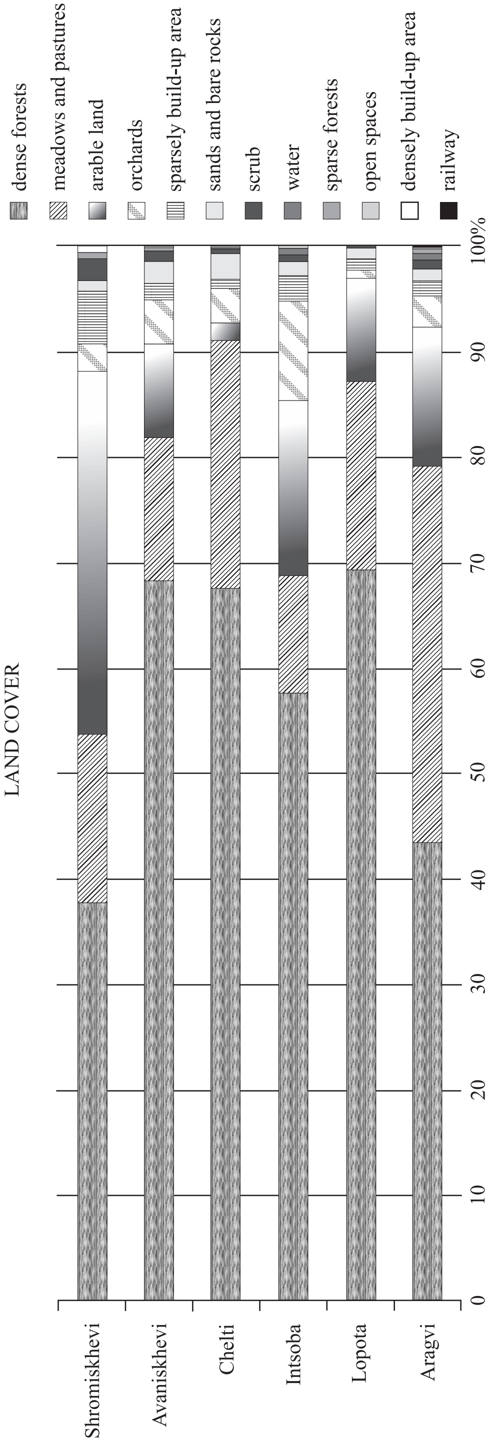


Fig. 2. Structure of land cover in the catchments
Ryc. 2. Struktura użytkowania ziemi

Density of the river network in these five catchments is between 0.94 km · km^{-2} (for the Shromiskhevi that has a relatively narrow catchment and short tributaries) and 1.31 km · km^{-2} (for the Avaniskhevi). Out of the modeled rivers, the Shromiskhevi has the greatest mean slope of the river (9.1°), and the smallest mean slope of the catchment (15°). The Lopota catchment has relatively the largest mean slope (25°) among the modeled rivers from Kakhti. Mean catchment altitude ranges from 976 m a.s.l. for the Shromiskhevi to 1369 m a.s.l. for the Chelti.

The pattern of land cover is similar in all five catchments. The mountain slopes above approximately 500–700 m a.s.l. are covered mainly by deciduous forest (beech, oak, hornbeam) and the ridges above approximately 2100–2200 m a.s.l. are covered with grassland – meadows and pastures. The terrain in the foreground of the mountains is flattened and occupied by build-up areas and arable lands. Riverbeds in the lower part of the catchments are covered with bare rocks. Villages and towns are usually surrounded by small patches of vegetable gardens, orchards and vineyards. The biggest villages are Akhalsopeli located between the Avaniskhevi and its left tributary the Shorokhevi, Lagodekhi and Shroma lying by the Shromiskhevi, Shilda located on the left bank of the Intsoba, and Naperuli situated on the left bank of the Lopota.

The highest areas of the catchments are covered by leptosols, cambisols and cryosols that coat the mountains ridges. Beneath, there are dystric cambisols. Still lower areas comprise eutric cambisols in the catchments of the Avaniskhevi and the Shromiskhevi and calcic kastanozems in the Lopota, the Intsoba and the Lopota catchments. Dystric fluvisols cover the lowest parts of all catchments in the foreground of the mountains.

METHODS

To perform hydrological calculations for modeling purposes it is necessary to first get acquainted with theoretical basis for the application of a hydrological model of rainfall--runoff type for the simulation of floods in an ungauged catchments and then perform the calculations involving the input parameters (meteorological and physiographic characteristics of the catchment) essential to work independently with hydrological models in ungauged catchments.

These characteristics are the basis for hydrological calculations using the hydrological model of rainfall-runoff type and then for carrying out a flood wave transformation with a hydrodynamic model and determination of flood hazard zones.

Prior to the calculations it is necessary to have a database consisting of:

1. A series of maximum daily rainfall per year of a multi-year observation for the precipitation stations
2. Products obtained under training related to the use of GIS techniques:
   a. Digital Terrain Model
   b. The course of the river network, and primarily the length of flow paths
   c. Land cover and the types of soils

Rainfall data in the form of annual peak daily totals were obtained in the Kvareli, Lagodheki, Telavi and Pasanauri stations for the multi-annual period 1966–2014.

Verification of the precipitation data involved checking their independence and the same probability distribution. Another aspect was detecting the presence of a trend.

The Mann-Kendall-Sneyers (MKS) test was used for this purpose [Khaliq et al. 2009, Schumer 2014]. Empirical rainfall data were approximated with Fisher-Tippett distribution type I_{max} and III_{min}. These two distributions were selected because they are commonly used in Poland to describe the precipitation distribution and they are recommended by the World Meteorology Organization (WMO). Fisher-Tippett distribution type I_{max} density function is given by Węglarczyk [2010]:

$$f(x, \alpha, \mu) = \alpha e^{-\alpha(x-\mu) - e^{-\alpha(x-\mu)}}, \ \ \alpha > 0 \tag{1}$$

Distribution parameters α and μ were determined by maximum likelihood method, where the log-likelihood distribution is represented by the following equation:

$$\ln L = N \ln \alpha - \alpha \sum_{i=1}^{N} x_i + N\alpha\mu - e^{\alpha\mu} \sum_{i=1}^{N} e^{-\alpha\mu} \tag{2}$$

Quantile of the random variable x_p of Fisher-Tippett distribution type I_{max} was calculated using the formula:

$$x_p = \mu - \frac{1}{\alpha} \ln \ln \frac{1}{1-p} \tag{3}$$

On the other hand, Fisher-Tippett distribution type III_{min} density function is defined using the formula:

$$f(x, \in, \alpha, \beta) = \beta\alpha^{\beta}(x - \in)^{\beta-1} e^{-\alpha^{\beta}(x-\in)^{\beta}}, \ \ x > \in, \alpha, \beta > 0 \tag{4}$$

Function logarithm of the distribution likelihood is as follows:

$$\ln L = N \ln \beta + N\beta \ln \alpha + (\beta - 1) \sum_{i=1}^{N} \ln x_i - \alpha^{\beta} \sum_{i=1}^{N} x_i^{\beta} \tag{5}$$

Distribution parameters α and β were determined using the maximum likelihood method for a specified lower limit ε. Quantile of the random variable x_p of Fisher-Tippett distribution type III_{min} was calculated using the formula:

$$x_p = \in + \frac{1}{\alpha} \left[-\ln (1-p) \right]^{1/\beta} \tag{6}$$

The Kolmogorov test was used for each theoretical distribution in order to verify the hypothesis concerning its compliance with the empirical distribution. The method used to estimate the parameters of distribution was the maximum likelihood method.

Eventually, output function was selected to develop the design rainfall from the examined distributions based on Schwartz information criterion (BIC) [Tompór et al. 2014]:

$$BIC = -\frac{2 \ln L}{N} + \frac{k \ln N}{N} \tag{7}$$

where:
lnL – function logarithm of particular distribution likelihood,
N – number of observations,
k – number of estimated parameters.

The model for which the information criterion (BIC) achieved the lowest value was chosen as the best one.

The models with concentrated parameters usually assume uniform rainfall distribution within the catchment area. Precipitation depth determined from point data analysis (for one pluviograph station) can be accepted as representative for only very small catchments with the area up to approximately 10 km^2.

When there is only one precipitation station in a catchment, the average amount of precipitation is determined by means of precipitation reducing curves [Ven Te Chow et al. 1988]. As Georgia is a mountainous country, extreme flood events are usually caused by short (4–6 hours) intensive rainfalls. NEA database provides mainly data on daily rainfall. Beta distribution is used for the distribution of intense rainfall to get the observed maximum (peak) water discharge.

The input data for a hydrological model include the intensity of an effective rainfall. This parameter was determined using SCS-CN method [Ponce and Hawkins 1996, Mishra and Singh 2002, Michel et al. 2005, Váňová and Langhammer 2011, Chauchan et al. 2013, Banasik et al. 2014a, 2014b, Kowalik and Wałęga 2015, Wałęga et al. 2015]. The popular form of the SCS-CN method is expressed as:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \quad if\ P > I_a \tag{8}$$

$$Q = 0 \text{ otherwise}$$

$$I_a = \lambda S \tag{9}$$

where
Q – direct runoff, mm,
P – total precipitation, mm,
I_a – initial abstraction, mm,
S – potential maximum retention, mm,
λ – initial abstraction coefficient.

The parameter S of the NRCS-CN method depends on soil type, land use, hydrological conditions, and antecedent moisture conditions (AMC). The parameter S is expressed as:

$$S = \frac{25\,400}{CN} - 254 \tag{10}$$

CN = 100 represents a condition of zero potential maximum retention (S = 0), that is, an impermeable catchment. Conversely, CN = 0 represents a theoretical upper bound to potential maximum retention (S = 1), that is an infinitely abstracting catchment. A theoretical value of CN parameter was determined based on an orthophotomap, with reference to current land use and 1 : 25 000 scale soil maps. It was found to correspond to normal catchment moisture conditions AMCII. Each elementary catchment was divided into so-called task catchments and then, based on soil maps and land cover, the value of CN parameter was found in the tables [USDA 2004]. Next, the weighted average value of CN was found for each of the elementary catchments and the level of effective rainfall was calculated from formula (8).

The map of soils impermeability was developed based on geological 1 : 50 000, 1 : 200 000, and 1 : 500 000 soil maps. GIS layer with land cover was updated based on visual interpretation of optical satellite images (Landsat 8, Sentinel-2A) and aerial photomaps. The images had various spatial resolution, from 30 m for Landsat 8, 10 m for Sentinel-2 to very high resolution aerial photomaps.

Transformation of an effective rainfall into direct runoff is a final step of the computations. In the absence of rainfall-runoff data, unit hydrograph can be derived by synthetic means. A synthetic unit hydrograph (SUH) is a unit hydrograph derived from an established formula, without the need for rainfall-runoff data analysis [Ponce 1989]. The unit hydrograph according to SCS was used. In this method, SUH shape is determined based on the non-dimensional q/q_p vs. t/t_p hydrograph (Fig. 10), the peak discharge q_p and the time to peak t_p and it is computed as follows:

$$q_p = \frac{2.08 \cdot A}{t_p} \tag{11}$$

$$t_p = \frac{t_r}{2} + T_l \tag{12}$$

where:
A – the area , t_r is the duration of rainfall,
T_1 – the lag time from the centroid of the rainfall to peak discharge.

T_1 may be calculated from the catchment characteristics using main stream length L, catchment slope s and curve number (CN):

$$T_l = \frac{(3.28 \cdot L \cdot 1000)^{0.8} \left(\frac{1000}{CN} - 9\right)^{0.7}}{1900 \cdot s^{0.5}} \tag{13}$$

RESULTS

Later in this paper, detailed results of analyses obtained for the Chelti catchment are shown. The same methods were also used for the other catchments. A preliminary analysis of the rainfall data indicated that information on the peak daily total rainfall for the year 2000 and the years 2007-2014 for the Kvareli rainfall station, which is nearest to the analyzed Chelti catchment, was incomplete. Therefore, it was necessary to extend the data sequence. The rainfall data sequences were extended based on information obtained in the nearest rainfall stations: Lagodheki, Kvareli and Telavi. In order to fill in the missing data in the daily total rainfall, the model [Ponce 1989] was used:

$$P_K = \left(\frac{1}{2}\right)\left[\left(\frac{N_K}{N_L} P_L + \frac{N_K}{N_T} P_T\right)\right] \tag{14}$$

where:

P_K – peak daily total in the *i*-th year, Kvareli station, mm,
N_K – average sum of peak daily totals per year in a multi-annual period, Kvareli station, mm,
N_L – average sum of peak daily totals per year in a multi-annual period, Lagotheki station, mm,
N_T – average sum of peak daily totals per year in a multi-annual period, Telavi station, mm,
P_L – peak daily total in the *i*-th year, Lagodheki station, mm,
P_T – peak daily total in the *i*-th year, Telavi station, mm.

Furthermore, an opportunity to fill in rainfall data based on Formula (14) with data obtained in one station Lagodheki and Kvareli was assessed. In order to obtain verifiable results, the calculations were begun on multi-annual data for the years 1966–1999, for which complete data sequences were available for all rainfall stations. More specifically, the values N_K, N_T and N_L were calculated for the multi-annual period 1996–1992 and then rainfall was calculated for the period 1993–1999 for the Kvareli rainfall station. The results, shown in Fig. 3, seem to indicate that the model based on the rainfall stations in Lagodheki and Telavi was of the best quality, as suggested by the value of the correlation coefficient $r = 0.62$.

For the other models, the correlation coefficients had much lower values. It is important to observe that the highest impact on the total values of rainfall data in the Kvareli

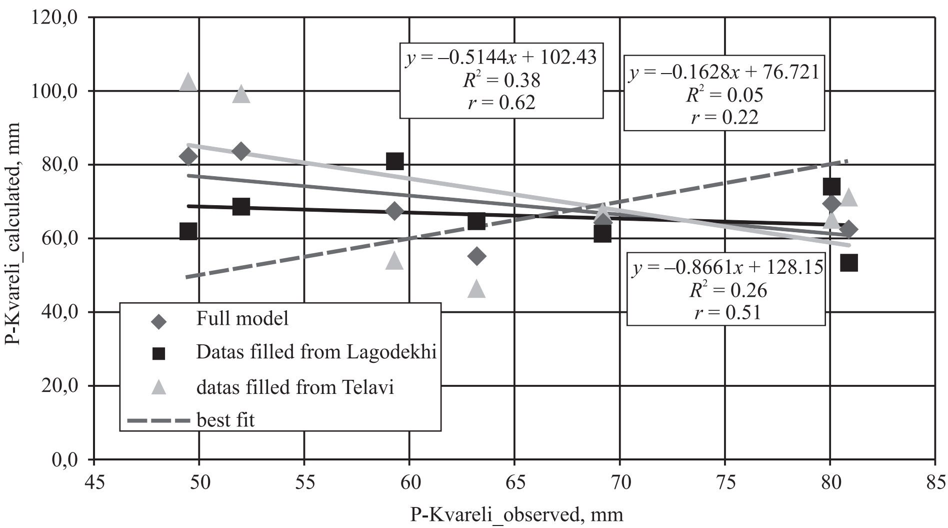


Fig. 3. Verification of the model for filling in missing precipitation data
Ryc. 3. Weryfikacja modelu do uzupełniania danych opadowych

station is that of the Lagodheki station, even though it is located much farther from Kvareli than the Telavi station. The daily total rainfall in the years 1966–1992 in the Lagodheki station is 98% of the value recorded for the same period in the Kvareli station. For the Telavi station, the daily rainfall is 79% of that for the Kvareli station. Such considerable convergence in the rainfall data between the Lagodekhi and Kvareli stations results from similar land profiles in the places of their location, in the foothills of the same ridge of the Caucasian mountains.

The next stage of the project included a statistical analysis of the peak daily total rainfall in the years 1966–2014. To begin with, the hypothesis that no trend in the rainfall data is observed was verified using the MKS test mentioned earlier in this paper. Fig. 4 shows the results of the MKS test for the Lagodekhi station.

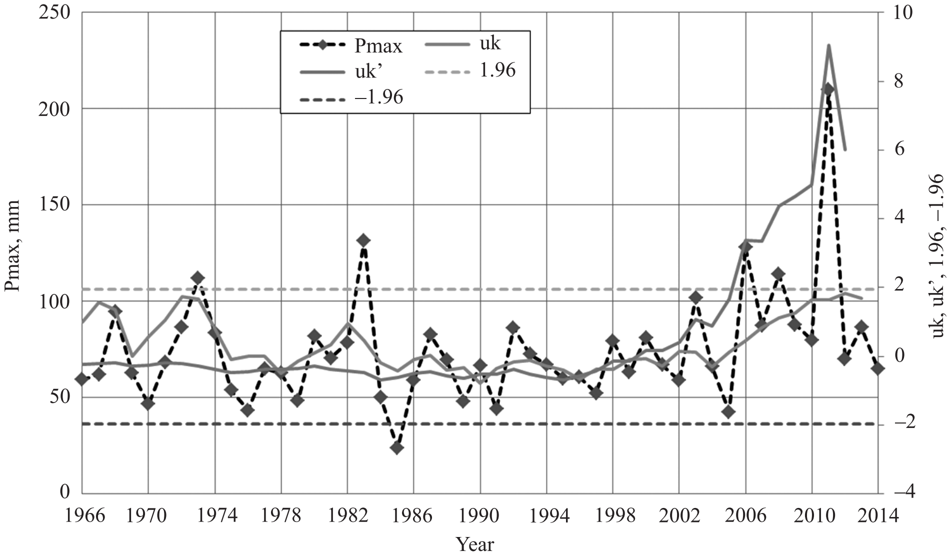


Fig. 4. The results of trend analysis for the peak daily total rainfall in the years 1966–2014 for the Lagodheki rainfall station (P_{max} – peak daily total in year; *uk* – MKS test statistics for data in chronological order; *uk'* – MKS test statistics for data in reversed order; –1.96 and 1.96 – confidence intervals of MKS test)

Ryc. 4. Wyniki analizy trendu maksymalnych dobowych w roku sum opadów w latach 1966–2014 dla stacji opadowej Lagodheki (P_{max} – maksymalna dobowa suma opadów w roku; *uk* – statystyka testu MKS dla danych w układzie chronologicznym; *uk'* – statystyka testu MKS dla danych w układzie odwróconym; –1.96 i 1.96 – przedział ufności testu MKS)

The analysis indicates that there is no significant trend in the rainfall data: this is proved by the values of uk statistics for data in the chronological order, and uk' statistics for the reversed order of data on the peak daily total values. This means, at the confidence level $\alpha = 0.05$, that the profile of peak daily rainfall data in the multi-annual period of interest is random. Despite a slight increasing tendency in the rainfall data since 2004, the final result of the analyses was unaffected. Comparable results were obtained for the other analyzed rainfall stations. Following data verification, the values of quantiles of peak daily rainfall were assessed. The Fisher-Tippet distribution types I_{max} and III_{min} were used for the purpose. The distribution quantiles were assessed using the highest credibility method. Fig. 5 shows examples of curves of empirical and theoretical probabilities of peak daily rainfall for the Lagodheki station. The calculations indicated that both the proposed theoretical distributions well approximated the empirical probability curve for the peak daily rainfall. All the same, it seems that the curve for the Fisher-Tippet distribution type III_{min} describes empirical data somewhat better, especially in the zone of low probabilities, which are of special importance for hydrological calculations. The Kołmogorow demonstrated that there was no reason for rejecting both of the proposed distributions. The Schwarz (Bayesian) criterion was used for choosing the ultimate statistical distribution. Examples of calculations for the Lagodheki stations showed that the value of the BIC function for the Fisher-Tippet distribution type III_{min} and type I_{max} was 8.741 and 9.257, respectively. Eventually, the Fisher-Tippet distribution type III_{min} was selected as the recommended solution for all the rainfall stations.

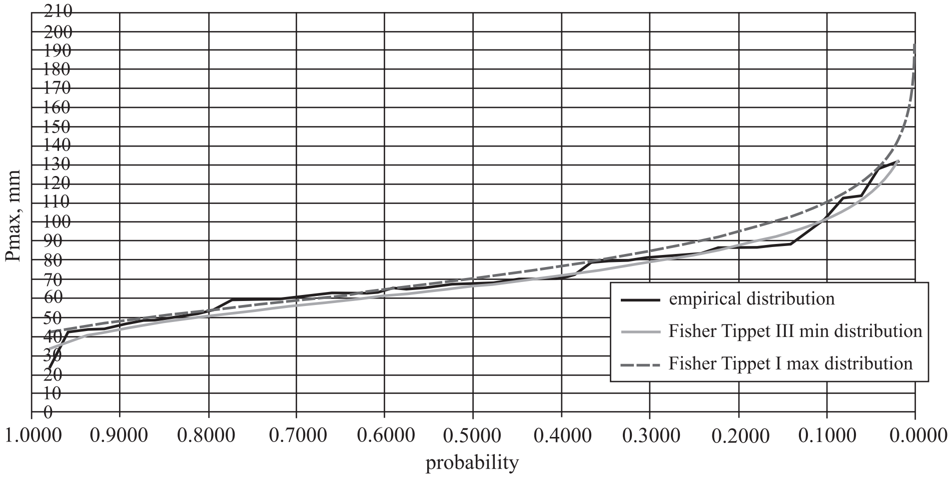


Fig. 5. Curve of empirical and theoretical distributions for the Fisher-Tippet distribution type I_{max} and III_{min} for peak daily total rainfall, Lagodheki station

Ryc. 5. Empiryczny i teoretyczny rozkład Fishera-Tippeta typu I_{max} i III_{min} dla maksymalnych dobowych sum opadu w roku, stacja opadowa Lagotheki

Further analyses were based on the hyetograms of rainfall with a set exceedance probability. According to the adopted methodology, the hyetograms were based on beta distribution [Wałęga et al. 2012]. Fig. 6 shows a typical hyetogram for a rainfall with the exceedance probability of p = 1% and duration t = 24 h for the Chelti catchment. The hyetogram in which the peak rainfall intensity was in the middle of the time of the event was chosen as the recommended solution. Similar rainfall distributions in time were adopted for the other catchments.

The entire runoff modeling process was carried out using the HEC-HMS software [US ACE 2010]. It is applied for simulations of surface runoff and flood wave transformation in the watercourse system in catchments with dendritic hydrographic layout. Generally,

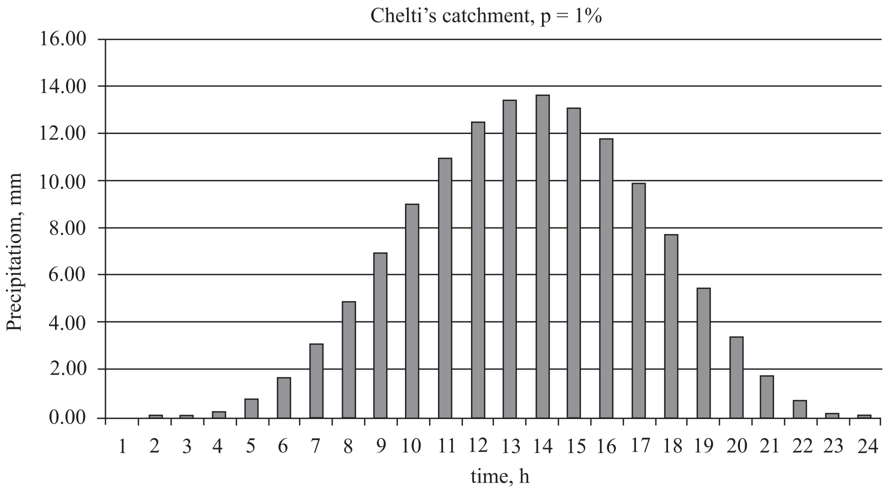


Fig. 6. Hyetogram of total rainfall with the exceedance probability of p = 1% in the Chelti catchment

Ryc. 6. Hietogram opadu całkowitego o prawdopodobieństwie przewyższenia p = 1% w zlewni Chelti

this program constitutes a rainfall-runoff type of models, where the input parameters are the components representing meteorological factors such as precipitation, evaporation, and snowmelt water. Additional modules allow for determining a loss to infiltration and supply of watercourses by groundwater. The catchment parameters include area, length of watercourses, ground properties, etc. [Wałęga 2013].

In order to reflect with as much detail as possible the complexity of physical and geographical characteristics of the investigated catchments, task catchments were sectioned off in each catchment of interest and simulations were made for the test catchments. Momentary flows were summed up at nodal points, enabling runoff from the entire catchment to be calculated. Fig. 7 shows the example of a model diagram in the Chelti catchment, obtained using the HEC-HMS software.

Model parameters were specified separately for each of the task catchments. The key elements in the runoff modeling are the rainfall losses, identified with what is called an effective rainfall. For the catchments of interest, the effective rainfall was calculated using the SCS-CN method, of which the details are described in Methods. Fig. 8 shows the distribution of soil groups, utilization and distribution of the CN parameter using the example of the Chelti catchment.

The values of CN were found for average conditions (soil moisture level II). Compared with the original SCS tables in [USDA 2004], additional information, specifying the type of land cover, typical of the Caucasian catchments, was required. In each of the analyzed catchments, areas with considerable amounts of accumulated sand were present in large fragments of river valleys. Such accumulation of sand resulted from the accumulation of rock debris due to the flow of water during a flood event. The analyzed rivers tend to carry large amounts of rock material and the related flood events are mud-and-stone floods. For the purpose of these calculations, it was assumed that such areas are covered by water.

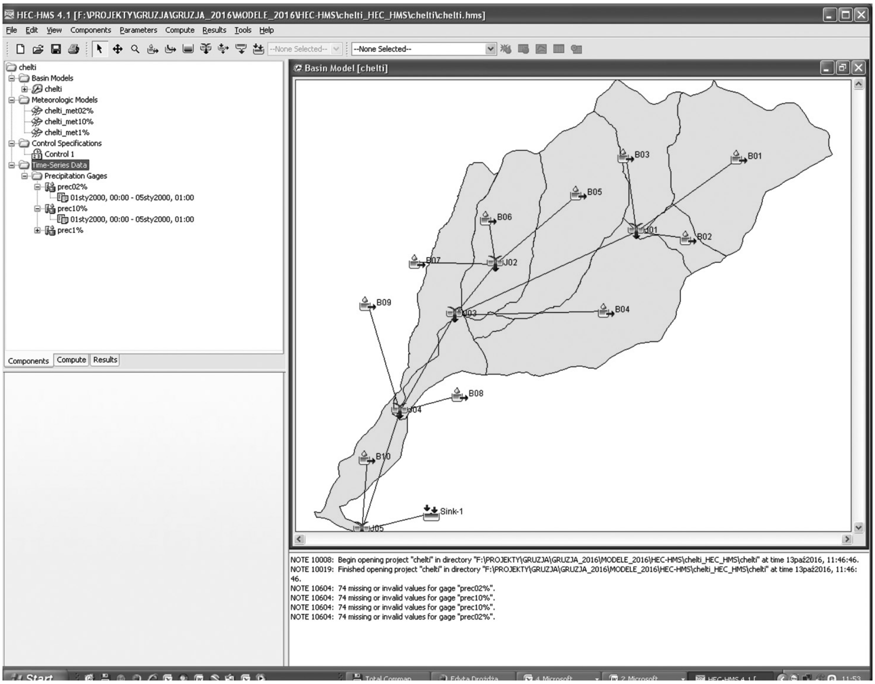


Fig. 7. A catchment, as implemented in the HEC-HMS software
Ryc. 7. Implementacja zlewni w programie HEC-HMS

a)

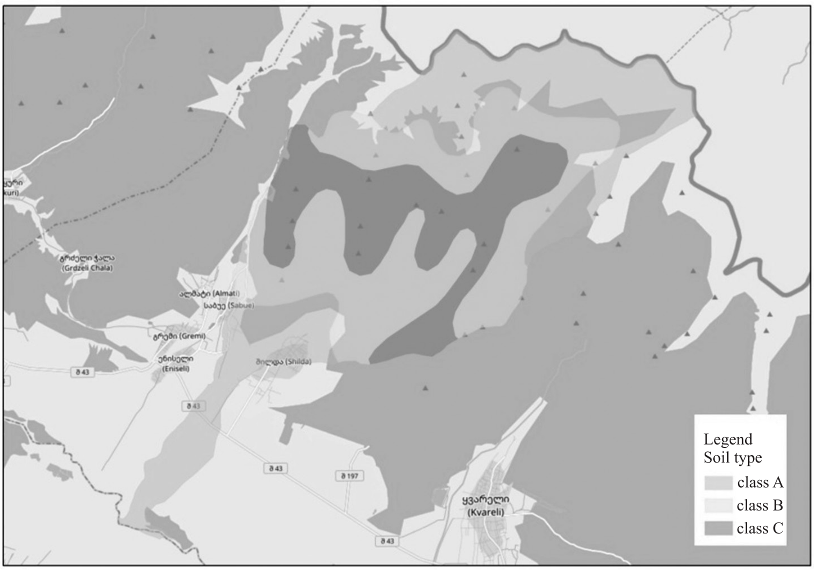
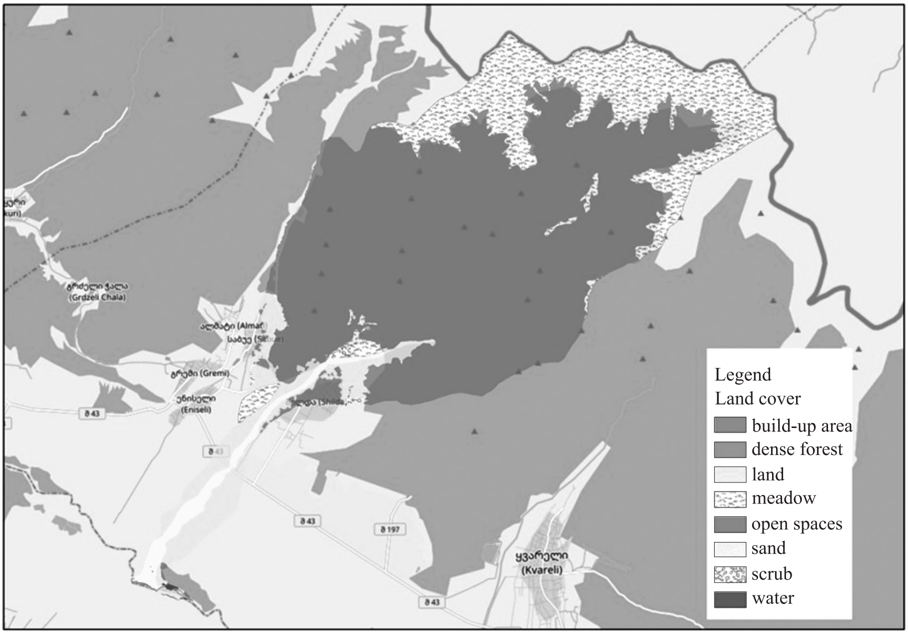


Fig. 8a. The distribution of soil groups, utilization and distribution of the CN parameter in the Chelti catchment
Ryc. 8a. Rozkład grup glebowych, użytkowania i parametru CN w zlewni Chelti

b)



c)

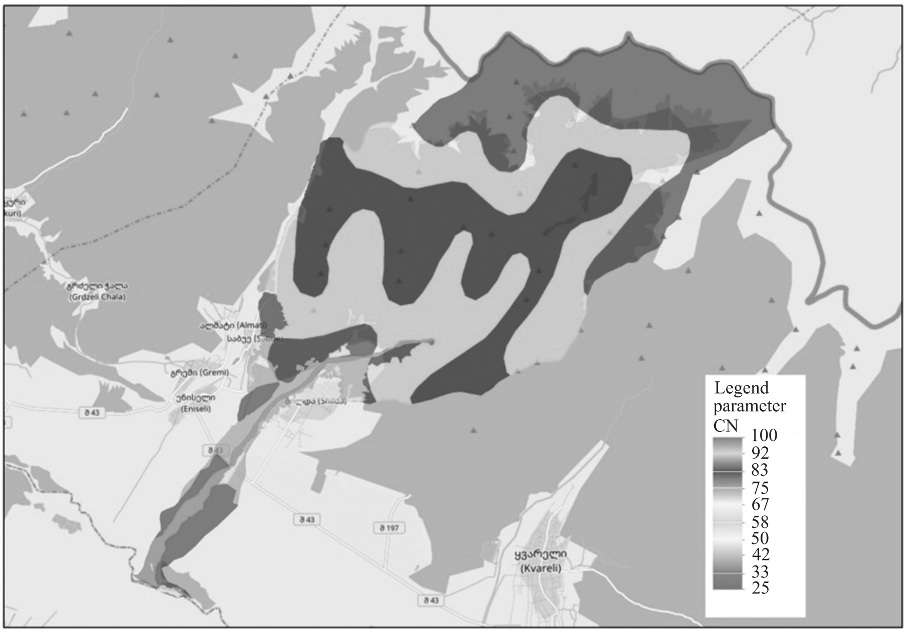


Fig. 8b, c. The distribution of soil groups, utilization and distribution of the CN parameter in the Chelti catchment

Ryc. 8b, c. Rozkład grup glebowych, użytkowania i parametru CN w zlewni Chelti

Based on a numerical model of the area (Fig. 9), water discharge paths were delineated for each task catchment and then the SCS-UH model parameters were calculated: length and slope of the discharge path. This enabled the delay time to be calculated according to Formula (13). Table 3 shows the parameters which are indispensable for the runoff calculation for the Chelti task catchments.

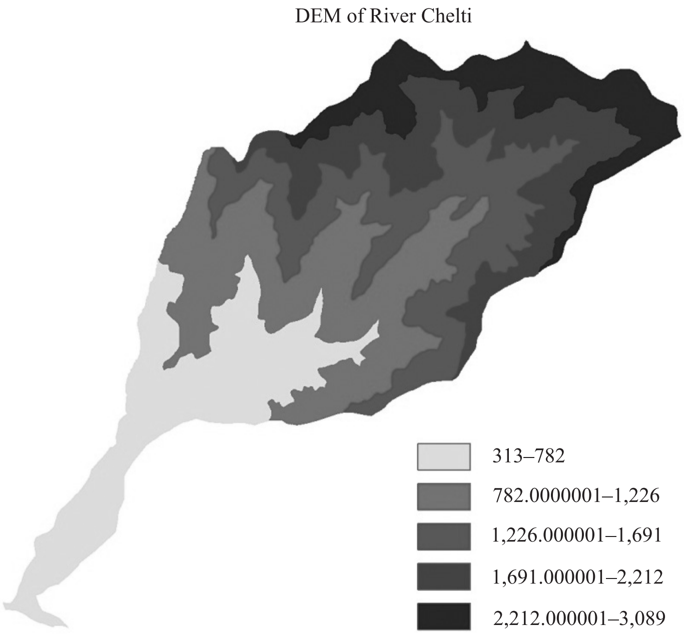


Fig. 9. The numerical model of area for the Chelti catchment
Ryc. 9. Model numeryczny terenu dla zlewni Chelti

Table 3. Values of the SCS-UH model parameters in the Chelti catchment
Tabela 3. Wartości parametrów modelu SCS-UH w zlewni Chelti

Model Catchment Zlewnia modelowa	Area – Powierzchnia	*CN*	T_{lag}	*S*
	km^2		min	mm
B01	30.92	39.12	101.16	395.28
B02	4.25	44.05	91.25	322.62
B03	13.52	52.90	52.99	226.15
B04	30.54	60.39	62.65	166.60
B05	25.01	62.01	91.19	155.61
B06	16.95	53.51	102.39	220.68
B07	1.32	76.64	24.50	77.42
B08	6.01	67.68	95.31	121.30
B09	13.03	81.24	57.43	58.65
B10	7.92	82.96	165.86	52.17

CN – value of *CN* parameter – wartość parametru *CN*, T_{lag} – lag time – czas opóźnienia, *S* – maximum potential storage – maksymalna potencjalna retencja

Table 4 shows the collective values of peak flows with the exceedance probabilities of $p = 1\%$, 10% and 0.2% as obtained from the hydrological model. Next, Fig. 10 shows runoff hydrographs for the Chelti river-mouth cross section, for three exceedance probabilities.

Table 4. Peak flows with a specified exceedance probability for the analyzed catchments
Tabela 4. Przepływy maksymalne o określonym prawdopodobieństwie przewyższenia dla analizowanych zlewni

Catchment Zlewnia	Area – Powierzchnia km^2	Flow – Przepływ, $m^3 \cdot s^{-1}$		
		$p = 10\%$	$p = 1\%$	$p = 0{,}2\%$
Aragvi	2726	597	1123	1595
Lopota	275	255	480	682
Incoba	89	156	292	415
Chelti	150	195	366	520
Avanizkhevi	181	217	408	579
Shromiskevi	69	138	259	368

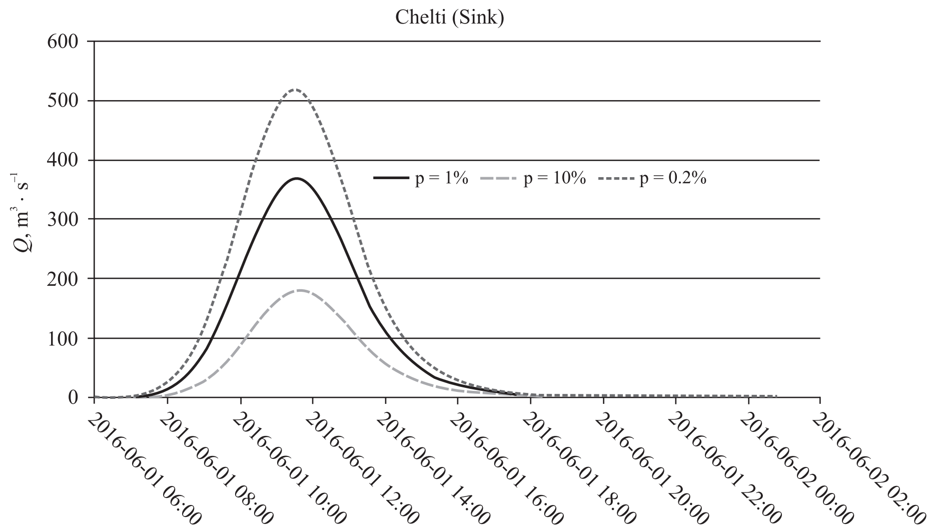


Fig. 10. Direct runoff hydrographs at the Chelti river-mouth cross section, for exceedance probability of $p = 0.2$, 1, and 10%
Ryc. 10. Hydrogramy odplywu bezpośredniego w przekroju ujściowym rzeki Chelti dla prawdopodobieństw przewyższenia $p = 0.2$, 1 i 10%

CONCLUSIONS

This paper describes the range of work related to the modeling of runoff for selected catchments in the east of Georgia, located in the Kakheti region. The calculations were made as part of the project "Study of hydraulic modelling against floods – 2nd stage –

support to the competence and readiness of Georgian institutions". Its objective was for Polish specialists to provide specialists in Georgia with instruction on the various steps of hydrological and hydraulic modeling thus providing them with the skills to delineate flood risk zones. Since the analyzed catchments are ungauged, it was decided that the Polish experience, acquired in the execution of projects related to flood risk, should be implemented. Basic characteristics of catchments, required for modeled calculations, were found by means of a rainfall data base and DEM topographical maps. The performed analyses provided the opportunity to fill in missing data on rainfall based on the observation of rainfalls in the adjacent stations. The analysis of long sequences of data on peak daily totals for the multi-annual period 1966–2014 revealed that the Fisher-Tippett distribution type III_{min} is optimal for the assessment of the quantiles of peak daily total rainfall with a specified exceedance probability. The unit hydrograph model SCS-UH was used for obtaining the direct rainfall hydrographs from the catchments of the Lopota, the Intsoba, the Chelti, the Avaniskhevi, the Shromiskhevi, and the Aragvi. This particular model was chosen because it is simple and requires only a small number of easily found parameters. The model is suitable for the simulation of the direct rainfall from catchments which are similar to those analyzed in the project in question. The results of model calculations were used as the basis for building a hydrodynamical model of freshet wave transformation in rivers and, consequently, for delineating flood risk zones.

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APLIKACJA DOŚWIADCZEŃ POLSKICH WE WDRAŻANIU DYREKTYWY POWODZIOWEJ NA OBSZARZE GRUZJI – PROBLEMATYKA OBLICZEŃ HYDROLOGICZNYCH

Streszczenie. W artykule zaprezentowano przykład implementacji metodyki prowadzenia obliczeń hydrologicznych w aspekcie wyznaczenia stref zagrożenia powodziowego do warunków panujących w Gruzji. Przedstawione wyniki zostały uzyskane w ramach projektu „Nauka modelowania hydraulicznego dla zapobiegania powodziom – 2 stopień – wsparcie kompetencji i gotowości instytucji gruzińskich" wdrażanego przez Polskie Centrum Pomocy Międzynarodowej (PCPM) i współfinansowanego przez Ministerstwo Straw Zagranicznych Rzeczypospolitej Polskiej. Wyniki projektu dotyczyły zlewni: Lopota, Intsoba, Chelti, Avaniskhevi, Shromiskhevi leżące w Kahetii oraz Aragvi. Wszystkie wymienione zlewnie są niekontrolowane pod względem hydrologicznym, więc zaistniała konieczność wykorzystania modelu hydrologicznego typu opad–odpływ do wygenerowania hydrogramów hipotetycznych. Na podstawie maksymalnych dobowych sum opadów z wielolecia 1966–2014 obliczono wartości kwantyli opadów o określonym prawdopodobieństwie przewyższenia. Hietogram opadu określono w oparciu o funkcję rozkładu beta, a opad efektywny obliczono z wykorzystaniem metody SCS-CN. Informacje o rzeźbie terenu, warunkach glebowych i pokryciu uzyskano z numerycznego modelu terenu i wytworzonych w ramach wspomnianego projektu map. Transformację opadu efektywnego w odpływ dokonano za pomocą prostego modelu SCS-UH opartego na syntetycznym hydrogramie jednostkowym. Badania wykazały, że sumy dobowe opadów jednorodnych wykazują charakter losowy i można je opisać za pomocą rozkładu Fishera-Tippetta typ III_{min}. Wyniki uzyskane z modelowania stanowiły warunki brzegowe w modelu hydraulicznym transformacji fali powodziowej w rzekach.

Słowa kluczowe: strefy zagrożenia powodziowego, model hydrologiczny, opady maksymalne, metoda SCS, region Kachetii

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