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CONTENTS

MONITORING AND INVESTIGATION OF INTERMITTENT RIVERS IN BULGARIA

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ABSTRACT

River flows could be defined according to their surface hydrologic stream duration as either perennial or temporary. Normally perennial streams flow throughout the year, while temporary streams lack surface flow for some periods of the year. Temporary streams are classified as intermittent or ephemeral. Intermittent streams flow in some periods as result of snowmelt and eventually elevated groundwater tables during the periods of increased precipitations. Intermittent streams are poorly represented in existing river monitoring programs in Bulgaria and seldom are objects of regular monitoring. Only in several gauging stations exist hydrological time series. Furthermore, intermittent and ephemeral streams are not adequately protected by current legislation and management strategies in Bulgaria and generally are neglected.

The authors discuss the climatic, hydrological and soil conditions in different part of the country as the major factors determining their origin and distribution. Covering the whole territory of Bulgaria the authors identify four main types of intermittent streams as: 1) intermittent flows as result of Mediterranean climatic impact located in the southern part of the country; 2) sinking intermittent flows as result of specific geological and soil characteristics, 3) intermittent flows in large karst and loess areas and finally 4) the sinking flows in alluvium depositions mainly along the large mainstreams. Nevertheless, the limited number of gauging stations built up at these rivers some hydrological information is collected and statistical results are presented as duration curves of temporal rivers, hydrographs with seasonal characteristics etc.

Intermittent streams have a hydrologic flow regime with very specific characteristics that place them as interact between land and water. Unfortunately, in Bulgaria there are poorly mapped, recognized, and protected but they have a critical influence on the ecological health of networks. There exists a strong need for new approaches to scientifically study, the structure and function of temporal streams. The construction of monitoring network for the regular registration of their hydrological regime is surely the first required step for their future detailed ingestions, use and protection.

Keywords: intermittent rivers, mapping, regime, hydrology

INTRODUCTION

The interest in the drying rivers due to climate change and ecological importance, as well as the lack of water, increases worldwide (Bond et al., 2008, Skoulikidis et al., 2017, Snelder et al., 2013). The intermittent rivers have always been underestimated, including in Bulgaria. Currently the increased European interest is expressed in a special European project called COST Action Ca 15113 Science and Management of Intermittent Rivers & Ephemeral Streams (SMIRES) with the participation of National Institute of Meteorology and Hydrology seeking to summarize our knowledge of these rivers including from hydrological point of view. (Sauquet et al., 2019, Datry et al., 2019). The present material summarizes the first results in Bulgaria combining the statistical processing of historic time series and field surveys along drying streams in the frame of different projects in the past.

Understanding the drying river is a basis for further understanding of the ecohydrological processes of the river basins and is a strong indicator of climate changes in the regions. We should not underestimate the value of these rivers in conditions of water deficit. Understanding the flow intermittence in the regions is a necessary step for effective water resources management.

Temporary streams represent a significant and particularly vulnerable portion of river networks. While the vast majority of stream and river research to date has focused on flowing waters, recent work reveals that temporary streams are not only abundant and widely distributed, but also play a significant role in the hydrological and ecological integrity of networks (Thibault at al., 2019). Defining temporary streams and their hydrology and highlighting their abundance and extent, we can consider and assess the ecological significance of temporary streams, including their role as faunal and floral habitat providers, biogeochemical processors, and connectivity corridors within river networks.

Intermittent streams are poorly represented in existing river monitoring programs because most sites located on higher-order perennial streams (Thibault at al., 2019).

METHODS AND DATA (STUDY AREA)

The river runoff on the territory of Bulgaria is formed under the influence of three climatic zones - temperate continental; transitional-continental; continental-Mediterranean; as well orohydrographic, geological and hydrogeological characteristics of the catchments. Cases of drying up of individual rivers or river segments have been registered or observed in all three climatic zones of the country. Unfortunately, until now there is no comprehensive survey and systematization of information on the drying up of rivers in Bulgaria. The present investigation is the first one in the country based on available information from gauging stations and field surveys along rivers within different projects in the past. In this sense, the study has no claim to cover all rivers in Bulgaria which dry up due to the relatively low density of the regular monitoring network and sporadic additional field trips. Nevertheless, the most significant river catchments and dry river regions are covered. The study area is a whole territory of Bulgaria.

The investigation has three objectives: 1) characterizing the spatial distribution of the drying rivers on the territory of Bulgaria; 2) study of the genesis of drying of the main types of drying rivers; 3) frequency of occurrence and duration of the phenomenon over the years.

The survey is based on historical time series of the daily flows from the State hydrometric network on the territory of the country - 216 gauging stations (200 among them active at present and 16 temporally closed the last years). The referent period of investigation covers 37 years from 1981 to 2017. The accepted period includes a low-water phase registered on the territory of the country - 1981-2000 and a phase with a trend of increasing flows 2001-2017. In addition, field survey research information was used to clarify rivers without regular measurements. The criteria for the selection of drying rivers were adopted by the Working Group 1 of project Science and Management of Intermittent Rivers & Ephemeral Streams (SMIRES) in 2017 (Sauquet et al., 2019, Datry et al., 2019). According to them, intermittent rivers should meet the following criteria: a) at least one event with discharge lower or equal to one liter per second for daily data; b) for weekly data seven consecutive days (i.e. one record) with this discharge value; c) for monthly – one month; the minimum time series length is 10 years, with less than 5% of missing days.

The 37 years period of investigation (1981-2017) meets the above criteria for all active stations. Among the sixteen closed gauging stations with interrupted regular measurements, seven are situated on drying rivers. Only for those seven stations in the statistical processing, the number of years is reduced to the year of closure. Statistical processing of hydrological series for all the rest gauging stations with registered drying flow has been carried out for the whole period. The total number of gauging stations with registered zero-flow days is 42 (among them: 38 stations with numerous registered zero-flow days in the studied period and 4 with accidently registered zero-flow days) – Table 1 below.

Among the characteristics of zero-flow periods revealed and presented in Table 1 are: $\boldsymbol{n_0}$ is the total number of days with zero-flow, ***f*** is the fraction of zero-flow years which is the number of years with zero-flow divided by the total number of years, ***ma*** is the mean annual number of zero-flow days which is the total number of zero-flow days divided by the number of years, ***max days*** - maximum number days zero-flows in the one year for the period, ***min days*** - minimum number days zero-flows in the one year for the period, ***mean days*** - mean number days zero-flows in the one year for the period, $\boldsymbol{C_v}$ -coefficient of variation of the days with zero-flow. These characteristics reflect the frequency and the amplitude of change of zero-flows in the studied period.

RESULTS AND DISCUSSION

As a result of both field surveys and statistical processing of the hydrological historical series at the monitoring stations, four major regions were identified with drying rivers meeting the aforementioned criteria. The specific type of drying rivers has been identified in the next regions - the Eastern Rhodopi and Sakar Mountain; the southern parts of the catchment area of the Struma River; the Southern Black Sea area and Dobrudja region. These regions are presented and displayed on the map with their geographical location on the territory of Bulgaria - Fig. 1.

The runoff in these rivers is characterized by periods of complete drying up with varying frequency of occurrence over the years. With the exception of Dobrudja region, the runoff of these rivers is shaped under the influence of the Mediterranean climate.

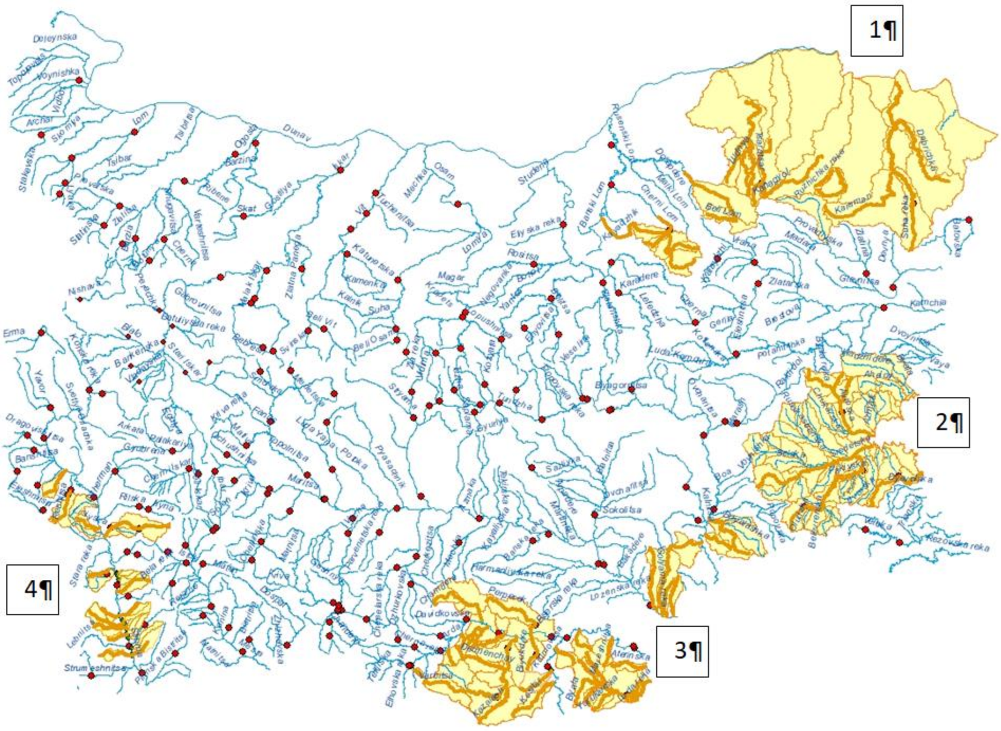

Fig. 1 Geographical distribution of drying rivers:

[1]- Dobrudja sinking rivers region; [2]- Southern Black sea region;
[3]- Eastern Rodopi region and Sakar; [4]- Struma watershed region

1. Dobrudja sinking rivers region [1]

The Dobrudja rivers flow into the Dobrudja Plateau and parts of the Ludogorie area in wide or canyon-shaped river valleys. Humidity, cloudiness and rainfall in the region are less due to the very specific “rainfall shadow” which characterizes and distinguishes the region. This area is characterized by a small outflow coefficient of rainfall, one of the lowest determined on the territory of Bulgaria – only 2%.

In the region of Dobrudja and Ludogorie are distributed mainly carbonate rocks (limestones with lower Cretaceous and Neogene age). These rocks form three main ground aquifers - the Malm-Valange, Barrem-Apt and Neogene (Sarmatian). Surface runoff is submerged in the all three horizons. Dobrudja area is characterized by negligible surface runoff and very large karst groundwater resources. The low rainfall and karst character of the area limits the surface runoff after prolonged heavy rainfall. Characteristic of the Dobrodzha rivers is the absence of a true estuary, submersion and groundwater feeding; truncated or unformed shallow river beds. The rivers are dry, with mainly ground feeding and most often large catchments with an altitude of less than 300 m.

Kanakiol river

Senkobetz river

2. Southern Black Sea region [2]

The rivers in the Southern Black Sea region form their runoff under the influence of the Mediterranean climate but with specific features of the Black Sea area.

The region is characterized by diverse geology. The northern part of the area is dominated by sedimentary rocks of Cretaceous, Paleogene and Neogene age. To the south, the terrains in the catchment areas of the small and medium-sized Black Sea rivers are made up mainly of silicate rocks (upper Cretaceous volcanics): andesite, tuff, tuffite; as well clays, sands, poorly soldered sandstones, marls, conglomerates and limestones.

Most of the region is characterized by the lack of significant aquifers. The specific Black Sea climatic influence and the lack of significant ground feeding are the main factors for the seasonal drying up of rivers in the region. The Southern Black Sea region is characterized by low water content with low runoff (11%). Typical for the region is the great diversity in the annual runoff distribution, which is strongly influenced by the nature of rainfall and their distribution over the years. There are years of prolonged drought due to low rainfall, as well as years of prolonged rainfall and significant river runoff that means the interannual flow distribution varies very much. This is illustrated in Figure 2 for the Fakia River.

Otmanli river

Aheloj river

Sredetzka river

3. Eastern Rodopi and Sakar Mountains region [3]

The region covers the catchments of the rivers originating in the southeastern and northeastern part of the Rhodopi, Sakar and part of the southernmost tributaries of the Tundja River with springs in the Strandja Mountain.

A specific river type for this region are the sub-Mediterranean small and medium-sized rivers, characteristic of all tributaries of the Arda River flowing into the section from the Kardzhali Reservoir to the border. The right tributaries of the Arda - Varbitsa and Krumovitsa Rivers are the special and very typical case of the sub-Mediterranean mountain rivers, characterized by rapid outflow concentration, formation of extreme high waves and severe shallow water afterward - Fig. 3. During periods of low water these rivers are in process of drying up or are in a state of entirely dry river beds. The specificity of the river types in the valley of the Arda River (main streamflow in the region) is determined by the morphostructure of the relief of the Arda valley (strongly indented by valley extensions) and the climatic characteristics with strong Mediterranean impacts.

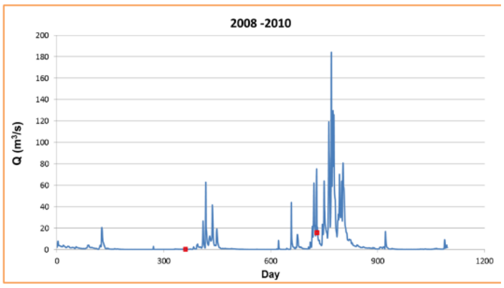

Fig. 2 Hydrograph of Fakijska river - Mediterranean impact in the Black Sea area - Region 2

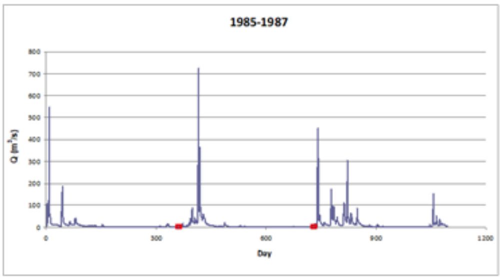

Fig. 3 Hydrograph of Varbitza river - Mediterranean impact in the mountain area, Eastern Rodopi region and Sakar - Region 3

The catchment areas are composed mainly of silicate (magma and metamorphic) rocks: southern Bulgarian granites, gneisses, shales, rhyolites, etc. The specified rock formations lack the conditions for the formation of significant resources from groundwater type cracks. In general, areas with the distribution of these rock formations are estimated to be poorly waterlogged. The Mediterranean climate, the lack of significant aquifers and the natural drainage of the terrain are the main factors for the observed seasonal dryness of these rivers and their torrential character.

The small left tributaries of the Maritza River, originating from the Sakar Mountains, are also attached to this region.

Uvadjik river

Tcham dere river

Elbasan dere river

Biala reka river

Luda reka river

Hambar dere river

4. Struma watershed region [4]

Mediterranean influence on runoff formation (Continental-Mediterranean climatic region) covers the middle reaches of the Struma River, where drying, mostly small left and right tributaries have been observed, for example as the Lisiyska River, the Kamenitza River, the Zlina River, the Sedelska River, Rybnik, Sklavska River and more.

The catchment areas are composed mainly of silicate (magma and metamorphic) rocks: southern Bulgarian granites, gneisses, shales, rhyolites, etc. In the mentioned rock formations, there are no conditions for the formation of significant resources from groundwater type in the cracks. Generally, areas with the distribution of these rock formations are estimated to be poorly waterlogged. The Mediterranean climate, the lack of significant aquifers and the natural drainage of the terrain are the main factors for the observed seasonal drying up of these rivers and the torrential nature of some of them, such as the Potoka River and others (look at photos below).

Suha reka river

Ribnik river

Voitcha river

The reasons for the drying up of the rivers in the four identified regions have different genesis. The regions located in the eastern part of the Rhodopi Mountains and the catchment area of the Struma river are exposed to the Mediterranean climate, which is reflected in hot and dry summers with little rainfall and prolonged drought. In the southern Black Sea region and the Strandja Mountains, there is a mixed influence of the Mediterranean climate and the specific influence of the Black Sea, characterized by wet winters and autumns and drier spring and summer. The genesis of the drying up of the rivers in Dobrogea is quite different. The main reason is the geological structure of the area and the sinking of the rivers in quaternary alluvial and diluvial deposits in the karst region. An acute continental climate with prolonged summer droughts is another important factor.

The following statistical characteristics are presented in the annexed Table 1 – n_0 is the total number of days with zero-flow, f is the fraction of zero-flow years which is the number of years with zero-flow divided by the total number of years, *ma* is the mean annual number of zero-flow days which is the total number of zero-flow days divided by the number of years, max days – maximum number days zero-flows in the one year for the period, min days – minimum number days zero-flows in the one year for the period, mean days – mean number days zero-flows in the one year for the period, C_v – coefficient of variation of the days with zero-flow. The statistical characteristics in question cannot be considered as being fully representative for the regions since they only cover information from observed rivers. There are drying rivers that are not covered by regular hydrological monitoring or field observations. Nevertheless, the information presented below is indicative for the nature of the drying process in Bulgarian rivers.

On average per year, during the investigated period, the number of days with zero-flow days varies widely from 1 day to 200 days, with the smallest amplitude in Region 4 – from 4 to 23 days (Table 1). The annual registration (each year) of zero-flow days is observed only in the Eastern Rhodopi region, which as noted above, is characterized by sudden high waves followed by long periods of drought and the impact of Mediterranean climate is s.

In all other regions, there are no annual (or almost every year) entirely dry beds. They vary for different rivers, with the less frequent occurrences being recorded in the rivers in the catchment area of the Struma River. Also, in this region, dry rivers are only medium and small tributaries of the mainstream but never Struma River itself. They do not form distinct sub-regions but are scattered along the main river, mainly in its middle reaches. Usually they come from a lower altitude.

The Table 1 also shows the maximum, average and minimum number of days of drying for the considered period. No regularity is found in the recurrence of zero-flow days when they do not occur every year obviously it is a direct consequence of the meteorological situation in the respective year but depends on the geological condition at any catchment as well.

Table 1. **Statistical characteristics at gauging stations with zero-flow daily data**

Region	River	Location	n_0	*ma*	*f*	max d	min d	mean d	Cv
	Kanagiol	Osenovez	488	70	71	244	30	98	0.87
	Senkovez	Golyamata voda	439	12	11	141	63	110	0.30
Region 1	Zarzar	Golyam porovez	2004	200	70	365	148	286	0.34
	Fakiiska	Fakia	294	8	22	81	6	37	0.76
	Fakiiska	Zidarevo	349	9	24	76	11	39	0.43
	Ropotamo	Veselie	114	3	12	48	9	28	0.73
	Aitoska	Kameno	634	18	31	146	10	58	0.72
	Sredezka	Prohod	561	20	25	143	9	80	0.59
	Hadjiiska	Rujiza	42	5	44	17	8	11	0.40
	Provadiiska	D.Voinikovo	1868	144	62	365	20	186	0.80
	Golyama Kamchia	Ticha	74	2	3	48	26	37	0.42
Регион 2	Kriva	Novi Pazar	33	1	12	20	5	11	0.72
	Vurbiza	Vurli dol	31	1	8	18	5	10	0.66
	Vurbiza	Djebel	62	2	8	45	2	21	1.07
	Gilemiza	Tatul	256	51	80	140	24	64	0.81
	Byala	Dolno Lukovo	815	22	41	119	22	63	0.44
	Skut	Nivnyani	273	7	8	138	23	91	0.66
	Desna bara	Burzia	45	2	7	31	14	23	0.53
	Veshtichka	Veshtiza	232	6	16	85	6	39	0.87
	Ochushniza	Ochusha	67	2	14	31	8	13	0.74
	Luda Yana	Sbor	125	7	26	58	11	25	0.82
	Strelchenska	Strelcha	167	5	8	112	23	56	0.88
	Devinska	Beglika	1698	154	100	274	82	154	0.36
	Tenesdere	Giovren	4470	179	93	290	48	179	0.35
	Fanos	Poibrene	1371	152	100	188	91	152	0.19
	Venkovska	Venkovez	185	19	60	77	1	31	0.98
	Byala	Kurtovo	96	3	8	28	8	16	0.54
	Omurovska	Partizan	825	83	60	272	45	138	0.61
	Chinardere	Dulbok Izvor	47	5	5	40	7	24	0.99
	Sutliika	Rakitniza	173	5	8	101	16	58	0.74
	Golyama	Svilengrad	976	98	70	239	94	139	0.35
	Turiiska	Turia	1347	36	70	112	8	52	0.61
Region 3	Marash	Lozenez	295	30	40	144	7	74	0.96
	Rechiza	Vaksevo	365	10	8	130	110	121	0.12
	Bl. Bistriza	Slavovo	157	4	14	38	15	31	0.51
	Bl. Bistriza	Blagoevgrad	868	23	46	197	7	51	1.08
Region 4	Byala	Razlog	566	22	15	164	99	142	0.21
	Accidentally zero-flow								
Region 2	Gospodarevska	Svetlina	39	2	6	-	-	-	-
	Gradevska	Gradevo	16	0	3	-	-	-	-
	Konska	Batanovzi	23	1	3	-	-	-	-
Region 4	Sov. Bistriza	Gurlyano	25	1	3	-	-	-	-

5. Flow regime in the four regions with drying rivers

There are presented hydrographs and flow duration curves at three selected characteristic rivers for the studied 1981-2017 and for a year with highest proportion of zero flows (in violet); and median in interquartile ranges between Q25 and Q75 (in blue shaded areas) and median (in red). The selected characteristic rivers are Fakijska at the Black see region, Senkovec at Dobrudja and Bistriza River at Struma watershed. The selected rivers have a different year with highest proportion of zero flows as follow – 2001 for Fakijska and Bistritza and 1987 for Sencovec. The hydrographs and flow duration curves demonstrate the very different flow regime and interannual distribution in the different geographical region.

Comparison of the hydrographs on the Black Sea rivers shows a strong decrease of runoff after the peak of the spring high flows and a visible increase of runoff in the autumn-winter period (only in this region). This is in fact the specific Black Sea influence on the Mediterranean climate of the area and the mixing of the two marine impacts. In the Dobrudja region, the river hydrographs have low amplitude of Q25-Q75 outflow variation, as well as the median, due to the geological and hydrogeological conditions mentioned above. They lead to the formation of low runoff feeding mainly the underground horizons but not surface water. In these rivers there is no pronounced high water and floods are very rare. In the catchment area of the Struma River, the internal distribution of the runoff has a pronounced peak of high water in spring and a sharp decline and a prolonged period of drought. For the year with the most days dry, the hydrograph retains the specifics of the area, but the outflow this year is below quantile Q25. On the Figures 4, 6 and 8 are shown the hydrographs for selected typical rivers in the Southern Black Sea region, Dobrudja and Struma watershed demonstrating different flow regimes.

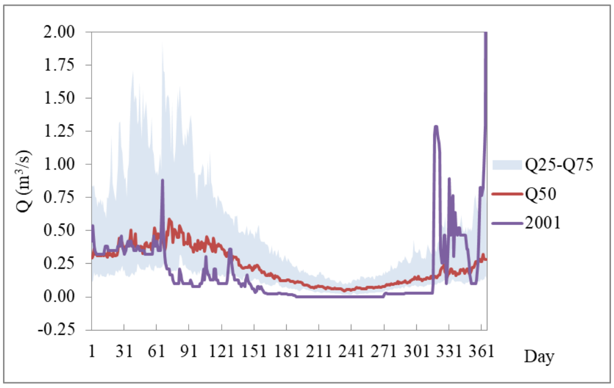

Fig. 4 Hydrographs of the Fakiiska River at Fakia – (1981-2017) Southern Black sea region

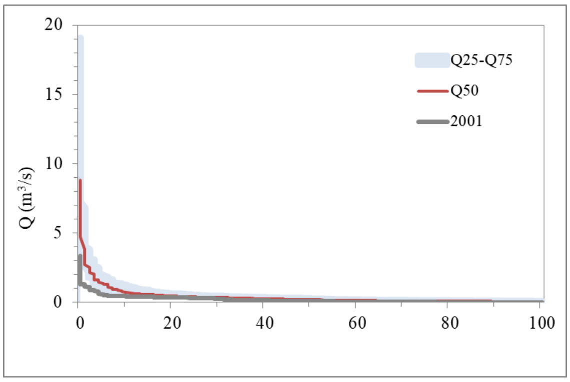

Fig. 5 Flow duration curves of the Fakiiska River at Fakia

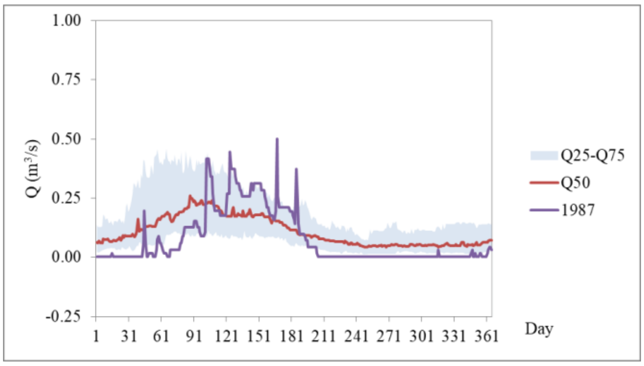

Fig. 6 Hydrographs of the Sencovez River– (1981-2017) Dobrudja sinking rivers region

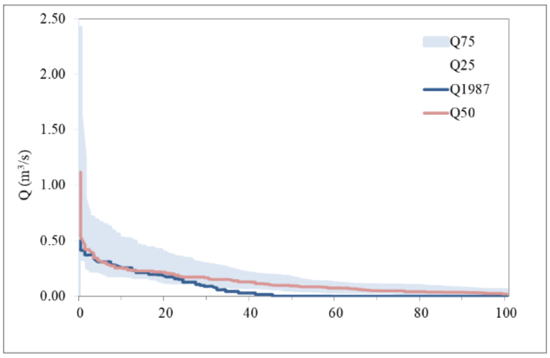

Fig. 7 Flow duration curves of the Sencovez River

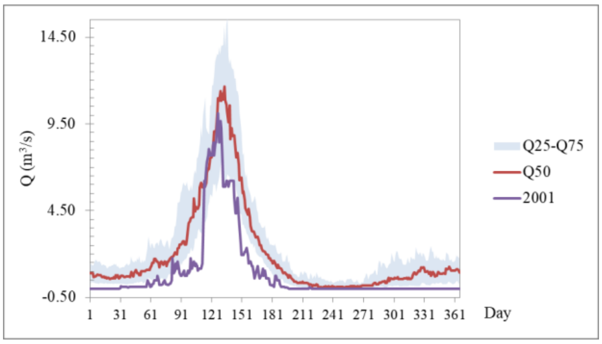

Fig. 8 Hydrographs of the Bl. Bistriza River-(1981-2017) Struma watershed region

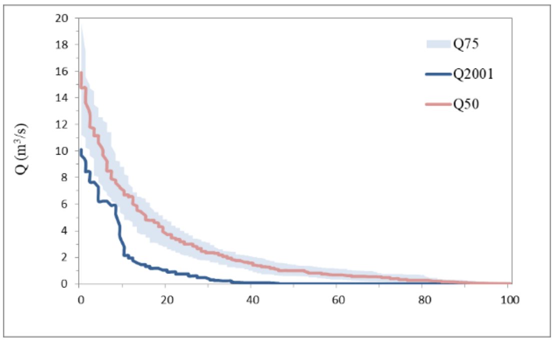

Fig. 9 Flow duration curves of the Bl. Bistriza River

The presented flow duration curves (Figures 5, 7 and 9) confirm also the significant difference in the regime of the drying rivers in the different regions. The genesis of the drying of rivers is very different, which affects the durability of dry periods, as well as the dynamics of runoff change, especially when passing from wet to dry periods. The duration curves are important not only from an environmental point of view, but also from the point of view of water management, the use of water resources and the water consumption (Karagiozova et al., 2017, Ninov et al., 2017).

CONCLUSIONS

The present study reflects some of the results of the investigation on the spatial distribution, the genesis of drying up and the regime of the rivers with zero-flow days in Bulgaria. It combines statistical processing of available hydrological information for 42 gauging stations. Information from these hydrometric stations with registered zero-flow days and field survey in the frame of the various projects in the past is the base for the present study. For the first time, regions with dried beds are identified and mapped on the territory of the Bulgaria.

The current pioneering investigation for the country may be a good basis for future exploration of drying rivers. Areas with information on the existence of single drying rivers outside the monitoring network should be included in the survey in the future. The publication reflects the concerns of hydrologists in Bulgaria about deepening climate changec in the world and their impact on water resources.

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MONITORING AND EVALUATION OF GROUNDWATER LEVELS AT LADNÁ HYDROPEDOLOGICAL PROFILE

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ABSTRACT

The planned construction of Oder-Danube canal was one of the largest activities, which led to the realization of research projects, which also included construction of boreholes for monitoring groundwater levels. Hydropedological profiles (HP) consist of boreholes, which are situated usually across the route of the canal and across longitudinal axis of valleys or flat Moravian hollows. They belong to basins of Oder, Bečva, Dyje (Thaya) and Morava rivers. First observations started back in 1933, subsequent followed after 1940. Nowadays these objects serve for obtaining general idea about the groundwater regime in valley profiles of these rivers. From geological perspective, these HP profiles are in an area of Quaternary sediments. Groundwater level monitoring at HP is important especially because of relating the profile to a particular watercourse and duration of the continuous monitoring. It can be used for determination of hydraulic link between surface water and groundwater. These values can be very useful especially in the determination of spread of potential groundwater pollutants via surface waters. Aim of the work is to assess course of groundwater levels at the Ladná profile of interest and to evaluate the effect of river engineering of the Dyje River on the groundwater regime, taking into account the drought period. Next aim of the work was to show the relationship with surface waters and evaluate the relationship between individual boreholes and the watercourse in the entire profile. In addition, long-term data series of groundwater level monitoring were used to perform evaluation of course of groundwater levels during various time periods, in particular during the individual reference periods, as specified by the CHMI, i.e. 1931-1960, 1931-1980 and the current reference period 1981-2010. Subsequently, the period 1991-2018 was also analyzed as a period associated with the current situation and finally also the entire period of monitoring, i.e. 1948-2018, a total of 70 years.

Keywords: groundwater, surface water, groundwater regime, quaternary sediments, hydraulic continuity

INTRODUCTION

Decreasing landscape retention ability in basins, river modifications, increasing demands for drinking water abstraction from surface and groundwater and more frequent occurrence of torrential rains lead to fluctuation of water regime in riparian forests of south Moravia and subsequent change in ecological conditions and reduced water availability for forest vegetation. Due to decreasing landscape retention ability there is a long-term increased run-off and associated disruption of water balance in landscape. Result of this is a decrease in groundwater reserves and also water sources in general. Strategic role of water lies especially in the field of food production, because 50-80% of water use is irrigation. Water availability is therefore becoming a global problem of the planet. It is likely that the Czech Republic will also face water availability problems in the future. Up to half of Czechs could be faced with potential water insufficiency, groundwater reserves are getting smaller. The entire problem of decreasing water reserves is caused by the overall effect of several major factors such as global climate change, irregular precipitation distribution throughout the year, undesired anthropogenic actions in landscape by farmers and water managers, which lead to decreased landscape retention ability, strategy for surface and groundwater abstraction, more frequent torrential rains, which due to fast run-off from the area via straightened river bed do not fill dams, lead to floods and landslides and associated damages and potential life losses. Expert prognosis is not very optimistic and groundwater reserves will be threatened, especially in spring. Recent significant drought periods in the Czech Republic occurred in 1982-1984, 1990-1995, 2003-2004 and the latest drought episode lasts up until now since 2014. The issue of drought is also very relevant for the region of South Moravia, in particular in water meadows of riparian forests.

Planned construction of Oder-Danube canal was one of the most significant actions, which led to realization of exploratory works, one of which was the construction of boreholes for monitoring groundwater levels. Since 1996 the area is protected for the prospective canalization of the Morava and Oder rivers and the route of the proposed Danube-Oder-Morava canal. This would also fulfil the original aim of monitoring long-term time series of groundwater levels. Hydropedological profiles

(HP) consist of boreholes, which are situated usually across the route of the canal and across longitudinal axis of valleys or flat Moravian hollows. They are located on Oder, Bečva, Dyje (Thaya) and Morava rivers. First observations were between 1933 and 1934, additional were being added until 1940. Nowadays these objects are used for general understanding of groundwater regimes in valley profiles of these rivers. From geological perspective, these HP profiles are in an area of quaternary sediments. At the particular location of these profiles the soil types are predominantly light soils, sandy soils and slightly loamy and loose sands.

The studied Ladná profile is located above Břeclav and passes through the cadastral area of Charvatská Nová Ves and ends on the outskirts of the city of Lednice. Its total length is 4.98 km and crosses the rivers Dyje, Trkmanka and Včelínka. It was built in 1948, which means there is an almost 70-years long continuous monitoring series. Over the years the location underwent several changes, most important of which was the construction of the Nové Mlýny dam and modification of the Dyje river bed. Assessment of the hydropedological profile uses basic statistical methods used for large data set analysis. This includes analysis of dynamics of groundwater level in relation to surface run-off, precipitation and geological profile in various reference periods. The obtained findings from the individual reference periods are analyzed and thoroughly assessed. One of the assessed factors is the impact of drought in the period between 2014 and 2018 on the profile in relation to the distance from the watercourse and climatological conditions, including the effect on the overall historical series of groundwater level monitoring.

Aim of the work is to assess course of groundwater levels at the Ladná profile of interest and to evaluate the effect of river engineering of the Dyje River on the groundwater regime, taking into account dry periods. Next aim of the work was to demonstrate the relationship with surface waters and evaluate the relationship between individual boreholes and the watercourse in the entire profile. Two periods were selected for the evaluation of the effects of river engineering of the Dyje River on groundwater regime. First period, from 1948 to 1972, only deals with Dyje River engineering, i.e. does not take into account the effect of the Nové Mlýny dam and the period from 1974 to 2018, i.e. after the construction of the Nové Mlýny dam and river engineering of Dyje in the stretch between Břeclav – Nové Mlýny. In addition, long-term data series of groundwater level monitoring were used to perform evaluation of the course of groundwater levels during various time periods, in particular during the individual reference periods, as specified by the CHMI, i.e. 1931-1960, 1931-1980, 1961-1990 and the current reference period 1981-2010. Subsequently, the period 1991-2018 was also analyzed as a period associated with the current situation and finally also the entire period of monitoring, i.e. 1948-2018, a total of 70 years.

METHODS AND DATA

The area of interest underwent significant changes in land use in the second half of the 20th century as a result of the construction of the Nové Mlýny reservoir. This meant that the total water area saw a largest increase from the original 2.01 % to 24.90 % of the total surface area (12618.37 ha). In 1960, largest water bodies were the restored ponds Strachotínský and Šakvický. Šakvický pond at Štínkovka became completely part of the lower Nové Mlýny reservoir. The Strachotínský pond remained partially delimited, but is in fact also mostly part of the central section of the reservoir. Main watercourses were Dyje, Svratka and Jihlava. The confluence of Svratka and Jihlava and river beds were artificially modified already in 1960. Also the Dyje river channel is regulated down to Dolní Věstonice. Significant ratio of these water bodies is represented by a large number of small pools – abandoned river beds and oxbow lakes along Dyje and Jihlava rivers, existence of which allowed hydraulic connection with the main channel of Dyje and Jihlava, as well as frequent outflow of these rivers. There were 133 water bodies in total in 1960. Practically all these pools became part of the current reservoirs. Water area in 2019 mostly consists of flooded areas of the Nové Mlýny reservoir and associated constructions. Following the change in water management conditions, only few watercourses in the area of interest remained that have their channel in its original position. They are 4 streams that had their channel modified already in 1960 – Dunajovický stream, Klentnický stream, Popický stream and Štínkovka. End sections of these streams are now shorter and became part of the current Nové Mlýny reservoir. At the end of the Klentnický stream water passes through a drainage canal along the lower part of the reservoir down to the dam, where it flows into the Dyje river. Popický stream and Štínkovka end in small water management objects, where the water is pumped to the lower part of the reservoir. Position of the Jihlava and Svratka confluence remained intact. Only the lower part of Svratka and the channels of both rivers were modified (extended embankment). All newly created small streams are related to the overall water management modifications of South Moravia. The entire Nové Mlýny reservoir is surrounded by drainage canals, which collect water soaked from the reservoir. One entirely new irrigation channel is the Brod-Bulhary-Valtice channel. From the central part of the reservoir, water is pumped approximately 700m over the ridge of Dunajovické hills from where it flows southeast by gravity via Dolní Dunajovice and further in the direction of Mikulov and Valtice.

Back in 1960, a significant ratio of the total area of interest consisted of permanently wet water meadows (3.14%). Usually this meant a number of small water bodies often surrounding the above mentioned abandoned river channels (163 individual wetland areas). Two wetlands are larger – one lies between Strachotín and Šakvice, the other one is situated northwest of Nové Mlýny on the right bank of the Dyje River. However, in 2018 permanently wet meadows only represent the least frequent category (0.24 %) and are only found close to the banks of the Nové Mlýny reservoir. Also the total area of the forest category decreased in the area of interest, from 13.65% down to 7.46% of the total area. Most of this decrease is caused by logging of the alluvial forests and subsequent flooding of these areas. Part of the former forested area is now arable land and also the forest islands west of Pasohlávky transformed into agricultural land. Decrease of forested area is partially compensated by an extension of forests in the area of Pavlovské and Dunajovické hills. Small forested areas were also created southeast of Brod nad Dyjí.

Change in hydraulic relationships in rock environment also affected groundwater. Embankment prevented floods in the alluvial areas and thus also prevented soaking into groundwater and increasing groundwater levels. Most scientific studies prove decrease of maximum groundwater levels and shorter duration of these maxima. A floodplain is affected by water regime of the particular watercourse as well as rock type, terrain, soil type and climate in the entire basin. Floodplain is therefore not just a product of a particular watercourse, but reflects state of the entire basin. This broader concept of floodplain is well described by the following characteristic: *"Floodplains are very specific environments, completely different, or even in contrast with other landscapes. They form an axis, an aorta of landscape. They reflect development, life and history of the entire basin. Plains are never autonomous parts of the Earth, their evolution is affected by all parts of landscape, even by mountain forests in distant water divide. Anything that is taken away from the basin, what is washed away, enriches the floodplains…. Floodplains always form the highways for matter transport in landscape, highways for the spread of fauna and flora. Axis of a floodplain is always a watercourse, a river. It is the character of this river that is always crucial for the appearance of a floodplain, its child…"* (Culek, 1992). Based on Prach (2003), the uniqueness of floodplains lies especially in the following properties. Energy, matter and information flows in floodplains are very fast and are of an open nature. For a specific ecosystem in floodplain, inputs and outputs (energy, nutrients, information) can many times exceed their transport within the ecosystem. Floodplains are characterized by high temporal-spatial heterogeneity. Floodplain ecosystems show a high productivity.

The Dyje basin is a very large area of over 13 419 km^2 and watercourse length of 306 km. Czech Hydrometeorological Institute has 6 stations measuring surface water levels of Dyje – Podhradí, Vranov-Hamry, Znojmo, Trávní Dvůr, Nové Mlýny and Ladná. It operates 25 boreholes for monitoring groundwater levels and also small-diameter hydropedological boreholes, the so-called HP profiles – a unique feature only found in South and North Moravia.

They were created as a result of the Oder-Danube channel construction project. Preparation of this project brought about realization of many exploratory works, including construction of probes for monitoring groundwater levels. These were positioned in lines – profiles, which were labeled as hydropedological. They were usually situated across the route of the channel and also across the longitudinal axis of the valley or plain Moravian valleys. They can be found in the basins of Oder, Bečva, Dyje and Morava. First observations were made between 1933 and 1934, additional were being added until 1940. Nowadays these objects are used for obtaining general understanding of groundwater regimes in valley profiles of these rivers. In South Moravia they are currently aggregated into 4 units – HP0262 Podovín-Lednice, HP0263 Ladná-Charvatská Nová Ves, HP0266 Nové Mlýny and HP0267 Šakvice. Currently, groundwater levels are being monitored using automated devices at a total of 29 boreholes and one staff gauge on the Ladná-Charvatská Nová Ves profile. Originally there were 53 boreholes and 8 staff gauges on these profiles. The HP0266 Nové Mlýny profile was mostly flooded as a result of the construction of the Nové Mlýny reservoir and only 2 boreholes remained. Other profiles were reduced as a result of the need to reduce costs associated with operation of the monitoring network. Given the extent of the Dyje basin and the number of boreholes available in this area, it is not possible to concentrate on the entire area. Detailed analysis was therefore performed for the area near Břeclav, in particular the HP0263 Ladná-Charvatská Nová Ves profile, which is typical for the Dyje floodplains and has most boreholes directly linked to the surface station on the Dyje River.

Břeclav lies on the Dyje River and is surrounded by forests from three sides. Riparian forests lining the Dyje and Morava river represent an area of over 3500 ha, making it the largest complex of its kind in central Europe. Forests full of channel networks, oxbow lakes and pools were added to the list of Ramsar Convention in 1993 as “Mokřady dolního toku Dyje” (Wetlands of lower Dyje). Northwest of Břeclav lies Kančí obora (Kančí game preserve), a riparian forest with predominance of common oak and narrow-leafed ash. South of Břeclav is the most extensive complex of riparian forests, extending to the confluence of Dyje and Morava, with partially preserved riparian meadows and alluvial pools. This area is one of the most valuable areas of the primary forest reserve Ranšpurk and Cahnov – Soutok. On the west is the southeastern edge of the national natural reserve Lednické rybníky (Lednice ponds).

Two periods were selected for the evaluation of the effects of water management and engineering on groundwater regime. First the period between 1948 and 1972, only in terms of Dyje, i.e. without the effects of reservoirs close to Nové Mlýny. Second, the period from 1974 to 2018, i.e. after the construction of the Nové Mlýny dam and modification of Dyje in the section between Břeclav and Nové Mlýny. In the meantime, based on long-term time series of groundwater levels, an assessment of the course of groundwater levels for several time periods was made – in particular for the individual reference periods as they were proposed by the CHMI (1931-1960, 1931-1980 and the current reference period 1981-2010). In addition, the period between 1991 and 2018 was also analyzed as a representation of the current situation. The entire period of 70 years cannot be assessed because of the Nové Mlýny dam construction.

Evaluation of the relationship between groundwater and surface water was performed using knowledge of average monthly flow rates for Dyje during the period of interest. Data was used from surface stations Dolní Věstonice (Nov 1948 to Oct 1988), the next downstream station Nové Mlýny below the dam (Nov 1988 to Dec 1994) and data from the Ladná station, which lies directly in the HP profile and has been monitored since Nov 1987 until now. Last station used for the assessment was the station Břeclav-železniční most (Břeclav – train bridge), where flow rates were analyzed in the period between Nov 1965 and Oct 1987. The Ladná station replaced the Břeclav-železniční most station, which stopped operating on Nov 1, 1987 and was used to derive flow rates also for the station Nové Mlýny in the period 11/1988 to 10/1994. Not all water was present in the station Břeclav – žel. most during flow rates exceeding 350 $m^3.s^{-1}$, because the channel does not have a sufficient capacity. Such higher flow rates were distributed by a weir on the outskirts of Břeclav away from the main watercourse channel to a discharge branch, which flows back to the main channel below the station.

Based on a hydrological map one can see that Ladenský profile is a fluvial sand-clay sediment with occasional boulders (flood gravel) and sediments of artificial water bodies, deluvio-fluvial sandy sediments (between Ladná and Charvatská Nová Ves) and fluvial sandy gravel (directly in Ladná and Charvatská Nová Ves). Ladenský profile boreholes belong to the hydrogeological region 1652, which includes quaternary fluvial sediments of the Dyje River. Groundwater level is free. Sediments of the floodplain belong to a structure of fissure groundwater with a characteristic hydrogeological link with surface flow. From the geological perspective the profile has the following structure (Fig. 1): dominant are sandy clays in the highest layers, followed by predominantly clay sand with a depth up to 0.9 m. Deepest layers are mostly sand gravel. Layer of clay soils is not present in the hydropedological profile at all, occasionally one can find clay sand soil or clay sand.

		DEPTH OF GEOLOGICAL LAYER FROM THE TERRAIN [m]				
1	KB0689	0,0-0,4 loamy sand soil	4,6-6,7 incoherent sand-gravel	0,4-1,3 clay sand	1,3-2,3 medium-grained sand	2,3-4,6 sandy-dusty clay
2	KB0690	0,0-0,5 sandy clay	3,9-5,9 dusty clay	0,5-2,7 clay sand	2,7-3,2 dusty clay	3,2-3,9 dusty clay with sand
3	KB0691	0,0-0,5 sandy clay	0,5-2,1 clay-sand soil	2,1-2,9 clay with gravel	2,9-4,6 sand gravel	
4	KB0692	0,0-0,5 sandy clay	0,5-2,7 clay sand	2,7-5,6 sand gravel		
5	KB0693	0,0-0,7 sandy clay	0,7-2,2 clay sand	2,2-4,6 sand gravel		
6	KB0694	0,0-1,0 sandy clay	3,8-5,7 sand-gravel	1,0-2,5 loamy sand soil	2,5-3,1 clay sand	3,1-3,8 non-clay gravel sand
7	KB0695	0,0-0,8 sandy clay	0,8-2,2 clay sand	2,2-6,1 sand gravel		
8	KB0696	0,0-0,7 sandy clay	0,7-1,5 dusty clay	1,5-2,3 clay sand	2,3-5,4 sand gravel	
9	KB0697	0,0-1,7 loamy sand soil	1,7-2,3 clay sand	2,3-5,9 sand gravel		
10	KB0698	0,0-1,6 clayey soil	1,6-2,5 clay sand	2,5-4,6 sand gravel	4,6-5,2 loamy sand soil	
11	KB0699	0,0-2,1 clayey soil	2,1-3,1 loamy sand soil	3,1-5,1 gravel sand		
12	KB0700	0,0-0,7 mica clay	3,5-5,6 sand	0,7-1,6 loamy sand soil	1,6-2,5 clay-sandy soil	2,5-3,5 clayey-dusty soil
13	KB0701	0,0-0,6 mica clay	0,6-1,5 loamy sand soil	1,5-4,2 sand gravel		
14	KB0703	0,0-0,8 clay sand	0,8-2,5 loamy sand soil	2,5-3,1 sand	3,1-5,9 sand gravel	
15	KB0704	0,0-2,3 mica clay	2,3-3,1 sand	3,1-5,8 sand gravel		
16	KB0705	0,0-0,8 heavily clay sand	3,6-6,4 clayey sand-gravel	0,8-1,5 mica clay	1,5-2,6 sandy-dusty clay	2,6-3,6 coarse grained sand
17	KB0706	0,0-1,4 sandy-dust soil	4,1-5,7 medium-grained sand	1,4-2,3 dust soil	2,3-3,4 sandy soil	3,4-4,1 clay sand
18	KB0707	0,0-1,0 sandy-dust soil	1,0-2,1 loamy sand soil	2,1 - 5,1 medium-grained sand		
19	KB0708	0,0-1,4 clay-sandy soil	1,4-2,5 clayey soil	2,5-3,6 clay sand	3,6-5,8 sand gravel	
20	KB0710	0,0-0,8 clay-sandy soil	2,5-5,2 sand gravel	0,8-1,7 sandy clay	1,7-2,1 clay sand	2,1-2,5 clay sand
21	KB0711	0,0-1,0 sandy clay	1,0-2,3 clay sand	2,3-5,3 sand gravel		
22	KB0712	0,0-0,6 clay with gravel	0,6-1,7 clay sand	1,7-5,4 sand gravel		
23	KB0714	0,0-1,9 clay sand	1,9-6,1 sand gravel			
24	KB0715	0,0-0,5 sand-dust vlay	0,5-1,3 dusty clay	1,3-2,4 sand gravel	2,4-5,2 sand	
25	KB0716	0,0-2,4 loamy sand soil	2,4-2,7 sand	2,7-5,8 clay sand	5,8-6,5 dusty clay	
26	KB0717	0,0-0,8 loamy sand soil	0,8-2,4 loamy-dust-sandy soil	2,4-6,5 sand gravel		
27	KB0718	0,0-1,8 clay sand	1,8-5,3 gravel sand			
28	KB0719	0,0-2,4 clay-dust soil	2,4-5,4 sand gravel			

Fig. 1. Geological profile

The original profile had 28 probes, after several changes it now has 25 probes, out of which a total of 16 probes now has automated systems with daily measurements and one staff gauge, surface station Ladná nad Dyjí, which lies on the profile axis (Fig. 2). Groundwater levels are being monitored since 1948. There are three watercourses crossing the profile – Dyje, Ladenská strouha and the left tributary Včelínek.

Fig. 2. Monitored probes as of 2019

In 1949, the hydropedological profile had a total length of 4986.4 m, with an average elevation of 160.46 m above sea level (Fig. 3).

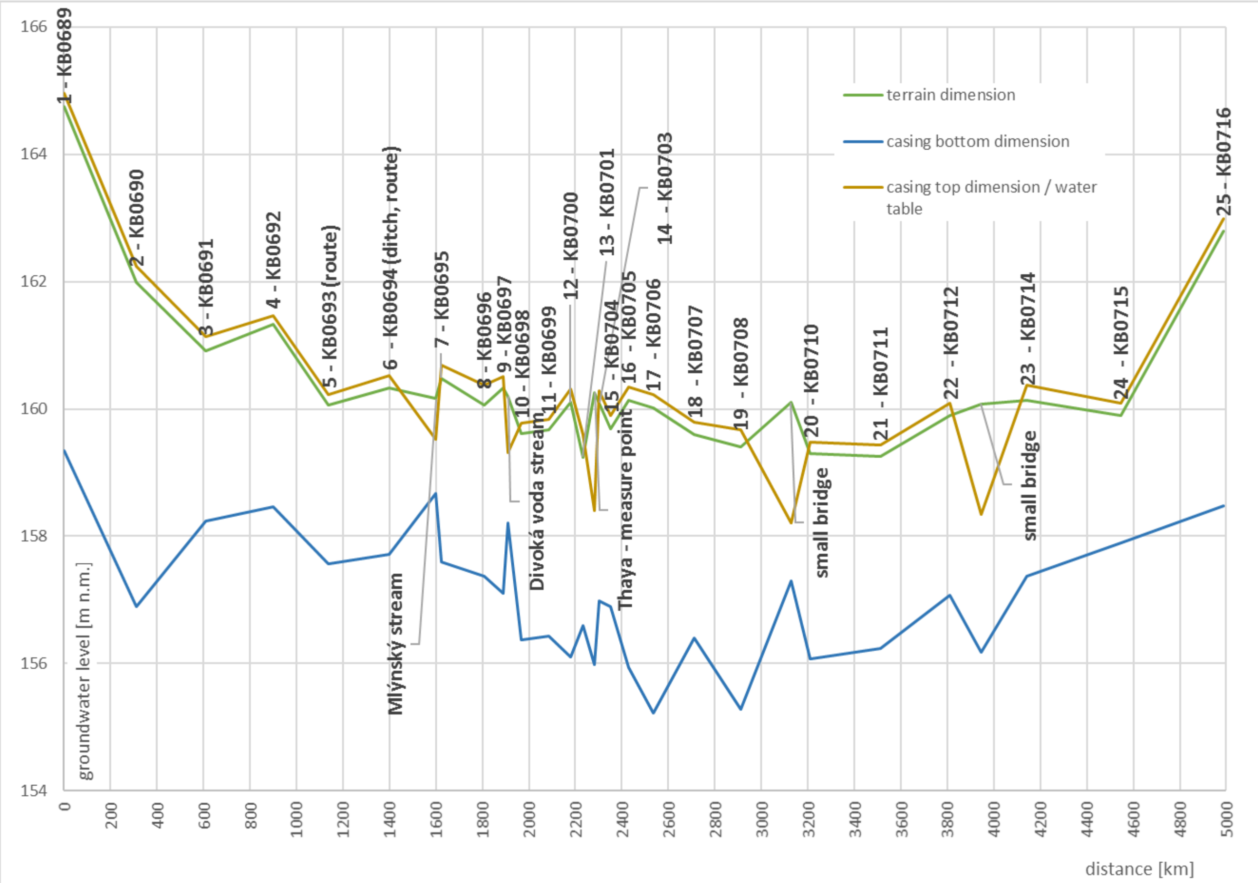

Fig. 3. Horizontal profile HP0263 Ladná – Charvatská Nová Ves

In 1962 three new probes were added, in particular the probes KB0717 and KB0718 between the probes KB0714-KB0716, because these two were quite far apart from each other (approximately 300 m). The probe KB0719 was added between the probes KB0710 and KB0711. In 1963 the entire profile was redrilled, in 1980s and 1990s the probes were deslimed and cleaned. In 1969 monitoring ended at the KB0703 probe, because it was destroyed. In 1970 the same happened to the probe KB0701. In 1975 also the KB0697 was destroyed and in 2005 two other boreholes – KB0692 and KB0714. In 2010 the monitoring network was reduced, 16 currently operating probes were chosen, which were equipped with automated devices in 2012, with hourly groundwater level data. The remaining probes are not currently being monitored, but in the future, it is planned to include them in the network again. The last probe that stopped operating was the KB0691 probe, because it had to be removed in 2018 as it stood where houses were to be built.

The KB0702 probe indicated the staff gauge on Dyje, which was in operation from 1948 to 1982. However, water at the gauge often froze, data was not available due to deposits carried by the river and the data is therefore incomplete (Fig. 4). In 1982 it was replaced by a staff gauge at the surface station, originally at the station Břeclav – žel. most, then directly in Ladná, where the profile is located.

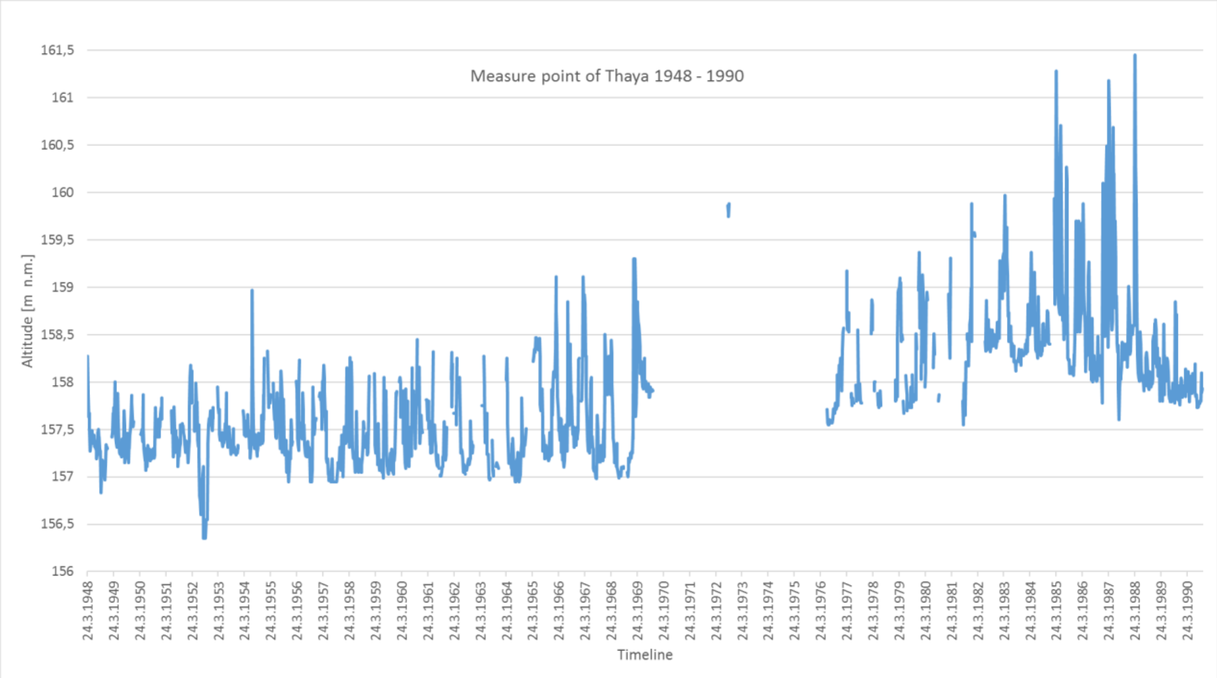

Fig. 4. Measurements from the KB0702 staff gauge between 1948 and 1982

In order to assess groundwater regime in relation to surface waters it is also important to know the occurrence of critical years in terms of hydrology and climatology (Fig. 5). First dry year in the period 1900-2018 was the year 1912. The year 1914 was characterized by highest daily maximum precipitation. Average maximum across all stations in South Moravia was 64 mm. First half of the 20th century was variable, without significant extremes. Driest period were the years 1931-1935 then followed by floods in 1938. Also 1942 was a very dry year, especially in Bohemia, followed by another relatively dry year 1943. Year 1947 saw a catastrophic drought (between April and September, monthly precipitation amount only ranged between a few mm and approximately 20 mm). Beginning of the 1950s was also variable, in 1954 there were floods on Vltava (Bohemia), which almost destroyed the Slapy dam, which was in construction at that time. Water in the reservoir overflew and the dam was not yet completely finished. The year 1959 had the longest dry period, i.e. most consecutive days without rain. There was no rain in the entire Czechoslovakia in August, September, October and first week of November. Years 1961-1964 were also dry, in 1964 tree leaves in Vysočina turned yellow already in August. Next year, in 1965, the Great Rye Island (SW Slovakia) was flooded, southeast part of the republic was also affected, especially the Morava basin, where the Vranov reservoir overflew. Another dry period occurred between 1971 and 1974, with the exception of Vysočina, where June and beginning of July were wet. The year 1975 was rather wet, however it was followed by another dry year in 1976 – in South Moravia, corn and beet grew “like telegraph posts – 25 m apart”. It then rained in July and the dormant seeds germinated leading to problems with harvest. Dry years were also 1982-1984, with a significant windstorm in the summer of 1984, which caused significant damages in the forests around Velké Meziříčí. At some places not a single tree remained standing. As can be seen, drought episodes are encountered approximately every 10 years, which is also proved by dry years 1990-1995, after which catastrophic floods occurred in 1997. Another flood occurred in 2002, followed by a dry year 2003 and 2007. Floods were also encountered in 2006. In 2010 there were heavy rain episodes in Moravia, making it the second wettest year since 1900, 1941 being the wettest. Year 2012 was again rather dry, in 2013 there were floods in Bohemia as a result of strong thunderstorms. Since 2014 until now there is another episode of drought.

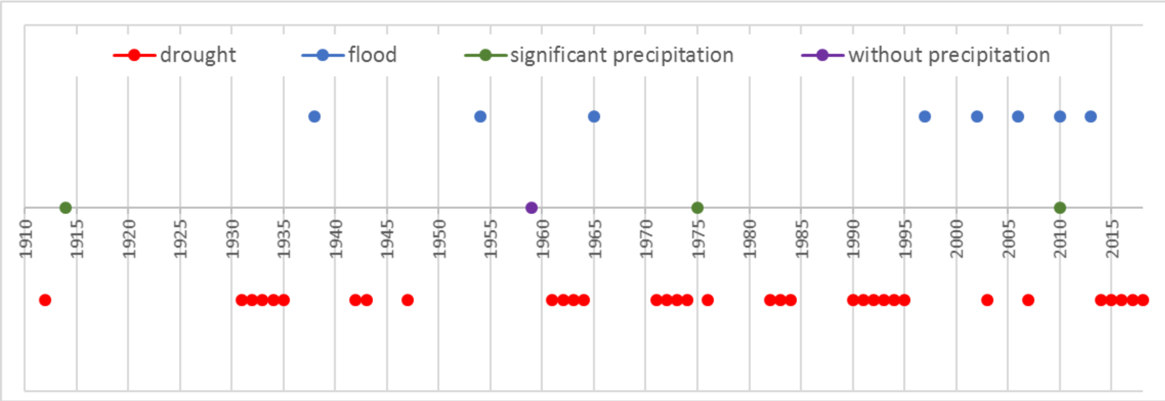

Fig. 5. Critical years from the perspective of drought and floods

RESULTS AND DISCUSSION

Four probes were selected to assess the effect of water management modifications at Dyje River and interactions with surface waters, in particular the KB0689, KB0706 probes in operation since 1948 and probes KB0718 and KB0719, which operate since 1962. Their location in the profile and distance from one another is given in Fig. 6. The probe KB0689 lies 2.3 km away from Dyje on the edge of a field, the probe KB0706 is closer to the watercourse (0.2 km), in a dense riparian forest. KB0719 probe is 1.1 km far from the river in a forest and KB0718 is 2 km from Dyje, on a field in a close vicinity to a newly constructed pond.

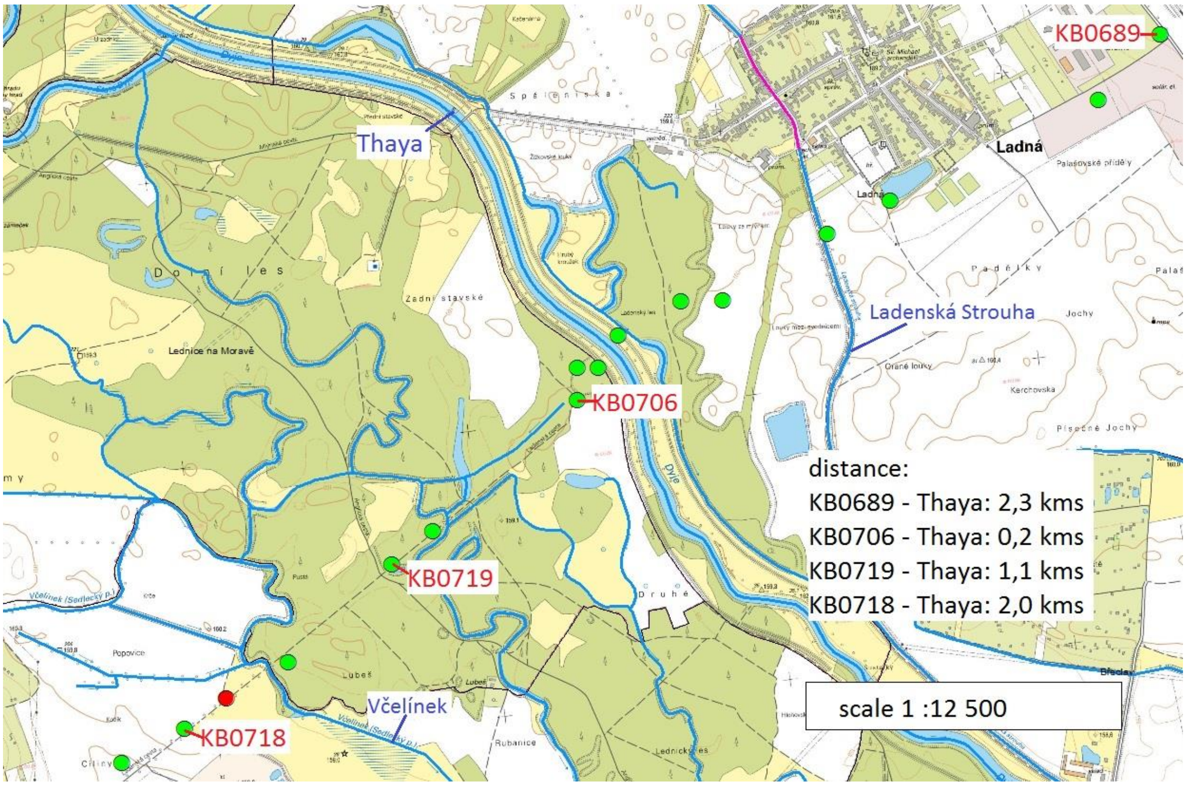

Fig. 6. Location of assessed probes in profile

For each of the probes, the following data was evaluated: long-term averages, minima and maxima for the periods 1931-1960, 1931-1980, 1981-2010 (current reference period) and 1991-2018. Then, for each probe a drought threshold was determined, which represents 85 % of long-term monthly cumulative frequency curve (hereafter DMKP). Graphs then show monthly course of groundwater level elevation in the probe, together with flowrates of Dyje as measured by surface gauges, in particular at the stations Dolní Věstonice, Nové Mlýny below dam, Ladná and Břeclav – železniční most.

The KB0689 probe is 6.7 m deep with 0.0-0.4 m loamy sand soil, 0.4-1.3 m clay sand, 1.3-2.3 m medium-grained sand, 2.3-4.6 m sandy-dusty clay and 4.6-6.7 m incoherent sand-gravel. Elevation of the profile is 164.13 m a. s. l. Over the entire period of monitoring, i.e. since 1948, there was a continuous measurement. In 1959 the borehole dried up for the entire year, as well as in 1975-1976 (Fig. 7).

Based on the assessment there is a significant decrease in groundwater level during the period of construction of the Nové Mlýny reservoir and monitoring was interrupted by drought in 1975-1976. Another reason for the decrease of groundwater could be soil amelioration at the beginning of 1980s. The probe is situated on a field and it is possible that the course of groundwater level is affected by the amelioration work. Prior to the construction of the Nové Mlýny reservoir there are obvious 10-year periods, which were disrupted by the Nové Mlýny dam construction and have not stabilized until today. From the perspective of the individual reference periods, all the periods are comparable in terms of average groundwater level. When looking at the variability, i.e. the minima and maxima in the individual periods, the least variable is the period 1931-1960 (more precisely 1948-1960 – beginning of measurement), when the difference was only 1.36 m. In contrast, the most variable levels were seen in the period 1981-2010, 2.73 m. In the period 1931-1980 it was 2.26 m and in 1991-2018 2.05 m. Most significant change in terms of minimum groundwater level can be seen between the period 1931-1960 and the period 1931-1980, where the long-term minimum level decreased by 1.16 m. In contrast, in 1991-2018 the long-term minimum increased compared to 1981-2010 by 0.52 m. Significant change between long-term maximum is between 1931-1980 and 1981-2010, when the maximum increased by 0.6 m. From the perspective of long-term drought threshold, i.e. 85% of long-term cumulative frequency curve, one can see a decrease in groundwater level between the period 1931-1960 and 1931-1981 by 0.82 m, since 1931-1980 the drought threshold constantly increases, first by 0.28 m (1981-2010), subsequently by 0.34 m (1991-2018).

Periodicity of annual course of levels has in recent years been very disrupted, mostly by the effect of the very dry years 2014-2018.

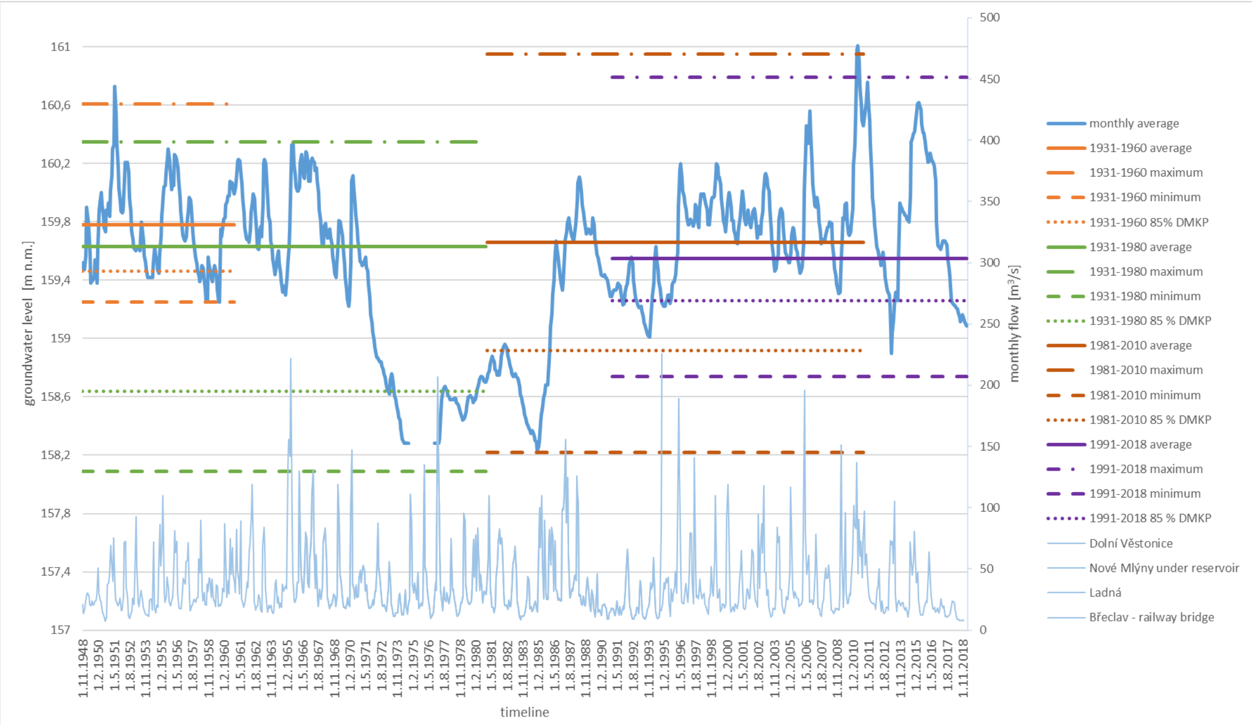

Fig. 7. KB0689 probe assessment

The KB0706 probe is 5.7 m deep. 0.0-1.4 m is sandy-dust soil, 1.4-2.3 m is dust soil, 2.3-3.4 m is sandy soil, 3.4-4.1 m is clay sand, 4.1-5.7 is medium-grained sand. The probe is located at an elevation of 159.74 m a. s. l. There is a continuous data series available since 1948, in November 1988 a continuously operated water pump has been installed for waterworks in Břeclav.

Data analysis (Fig. 8) shows a significant decrease in groundwater level at the time when the pump was installed close to the probe. This pumping affected the borehole significantly until 1997, when the values stabilized at the original values observed prior to the pumping again, however, are still lower than the levels observed before the construction of the Nové Mlýny dam. It can be seen that this construction affected the groundwater levels, however, in a lesser extent than the KB0689 probe, because the KB0706 probe is in a close vicinity to the Dyje River and corresponds to the flow rate of surface water. From the perspective of the individual reference periods, all the periods are comparable with regards to the average groundwater level, with the exception of the period 1981-2010, when long-term average decreased by 0.2 m. Regarding the maximum and minimum levels, i.e. the overall borehole groundwater level variability, the most variable was the period 1931-1960 (more precisely 1948-1960 – beginning of measurement), where the groundwater level variability was 2.72 m. Least variability of groundwater levels was observed in the period 1931-1980 and 1991-2018, 2.33 m. In the reference period 1981-2010 the groundwater level variability was 2.47 m. Most significant change with respect to minimum groundwater levels was between the period 1931-1960 and 1931-1980, when the long-term minimum level decreased by 0.43 m, other periods are comparable. Significant change in long-term maxima can be seen between the periods 1931-1960 and 1931 and 1980, when there was a decrease by 0.43 m and in the subsequent period 1981-2010 by a further 0.3 m. From the perspective of long-term drought threshold, i.e. 85 % of long-term cumulative frequency curve, one can see a decrease between the periods 1931-1960 and 1931-1980 by 0.2 m, with a decreasing trend in the subsequent period – in 1981-2010 a decrease by 0.32 m. Increase in the drought threshold was observed in the period 1991-2018, when the threshold increased by 0.37 m.
Also, in this case there is an obvious disruption of annual groundwater level regime, especially due to the very dry years 2014-2018.

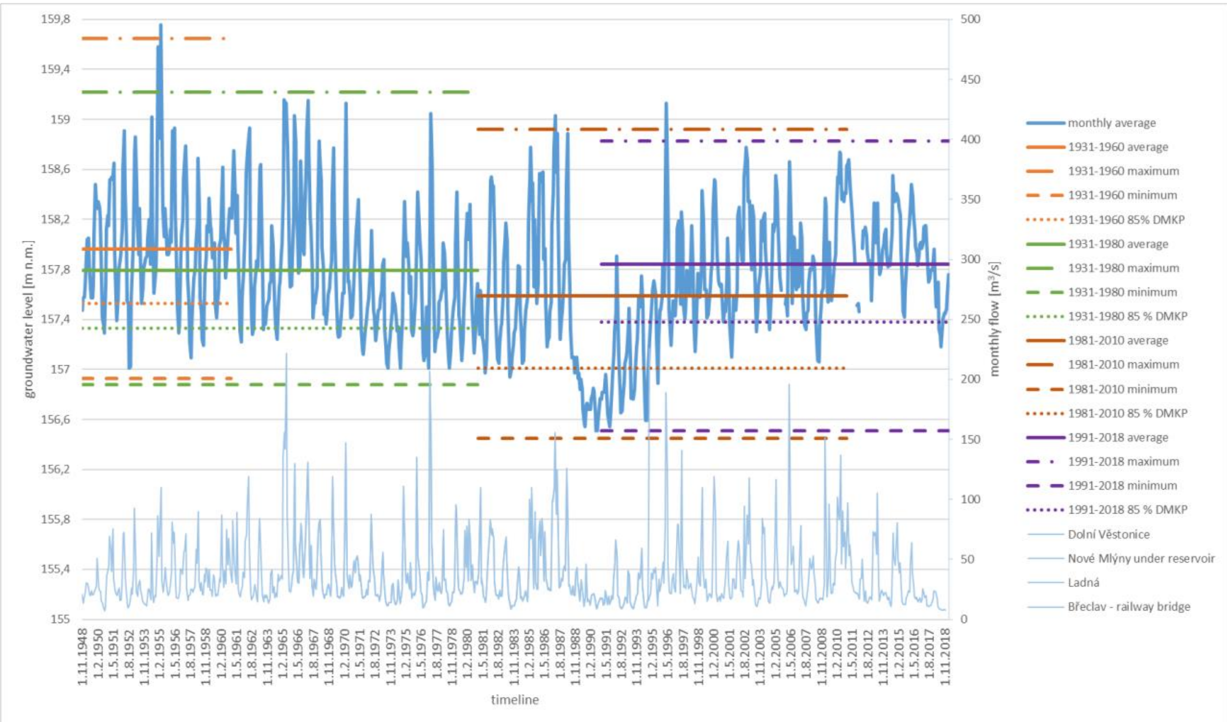

Fig. 8. KB0706 probe assessment

The KB0719 probe is 5.8 m deep, with 0.0-2.4 m clay-dust soil and 2.4-5.8 m sand gravel. It is situated at an elevation of 159.23 m a. s. l. There is a continuous monitoring since 1962, in 1997 the borehole was redrilled after a flood and deslimed in 1985 and 2006. After the construction of the Nové Mlýny dam, a riparian forest drainage canal has been constructed close to the borehole, which is constantly full of surface water.

Data analysis (Fig. 9) shows an obvious decrease in groundwater level after the construction of the Nové Mlýny dam and before the water management modifications. As a result of a drainage canal, however, there is a permanent increase in groundwater levels. From the perspective of the reference periods there is an obvious increase in groundwater levels. Between the period 1931-1980 (more precisely 1962-1980 – beginning of measurement) and the period 1981-2010 there is an increase in long-term average groundwater level by 0.38 m, in the subsequent period by a further 0.19 m. Following the construction of the Nové Mlýny dam there is a larger variability in the groundwater levels, in the period 1981-2010 it was 2.38 m, in the current period (1991-2018) it is 1.98 m. Most significant change in terms of minimum groundwater levels is between the period 1931-1980 and 1981-2010, when there is a decrease by 0.39 m, but in the subsequent period (1991-2018) the long-term minimum increased by 0.45 m, i.e. by 0.06 m compared to the period 1931-1980. There is no significant difference between the individual periods in terms of long-term maximum levels. Regarding the long-term drought threshold, i.e. 85 % of cumulative frequency curve, one can see increasing trend, where the threshold increased by 0.2 m between 1931-1980 and 1981-2010 and by a further 0.33 m in 1991-2018. Periodicity of the annual groundwater regime is also quite disrupted in recent years, especially by the effect of the dry years 2014-2018 and the associated decreasing trend.

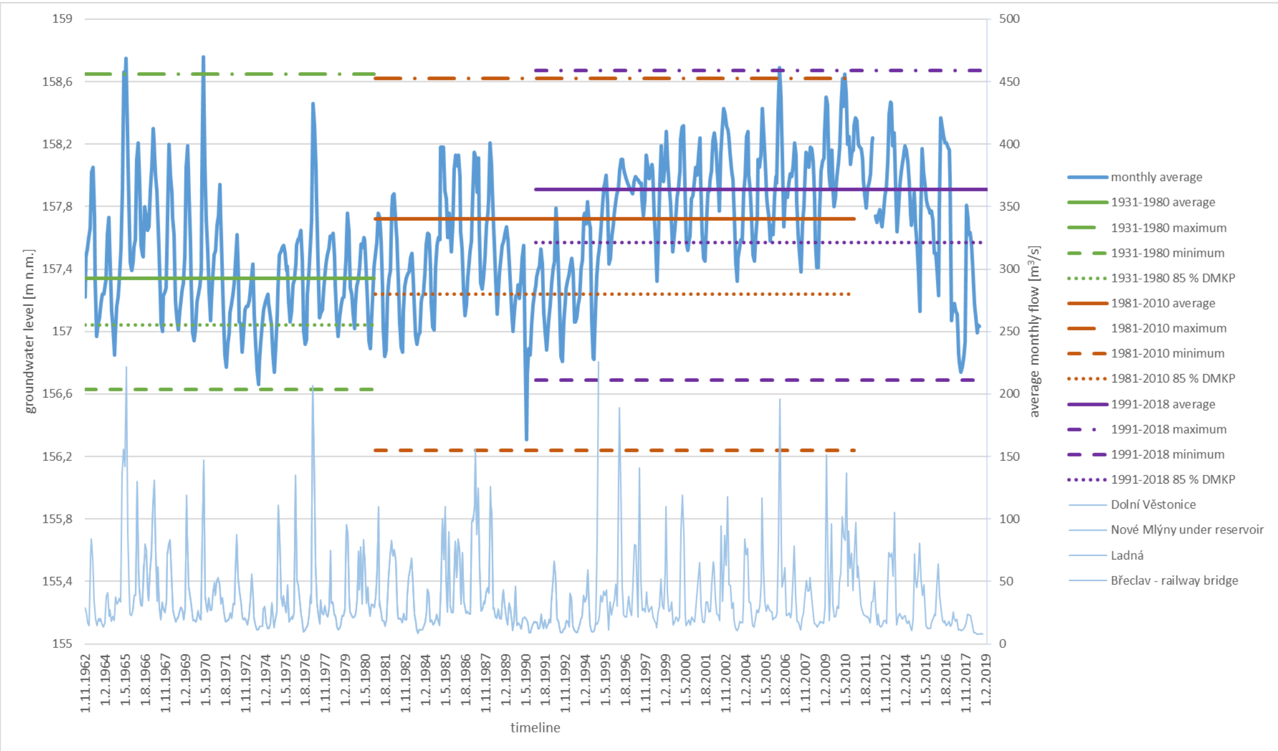

Fig. 9. KB0719 probe assessment

The KB0718 probe is 5.3 m deep with 0.0-1.8 m clay sand and 1.8-5.3 m gravel sand. It is located at an elevation of 160.15 m a. s. l. There is a continuous monitoring since 1962 and the borehole was redrilled in 1997 after it was flooded.

Data analysis (Fig. 10) very well illustrates the dry periods, which repeat approximately every ten years. As a result of the Nové Mlýny dam construction there was a significant decrease in groundwater levels, which is also obvious from the long-term characteristics of the individual periods. There is no other significant watercourse nearby apart from Dyje, it is therefore fully dependent on surface water inflow and precipitation. Groundwater levels correspond to the Dyje River levels, during the period of Nové Mlýny dam construction this relationship between surface and groundwater levels was disrupted. From the perspective of the individual reference periods they are all comparable in terms of average groundwater levels, with a slight increase in the 1981-2010 period by 0.09 m. Regarding minimum and maximum levels, i.e. the overall variability, the most variable periods are the periods 1981-2010 and 1991-2018, when the variability in minimum and maximum level was 1.53 m. In contrast, least variability in groundwater levels was observed in the period 1931-1980, 1.42 m. Differences between long-term minima are also very small, in the period 1981-2010 the minimum increased by 0.09 m, in the subsequent period it was constant. With regards to the long-term drought threshold, i.e. 85 % of long-term cumulative frequency curve, there were no significant changes over the entire period of monitoring, in the period 1981-2010 the long-term threshold of DMKP increased by 0.08 m, in 1991-2018 by a further 0.05 m. More significant are the changes in long-term maximum, where there is an increase by 0.21 m in the period 1981-2010. Periodicity of annual groundwater level course has not recently been as disrupted as in the case of other probes, however the dry period 2014-2018 also significantly affects the probe and there is a decrease in groundwater levels.

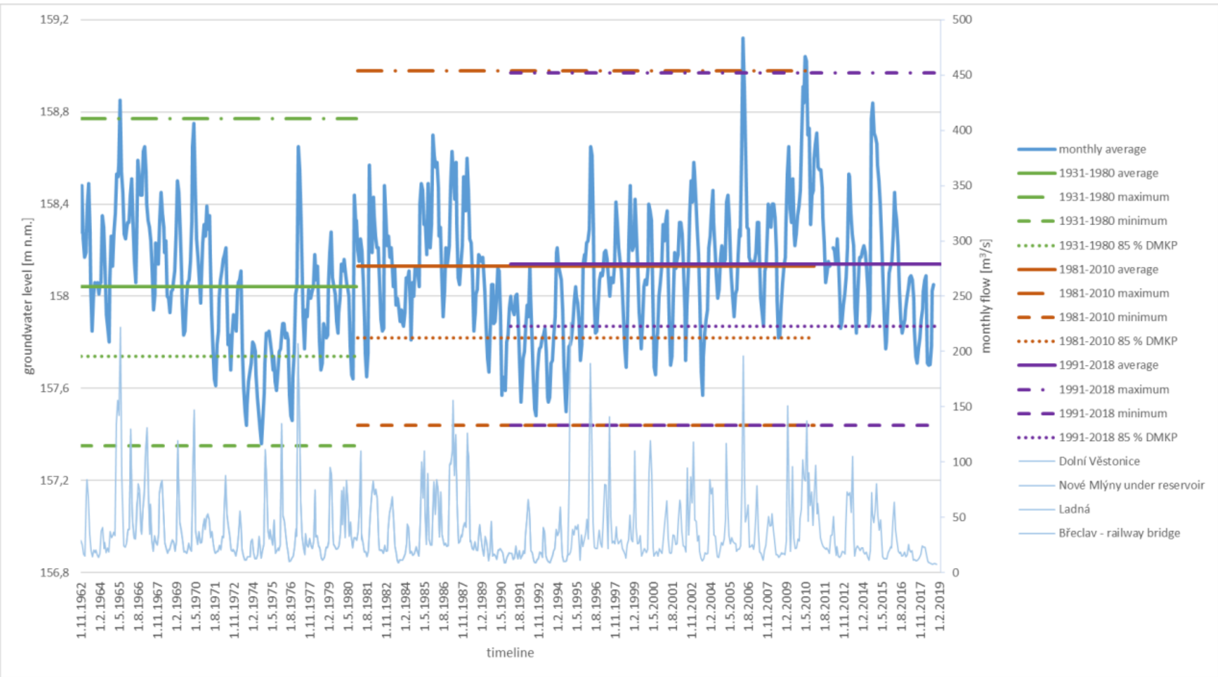

Fig. 10. KB0718 probe assessment

Water management modifications brought about many changes, which had a significant impact on natural and anthropogenic systems in the area of interest. Extensive forest areas, meadows, pools were flooded, watercourse channels were altered, as well as land use. Water management modifications associated with the constructions of the Nové Mlýny dam significantly disrupted "natural" conditions for the development of floodplain geobiocenosis. It leads to a disruption of fluvial processes, as well as the overall hydric regime of the area. Modifications which changed the moisture and fluvial relationships in the area include construction of new river channels, dams, channel shortening etc. Dams are sort of an unnatural barrier. Channel shortening leads to formation of many abandoned meanders. These abandoned river stretches are usually not in hydric contact with the main river flow and therefore cannot be restored, i.e. they gradually degrade. Construction of the Nové Mlýny reservoir changed the overall hydric regime of the area. Hydrological conditions were disrupted at all types of floodplain biocenoses. Drought also affected floodplain meadows, where there is an obvious decrease in grass-herb associations with dominance of hygrophilous or wetland species. The above mentioned proves countless studies (Buček et al., 2004).

Data from the probe at HP Ladná leads to the following conclusions. Each probe in the profile is unique and its assessment therefore requires taking into account several factors, such as landscape and vegetation conditions near the probe, geological profile, potential effect of other watercourses, not just the main one, which in all these cases is the Dyje River. All probes interact with surface waters, however, what is important is the distance from the watercourse, which affects the dynamics of groundwater levels.

Construction of the Nové Mlýny reservoir led to a decrease in groundwater levels at the KB0706 probe because it is directly dependent on regulations of the Dyje River. In case of other probes there is an obvious decrease in groundwater levels after the construction of the Nové Mlýny dam. During 1990s there is an increase in groundwater levels, which manifested itself in long-term characteristics of the two recent periods. This increase is caused especially by regular floods in the area, because it is an area of riparian forests. These changes directly affected the probes KB0719 and KB0718. The KB0689 probe lies outside the flooded area, however increase can also be observed here and it has less significant fluctuations compared to the other probes. 1990s were quite rich in terms of groundwater thanks to floods groundwater levels could increase and reach their normal values. Since 2010, however, one can see a decreasing trend in groundwater levels, with only seasonal increases.

CONCLUSION

Groundwater level observations at hydropedological profiles are significant especially because of relating it to a profile and a particular watercourse and because of the duration of continuous monitoring. Apart from other uses it can be used for determination of hydraulic relationships between surface water and groundwater. This data can be useful especially for the determination of potential spread of groundwater pollution from surface waters. Knowledge of groundwater regime at a profile (during standard climatological and hydraulic year) allows one to conclude that in long-term, the annual course of groundwater level at all boreholes is roughly the same, with a minimum in October and maximum in April, between which there is a gradual change of the groundwater levels. Groundwater level at a specific borehole is affected by river flow rates, very little by precipitation. Groundwater level does not lie deep below the ground. Deepest it gets is 5 m below the terrain, maximum levels close to a river can reach above the ground. Fluctuation of groundwater level is quite large given the overall thickness. Difference between maximum and minimum level is on average approximately 1 m. Highest values are observed at boreholes close to rivers, where this difference can be up to 2.5 m. Based on long-term time series it is possible to also assess specific periods. The most important period at most boreholes is the 12-month period, which corresponds to seasonal replenishment of groundwater. In case of 70-year long series one can also see statistically significant 30-year periods. Occurrence of these periods is also related to the occurrence of minimum groundwater levels, which occur with approximately 10-year period. In the Dyje basin, groundwater level decreased by approximately 0.5 m after 1972 and fluctuations are less prominent, which is due to the modifications of the Dyje River.

Up to three zones (narrower, water and outer) can be distinguished in terms of the effect of a watercourse (river) on a groundwater in its floodplain. In the narrow belt along the watercourse channel, every significant deviation of water level in the river channel results in a significant change in groundwater level. As the distance from the watercourse increases, this deviation decreases and there is a certain time delay. A groundwater level regime in a floodplain is characterized by alternation between a period when water is received by infiltration of surface water and a period when it is the other way around, i.e. groundwater flows to the watercourse, which occurs when surface water levels are low. In the wider zone the immediate effect of surface water deviations is reduced, only long-term exceptional increases in water levels or their long-term high levels manifest themselves by increase of groundwater levels. In the outer zone the groundwater level is only affected by the river if increased river water levels lead to increase in shallow groundwater levels in the narrower and wide zone, which increases the potential for flow off of groundwater into the outer zone. Result of such increase is an increase in groundwater levels in the outer zone.

Shallow groundwater in floodplain sediments can therefore be donated not just by water coming from precipitation or by water from e.g. valley hillsides, but also by infiltration of surface water from watercourse channels. Its extent depends on the mutual position of surface and groundwater levels, its slope and hydraulic link. This depends on the depth and width of the channel and river bed and river bank permeability, which can be affected by secondary barrier in the form of fine-grain sediments, forming a colmatation barrier. Changes in surface water levels in a watercourse result in slope variability of groundwater levels, as well as the direction of its movement. In general, during high water levels groundwater in a floodplain flows away from the watercourse towards the surrounding area and likewise during low water levels (low flow rates) vice versa. However, apart from that groundwater in permeable sediments of floodplains also moves downwards, i.e. most commonly in the direction of river flow. Shallow groundwater levels therefore fluctuate in accordance with deviations in surface water levels, but always with a certain temporal delay. Amplitude of this fluctuation decreases with increasing distance from the watercourse channel. Predominant effect of a river on shallow groundwater in quaternary fluvial sediments of a floodplain is therefore apparent under the conditions of hydraulic linkage. Contrarily it can be said that a characteristic feature of shallow groundwater of a floodplain is its temporal and spatial dependence on river flow rate regime. River water levels affect fluctuation of groundwater levels and direction of flow of shallow groundwater in a floodplain.

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DETERMINING ACCURATE ICE COVERAGE ON DANUBE BY WEBCAMERAS

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ABSTRACT

For most Hungarian rivers, especially the Danube, floods and other damages caused by ice have produced and are producing serious problems. Meanwhile, the number of national research on ice that improve the effectiveness of ice protection is low, and technical development is not significant at this point. The main focus of the research presented in this article emphasizes the advancement of this research and to the further develop of the river ice monitoring methodology.

The key objectives are listed in the following points:

Develop a fast, automated, cost effective, and continuous ice-collection method based on web camera images with a precision far beyond their manual or estimation procedures. Verification of the developed solution through error analysis. Solutions that do not require specialized software were preferential.

Analyze the time pulsation and daily travel curve of the ice jam coverage ratio of the Danube with the developed high frequency measurement process.

The aim of this paper is to promote modernization of the Hungarian ice-observations and to provide a numerical basis for scientific research related to this topic.

I have demonstrated that the web-based, automated river ice-monitoring system can be used as a detailed hydrographic tool and can provide more accurate results than the currently used estimation or manual image processing methods.

I have proved that from the images of webcams to determine the rate of ice coverage, it is enough to imagine the views of the cameras in advance, with a single spatial perspective transformation, it is not necessary to use georeferencing, orthorectification, or complicated form recognition procedures for each frame. From the perspective mapping, the aspect ratio of the pixels (pixels) to the water surface in the image being examined can be calculated, and it is sufficient for the computation of ice coverage in all images with the same viewpoint. By doing this, I've narrowed the task to the grading of the water-ice pixels. A simple numerical method was developed and verified to determine the area ratio of pixels to the surface of the water. I have developed an automatic, adaptable threshold value, which distinguishes between ice and water with appropriate precision as picture points (pixels).

With my method of ice coverage determination, I observed significant temporal pulsation and daily periodicity in the ice movement of the observed Danube reach. I have found that the small number of daily estimates are not representative to determine daily average ice coverage. I recommend continuous webcams monitoring.

The new findings contribute to a more accurate understanding of the spatial and temporal structures of ice floes in rivers, as well as the methodological development of their measurability and reproducibility.

My work creates the basis for the modernization of the Hungarian ice-monitoring network. The operation of such a network provides the condition that in the future on the larger rivers ice floe forecasting and alarm systems may be established. The time series collected over the past decades provide data for national research on river ice phenomenon's too.

Keywords: fluvial ice, webcamera, ice coverage, ice observation, hyrdomethry

INTRODUCTION

Despite the processes of global warming, that can be observed from the hydrological data during the past decades, the unfavourable mix of hydrometeorological factors can cause severe ice-drift on the Danube in winter, resulting ice-floods. In 2002 I placed a web camera on top of a tall building on the Danube bank of Baja, based on the results of traditional ice photography experiment in the 70's. The success of my initial ice observation in 2008 resulted the construction of 5 additional cameras. The saved images recorded one of the special 30 to 40 km sections of the Danube (130 km) reach managed by the ADUVIZIG (Lower Danube Valley Water Directorate, Hungary). In 2009, 2010 and later during the winter of 2012, ice floes were produced in the examined sections. The recordings helped to improve ice forecasting, reduce the burden of the ice-breaker patrol service, and further research work. Unfortunately, the January 2017 event was only partially recorded due to the lack of maintenance of the camera system.

The revised and possible rethinking of the Technical Guidelines and Water Technical Assistance about the topic of ice detection, is a timely issue for the water resources service agencies. The revitalization is not justified primarily by the age of these documents, but by the fact that the water resources service agencies has been heavily restructured. There has been a lot of change in the number, qualifications, tools and financial background of the water resources industry, which suggest a re-examination of the above listed regulations.

The more important, and obvious reason to study river ice is that the most devastating floods were caused by ice floes in the lower part of the Danube in Hungary. During the last 180 years, extreme ice floods on the Danube occurred on the following occasions: 1838, 1839, 1850, 1876, 1878, 1883, 1891, 1920, 1923, 1926, 1929, 1940, 1941 (Lászlóffy, 1934) and finally the highest level was recorded in 1956.

We do not need to go too far back to look at past events; we only need to look at the damage caused by the recent river ice incidents in 2017 (recent). The ice floe in January 7, 2017 (without any warning) extended for almost the whole Hungarian Danube reach damaged the river signs and caused serious damage. In mid-February, the mass of ice in the river Tisza caused a lot of damage to the water equipment at most riverside towns. Perhaps the most celebrated event in the media, was the incident of the Tiszacsege ferry, where only with a little luck was a fatal accident avoided.

Protection against less frequent natural disasters, even if they cause serious damage, are only briefly given appropriate attention. Therefore, there is not enough interest to reveal the true cause and effect relationship. At these events, typically event-follow-up actions dominate, which often lacks a careful and detailed consideration for decision making. My work cannot solve all river-ice problems, but it tries to show as many aspects of it as possible. The main goal of the work is to modernize ice observation, which can provide a good basis learning the phenomenon more thoroughly and to analyze it scientifically.

This paper is a short outline of my PhD dissertation and that is the reason of using first person singular in the text, I sincerely hope it doesn't hurt anyone.

OBJECTIVES

For most Hungarian rivers, especially the Danube, floods and other damages caused by ice have produced and are producing serious problems. Meanwhile, the number of national research on ice that improve the effectiveness of ice protection is low, and technical development is not significant at this point. The main focus of the research presented in my dissertation emphasizes the advancement of this research and to the further develop of the river ice monitoring methodology.

The key objectives are listed in the following points:

- Historical overview of the current practice of river ice-detection in Hungary, a critical overview of the solutions available in international literature, and the demonstration of domestic development opportunities, highlighting the use of webcams for objective determination of river ice coverage and its operational experience. Confirmation that these tools can be used to produce efficient and accurate hydrographical data that, can direct ice defense, and can serve scientific research.
- Develop a fast, automated, cost effective, and continuous ice-collection method based on web camera images with a precision far beyond their manual or estimation procedures. Verification of the developed solution through error analysis. Solutions that do not require specialized software were preferential
- Analyze the time pulsation and daily travel curve of the ice jam coverage ratio of the Danube with the developed high frequency measurement process.
- In addition to web-based ice-detection detection, development of a measuring instrument for direct measurement of the spatial shape of the running ice tables and verification of the device operation on the Danube.

The aim of this research was to promote modernization of the Hungarian ice-observations and to provide a numerical basis for scientific research related to this topic.

PRACTICAL APPLICABILITY OF WEB CAMERAS

In 2002, I installed my first webcam for ice-observation in Hungary, followed by several others. By presenting the operating experience and the wide use opportunities of cameras (modeling, flow estimation, ice forecasting, etc.) I explained and demonstrated the justification of the monitoring system.

The practical applicability of the web camera system is broader than just the ice coverage ratio detection determination. Some example of usage as follows:

- Fluvial accidents
- Characteristics of drifting floe
- Study of the hydrodynamic conditions
- Hydrodinamic modelling
- Discharge estimation

In 2018 I have developed an automatic, cost-effective image processing method that has a significant outcome that the system can be used as a hydrographic tool. I have verified by error analysis (Table 1) that the Self-Developed Auto Solution provides more accurate results than the official Hierographic data, any of the Estimating Methods, and even better than Manually Image Processing. Using the individually calibrated, transformed and evaluated camera images as reference, the square medium error (RMSE) was the lowest for the Automatic process:

Table 1. Error of ice coverage determination methods

Method:	**Hydrographic**	**Estimation1.**	**Estimation2.**	**Manual**	**Automatic**
RMSE:	13,15 %	9,03 %	9,59 %	10,18%	**5,94 %**

I have demonstrated that the web-based, automated river ice-monitoring system I have developed in the domestic water management practice can be used as a detailed hydrographic tool and can provide more accurate results than the currently used estimation or manual image processing methods.

I have shown that the practical applicability of the web camera system is broader than just the ice coverage ratio detection determination.

SIMPLE AND EFFECTIVE IMAGE TRANSFORMATION

After a thorough reading of the literature (Duguay et al., 2015; Chu et al., 2016; Kraatz et al., 2016; Ansari et al. 2017; Tóth, 2017) a kind of a general solution outlined, but it was not suitable for my problem. Solving the task of image evaluation the necessary steps were these:

- Convert the original photoes to grey shadow image
- Ortorectification by georeffered points
- Adjust the contrast of the image (Gamma filter)
- Make a binary image (Black and White)
- Select and investigated area on the image
- Calculate the coverage

Instead of this process I used the image transformation process of Gálai (2008) for the first time in practice with three independent cameras (Paks, Baja, Mohács). The principle of this process is that I photographed a well-coordinated square grid plate in front of the camera in several positions. From the pictures I read the coordinates of the plane grid square in pixels (Fig. 1.). The more pictures I have been able to process, the more accurate I got the internal parameters describing camera distortion. The water surface of the river, where I observed ice floes (in the test section), was approximately horizontal.

Fig. 1. Well-coordinated square grid plate

The average slope of the Danube here is negligible. I put my calibration plane horizontally with the help of two water levels perpendicular to each, and the observed area was opened in front of the camera, and in parallel plane I interpreted a parallel coordinate system. By this the necessary transformation (Fig. 2.) has become simpler.

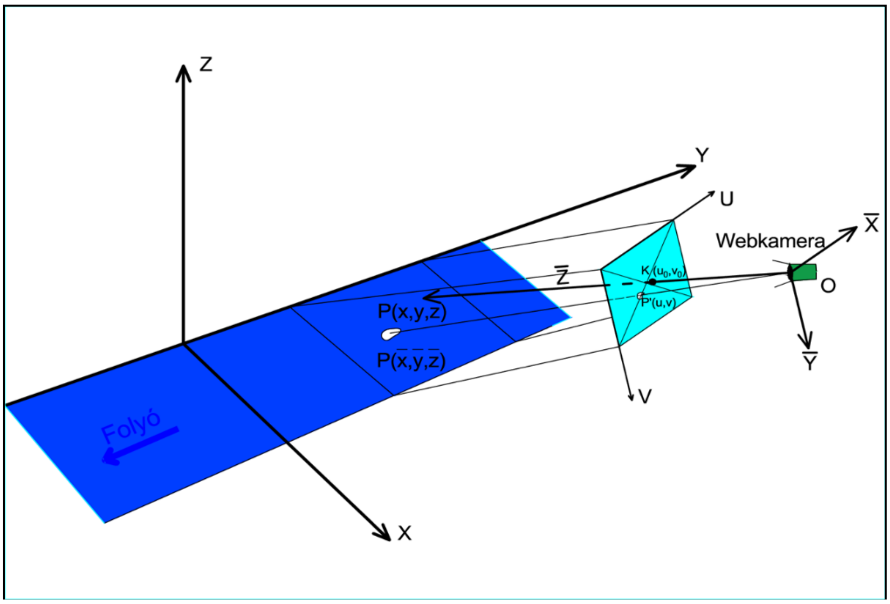

Fig. 2. Sketch of coordinate trasformation task

This coordinate system calculated the transformation function (equation 1) between image and reality (x, y, z) in the pixel of the camera (u, v). The ratio between water and ice can be interpreted in planes parallel to the water surface, so a single determination of the transformation between the horizontal plane plate and the camera image can be used to analyze the ice coverage at any water level. I also used the simplification that, due to the horizontal plane, the height of the spatial coordinates “z” is zero

$$\begin{bmatrix} u \\ v \end{bmatrix} = f\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right) = f\left(\begin{bmatrix} x \\ y \\ 0 \end{bmatrix}\right) \rightarrow \begin{bmatrix} x \\ y \end{bmatrix} = \boldsymbol{f}\left(\begin{bmatrix} u \\ v \end{bmatrix}\right) \quad \textbf{(1)}$$

Using this function, I calculated the spatial coordinates of each pixel of the camera's images. The procedure was verified by the area computation of any square grids of the plane used for the calibration, where the biggest error was within 3%.

I have proved that from the images of webcams to determine the rate of ice coverage, it is enough to imagine the views of the cameras in advance, with a single spatial perspective transformation, it is not necessary to use georeferencing, orthorectification, or complicated form recognition procedures for each frame. From the perspective mapping, the aspect ratio of the pixels (pixels) to the water surface in the image being examined can be calculated, and it is sufficient for the computation of ice coverage in all images with the same viewpoint.

Instead of expanding the Jakobi determinant proposed by Gálai (2008), I used a more practical, numerical solution of area calculation determined from real-coordinate squares of the pixel corner points. The pixel treated so far as a point can be treated as a square, which is apparent after an appropriate magnification. The square, however, has a planar extension, a surface area, and the area can be calculated based on its corner points. The idea was no matter how elementary I never found to be used for calculating ice coverage. I used the approximated that sides of the rectangles stay straight from transformation from (u, v) to (x, y). This is also true for small pixels.

The corner points of each pixel selected for observation were calculated using the four angular coordinates shown in Figure 3 Starting from the upper left corner, I numbered the corner points clockwise to 1-4. Using this sequence, which I use as the index (i) of the calculated real x, y coordinates, I calculated the actual area of each pixel I want to observe with the following (2) relation.

$$A = \frac{1}{2}\sum_{i=1}^{5}(x_i y_{i+1} - x_{i+1} y_i),\ \ where\ (x_1; y_1) = (x_5; y_5) \quad \textbf{(2)}$$

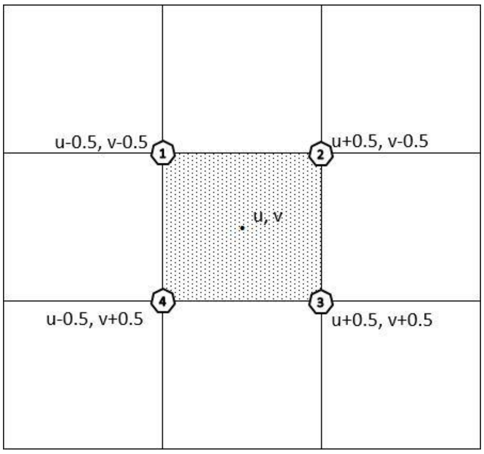

Fig. 3. Corner coordinates used for pixel area calculation

The calculated areas are placed in a matrix indexed with the u, v coordinates of the pixels, which provide the actual area of the pixel in question while moving in the area being investigated. By the described process, I have narrowed the task to the grading of the water-ice pixels.

ICE AND WATER SEPARATION

I converted colour images provided by cameras to grey shades. Subsequently, I determined an area variable threshold value for distinguishing between ice and water. The use of a single threshold value in the picture has yielded insufficient results.

I have noticed that on the camera images, regardless of the day, the reflection on the water is always in the same direction. Along the direction of reflection, a lower and an upper threshold was linearly distributed, and this way the ice can be separated from the water with enough precision. My further development was to use the interpolation to determine the lower and upper threshold values using the sky from the earlier cameras images and the clearly identifiable, permanently identifiable surface features. After the ice-water separation and area ratio determination functions were successfully resolved, the examined areas of the cameras were divided into 40 downstream lanes and the coverage ratios in these lanes were defined. The results were saved in the form of pictures (Fig. 4.) and data series.

Fig. 4. Graphic result of the determination of ice coverage in the band under the Bay of Baja

I have developed an automatic, adaptable threshold value, which distinguishes between ice and water with appropriate precision as picture points. Finally, the reliability of the automatic method was verified by error analysis (Table 1.).

RESULTS AND DISCUSSION

In all examined Danube profiles, the variable amplitudes pulsation of the ice coverage with time was observed. This pulsation is considerably higher than for example at water velocity measurements. Observations that vary this way are characterized by time-averaged values in the water resources industry. That is why I think it is justified to introduce this method at ice jams, along the use of cameras. In the domestic practice, the ice coverage of a river section is currently characterized by one to five estimates per day, although the intra-day period is not negligible. The arithmetic means of the small number of samples, therefore, is significantly different from the mean values derived from accurate steady, high-frequency observations. My results help to determine the optimal observational period of ice jams, whose information density can thus be traced to other hydrological and meteorological data, creating the basis for temporal and spatial analysis of the ice evolution and melting process based on observation.

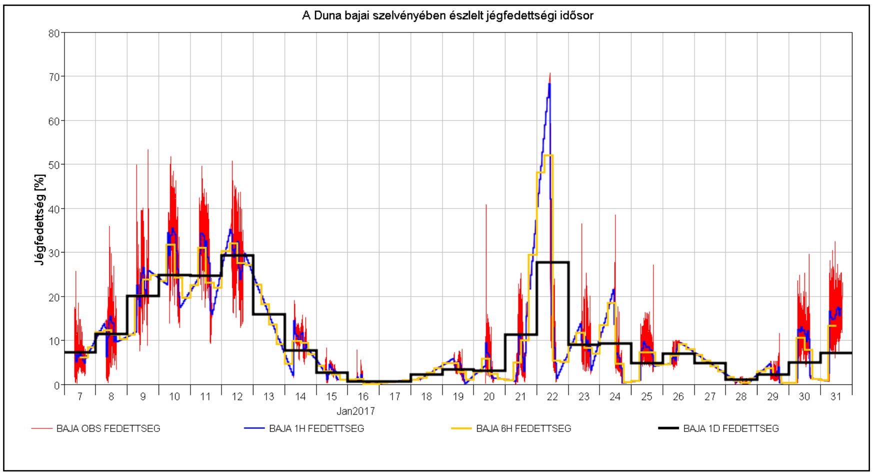

Fig. 5. Ice Coverage Curve during the January 3, 3-week ice-jam of the Danube Baja section. Legend: calculated by the ice observation camera (red), 1 hour average (blue), 6 hour average (orange) and finally average daily (black) time series.

Figure 5. shows the rapid fluctuation of the instantaneous ice cover and the sensitivity of the mean values to time ranges. Note that webcam measurements only give the daylight hours, and during the nights I approached the curve with linear interpolation.

With my method of ice coverage determination, I observed significant temporal pulsation and daily periodicity in the ice movement of the observed Danube reach. I have found that the small number of daily estimates are not representative to determine daily average ice coverage. I recommend continuous webcams monitoring.

APPLICATION OF THE RESULTS

The new findings contribute to a more accurate understanding of the spatial and temporal structures of ice floes in rivers, as well as the methodological development of their measurability and reproducibility.

István Zsuffa's 1978 pioneering black-and-white industrial camera's continuous ice observation system has been revitalized and upgraded to create an ice-detect service based on ice coverage in real time, which is rarely can be found in the world. This system contributes greatly to the success of the ice floods and ice floe damage prevention work for the water resources agencies. In addition, it creates the possibility of scientific research on ice floes, data supply for in situ numerical modelling.

The research establishes and validates an automated process that can be used to measure the rate of ice coverage and the transverse distribution of the ice surface yield per unit width in consecutive flow cross section. Collection of the in-situ datasets requires serious effort, especially when the measurements are taking place on an icy river. Video recording is safe, but the thickness measurements needed to determine the ice volume flow must be carried out manually on the river. For the manual ice thickness measurements, I created and validated a device that allows simple and quick measurements on icebreaker ships. This result is extremely useful because from the dense timeseries of the transverse ice area ratio further analyses can be conducted.

My work creates the basis for the modernization of the Hungarian ice-monitoring network. The operation of such a network provides the condition that in the future on the larger rivers ice floe forecasting and alarm systems may be established. The time series collected over the past decades provide data for national research on river ice phenomenon's

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STATISTICAL ANALYSIS OF THE RUNOFF IN THE EAST MECSEK REGION (HUNGARY) IN ORDER TO UNDERSTAND CLIMATIC VARIABILITY BASED ON HYDRO-METEOROLOGICAL RECORDS

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ABSTRACT

Hydro-meteorological investigation of the small catchments of the East region of the Mecsek hills has been carried out since the 1960s. In frame of the research, daily water levels of the main creek of the region (Völgységi-creek) have been recorded at two gauging stations: for the upper reach in Magyaregregy settlement and for the lower reach in Bonyhád city. On the upper reach the water levels of one of the most important tributaries of the Völgységi-creek: Hodácsi-creek are also recorded. There are three rain gauges as well that record daily rainfall since the 1960s.

In our study we carried out statistical analyses of the 50 years long data series of the above-mentioned hydro-meteorological measurement stations, and we provide information about the changes that can be observed in the runoff characteristics of the creeks, we as well established correlations between the rainfall and the runoff characteristics and determined the extremities and the changes in their frequencies of occurrence.

The above studies can help us understand the climatic changes i.e. in the temporal distribution of the rainfall and runoff and may help us develop better strategies in order to prepare for the probably more frequently occurring flash floods.

INTRODUCTION

Flash floods are frequently associated with violent convection storms or thunderstorms of a short duration falling over a small area. Flash flooding can occur in almost any area where there are steep slopes; it is common in mountainous regions subject to frequent severe thunderstorms. Flash floods are often caused by heavy rain of short duration. Flooding caused by flash floods frequently washes away houses, roads and bridges over small streams and has a critical impact on communities living in these often-remote areas (Andjelic & Szöllősi-Nagy, 2019).

Rainfall events with high intensity in small catchments with a steep land surface slope like mountainous catchments can create so-called flash floods. They are characterized by a short time to peak as well as a relatively short flood event time, critical or supercritical flow (Bornschein, 2019).

Because of the steep surface the time of concentration is rather short: it takes a few ten minutes or a few hours in a few 10 km^2 catchment areas exposed to the rainburst. The fast concentration results in very intensive flooding. The intensity of water level rising can fall in the magnitude of meters in an hour. The intensive rising of water level is expected to cause fast change of water surface slope so the instant discharge of water can be surprisingly great. As extreme rainfall intensities cause the extreme discharge, the possibilities of forecast of flash flooding are similar to the cloudbursts. The earliest signal can be earned from the rainfall detection. The most direct solution is the water level detection. The rainfall based nowcast can be gained from real time measurement and sampling of rainfall, rainfall distribution of storm clouds by radar. The rainfall radar can give spatially continuous estimation of rainfall intensity distribution. The technical solutions of the radar estimation and the connecting technical and theoretical problems are discussed in several studies (Testic, Y. Firat, 2013).

The flood control against flash floods is very difficult. The fast moving character of the flash flood, the rapid runoff and accidental water level rising cause that operative flood control – building of defense lines for riverside territories – after a forecast (nowcast) or during the flood can be successful only in rare cases (Rácz, 2019).

METHODS AND DATA (STUDY AREA)

Völgységi creek can be found in the southwestern part of Hungary (Fig. 1) in the northern part of Mecsek hills, where it collects waters from the eastern part of the so-called Völgység region. The creek is not regulated on its upper reach, until the settlement Szászvár (Fig. 2). Along the creek there were artificial ditches for watermills in the past, which have by now been filled up in most locations. The creek first flows from the south to the north, and upstream the settlement Magyaregregy it turns eastwards. Downstream of Bonyhád town it once more turns to the north - northeast and finally discharges into the Sió channel, next to the settlement Sióagárd. The size of the catchment is around 560 km2 while the length of the creek is 53 km.

Fig. 1. Overview map of the study area

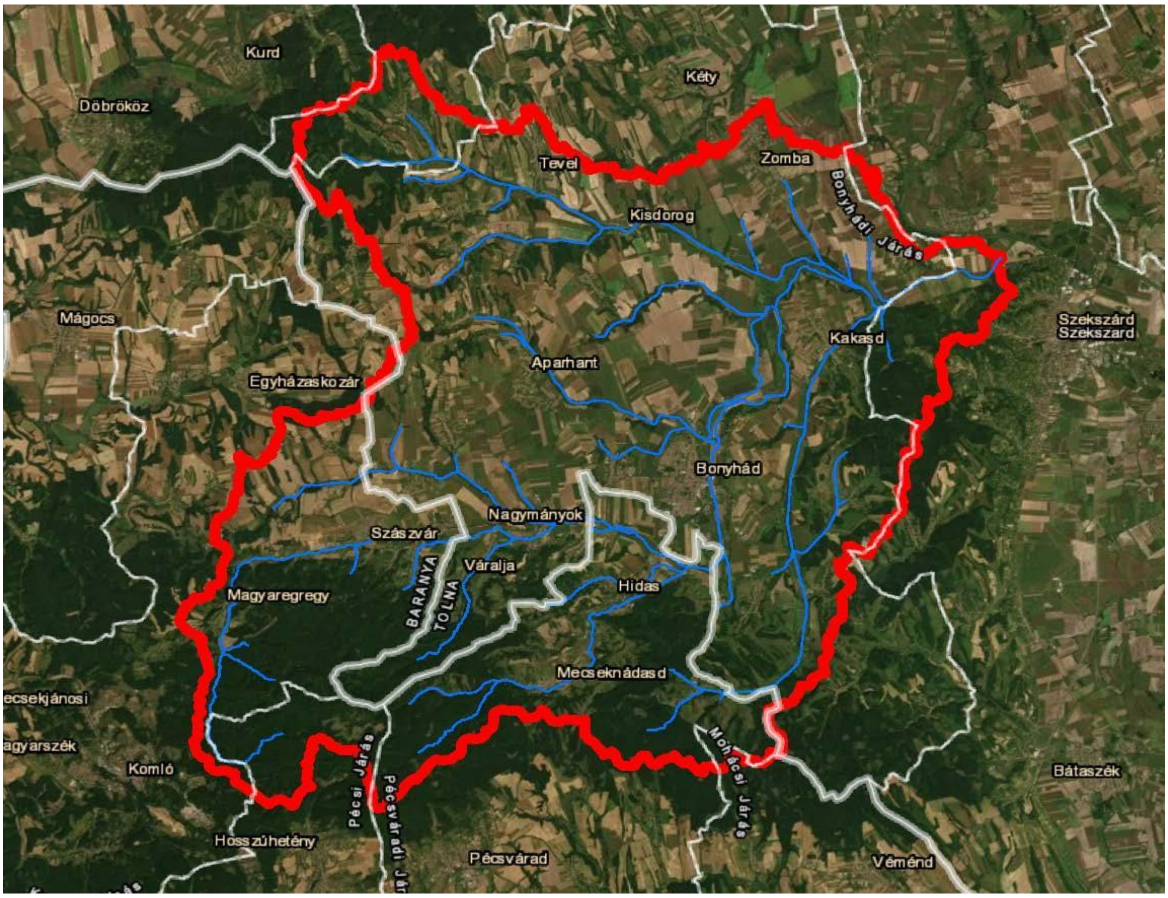

Fig 2. Overview of the Völgységi catchment

The main valley can be categorized into three parts: the upper reach stretches from the sources until Kárász settlement, the middle reach from Kárász to Nagymányok, while the lower reach from Nagymányok to Sióagárd.

On the upper reach from the Takanyó-valley to the Máré-valley there is a characteristic erosion area, the small creeks flow in rocky beds (Marosi, 1990). We can observe that the creek reacts very quickly to rainfall and can produce high floodwaves. Recession time is relatively long (Koch et al., 2019). On the relatively long reach from Kárász to Nagymányok the bedrock already cannot be found on the surface as there are thick alluvial layers on top of it. Along this reach the catchment can be divided into two parts, a hilly, high slope part which is to the south of the creek and a lower elevation, smaller slope part in the north.

Until Nagymányok there are 10 bigger tributaries of the Völgységi creek, transporting a large amount of sediments into the main valley. In the Völgység region there have been oak, ash and elm gallery forests while on the hilltops oaks and turkey oaks were dominant with steppe grasslands, but to date the agricultural utilization of the land has become predominant (Ádám et. al. 1981; Marosi, 1990).

The climate of the Völgység region forms an intermediary type between the continental and the subatlantic type of the surrounding regions. From the viewpoint of flash flood development the Mecsek hills are the most important, as the topographical system of the hills has a high impact on the climate of the region. In the Mecsek hills the sub-mediterranean effects can be observed well. There can be climatic differences between the northern and the southern hillslopes as the ridges act as climatic confines. The annual precipitation of the northern and higher areas is 800 mm while the other parts it is 700 mm. There are rain gauges installed in the catchment area which can record 24 h precipitation averages. Main wind direction is northeast - north. 34% of the annual precipitation falls between March and June, while 53-57% in the summer months. The number of sunny hours of the area is between 1950-2000 annually. On the contrary, the number of snowy days is only 30-50 per annum. Snow usually can be observed for a longer time on the northern slopes. The number of stormy days is above 44 days in the Mecsek hills, while in the northeastern part it is 32-36 days (Bezdán, 1995; Sziebert, 1998).

Gauging stations

For the analyses we had the data of all 3 installed gauging stations, 2 on the main river and 1 on one of the upstream right-bank tributaries, the Hodácsi-creek (Fig. 3; Fig. 4). The most upstream station out of the two on the main creek is at rkm 44,75 in Magyaregregy which is operated by the Southern Transdanubian Water Authority (hq in Pécs), where observation is continuous since 1969. The other station is at rkm 20,00 in Bonyhád town, which is operated by the Middle Transdanubian Water Authority (hq in Székesfehérvár). Here observations are recorded since 1953 daily. This latter station is a part of the master network of hydrological observations of Hungary. About the tributary there are data since 1968, operated by the Southern Transdanubian Water Authority. In the obervation sections we can find built-in measurement structures (Fig. 3) (Kovács, 2017; Töttösi, 2016).

Fig. 3. Gauging stations of the Völgységi creek (photo: T. Kovács; B. Töttösi)

Hydro-meteorological stations

For the analyses we used the data from 3 hydro-meteorological stations - rain gauges (Fig. 4). The station in Váralja is the oldest station of the eastern Mecsek which is still in operation, it was installed in the beginning of the 20th century. It is operated by the Meteorological Information Services of Hungary. The exact placement of the station has changed several times within the village, but it was always located within 1 km from the center. It has been relocated 3 times since the 2nd World War.

The hydro-meteorological station of Máza is the newest station of the eastern Mecsek which is still in operation. It is operated by the Meteorological Information Services of Hungary since 1990. At the moment this station is the only one in the region where several rain measurements are made daily. In the first years the station was situated in a place surrounded by buildings, thus in the years before 2000 inhomogeneity can be detected within the precipitation data series. But the data measured after March 2000 are of sufficient quality and continuous.

In Magyaregregy there is a raing gauging station that is operated by the Southern Transdanubian Water Authority since 1972. The station was, for a long time, located in the southern part of the village but in 2012 it has been relocated with a few hundred meters to the north, so it is now in the middle of the village. In our analyses we used the data from 1973 because the full year data series was available from that date (Szentes, 2015).

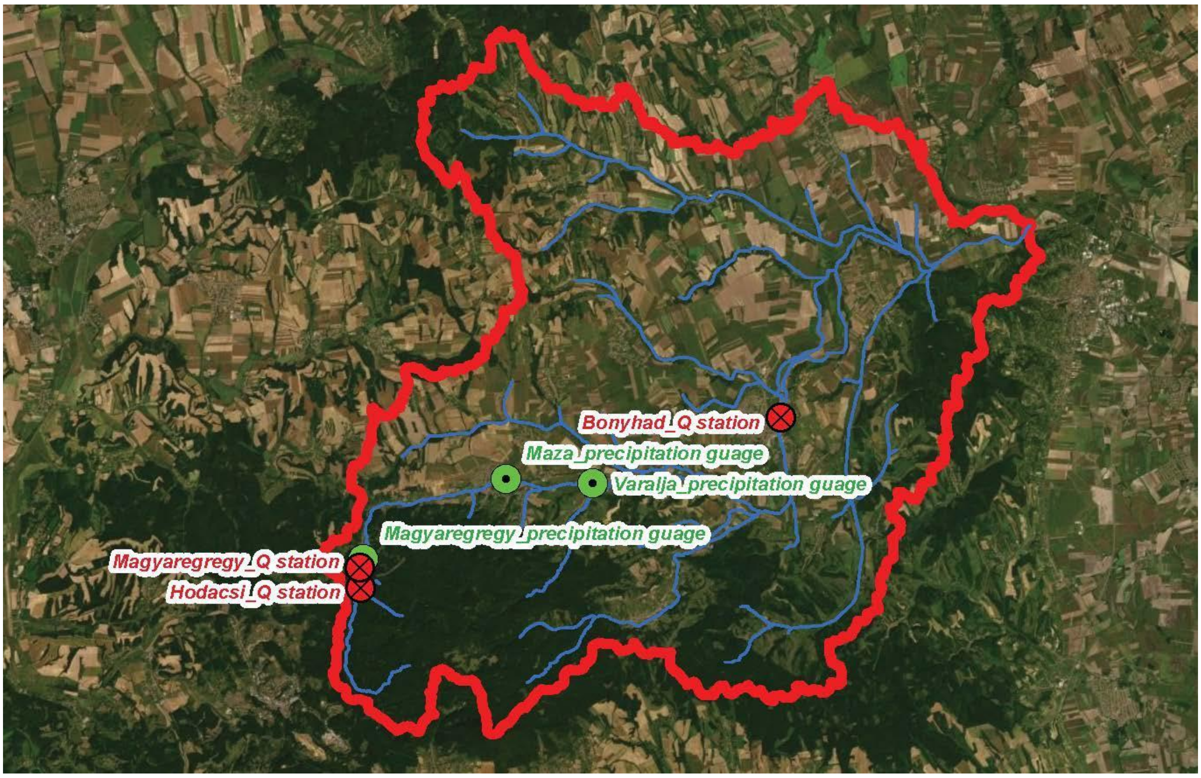

Fig. 4. Discharge and rain gauges in the study area

RESULTS AND DISCUSSION

Flash flood events are important to analyze because these events may reveal aspects of unexpected eventually before unobserved hydrological behavior. Thus, we have carried out a general evaluation based on the available discharge and precipitation datasets in order to conclude statements about the tendencies governing the processes in the studied catchment. We have determined the runoff maxima, minima and averages for all three gauging stations. We determined trends as well.

There are several rain gauges in and around the catchment but some of them are not representative for the study area or is located very close to the confluence where there is no runoff data available as the most downstream gauge is at km 20,00. This way we use the data of the 3 stations presented before. We determined the maxima of precipitation, the number of rainy days as well as the trends, in order to detect eventual effects of climate change.

During our study we had to face with the problem of the lack of systematic observational data, mainly in the case of water level gauges. We have to mention that data gaps were also present in all three data series, 1529 days at Bonyhád, 1019 days at Magyaregregy and 507 days on the Hodácsi creek.

However, our aim was to provide a contribution for the understanding of flash flood processes and to underline the need for developing a monitoring system for flash floods by showing that climate change really has an effect on the frequency of the occurrence of flash floods. Thus, before the investigations, the data set had to be prepared for statistical analysis. First of all, water levels were not uniformly recorded, which means that though there were at least one data every day, but the time of the records were not the same for every day. The other main problem we faced was that though during an event, as a flash flood, measurements were usually more frequently made, however these were not uniformly executed during the process, say every hour.

Since our aim was to investigate floods, we extracted the highest water level from each day from the data set to obtain a uniform time series showing the highest water level of each day. We used this transformed table to detect "interesting" days, were flood events were present, presuming that days when the peak water level was higher than 100 cm can be considered as days with flood events (Fig. 5).

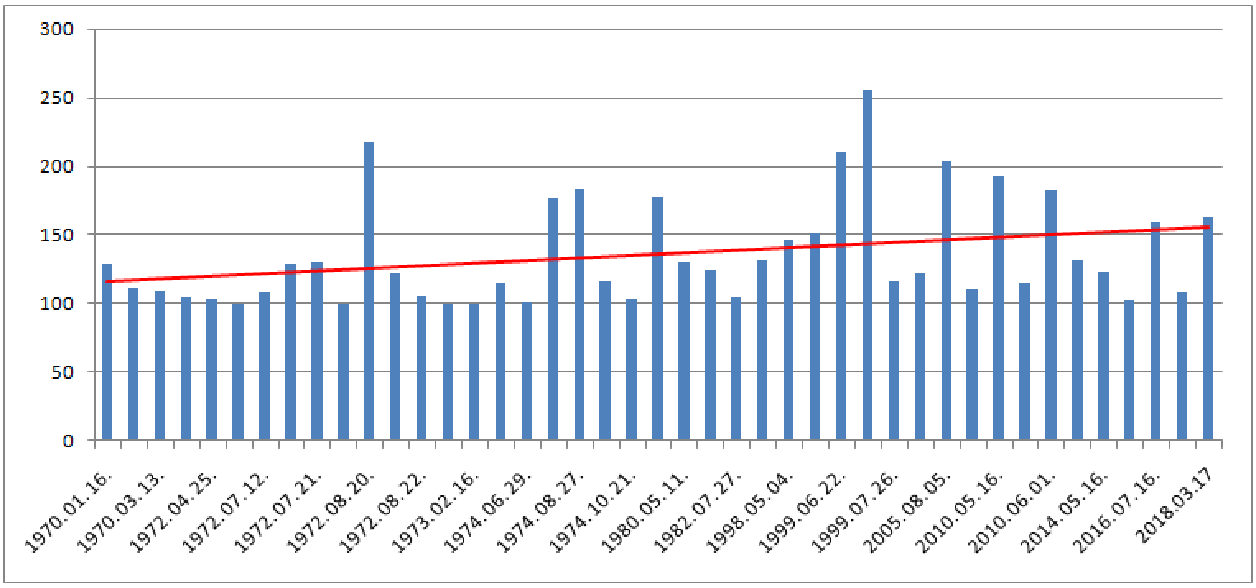

Fig. 5. Linear trend of water levels exceeding 100 cm at the Magyaregregy gauge

The diagram shows the linear trend of growth of the intensity of flood, i.e., the highest water level observed during the flood, over the investigated period. We can observe a slightly increasing trend, and we can state that the floods in the last few decades are more extreme. More precisely, there are 8 floods after 1999 with a peak level of at least 150 cm, while before in the period 1970-1999 there are only 4, which means the frequency of flood events have doubled. We could also observe that in the last ten years there were 6 floods, more than in any of the ten years periods before.

After detecting the time of the floods this way, we investigated each flood independently in order to characterize the runoff and to develop a model for a typical flash flood, eventually to determine the changes that could be observed. Unfortunately, here again we faced the lack of data. Since there were no uniform measures we do not have reliable information about the runoff and hence we could not make any comprehensive statistical analysis. However, we interpolated the missing data linearly in order to obtain some picture about the events. But we emphasize that especially in the case of flash floods these results can involve significant errors.

As a next step we considered the events such that the water level exceeds 100 cm. Since our aim was to investigate flash floods we defined F_1 floods as events where the water level increases at least 250 % in one day. The distribution of F_1 floods in the time period 1970-2018 regarding in 10 years periods is:

17%-12%-23%-13%-35%.

Here we see a significant growth in the last decade.

However, looking at the parameters and the runoff properties of the floods, we find it necessary to define the parameters of floods that should be considered in an analysis regarding flash floods requiring more conditions. For instance, one of the characteristic of a flash flood is the short time period of its runoff. This means that the slope of the celerity of the increase and decrease of the water level is great in magnitude. In order to give a measure for this we investigated the water levels a day before the peak, the peak and the day after the peak and determined the proportion of the water levels before and after the peak to the peak level itself. According to these parameters we defined F_2 floods as the floods where neither of these two numbers is greater than 50%. We found that the distribution of F_2 floods are different comparing to F_1 floods, namely:

0%-8%-30%-16%-46%.

We see that more than the 50% of F_2 floods occurred in the last 20 years.

We insert a diagram of the runoff of the flood in 2018 (Fig. 6) which shows up the typical characteristic of a flash flood.

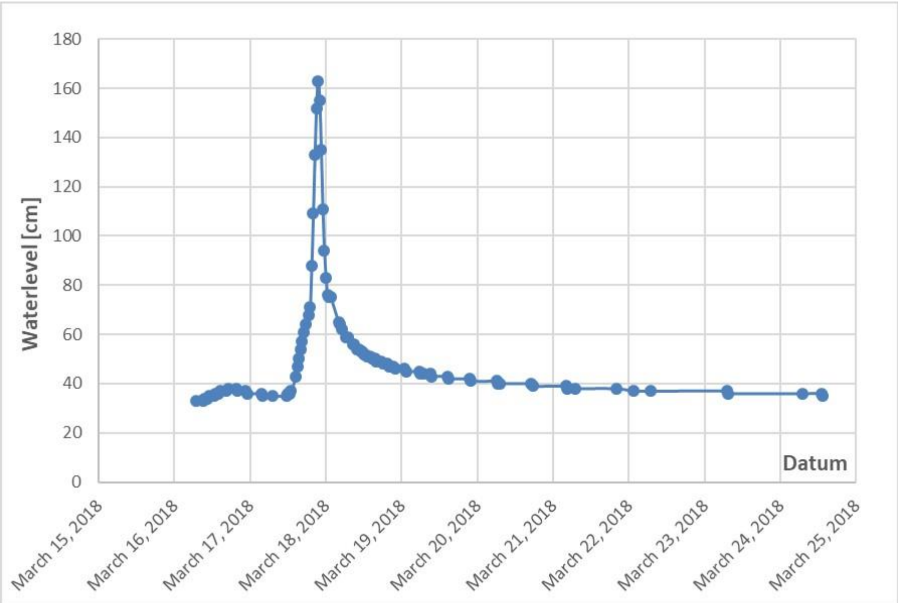

Fig. 6. Hydrograph of a typical flash flood at the Magyaregregy gauge (March 2018)

Runoff data analysis

From the diagram of the yearly maxima we can conclude that the number of high discharges has considerably increased during the past 20 years, increasing the ever-observed peak discharge of the creek several times. Calculating the linear trend of the longest (Bonyhád, 1952-2018) data series a significant increase is visible, which represents a 7.2 m^3/s increase (Fig. 7).

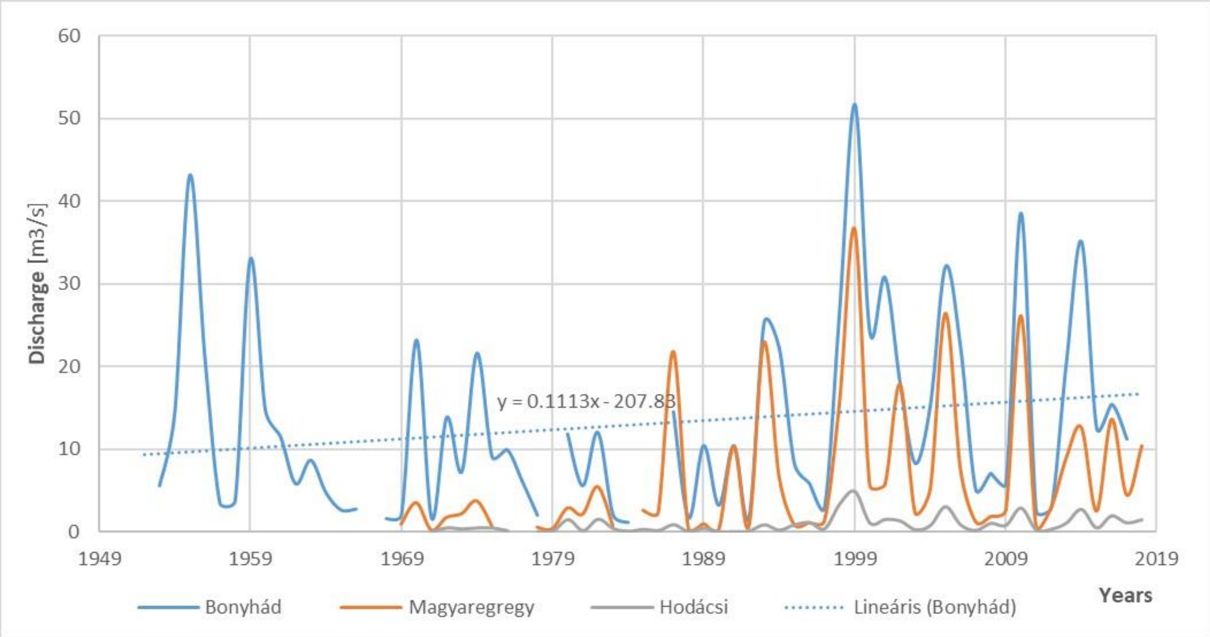

Fig. 7. Maximum yearly discharges of the 3 gauging stations, and their linear trend at Bonyhád

If we look at the mean discharges (Fig. 8) we can observe a slightly decreasing trend at Bonyhád station, while at the Magyaregregy station a slight increase can be seen, and at the Hodácsi tributary as well. This difference can be attributed to the different length of the data series. Here the data gaps are significant so we can suppose that the decreasing tendency would be present if the data series was long enough.

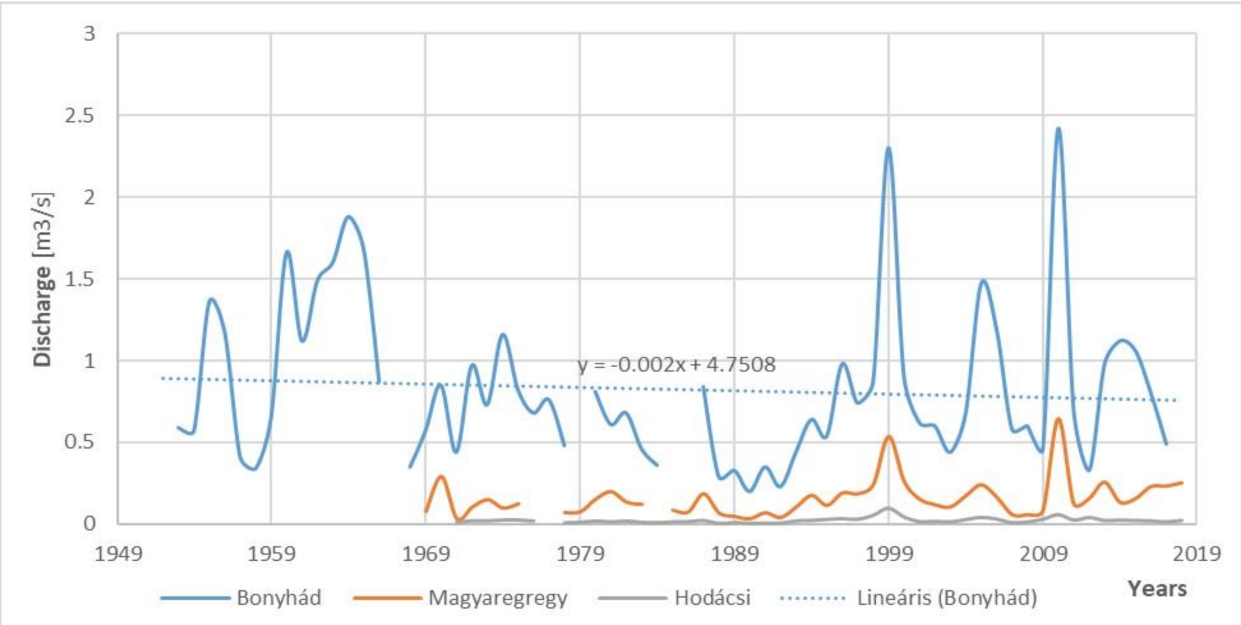

Fig. 8. Average yearly discharges of the 3 gauging stations, and their linear trend at Bonyhád

For the annual minima, we can see a slight decrease at all the three gauging stations, which is particularly true in case we look at the most recent 20 years (Fig. 9).

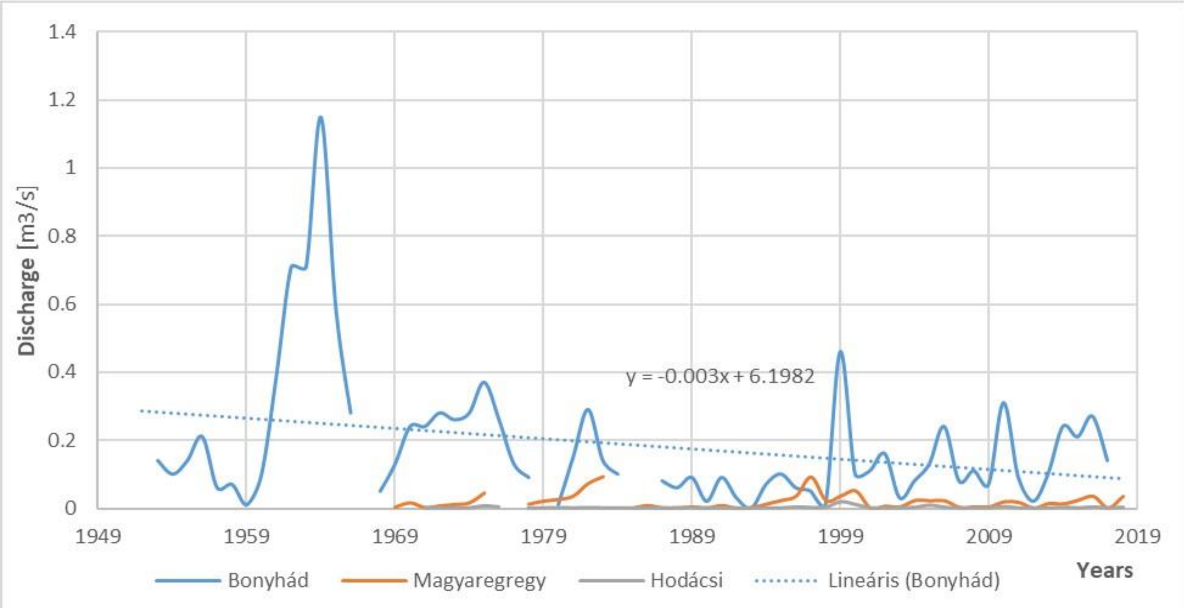

Fig. 9. Minimum yearly discharges of the 3 gauging stations, and their linear trend at Bonyhád

Precipitation data analysis

The processing and analysis of the precipitation data was made in order to control as well as verify the runoff tendencies. We analyzed the daily precipitation sums of the three rain gauges (Magyaregregy, Váralja, Máza). The longest of the data series is available for Váralja, since 1962. Data gaps in this data series comprise 366 days. At the Magyaregregy station data are available from 1972, with data gaps on 513 days. The last station Máza has unfortunately a very short data series which can only be used from the year 2005, with 61 days of missing data.

In case of annual maxima (Fig. 10), the Magyaregregy station which is closest to the sources shows consequently higher values, which can be explained with the effects of the variability of the terrain. If we compare the values to the runoff data, a correlation can be seen as expected, and the periodicity in the precipitation also results in a similar periodicity in the runoff.

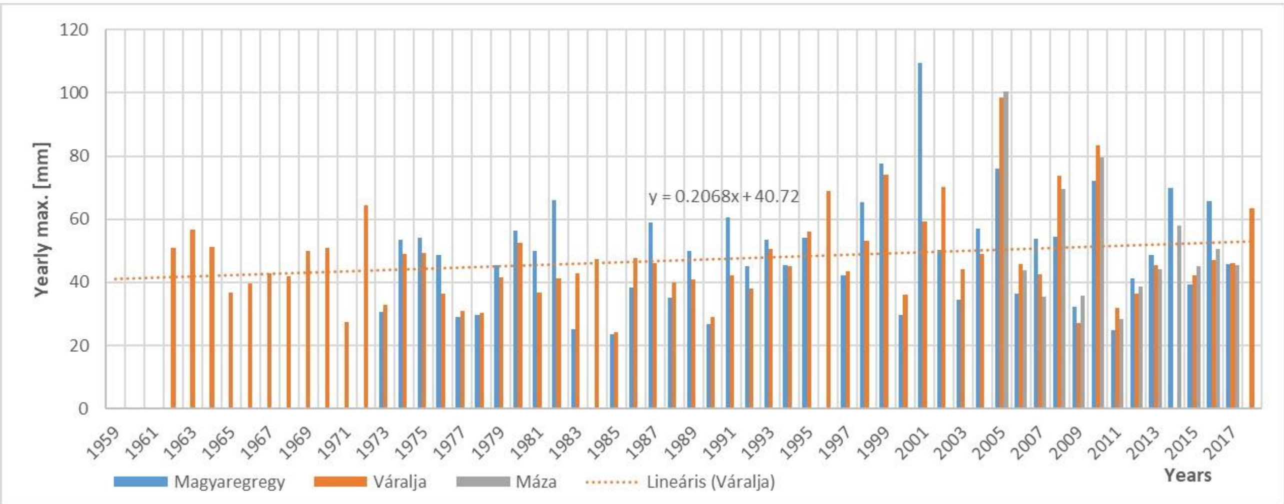

Fig. 10. Maximum yearly precipitation of the 3 gauging stations, and their linear trend at Váralja

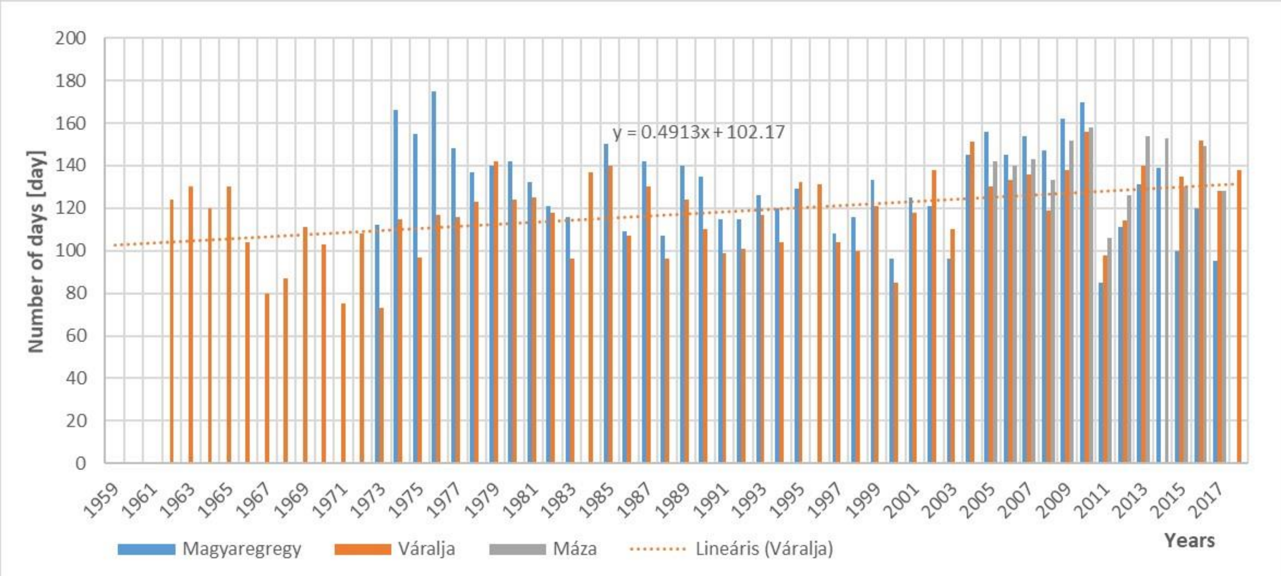

Fig. 11. The number of rainy days at the 3 gauging stations, and their linear trend at Váralja

If we analyze the number of rainy days (Fig.11) and the sum of precipitation (Fig. 12) at the three stations, the effects of climate change can be undoubtedly seen in the study area. The trends of both data series are significantly increasing, meaning a higher number of rainy days within a year and bigger precipitations as well. When we look at the connections with the runoff data, it is difficult to interpret the changes in the average and small discharge data series, but we think a more detailed analysis could show the characteristics causing these changes.

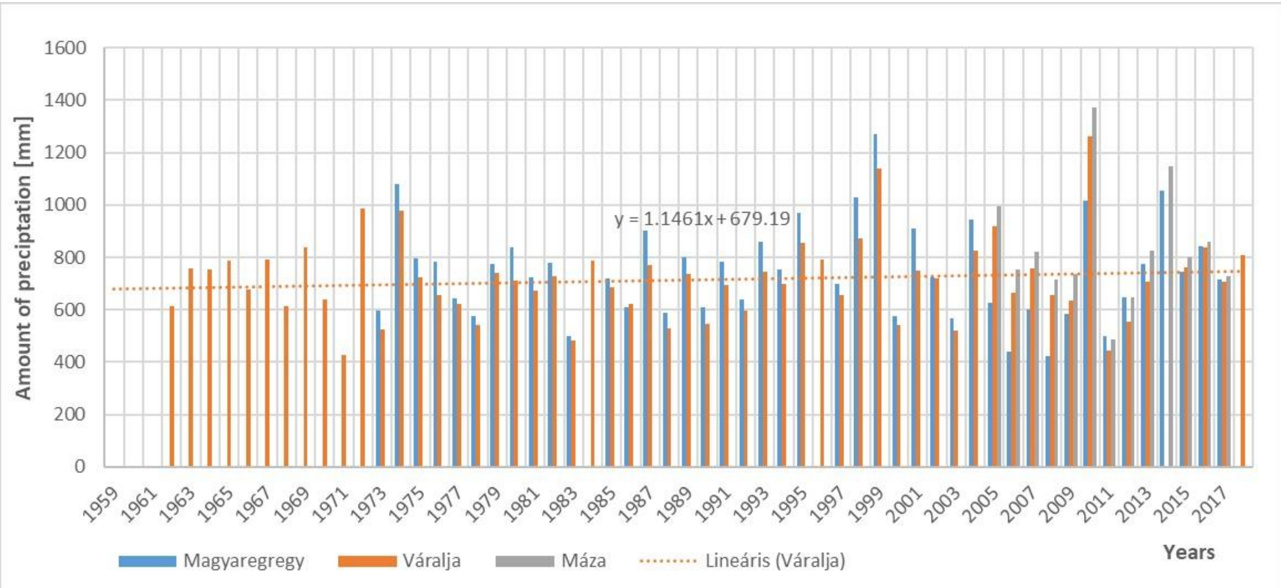

Fig. 12. The amount of yearly precipitation at the 3 gauging stations, and their linear trend at Váralja

Thus, the effect of climate change can already been observed in the study area, not only in the form of more precipitation but also in its extremities. In the past few years we have also witnessed the most numerous dry periods in Hungary, and a serious drought can also develop right after a very wet year. This is well illustrated by the precipitation sum observed in Magyaregregy in two consecutive years: 1260.6 mm in 2010 and only 445.6 mm in 2011.

CONCLUSIONS

From the analysis of the highest, average and lowest discharges and the precipitation data yearly we can conclude that the precipitation and runoff data series are well related in the case of high and medium discharges, but in case of small discharges this connection is not very evident. The reason for this can be that the smaller tributaries in the mountain range of the catchment dry out totally in longer dry periods.

Looking at the data series in details, we can distinguish between dry and wet periods which can change during a year or a few years. Therefore, trends can be much different depending on the period in which measurements started.

Our simple analyses clearly show that high precipitations and together with them high discharges, peaking at higher and higher levels and causing flash floods more often, have increased in the recent past, approximately during 20 years. We attribute this phenomenon to the effects of the heavy rainfalls which have increased in occurrence and intensity as an early result of climate change.

The small and medium discharges are greater in wet years, and a slight decreasing tendency can be observed in them. There can also be a climate-related answer to this effect which would need further analyses with a finer resolution time and space.

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ASSESSMENT OF STATISTICAL SIGNIFICANCE OF HISTORIC DANUBE FLOODS

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ABSTRACT

Data on historic floods along the Danube River exist since the year 1012. In the Middle Ages, floods were estimated based on historical documents, including original handwritten notes, newspaper articles, chronicles, formal letters, books, maps and photographs. From 1500 until the beginning of organized water regime observations, floods were hydraulically reconstructed based on water marks on old buildings in cities along the Danube (Passau, Melk, Emmersdorf an der Donau, Spilz, Schonbuhen and Bratislava).

The paper presents a procedure for assessing the statistical significance of registered historic floods using a comprehensive method for defining theoretical flood hydrographs at hydrological stations. The approach is based on correlation analysis of two basic flood hydrograph parameters – maximum hydrograph ordinate (peak) and flood wave volume. The PROIL model is used to define the probability of simultaneous occurrence of these parameters. It defines the exceedance probability of two random variables, in the specific case two hydrograph parameters of the form:

$$P\ \{Q_{max} \geq q_{max,p}) \cap (W_{max} \geq w_{max,p})\} = P \qquad (1)$$

where:
Q_{max} – maximum hydrograph ordinate (peak);
$q_{max,p}$ – maximum discharge of the probability of occurrence p;
W_{max} – maximum hydrograph volume;
$w_{max,p}$ – maximum flood wave volume of the probability of occurrence p;
P – exceedance probability.

Spatial positions of the lines of exceedance of two flood hydrograph parameters and the empirical points of the corresponding parameters of the considered historic flood in the correlation field Q_{max} - W_{max}, allow direct assessment of the exceedance probability of a historic flood, or its statistical significance. The proposed procedure was applied in practice to assess the statistical significance of the biggest floods registered along the Danube in the sector from its mouth to the Djerdap 1 Dam.

The linear trend in the time-series of maximum annual flows at a representative hydrological station and the frequency of historic floods in the considered sector of the Danube are discussed at the end of the paper.

Keywords: statistical significance, flood, correlation, exceedance probability, maximum hydrograph ordinate, flood wave volume, linear trend, flood frequency

INTRODUCTION

In general, a flood is a state of the water regime where the river stage (or discharge) increases and, as a rule, the river overtops its banks and floods the surrounding terrain. The increase in water level/discharge is relatively rapid and after a certain peak is reached, there is gradual decline. When a river overtops its banks, the discharges (flow rates) represent flood waves and are commonly depicted in flood hydrographs. The main parameters of a flood hydrograph are the maximum hydrograph ordinate (peak), flood wave volume, and flood wave duration.

Knowledge of flood discharges is essential for sizing hydraulic structures and of overriding importance from the viewpoints of safety and economical construction. Hydraulic structures sized on the basis of underestimated flood discharges lead toelevated risks of flooding, structural breaches and all the associated adverse effects. Overestimated river discharges reduce the risk but result in oversized structures, inconsistent with actual safety requirements and spending needs.

In addition to theoretical flood discharges, numerous structures need to be sized, or their conveyance capacity defined, on the basis of flood wave volumes and hydrograph shapes. Given that hydraulic structures are built to provide the required level of protection, design floods are determined by defining the theoretical values of flood hydrograph parameters: maximum hydrograph ordinate and flood wave volume of a certain probably of occurrence (or return period). When determining flood discharges and flood wave volumes, the initial assumption is that they are random quantities$X$, which conform to a certain probability distribution of the form:

$$P\ (X_{max} \geq x) = 1\text{-}F(x) \tag{2}$$

where:

$P\ (X_{max} \geq x)$ – probability that random variable X_{max} will exceed x;

X_{max} – maximum value of the considered random variable (river discharge or flood wave volume);

x –value of random variable X of the required probability of occurrence; and

$F(x)$ – theoretical distribution of random variable$X$.

Problems that involve extreme natural events are multi-dimensional, such that procedures which maximize the use of data and, at the same time, allow the estimation of parameters of a complex event and their correlations and probability of occurrence, have not been developed to a level that makes them easy to implement. For that reason, the World Meteorological Organization proposed in 1988 the transformation of marginal probabilities, which are generally not normally distributed, to form a normal probability distribution of multiple events. This approach is followed in many studies seeking a common probability of runoff hydrograph parameters, particularly peak and volume (Adamson, Metcalfe, Parmentier 1999).

Singh and Strupczewsky (2007) point out the importance of gaining insight into common exceedance probabilities of different runoff hydrograph parameters. They describe the role of examining the correlation between the flood wave peak and flood wave volume when modeling urban flood protection systems. There have been many attempts to adequately represent the correlation between the main parameters of a flood hydrograph and construct probability distributions in multivariate space.

Under natural conditions, river flood waves occur periodically and in different combinations of the main parameters: maximum ordinate and volume. Almost as a rule, the probabilities of these parameters do not coincide even though they are random variables. As such, when their probabilities are defined, they need to be considered jointly, as a bivariate random variable (X, Y), where X is the maximum hydrograph ordinate and Y is the flood wave volume. In such cases, the probability of the bivariate random variable (X, Y) is defined as:

$$P\ \{(\mathrm{X} \geq x) \cap (\mathrm{Y} \geq y)\} = p \tag{3}$$

The PROIL model (Ilić et al., 2017) was used in the present study to define the probability of a theoretical bivariate random variable (X, Y).

The proposed approach is discussed below, as applied to estimate theoretical flood hydrographs along the Danube River and its main tributaries, as well as to predict the simultaneous occurrence (coincidence) of the main parameters of theoretical hydrographs (maximum ordinate and flood wave volume) at the same river gauging stations.

METHOD – THE PROIL MODEL

The so-called "limiting runoff intensity" method (as described in detail in Prohaska and Petković, 1989) was used to define the main parameters of the theoretical flood hydrographs and their shapes. A predefined bivariate probability distribution of the two main parameters (peak ordinate and flood wave volume) was the basis for the selection of the constellations (combinations) of typical parameters for which theoretical hydrographs were defined. The hydrograph shape parameters were determined from actually observed flood hydrographs at a given gauging station.

The PROIL model (Prohaska and Ilić, 2017) is founded upon the practical application of the bivariate normal distribution function of two random variables, *X* and *Y*, or the bivariate normal distribution whose probability density is defined as follows (Prohaska, Marjanović, Čabrić, 1978):

$$f(x,y) = \frac{1}{2\pi \cdot \sigma_x \cdot \sigma_y \cdot \sqrt{1-\rho^2}} \cdot e^{-\frac{1}{2\cdot\left(1-\rho^2\right)}\cdot\left[\frac{(x-\mu_x)^2}{\sigma_x^2} - \frac{2\rho\cdot(x-\mu_x)\cdot(y-\mu_y)}{\sigma_x\cdot\sigma_y} + \frac{(y-\mu_y)^2}{\sigma_y^2}\right]} \tag{4}$$

where:

x and y – simultaneous occurrence of random variables *X* and *Y*, respectively;

μ_x and μ_y – mathematical expectations of *X* and *Y*;

σ_x and σ_y – standard deviations of *X* and *Y*;

ρ – correlation coefficient of *X* and *Y*.

The first step was to determine the marginal distribution density probabilities, $f(x,y)$, $f(x,\bullet)$ and $f(\bullet,y)$, as:

$$f(x,\bullet) = \int_{y=-\infty}^{y=\infty} f(x,y)dy \tag{5}$$

$$f(\bullet,y) = \int_{x=-\infty}^{x=\infty} f(x,y)dx \tag{6}$$

Then their cumulative probabilities are:

$$F(x,\bullet) = \int_{t=-\infty}^{t=x} f(t,\bullet)dt \tag{7}$$

and

$$F(x,\bullet) = \int_{t=-\infty}^{t=x} f(t,\bullet)dt \tag{8}$$

In this case, the cumulative probability distribution, $F(x, y)$, was defined as:

$$F(x,y) = P\left[X \le x \cap Y \le y\right] = \int_{t=-\infty}^{t=x} \int_{z=-\infty}^{z=y} f(t,z)dtdz \tag{9}$$

The second step was to determine the exceedance probabilities $\Phi(x,y)$ in bivariate space of probabilities (Prohaska, Marjanović, Čabrić, 1978):

$$\begin{aligned}\Phi(x,y) &= \int_{t=x}^{t=+\infty} \int_{z=y}^{z=+\infty} f(t,z)dtdz = P\left[X > x \cap Y > y\right] = 1 - P\left[X < x \cup Y < y\right] = \\ &= 1 - F(x,\bullet) - F(\bullet,y) + F(x,y)\end{aligned} \tag{10}$$

For the proposed approach to be applicable in statistical analyses of different flood hydrograph parameters, it was necessary to introduce additional simplifications. In essence, the simplifications are related to the assumption that each ofthe considered flood hydrograph parameters conforms to the normal (log-normal) distribution, which need not be the case. The detailed theoretical background for defining a bivariate distribution function applying the grapho-analytical approach (Abramowitz and Stegun, 1972) can be found in the literature (Prohaska et al., 1999).

STATISTICAL SIGNIFICANCE OF HISTORIC FLOODS ALONG THE DANUBE

The statistical significance was analyzed using the PROIL model and official data from hydrometeorological services of the Danube countries, collected from endorsed gauging stations. Time-series of the highest annual river discharges and mean daily orinstantaneous peak (daily) flows were used, from the time a given station was installed until 2013.

The following main parameters of flood hydrographs were considered: maximum annual river discharge (peak hydrograph ordinate – Q_{max}(m^3/s), maximum flood wave volume during the year – W_{max} ($10^6 m^3$), and duration of flood wave time base – T_b(hour), as shown in Fig. 1.

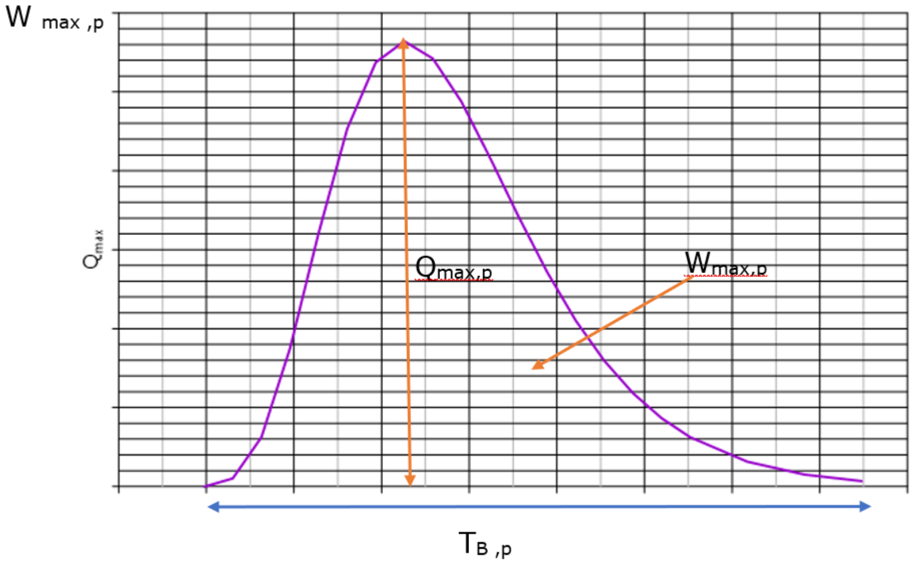

Fig.1. Shape of flood wave hydrograph

In the specific case, time-series of the highest annual discharges were uploaded directly from official hydrological databases. Time-series of maximum annual hydrograph volumes were generated on the basis of time-series of mean daily or daily discharges.

The largest annual flood wave volume $W_{max,j}$ in the j-th year was determined from the equation:

$$W_{\max,\, j} = \sum_{i=T_o}^{i^k = T_o + T_b} Q_{i,\, j} \cdot 86400 \tag{11}$$

where:

$Q_{i,j}$ – mean daily discharge on the i-th day in the$j$-th year;

T_o –first day of the hydrograph registered in the$j$-th year;

T_b –time base of the maximum hydrograph in the$j$-th year.

This resulted in a time-series of the largest annual flood wave volumes, $W_{max,j}$.

The maximum hydrograph ordinate(Q_{max})and the maximum flood wave volume were the main flood parameters whose statistical significance was assessed. Apart from the time-series of maximum annual river discharges, such an analysis also required time-series of mean daily discharges to arrive at time-series of maximum annual flood wave volumes per Eq. (11). The following gauging stations along the Upper and Middle Danube were selected for the study: Berg, Ingolstadt, Regensburg, Hofkirchen, Achleiten, Vienna, Bratislava, Bezdan, Bogojevo, Pančevo and Orsova.

Two bivariate time-series ($Q_{max,j}$: $W_{max,j}$), where j= 1,2,3, ….N, N – total number of data points (years), were generated from multiyear time-series of observed (empirical) maximum annual discharges and maximum annual flood waves, based on synchronous data (same years).

All the empirical points of the bivariate random variables ($Q_{max,i}$; $W_{max,i}$) were entered into the correlation field (Q_{max}– W_{max}) and using the PROIL model the following were defined:

- Density functions (lines of equal bivariate probabilities of occurrence): $F(Q_{max};W_{max}) = p$, for probabilities p = 0.1, 1.0, 5.0 and 50%.
- Distribution functions (lines of bivariate exceedance probabilities): P {($Q_{max} \geq q_{max,P}$)∩($W_{max} \geq w_{max,\ P}$) } = P, for exceedance probabilities$P$ = 0.1, 1.0, 2.0 and 5.0 %.

The empirical points ($Q_{max,j}$; $W_{max,j}$) above the exceedance probability line$P${($Q_{max} \geq q_{max,P}$)∩($W_{max} \geq w_{max,\ P}$)}= 1.0% in the correlation field were declared **historicpoints** and the related flood a **historic flood**.

RESULTS

Coincident occurrence of Q_{max} and W_{max} was defined for the selected gauging stations along the Danube. Figures 2/1 and 2/2 are examples of graphically represented results for the stations at Achleiten (Germany) and Bezdan (Serbia). The figures also identify the most significant floods in the study period, whose return periods were also determined.

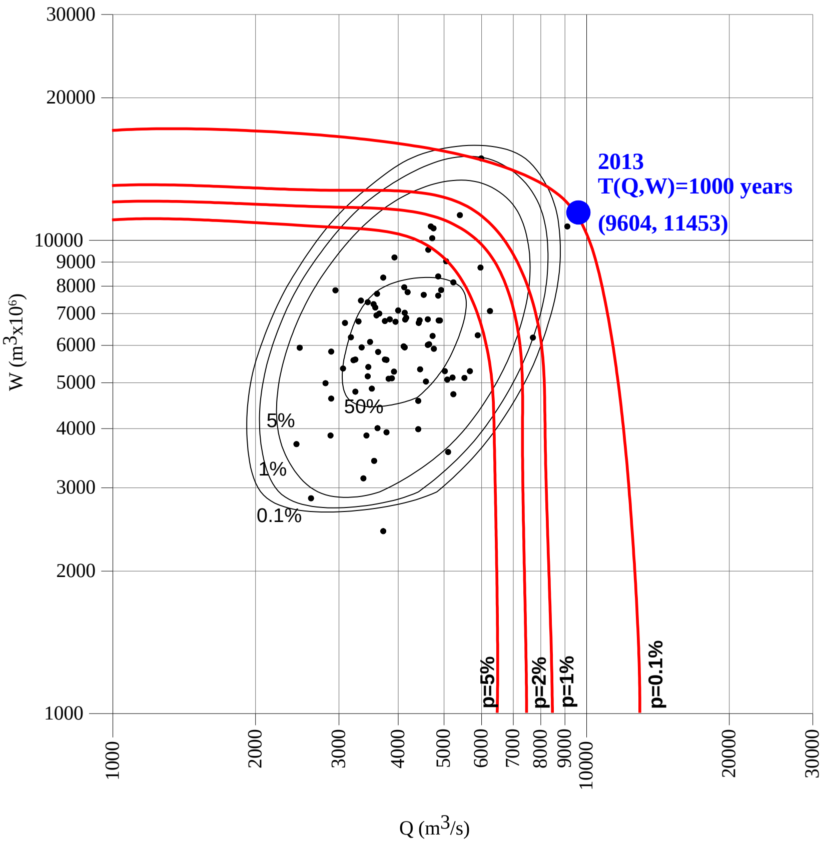

Fig. 2/1.Coincidence of main flood hydrograph parameters of the Danube at GS Achleiten and return period of the biggest (2013) flood

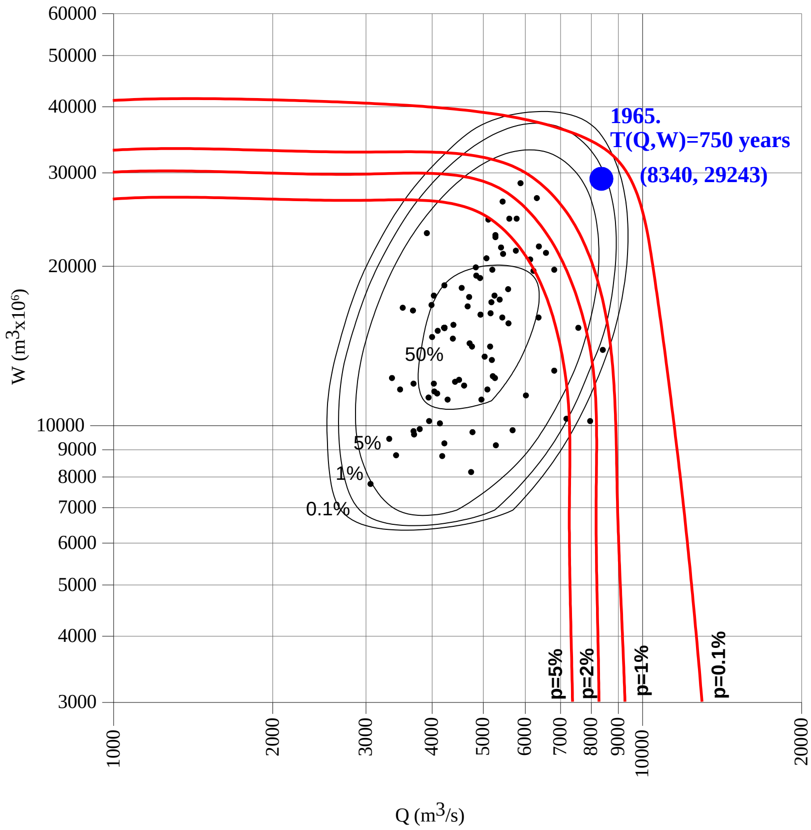

Fig. 2/2. Coincidence of main flood hydrograph parameters of the Danube at GS Bezdan and return period of the biggest (1965) flood

As shown in Figs.2/1-2, the return periods of the biggest floods recorded from the time the gauging stations were put into operation to the year 2013 are as follows:

- Gauging station at Achleiten: the return period of the 2013 flood (coordinates Q_{max}=9604m^3/s and W =11453 10^6/m^3) is $T(Q_{max};W)$ = 1000 years,
- Gauging station at Bezdan: the return period of the 1965 flood (coordinates Q_{max}=8340m^3/s and W=292453 10^6/m^3) is $T(Q_{max};W)$ = 750 years.

The return periods of floods that exceeded the probability:

$$P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,\,P})\} \geq 1.0\%,$$

or historic floods in the study period, were determined for all the considered gauging stations, including Achleiten and Bezdan. The results are shown in Table 1.

Table 1. Return periods of historic floods along the Danube from GS Berg to GS Orsova

№	Gauging station	Number of flood waves at GS	$P\{(Q_{max}\geq q_{max,P})\cap(W_{max}\geq w_{max,P})\} = P < p=1\%$		T (years)	Analyzed period
			Historic flood			
			Year	p		
1.	Berg	1	1988	0.33	300	1930-2007
2.	Ingolstadt	1	1965	0.20	500	1924-2013
		2	1999	0.20	500	

№	Gauging station	Number of flood waves at GS	$P\{(Q_{max} \geq q_{max,P}) \cap (W_{max} \geq w_{max,P})\} = P < p=1\%$ Historic flood Year	p	T (years)	Analyzed period
3.	Regensburg	1	1988	0.25	400	1924-2013
		2	2013	1.00	100	
4.	Hofkirchen	1	2013	0.65	150	1901-2013
5.	Achleiten	1	2013	0.10	1000	1901-2013
		2	1965	0.20	500	
		3	1954	0.20	500	
6.	Vienna	1	1965	0.20	500	1828-2006
		2	1975	0.25	400	
		3	1954	0.33	300	
7.	Bratislava	1	1965	0.20	500	1876-2015
		2	1899	0.33	300	
		3	2013	0.40	250	
		4	1876	0.90	110	
8.	Bezdan	1	1965	0.25	750	1931-2016
9.	Bogojevo	1	1965	0.80	125	1931-2016
10.	Pančevo	1	2006	1.00	100	1931-2016
11.	Orsova	1	2006	1.00	100	1840-2016

CONCLUSION

Based on this study, the historic flood on the Danube in 1965 was recorded at the largest number of gauging stations (six) from Berg to Orsova, followed by the floods in 2013 (four) and 1954 1954, 1988 and 2006 (two each).The frequency of historic floods was the highest at GS Bratislava (four), followed by GS Achleiten and GS Vienna (three each), and GS Inglolstadt and GS Regensburg (two each). The other studied gauging stations (at Berg, Hofkirchen, Bezdan, Bogojevo, Pančevo and Orsova), registered only one historic flood each in the multiyear study period.

The most statistically significant historic flood was registered at GS Achleitenin 2013, with a return period of 1000 years, followed by the flood registered by GS Bezdan in 1965, whose return period is 750, and those registered by four gauging stations (Ingolstadt, Achleiten, Vienna and Bratrislava) whose return period is 500 years. The third in order of statistical significance were historic floods in 1954 (Achleiten) and 1999 (Ingolstadt), whose return period is 500 years. Fourth place in terms of statistical significance is held by historic floods in 1975 (Vienna) and 1988 (Regensburg), with a return period of 400 years, and fifth place by historic floods in 1899 (Bratislava) and 1988 (Berg), whose return period is 300 years. The smallest historic floods along the Danube occurred downstream from the mouth of the Drava River, only once and with much shorter return periods: at GS Bogojevo in 1965 (return period 125 years) and at GS Pančevo and GS Orsova in 2006 (return period 100 years).

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THE MODERN MEDIUM-SCALE MAPPING OF THE AVALANCE DANGER IN THE UKRAINIAN CARPATHIANS

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ABSTRACT

There is a characteristic phenomenon of mountain landscape in Avalanche. Mountain development entails the need to take into account the avalanche hazard. The important task of the Hydrometeorological Service of Ukraine is to increase the effectiveness of forecasting avalanche danger in mountainous areas of Ukraine. One of the elements on the way to its solution is the digital display of mountain areas in the form of thematic maps. The intensive development of modern GIS technologies and the availability of digital terrain models make it possible to create various thematic maps. The avalanche activity is affected by meteorological and geomorphological factors. Using DEM based on SRTM 1, an avalanche hazard map of Ukrainian Carpathians was compiled. The map is based on the average maximum snow height and the steepness of the slopes. The proposed map will improve the quality of avalanche forecasts and will allow you to determine the need for avalanche exploration if the intended area of construction falls into the avalanche zone and protect users from unnecessary danger. An algorithm for constructing thematic (avalanche) digital maps using satellite data SRTM 1 has been elaborated.

Keywords: avalanche, avalanche hazard, map slope steepness, snow depth

INTRODUCTION

The modern intensive development of information technologies aimed at streamlining and qualitative processing of huge data sets has given impetus for creation of multifunctional geoinformation systems (GIS). Instead of traditional paper, time-consuming, routine assembly and processing, digital maps and electronic databases have come. These innovations have enabled scientists to significantly deepen their knowledge of avalanche science.

The avalanche is a natural component of the environment. They are very widespread and regular. Avalanches occur on mountain slopes and occupy a special place among the geophysical processes occurring in the hydrosphere. Like other natural phenomena, such as hail, people usually perceive avalanches as a danger - a natural disaster. Because of that, the term ***"avalanche danger"*** is widely used in the literature.

Due to the regularity of avalanches the following formulation of this concept was proposed: **avalanche danger** is a naturally occurring influence of avalanches on the natural environment and a fundamental possibility of their impact on the population and engineering structures (Bozhinsky A.N, Losev K.S, 1987).

There are different ways to classify the extent of an avalanche or avalanche hazard. The avalanches have great destructive power, especially when they reach large sizes. However, large and giant avalanches do not occur frequently. Usually there are also the most common landslides, small avalanches and avalanches of medium size in the mountains.

The climate of the region determines its avalanche regime. Avalanches can occur wherever there is snow cover and steep slopes, but they reach a truly devastating force in high mountain areas, where they are favored by climatic and orographic conditions.

Avalanche and avalanche hazards are of considerable interest for the development of mountain areas and the exploitation of economic facilities, engineering structures, communications and natural resources at risk of avalanche.

The occurrence of avalanches depends on a complex set of factors: climatic, hydrometeorological, geomorphological, geobotanical, physic-mechanical, etc.

Avalanches belong to especially dangerous hydrometeorological natural phenomena, because of the threat to human life. Under the natural conditions, the main physical cause of avalanches is the loss of snow resistance on a mountain slope. Violation of stability can occur due to displacement or subsidence, static deformation under the force of snow, precipitation, redistribution of snow by wind and other changes in the tangent and normal stresses in the snow. Even the local loss of stability can cause a dynamic process of avalanche formation under boundary equilibrium conditions.

The maps that are presented here are built using geoinformation systems (GIS) using geoinformation technologies and are geographic (Samoilenko V.M., 2010). In content, these maps belong to thematic maps of natural phenomena.

METHODS AND DATA

The digital elevation model (DEM) data were used for their development (Fig. 1). The digital terrain model is a file of elevation values. These marks are confined to the nodes of the small regular grid. The grid nodes are organized in the form of a rectangular matrix. It is a digital expression of the elevation characteristics of the relief on a topographic map (Fig. 2, 3). The DEM has a distance of 30 m in pixel and a vertical accuracy of about 15 m.

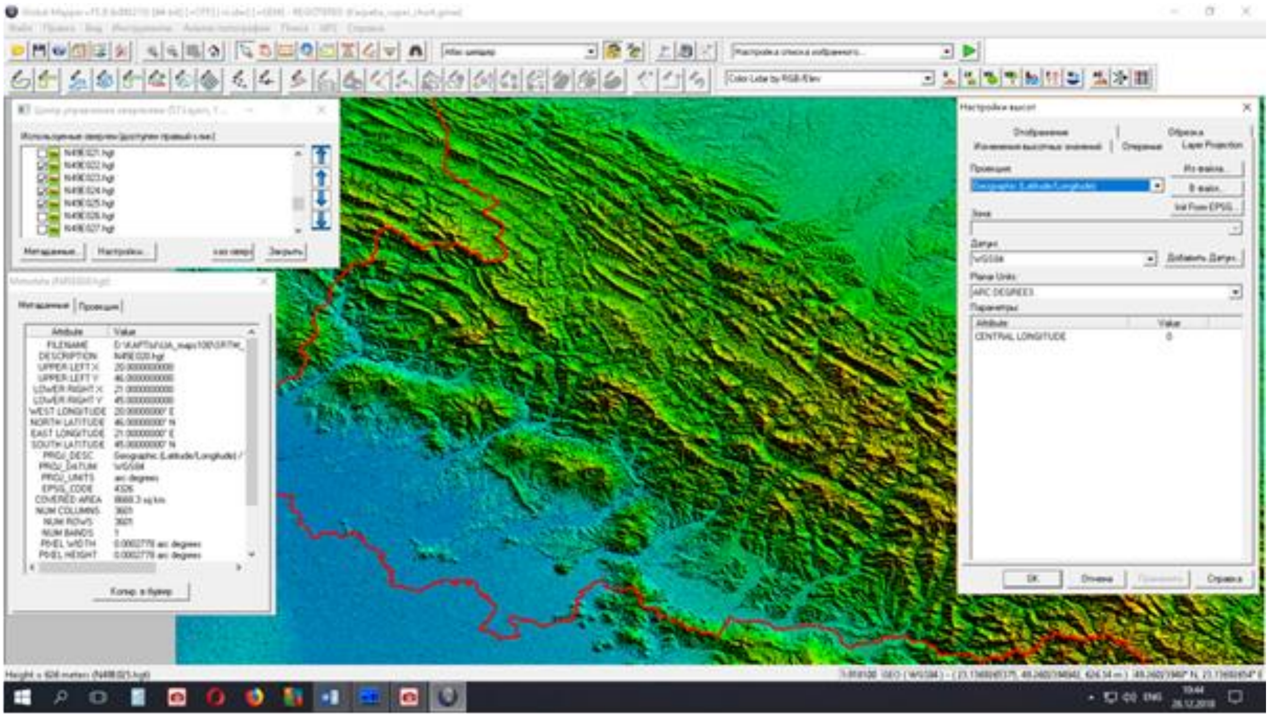

Fig. 1. Workspace of 12 files (N47E02-05, N48E02-05, N49E02-05) of digital elevation model (DEM) with *SRTM 1sec* space altitude data

SRTM 1 sec space altitude data were used to construct the topographic base. The Shuttle Radar Topographic Mission (SRTM) datasets are a joint effort of the both National Aeronautics and Space Administration (NASA) and the National Geospatial Intelligence Agency (NGA - formerly known as the National Assembly and Mapping Agency), and with the participation of the German and Italian Space Agencies, to generate an almost global digital terrain model (DEM) of the Earth, from about 60 ° north to 56 ° south, using radar interferometry. The SRTM tool consisted of an Imaging radar-C (SIR-C) spacecraft modified on an additional mast of a 60-meter antenna removed from the space station to form a baseline interferometer (Tom G. Farr, Mike Kabrick, 2000).

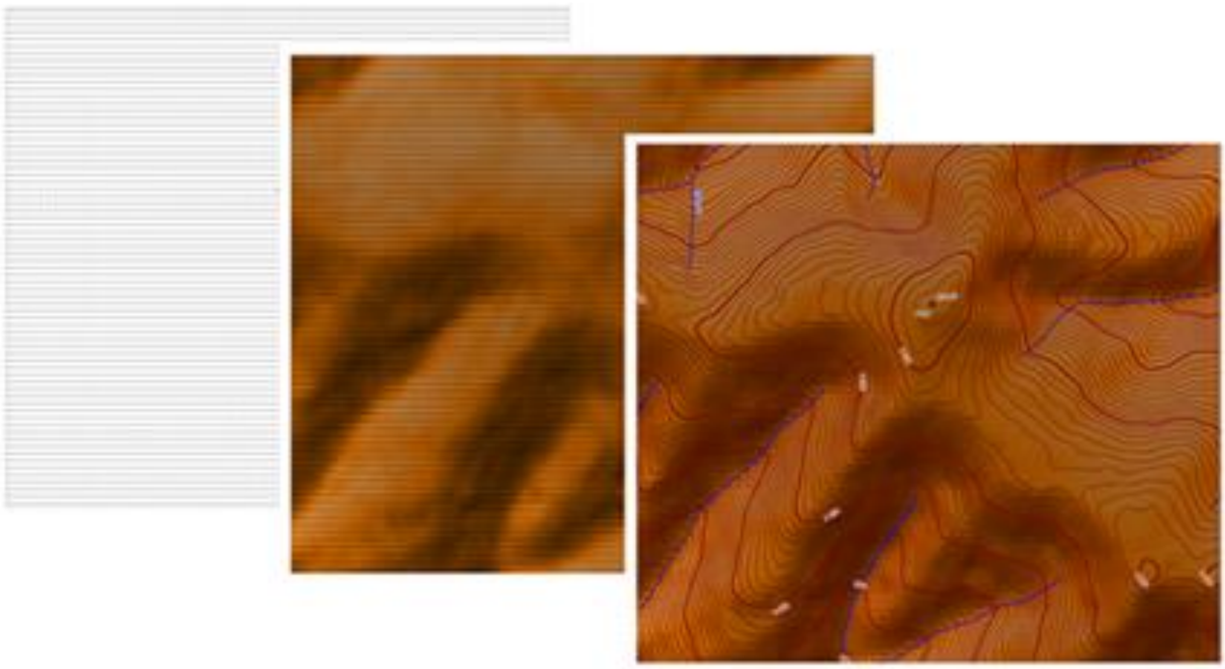

Fig. 2. Stages of construction of topographic basis of the map

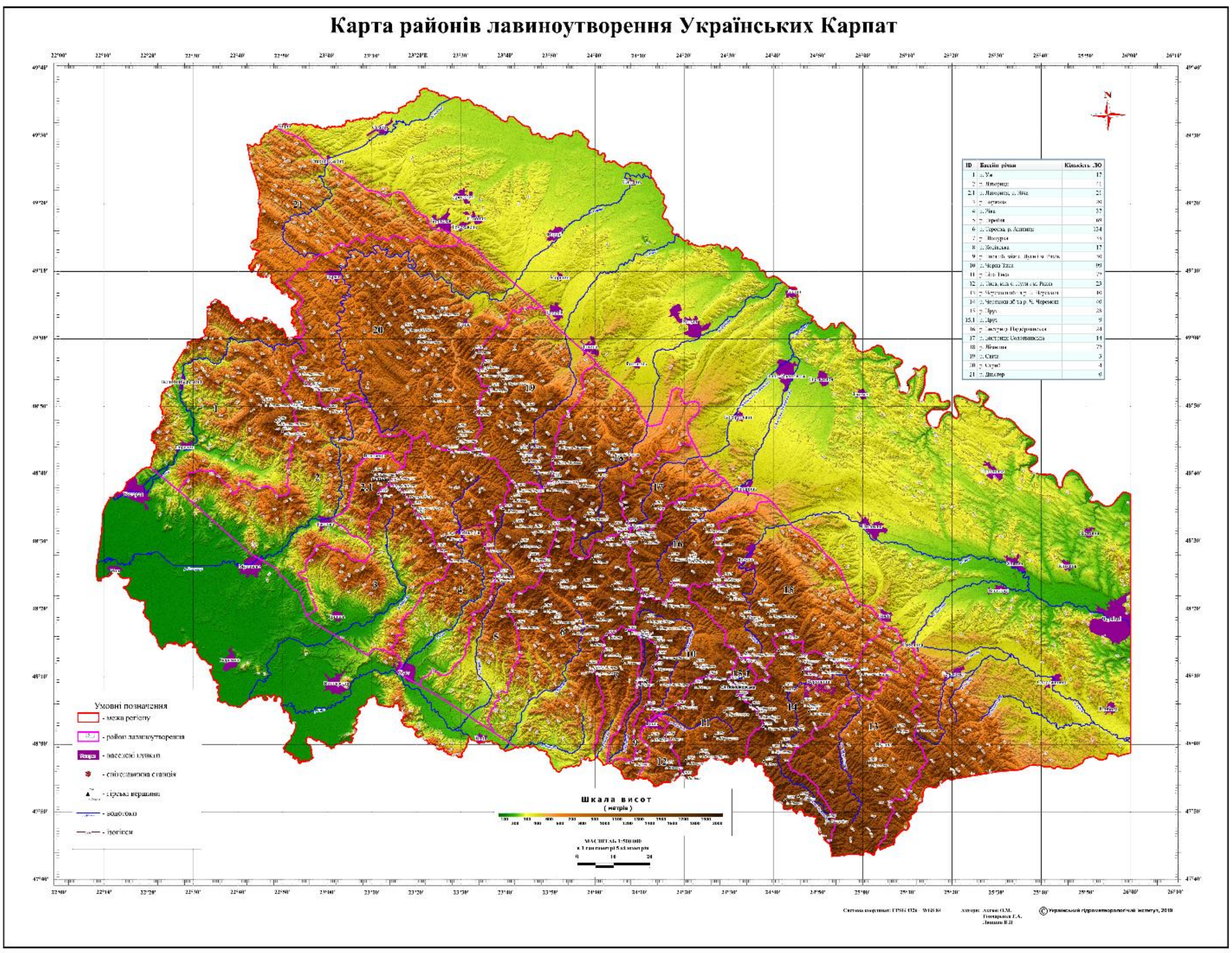

Fig. 3. Map of areas of avalanche formation of Ukrainian Carpathians based on the DEM

The maps presented in this work are built using GIS and are geographic. In content, these maps belong to the thematic maps of natural phenomena (Aksiuk O.M., Lanshin V.P. and Honcharenko H.A., 2018*)*.

The creation of an avalanche hazard map was preceded by the processing of long-term observations of snow cover on the state hydrometeorological network. Information was processed from 247 observation points (Grishchenko V.F., Aksiuk O.M. and Honcharenko H.A., 2013). A graphic-analytical analysis of the change in the thickness of the snow cover with the height of the area was carried out. The dependences of this variability on the southern and northern macro slopes are obtained (Fig.4).

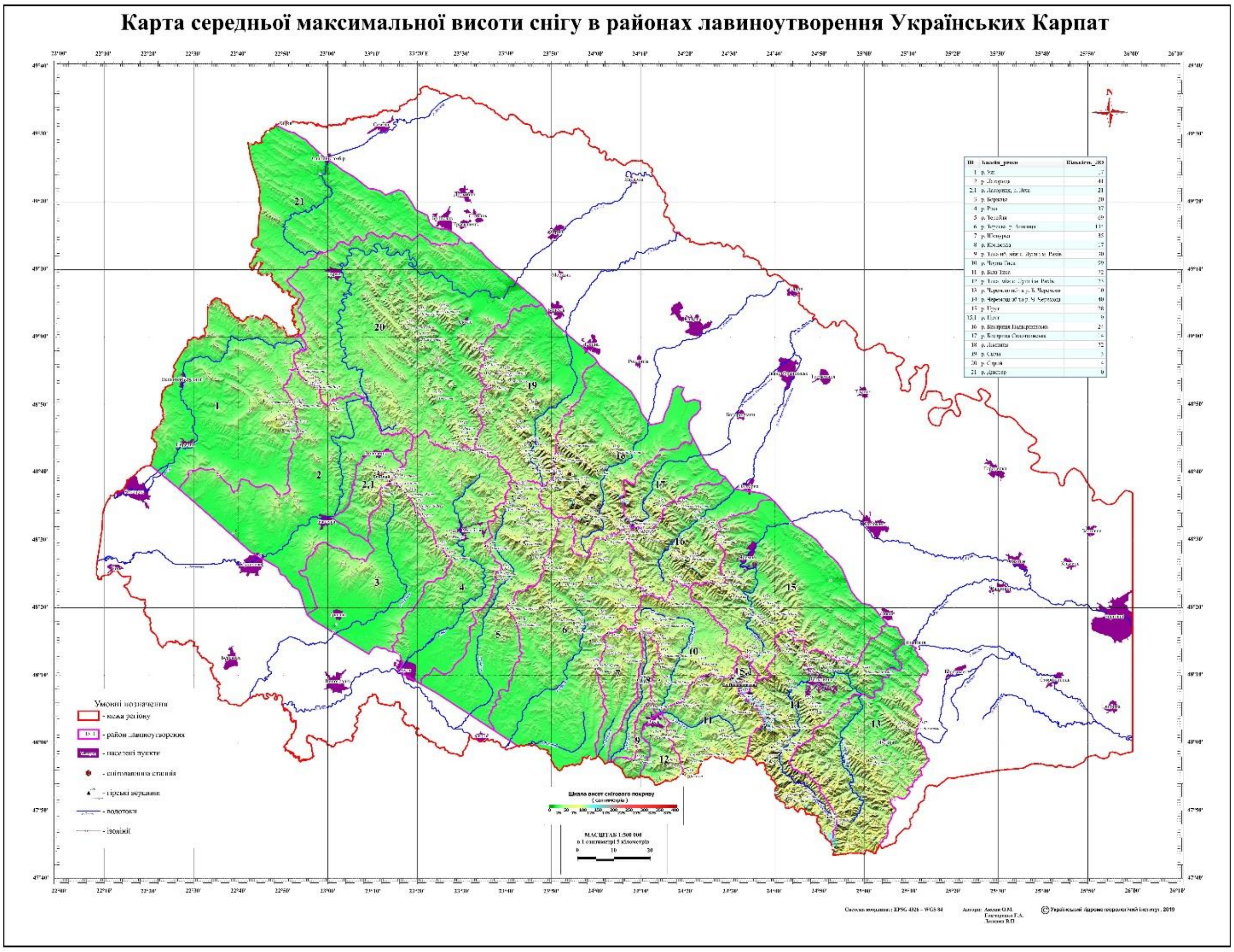

Fig. 4. Map of the average maximum depth of snow in the avalanche regions (Ukrainian Carpathians)

In the Ukrainian Carpathians there are about 1000 avalanche centers. More than 600 of them are located in the belt of mountain-glacial relief, that is, above the forest border. The slope of the surface of avalanches is small (20-40^0) in comparison with the Alps and the Caucasus. Cases of avalanches from surfaces of 18^0 are noted *(*Grishchenko V.F., Aksiuk O.M. and Honcharenko H.A., 2014).

Based on the calculations made, a map of the average maximum snow height is constructed. Taking into account the DEM, a map of the steepness of the slopes was built. The 8 ranges were selected taking into account the degree of manifestation of avalanche activity: 0-12^0, 12-25^0, 25-30^0, 30-35^0, 35-40^0, 40-45^0, 45-50^0,50-60^0 (Fig. 5-7).

To build an avalanche hazard map, a relief was identified within the areas of avalanche formation. The following gradations of the average maximum depth of snow cover were also identified - less than 30 cm, 30-50, 50-70, more than 70 cm. For the entire selected territory, the 4 levels of avalanche hazard were determined. It is generally accepted that for the formation of avalanches the lower limit of snow depth is 30 cm and the slope with a criticality of more than 12 degrees. The depth of snow is directly related to the height of the terrain and topography. Having identified 4 gradations (zones) of the depth of snow and setting a lower limit for the occurrence of avalanches, based on the obtained dependences, we constructed an avalanche hazard map. The selected zones respond: with a significant, moderate, weak and potential danger and with a zone with its absence (Fig.8).

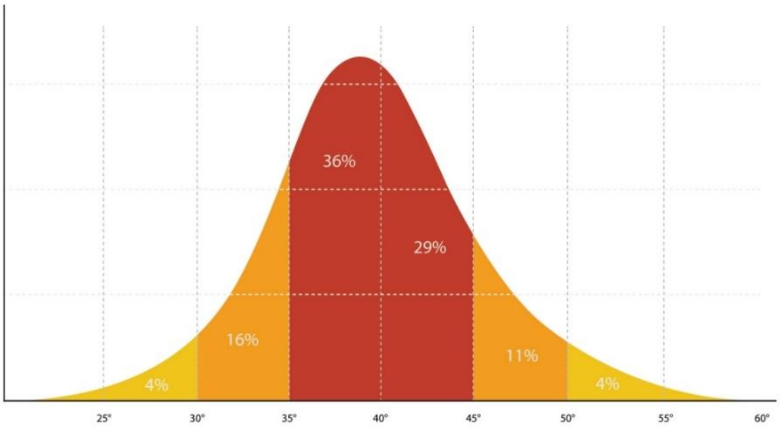

Fig. 5. Most avalanches occur on slopes 35^{0} to 45^{0}
(http://mountainacademy.salomon.com/en/demo/50/conditions-for-a-slab-avalanche**)**

Fig. 6. Map of steepness of slopes (Polonyna Borzhava, Ukrainian Carpathians)

Mountainous territory is divided into four avalanche danger zones with corresponding background values of the average maximum height of snow cover. The area with no avalanche danger is located on relatively flat terrain with an average maximum snow height of less than 30 cm. The average maximum height of snow cover in the zone of weak and potential avalanche danger is within 30-50 cm. The zone of moderate avalanche danger corresponds to the range of values of this characteristic 50-70 cm. The zone of significant avalanche danger covers the area where the average maximum height of snow cover exceeds 70 cm.

Fig. 7. Map of avalanche sites (Polonyna Borzhava, Ukrainian Carpathians)

CONCLUSIONS

The metadata conversion algorithm is developed and the technology of compilation of thematic maps using SRTM high-altitude data, aerospace images, raster and vector maps is worked out. The map is intended for scientific, geographic, recreational study of the territory.

The maps and developments offered in this work are capable of improving the quality of avalanche forecasts and enabling users to determine the need for avalanche exploration if the intended area of construction falls into an avalanche zone and protects users from unnecessary danger.

It should be remembered that an avalanche threat may increase if the "avalanche forests" are destroyed by pollution or unintentionally cut down.

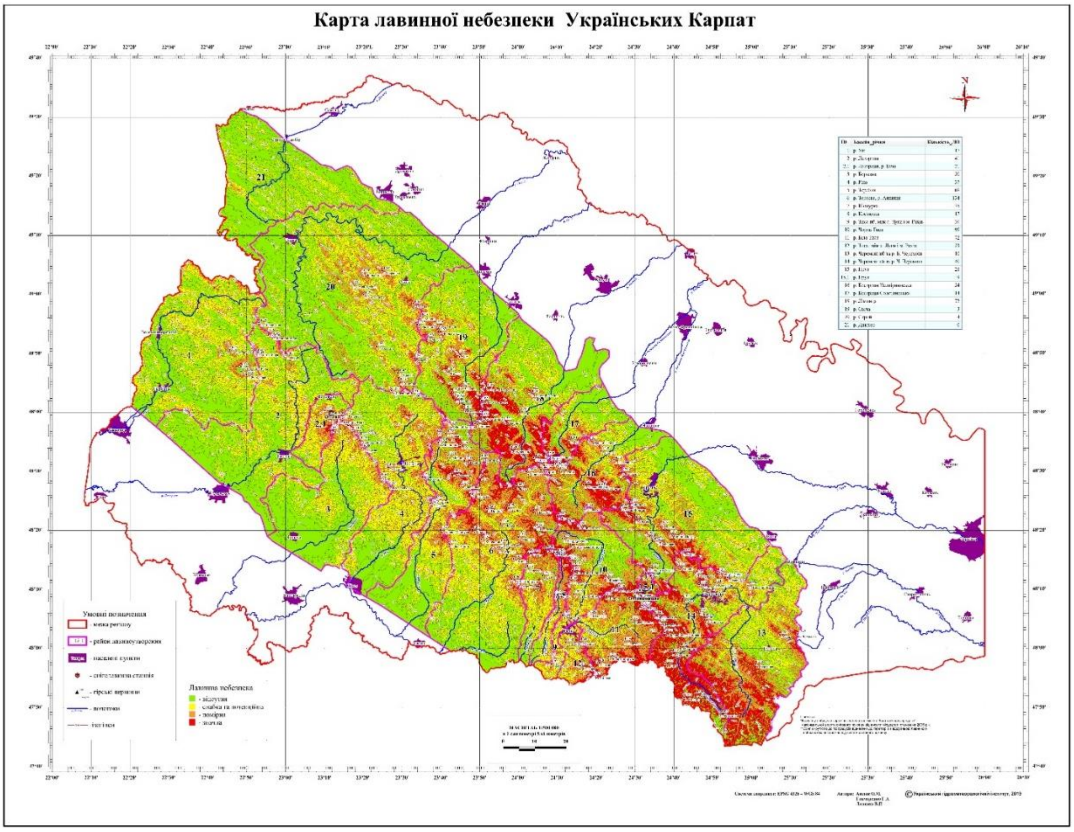

Fig. 8. Avalanche hazard map of Ukrainian Carpathians

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ESTIMATION OF MINIMUM AVERAGE MONTHLY RIVER DISCHARGE - YANTRA RIVER, NORTH BULGARIA

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ABSTRACT

Yantra river basin situated in North Bulgaria, is a part of Danube river basin directorate. This investigation is performed in the framework of the project with Bulgarian Ministry of Environment and Water. From the Ministry the points for each effluent or water abstraction facility are provided. For all points it was requested to evaluate 95% probability of occurrence for minimum monthly average river discharge. The provided from the project cross section (points) are along the main river body and also on the main river tributaries: Vidima, Rositza, Belitza and Drianovska rivers.

For the current study data from thirteen hydrological gauging stations in the drainage basin of Yantra river are used. Time series for the 1981-2014 study period are executed. Seven homogeneous regions were determined. Map with homogeneous regions for the Yantra river basin is elaborated and presented. Results are discussed.

YANTRA RIVER BASIN

Yantra river basin belongs to Danube river basin directorate, North Bulgaria. Dimitrov and Yordanova (Dimitrov et al., 2017) worked on trends assessment of meteorological factors, river flow and droughts in Nort-western Bulgaria. Yordanova A. et al., (Yordanova A. et al., 2017) used stoshastic modelling in water resources management. Orehova et al. (Orehova T., 2012) evaluated the potential groundwater recharge of the Ogosta river basin. Yordanova V. et al., (Yordanova V. et al., 2017) applied TOPKAPI model to Ogosta river in Nort Bulgaria. Vasileva et al. (Vasileva T. et al., 2017) investigated groundwater contribution to the river flow of the Osam river. Furthermore, Ninov and Karagiozova (Ninov et al., 2014; Karagiozova et al., 2017) determined surface water resources in Bulgaria in presence or absence of monitoring stations. In 2012 Hristova (Hristova, 2012) made an overview of river runoff of Bulgaria. Recently, Hristova and Seymenov (Hristova et al., 2019) worked on annual flow dynamics in basins with different sizes located in North Bulgaria.

The watershed of river Yantra is situated between Osam river basin from West direction, Rusenski Lom and Kamchia rivers from East, form North the border is Danube river. To the south Balkan mountain is a water divide with the rivers Maritsa and Tundja. Within these limits, the catchment area is about 7 862 km^2. The Yantra River originates from Mount Hadji Dimitar, approximately 1 340 m above mean sea level. The river is around 285 km long and at approximately 18 m altitude flows into the Danube River near Krivina village. Up to Veliko Turnovo town the river flows in north-east direction. After Veliko Turnovo the river turn in east direction making curve and since that is flowing in north direction.

The Yantra River has thirty tributaries over 10 km in length. More significant tributaries are: the Rositsa River, 164 km long and catchment area of 2265 km^2; Lefeja River - 92 km in length and catchment area 2424 km^2; Djulyunitsa River - 85 km in length and area of 892 km^2 etc. The river density in the watershed is varied. For the main river the density is 0.7 km/km^2. For the tributaries the density is in the range of 0.3 km/km^2 (Eliiska river) to 1.5 km/km^2 (Ostrazka river). The average altitude for the entire catchment area is 470 m and the average slope varies from 10.6 $^o/_{oo}$ (Stara reka River) to 48 $^o/_{oo}$ (for the Plachkovska River). River Yantra has an average slope of about 34 $^o/_{oo}$ in its upper stream, while at the mouth it reaches 0.25 $^o/_{oo}$, where it is also characterized by a high coefficient of curvature village.

The relief in the upper part of the catchment is mountainous and abounds in high mountain ridges and peaks. The middle part is characterized by many hilly heights. The lower stream, which crosses the Danube Plain, is characterized by smooth rounded hills, which cross the low terraces near the Danube.

INFORMATION PROVIDED FORM THE MINISTRY

The Bulgarian Ministry of Environment and Water was provided the points for each effluent or water abstraction facility. For all points it was requested to evaluate 95% probability of occurrence for minimum monthly average river discharge. The requested for the project cross section (points) are along the main river body and also on the main river tributaries. For the drainage basin of Yantra river the points are 195. The majority of the points are along the main iver body and also in the drainage basins of Vidima, Rositza, Belitza and Drianovska rivers (Fig. 1).

ESTIMATION OF THE MINIMUM MONTHLY AVERAGE RIVER DISCHARGE WITH 95% PROBABILITY OF OCCURRENCE AT THE POINT OF EACH EFFLUENT OR WATER ABSTRACTION FACILITY IN THE YANTRA RIVER BASIN

HYDROLOGICAL INFORMATION

In the catchment of Yantra rver, the monitoring network of National Institute of Meteorology and Hydrology (NIMH) consist of 13 hydrological gauge stations. Three of them are situated on the main body of Yantra river (at Gabrovo city (23650); Veliko Tarnovo town (23700) and Karantsi village - 23850) and others are on it's tributaries. In terms of area, the stations cover the whole catchment area, with their density in the upper and middle part of the catchment being greater than in the lower flat part.

The author performed extended studies conserning integrated river basin modelling of Yantra river (Bojilova, 2006; Bojilova, 2011). So far, the models with distributed (HYDROBEAM) and semi-distributed parameters (HEC-HMS) were applied. River basin modelling under future climate conditions was performed too (Bojilova, 2017).

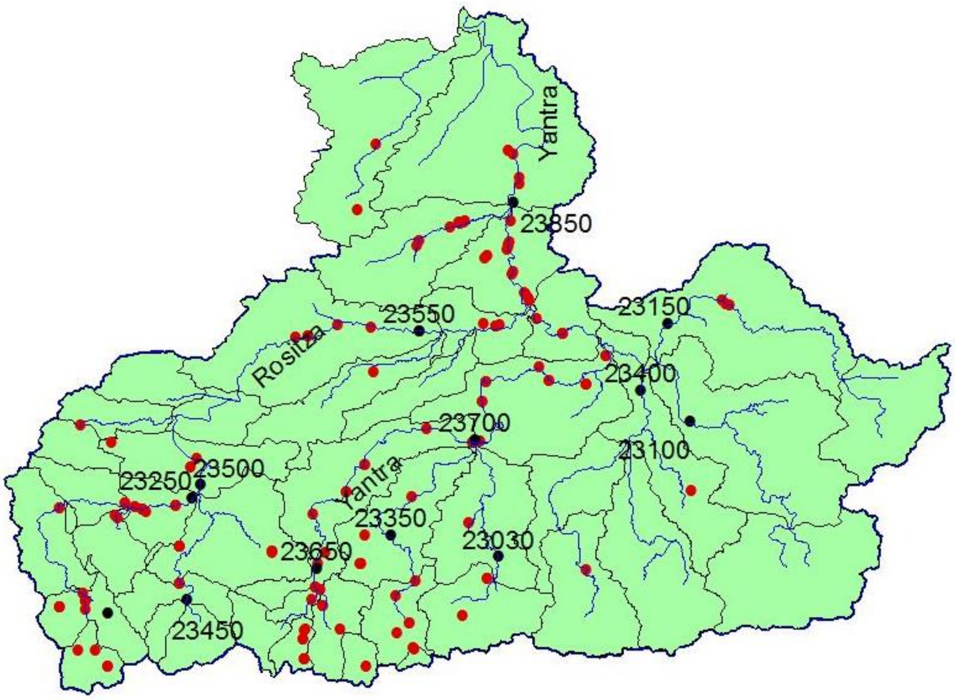

Fig. 1. Points for investigation (in red) and hydrological gauging stations (in black)

For the purposes of the curent study, time series with minimum average monthly river discharges from all stations are used. For the differentiation of the individual regions a comparative expert assessment of the conditions for formation of the runoff in the entire catchment was made. The upper stations are mountain with a large slope and a small catchment areas. Gradually the slope decreases, but the area does not grow so fast. Midrange stations have a smaller slope but have a larger area.

METHODOLOGY

A 1981-2014 observation period was selected. For the purposes of the study, time series with minimum monthly water discharge for all hydrological stations were formed. The used data range consists of 34 elements. The empirical distribution values of the minimum monthly runoff with 95% probability of occurrence are determined.

The method of hydrological regionalization has been used. The method is statistical by applying regression analysis. With its help, regional regression equations are created. Regression establishes a statistical relationship between the runoff (minimum monthly average water discharges with 95% probability of occurrence) and selected water catchment characteristics (the catchment area).

The methodology for hydrological regionalization does not allow determination of runoff in isolated water bodies with extremely small area (up to 10 km^2), since it is possible that the determined water quantity is not within the tolerable error for the method. The method of analogy and method of transfer of the drainage module from the station are also used. After a detailed analysis of the Yantra river basin, four homogeneous regions using the regional correlation method are obtained. Three regions were determined using the transfer method of the drainage module from the hydrological station to the point of any effluent or water abstraction facility.

Defined homogeneous regions

Region 1 – Dryanovska-Belitza-Djulyunisa rivers

For this region the station at village Vagletzi for Belitza river (23030), Dryanovska River – at Tsareva Livada (23350) and Djulyunitsa river (station 23400) are used.

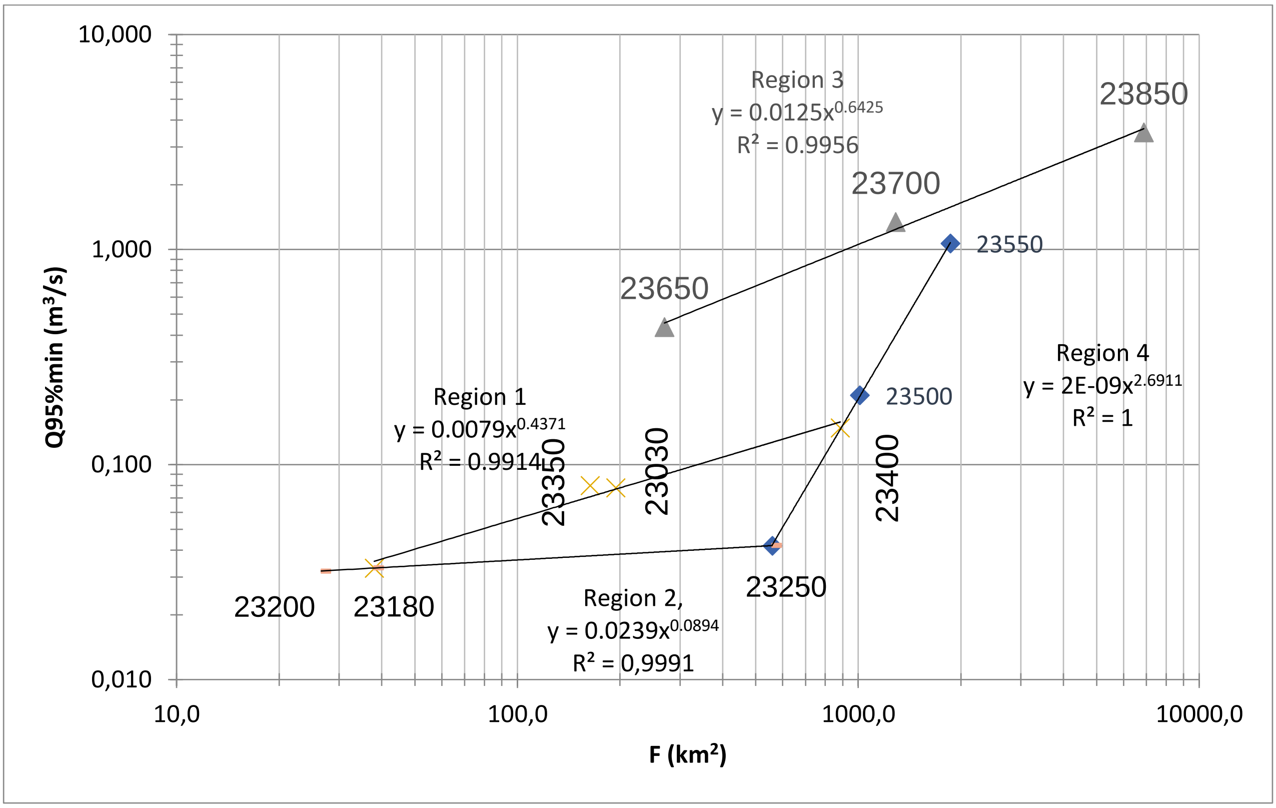

Fig. 2. Homogeneous regions for Yantra river basin

Region 2 – Vidima river

The following gauging stations are applied: Ostrezka river at Aprilovzi village (23200), Vidima river at Sevlievo city (23250) and Vidima river at village Vidima (23180).

Region 3 – Yantra river

The stations along the main river body are used: Yantra river at Gabrovo city (23650), Yantra River – Veliko Tarnovo town, in the district of Cholakovtsi (23700) and Yantra river at village Karantsi (23850). This is region on the main river body.

Region 4 - Rositsa River after Sevlievo

The used stations are: Vidima river at Sevlievo (23250), Rositsa River at Sevlievo (23500) and Rositsa River near the village of Vodoley (23550).

Region 5 - Rositsa River up to Sevlievo

This region covers upper part of Rositsa river to the station at Sevlievo city. One more station is utilized Rositza river at village Valevtzi (23450). The method of transfer of drainage module is used.

Region 6 – Lefedja and Golyama Reka rivers

The used stations are: Golyama Reka river near Strazhitsa village (23150) and Lefedja river (Stara Reka) at Slivovitsa (23100). The method of transfer of drainage module is used.

Region 7 - Eleeska river

We have been used for this region closed hydrological station Eleeska river at village Polski Trambej (23570). For this area we also applied the method of transfer of drainage module.

After determination of the homogeneous regions 95% probability of occurrence for minimum monthly average river discharge for the points for each effluent or water abstraction facility were evalueted. Seven regions were determined: four homogeneous regions using the regional correlation method and three regions using the transfer method of the drainage module from the hydrological station to the point of any effluent or water abstraction facility. Data for 195 points were calculated and presented to the Bulgarian Ministry. For visualisation, the map with the homogeneous regions in Yantra river watershed was prepared (see Fig. 3).

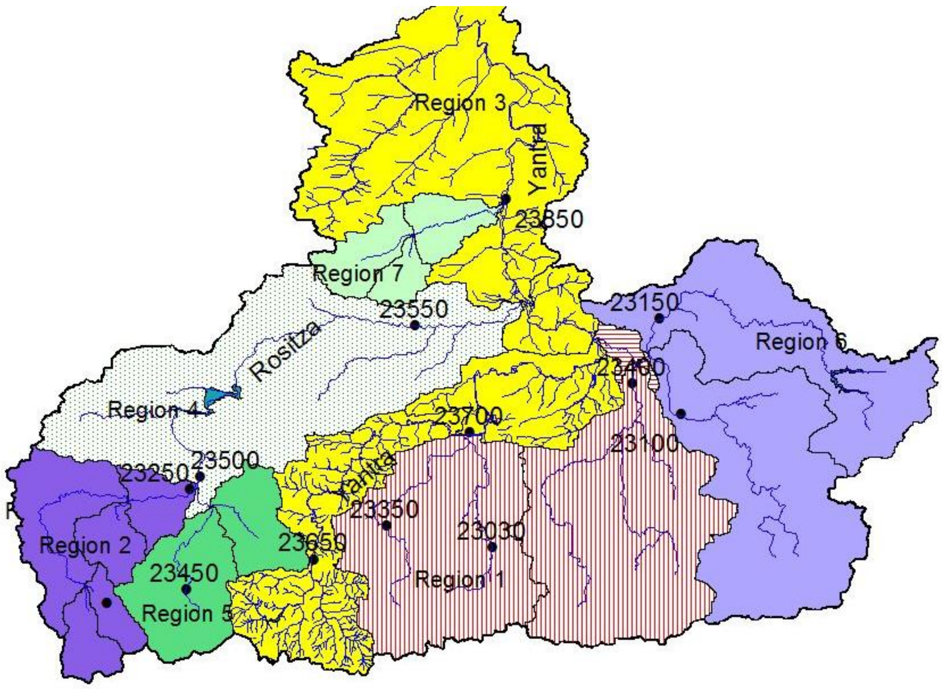

Fig. 3. Defined regions in Yantra river basin with 95% probability of occurrence for minimum average monthly river runoff

RESULTS AND DISCUTIONS

The Bulgarian Ministry of Environment and Water was provided the points for each effluent or water abstraction facility. For all points it was requested to evaluate 95% probability of occurrence for minimum monthly average river discharge.

The method of hydrological regionalization has been used. With its help, regional regression equations were created. Regression establishes a statistical relationship between the minimum monthly average water discharges with 95% probability of occurrence and the size of catchment area. The method of analogy and method of transfer of the drainage module from the station has been also used.

After a detailed analysis of the Yantra river basin, four homogeneous regions using the regional correlation method were obtained. Three regions were determined using the transfer method of the drainage module from the hydrological station to the point of any effluent or water abstraction facility. Map with homogeneous regions for the Yantra river basin was elaborated.

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AVERAGE ANNUAL RIVER DISCHARGE ASSESSMENT, YANTRA RIVER, NORTH BULGARIA

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INTRODUCTION

The study was performed for the needs of Danube river basin directorate in Bulgaria. The object of investigation is Yantra river basin situated in North Bulgaria.

The Bulgarian Ministry of Environment and Water was provided the points for each effluent or water abstraction facility. For all points it was requested to evaluate 10% of multiannual average river discharge. For the drainage basin of Yantra river the points are 195. The selected cross section (points) are along the main river body and also on the main river tributaries. The majority of the points are located in the drainage basins of Vidima, Rositza, Belitza and Drianovska rivers.

Three homogeneous regions were determined: upper mountain tributaries; middle part and lower part of Yantra river basin. Map with determined homogeneous regions for the drainage river basin is elaborated. The obtained results are discussed.

YANTRA RIVER BASIN

Yantra river basin belongs to Danube river basin directorate in Bulgaria. By the size of the catchment area (approximately 7 862 km^2), the Yantra River is the second largest in the Danube River Basin. The watershed of river Yantra is situated between Osam river basin from West direction, Rusenski Lom and Kamchia rivers from East, form North the border is Danube river. To the south Balkan mountain is a water divide with the rivers Maritsa and Tundja. The Yantra River originates from Mount Hadji Dimitar (Balkan mountain), approximately 1 340 m above mean sea level. The river lenth is around 285 km. Up to Veliko Turnovo town the river flows in north-east direction. After Veliko Turnovo the river turns in east direction making curve and since that is flowing in north direction. Yantra joins Danube River near Krivina village at approximately 18 m altitude.

The Yantra River has thirty tributaries over 10 km in length (for example: Rositsa River, Stara Reka, Djulyunitsa River, etc.). The average altitude for the entire catchment area is 470 m and the average slope varies from 10.6 $^{o}/_{oo}$ (Stara reka River) to 48 $^{o}/_{oo}$ (for the Plachkovska River). River Yantra has an average slope of about 34 $^{o}/_{oo}$ in its upper stream, while at the mouth it reaches 0.25 $^{o}/_{oo}$, where it is also characterized by a high coefficient of curvature.

The relief in the upper part of the catchment is mountainous and abounds in high mountain ridges and peaks. The middle part is characterized by many hilly heights. The lower stream, which crosses the Danube Plain, is characterized by smooth rounded hills, which cross the low terraces near the Danube.

Authors (see Dimitrov et al., 2017) worked on trends assessment of hydrometeorological elements in Nort-western Bulgaria. The stoshastic modelling in water resources management was performed (for exsample Yordanova A. et al., 2017). The TOPKAPI model for Ogosta river in Nort Bulgaria was applied and further used for short term river forecasts (Yordanova V. et al., 2017). Ninov and Karagiozova (Ninov et al., 2014; Karagiozova et al., 2017) investigated technology for determination of annual surface water resources in Bulgaria. In 2012 Hristova (Hristova N., 2012) made an overview of river runoff of Bulgaria. Furthermore, Hristova and Seymenov (Hristova et al., 2019) worked on annual flow dynamics in river basins with different sizes located in North Bulgaria. Furthermore, Orehova and Vasileva (Orehova et al., 2014) studied the atmospheric chloride deposition in the Danube hydrological zone of Bulgaria.

INFORMATION PROVIDED FORM THE MINISTRY

From the Bulgarian Ministry of Environment and Water are provided the points for each effluent or water abstraction facility. For all points it was requested to evaluate 10% of multiannual average river discharge. For the drainage basin of Yantra river the points are 195. The selected cross section are along the main river body and also on the main river tributaries. The majority of the points are located in the drainage basins of Vidima, Rositza, Belitza and Drianovska rivers (Fig. 1). There is a number of points along the main river body too.

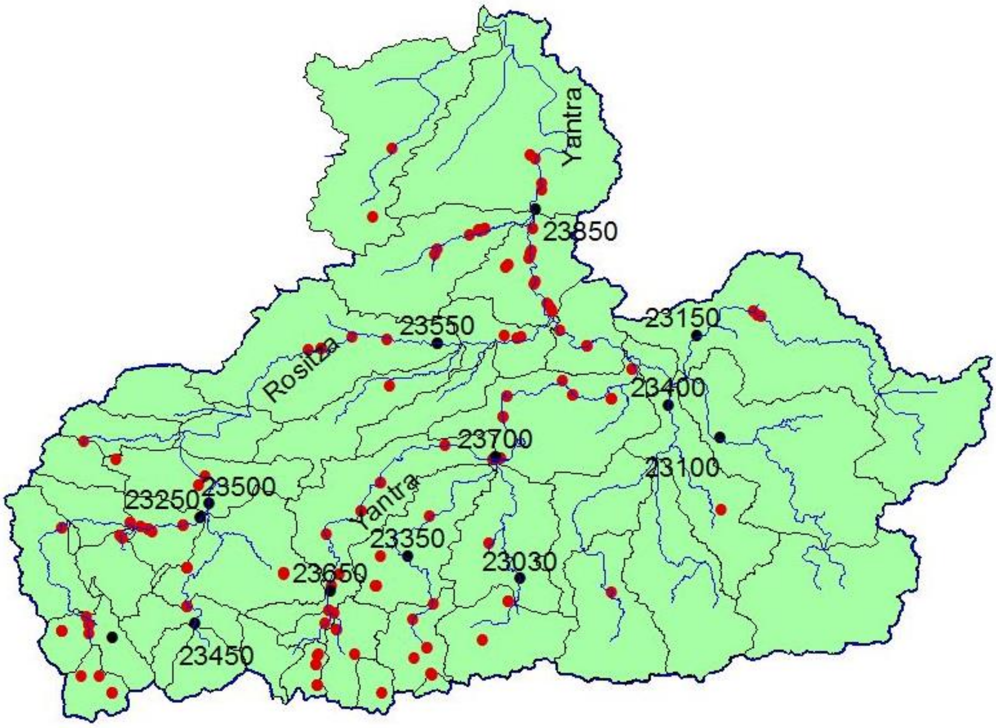

Fig. 1. Points (cross sections) for investigation (in red)

HYDROLOGICAL INFORMATION

The monitoring network of National Institute of Meteorology and Hydrology for the catchment of Yantra rver consist of 13 hydrological gauge stations (see Table 1). Three of them are located on the main body of Yantra river and others are on it's tributaries. More significant tributaries are: the Rositsa River, 164 km long and catchment area of 2 265 km^2; Lefedja River - 92 km in length and catchment area 2 424 km^2; Dzhulunitsa River - 85 km in length and area of 892 km^2. In terms of area, the hydrological stations cover the whole catchment area, with their density in the upper and middle part of the catchment being greater than in the lower flat part.

The author performed extended studies conserning integrated river basin modelling of Upper Yantra river (Bojilova, 2010). The high flows in drainage basin of Yantra river were evalueted (Bojilova, 2016). Furthermore, inter-annual distribution for the basin was investigated (Bojilova, 2017).

For the purposes of the study, time series with average annual water discharges from all stations are used. For the differentiation of the individual regions a comparative expert assessment of the conditions for formation of the runoff in the entire catchment was made. The upper stations are alpine with a large slope and a small catchment area. Gradually the slope decreases, but the area does not grow so fast. Midrange stations have a smaller slope but have a larger area.

ESTIMATION OF 10% OF THE AVERAGE ANNUAL DISCHERGES AT THE POINT OF ANY EFFLUENT OR WATER ABSTRACTION FACILITY IN THE YANTRA RIVER BASIN

The 1981-2014 time period is executed. Data from all available hydrological stations are used. The database is 34 years of records. 10% of the average annual discherges at the point of any effluent or water abstraction facility in the Yantra river basin are calculated.

Table 1. Used hydrological stations in Yantra river basin

Station N:	River	Location	Coments
23030	Beltza	Vaglevzi village	
23200	Ostrezka	Aprilovzi village	Limnigraph
23450	Rositza	Valevtzi village	Limnigraph
23650	Yantra	Gabrovo city	
23100	Lefedja (Stara Reka)	Slivovitsa village	
23500	Rositza	Sevlievo city	Limnigraph
23250	Vidima	Sevlievo city	
23350	Dryanovska	Tsareva Livada	
23400	Djulyunitsa	Djulyunitsa village	Limnigraph
23700	Yantra	Veliko Tarnovo town	Limnigraph
23150	Golyama Reka	Strazhitsa village	
23550	Rositza	Vodoley village	
23570	Eleeska	Polski Trambej	Closed
23850	Yantra	Karantsi	

The method of hydrological regionalization has been used. The method is statistical by applying regression analysis. With its help, regional regression equations are created. Regression establishes a statistical relationship between the runoff (in this case 10% of the average annual runoff) and selected water catchment characteristics (in this case the catchment area).

The methodology for hydrological regionalization does not allow determination of runoff in isolated water bodies with extremely small area (few km^2), since it is possible that the determined water quantity is not within the tolerable error for the method. Therefore, in the present study for catchments below 10 km^2 the water values have not been determined.

HOMOGENEOUS REGIONS

After a detailed analysis of the basin of the Yantra river there were identified three homogeneous regions using the regional correlation method as follows: upper mountain tributaries; middle part and lower part of the Yantra river basin.

Region 1 – Upper mountain tributaries

For the region of upper mountain tributaries four stations are utilised: the station at Vaglevzi village (23030) for Belitza river; Ostrezka river at Aprilovzi village (23200); Rositza river at village Valevtzi (23450) and Yantra river at Gabrovo city (Fig. 2).

Region 2 - Middle part of the Yantra river basin

The following stations are used: Lefedja river (Stara Reka) at Slivovitsa village (23100), Vidima river at Sevlievo city (23250), Dryanovska River - Tsareva Livada (23350), Djulyunitsa river (station 23400), Rositsa River at Sevlievo (23500) and Yantra River – Veliko Tarnovo town, in the district of Cholakovtsi (23700). The area is characterized by a gradual increase in the catchment area and homogenous factors for generation of river discharge (Fig. 3).

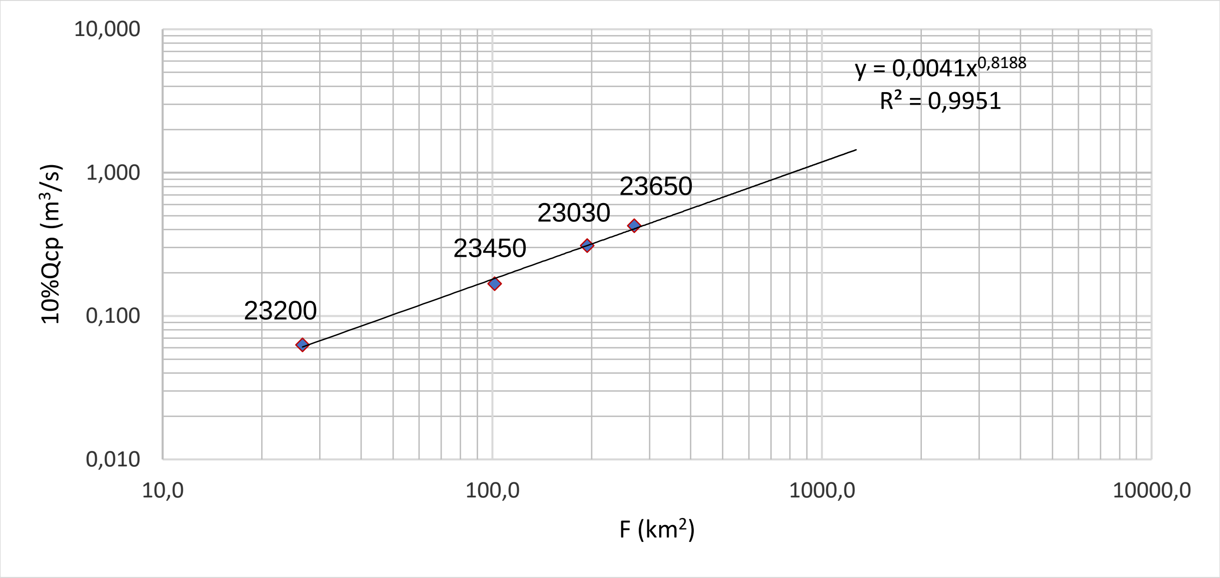

Fig. 2. Regional relationship for Region 1

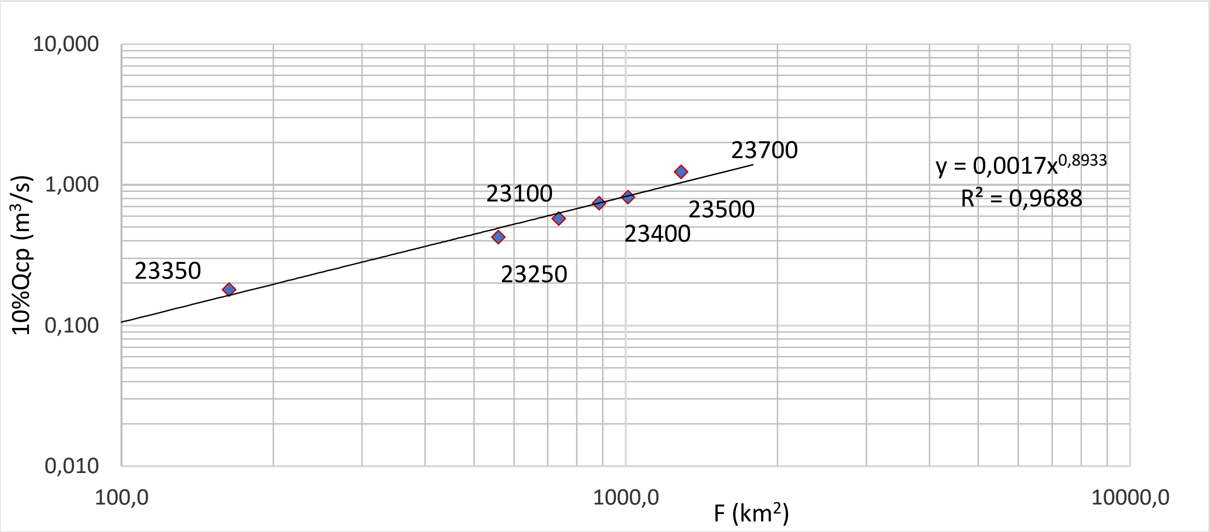

Fig. 3. Regional relationship for Region 2

Region 3 - Lower part of the Yantra river basin

The stations used are: Yantra river at village Karantsi (23850), 23570 closed station, Golyama Reka river near Strazhitsa village (23150) and Rositsa River near the village of Vodoley (23550). The resulting regional relationship is presented in Fig. 4.

After determination of the three homogeneous regions 10% of multiannual average river discharge for the points for each effluent or water abstraction facility were evalueted. Data for 195 points were calculated and presented to the Ministry. For visualisation, the map with the homogeneous regions in Yantra river watershed was prepared (see Fig. 5).

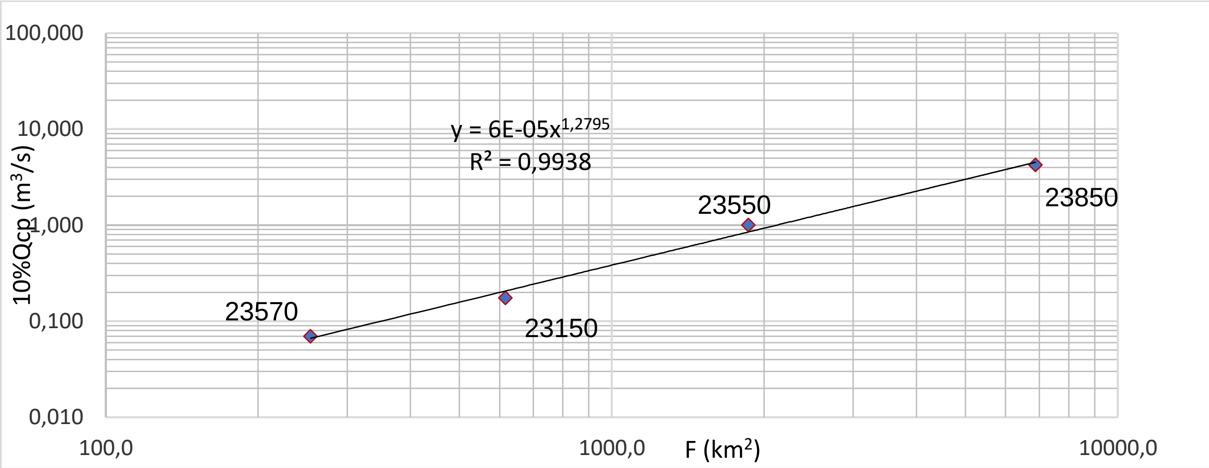

Fig. 4. Regional relationship for Region 3

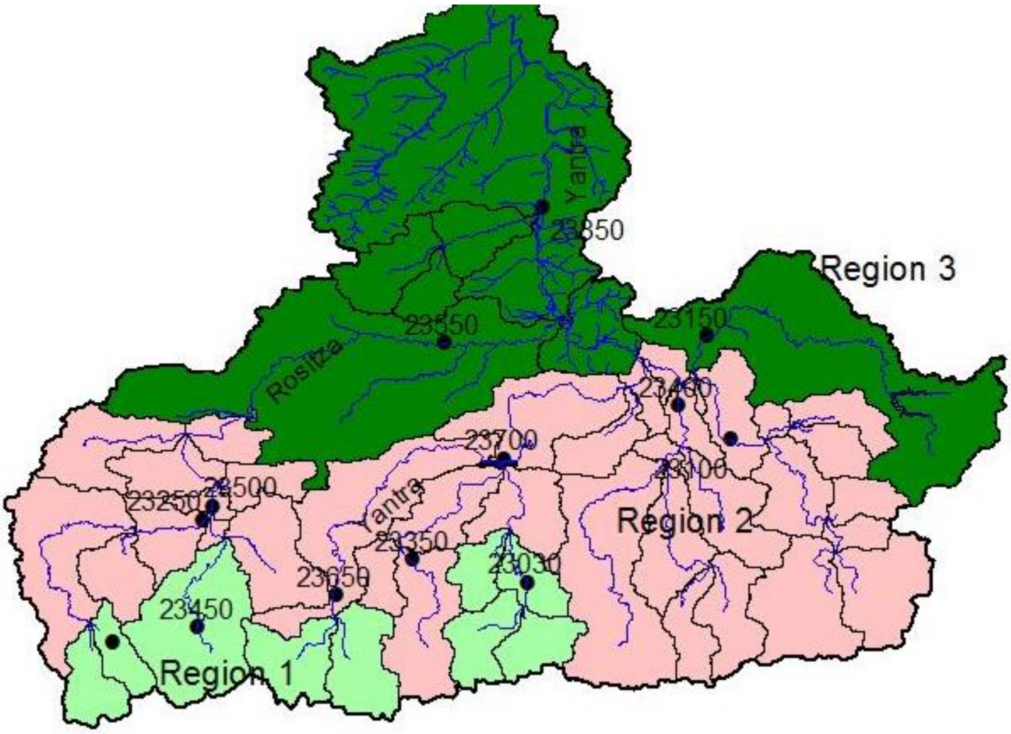

Fig. 5. Main homogeneous regions in Yantra catchment area for estimation of 10% of the multiannual average river discharge

RESULTS AND DISCUTIONS

The Bulgarian Ministry of Environment and Water was provided the points for each effluent or water abstraction facility. For all points it was requested to evaluate 10% of multiannual average river discharge. For the drainage basin of Yantra river, Danube river basin directorate, the points are 195.

The method of hydrological regionalization has been used. With its help, regional regression equations were created. Regression establishes a statistical relationship between the 10% of the average annual runoff and the catchment area.

Three homogeneous regions were determined: upper mountain tributaries – region 1; middle part – region 2, and lower part of Yantra river basin (region 3). Map with determined homogeneous regions for the Yntra river basin was elaborated.

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ESTIMATION OF THE *T*-YEAR SPECIFIC DISCHARGE USING THE REGIONALISED SKEWNESS COEFFICIENT OF THE LOG-PEARSON TYPE III DISTRIBUTION

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ABSTRACT

In this paper the results are presented of estimation of *T*-year specific discharge of several streams in two regions in Slovakia. The Q_{max} time series used in the study were observed at water gauges from lowland Slovak part of the Morava River basin, and from the mountainous Belá River basin. For estimating the design values we have studied the use of only one type of probability distribution, namely the Log-Pearson Type III Distribution (LP3 distribution). The use of only one type of distribution brings several benefits, e.g. possibility of the regionalization of the distribution parameters (in this study skew coefficient). In the first step the design values of the specific discharge series q_{max} (with historical data) were estimated and regional skew coefficients G_r of the LP3 distribution were computed. Regional skewness coefficient G_r was estimated to be 0.38 in the Morava River region, and 0.73 in the Belá River region. In many cases the estimate of the *1000*-year specific discharge is two times higher than the value of the *100*-year specific discharge. Then we have derived the empirical relations between station skew coefficient *G* and the elevation of the water gauge. In the second step we have derived the empirical relationships between *1000*-years specific discharge q_{1000} and the elevation of the water gauge for both regions separately. The derived empirical regional equations can be used to estimate the *1000*-years specific discharge of other streams in the region.

Keywords: floods, Log-Pearson Type III Distribution, Morava River basin, Bela River basin

INTRODUCTION

Many human settlements in the world are located on the banks of rivers. Slovakia is no exception. It is necessary to build up the settlements in such way that they are protected against the floods. Therefore, it is of high importance to know the possible magnitude of the floods and the frequency of their occurrence. The motivation of this study was the need to re-estimate and update the flood risk management plans according the EU Flood Directive (EP, 2007). The processing of the hydrological materials needed for creation of the flood risk maps is facing the basic problem that the unified system of flood maps is not approved within the EU countries. Even the primary estimation of *100-*, *200-*, *500-* and *1000*-year design values differs in individual EU countries and worldwide.

In former Czechoslovakia the water management had a long history and it was on high level. The first statistically based estimations of *100*-year design values were systematically processed for the Slovak rivers in the first half of the 20th century. The assessment of the *T*-year discharges and their consequent regionalization was done by Dub in 1940 (Kohnová and Szolgay, 1995, 1996). Similar estimation of *T*-year discharges for the whole territory of Czechoslovakia (250 gauging stations, out of them 75 in Slovakia) was published in 1970 in HMÚ (1970). The binomic and log-normal distribution was applied to estimate *T*-year discharges according to guidelines prepared by Sochorec (1966). After the floods in 1972 and 1974 the design discharges were re-estimated within the research project of the Slovak Hydrometeorological Institute (SHMI) „Recurrence of the maximum discharges of the Slovak rivers“(1977 and 1989). Later on the team of authors from SHMI prepared the guidelines and estimated the *T*-year maximum discharges within the research project „Assessment of hydrological characteristics – *T*-year maximum flows“ (Šipikalová et al., 2006). According to Sectorial technical standard of the Ministry of Environment of the SR (MŽP, 2003) the processing of the *T*-year maximum flows in the gauging stations is based on data series of the maximum annual peak flows (one datum per year). The design flows are as a rule assessed for $T = 1, 2, 5, 10, 20, 50, 100$-year. The Sectorial technical standard (MŽP, 2003) is not dealing with estimation of the *200-*, *500-*, up to *1000*-year flows.

The estimation of the floods with return periods of 200 up to 1000 years is very complicated task. The available data series are usually less than 100 years long. It is possible to extrapolate such series for *200* up to *1000* years periods by several approaches (statistical methods, rainfall-runoff models, etc.) and it always depends on the experience and knowledge of the expert which method he will decide to assess the *T*-year flows (Kohnová and Szolgay, 2003; Stanescu, 2004; Kohnová et al., 2006a, b; 2016; Šipikalová et al., 2006; Pekár et al., 2012; Pekárová et al., 2013; Gaál et al., 2010a, b; Merz and Blöschl, 2008a, b; Dysarz, 2019).

The aim of this study is to test one of the different methods of statistical processing of design flow values. Specifically, it is the method based on statistical processing of measured data series of the maximum annual peak discharges, during which the skewness coefficient of the Log-Pearson Type III Distribution is regionalised. The method is tested in two river basins in Slovakia with different physical-geografical characteristics (Fig. 1). The Morava River basin is mostly in lowland and hilly area. The Belá River basin includes high and middle mountain rivers (Fig. 2).

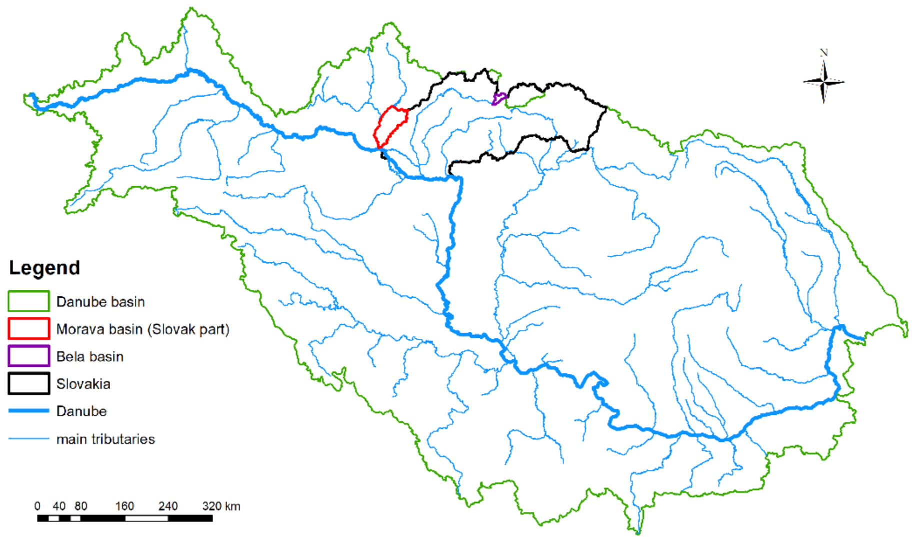


Fig. 2. Situation of study area in the Danube River basin

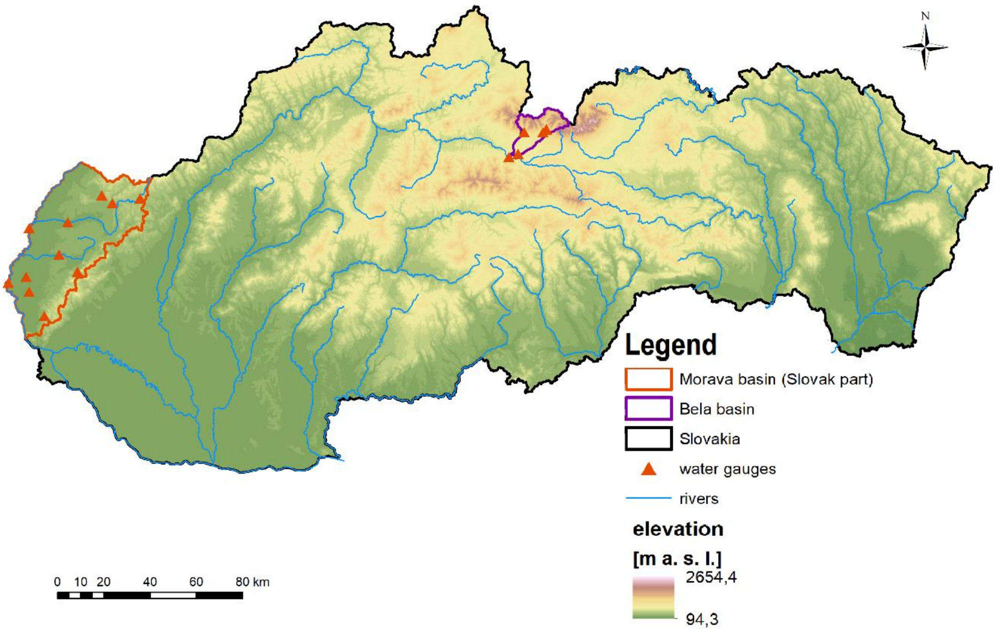


Fig. 2. Location of study basins in Slovakia with terrain

METHODS

According to the Sectorial technical standard (MŽP, 2003) the *T*-year maximum flows assessment in gauging stations proceeds from the series of maximum annual discharges (one datum per water year, when the water year starts on November 1 and terminates on October 31 of the next year in Slovakia). The design flows are as a rule assessed for $T = 1, 2, 5, 10, 20, 50, 100$-year. They are expressed in $m^3.s^{-1}$.

The basic procedures of the statistical processing of the *T*-year discharges are as follows:

1) Selection of discharge time series:
   a) series of maximum annual peak discharges Q_{max}, or
   b) series of flood wave peak discharges over certain threshold.
2) Statistical processing of selected discharge series to assess the empirical values.

Various data distribution types are used in hydrology to estimate the distribution functions of maximum annual discharges. In practice, several types of distribution are applied at the same time to estimate the *T*-year values and the different results help to estimate the uncertaintity intervals. The overview of the methods used to assess the design flows in selected countries worldwide was elaborated by Kohnová et al. (2006b).

According to the Sectorial technical standard (MŽP, 2003) following types of theoretical distribution are used in Slovakia to estimate *T*-year flows in the gauging stations:

- Pearson distribution (Gama distribution) P3,
- Logarithmic-normal distribution LN3,
- Logarithmic-Pearson distribution of the type III LP3,

But the application of other distribution functions is not ruled out.

Our invention was to supplement the series of maximum annual discharge by the data of the historical floods to improve the estimation of the extreme design flows with longer return periods (up to 1000 years). As it was mentioned, the Slovak Sectorial standard does not deal with estimation of the *200*-, *500*-, up to *1000*-year flows, and leaves it on the authors to select the method of estimation of the *1000*-year flows.

In this study we proceed according the methodology described in Bulletin 17B issued in 1981 in USA and modified by the Centre of water resources research of the Texas University at Austin (IACWD, 1982). According to these guidelines we are testing LP3 distribution used to estimate extremes in various natural processes and belongs to the most widely used theoretical distributions in hydrology. Procedures how to estimate parameters of the LP3 distribution are described in IACWD, (1982).

There exists quite significant uncertainty when estimating the skewness coefficient (third momentum) G from single gauging station data. In case of series with short observation period this momentum is particularly sensitive to extreme events. In order to achieve better estimation of this coefficient for the river basin it is possible to combine the skewness coefficient calculated for one gauging station G with the regional coefficient Gr to estimate the weighted coefficient Gw. If we assume that the regional skewness coefficient Gr is independent on station skewness coefficient G, it is possible to use the mean square error (MSE) of the skewness coefficient G and of the regional skewness coefficient Gr to estimate the weighted skewness coefficient. If the difference between the regional skewness coefficient Gr and the skewness coefficient G is more than 0.5, it is necessary to check carefully the input data and flood characteristics of the basin. Depending on length of the data series more weight can be given to the station coefficient G. Big differences between regional coefficients and station coefficients can indicate, that the characteristics in the station differ from characteristics of the region (Pekárová et al. 2018).

DATA

We were processing the series of maximum annual discharges of the individual water years in selected water gauging stations in the Slovak part of the Morava River basin and in the Belá River basin (Table 1.). The length of the series was various. The longest series are in station Morava: Moravský Svätý Ján (1895–2017), Belá: Podbanské (1928–2017) and Myjava: Šaštín-Stráže (1932–2017). Some series (Tichý and Kôprovský potok) were intermittent. If the discharge records of historical floods were available, they were added to the series (e.g. Belá River flood in 1813, Fig. 3).

Table 1. List of selected gauging stations with data on gauge zero datum, basin area and inception of the discharge monitoring

ID	water gauge	stream	elevation [m a. s. l.]	catchement area [km^2]	discharge since
5010	Lopašov	Chvojnica	272.7	31.13	1969
5025	Sobotište	Teplica	236.29	85.58	1974
5020	Myjava	Myjava	324.34	32.02	1974
5030	Šaštín-Stráže	Myjava	164.25	644.89	1932
5060	Sološnica	Sološnický p.	245.35	10.338	1971
5070	Studienka	Rudava	170.82	280.32	1971
5095	Jakubov	Malina	144.71	171.46	1964
5100	Láb	Močiarka	144.33	47.1	1961
5120	Borinka	Stupávka	217.2	33.76	1974
5040	Moravský Svätý Ján	Morava	146.24	24129.3	1895
5085	Záhorská Ves	Morava	139.86	25521.3	1976
5400	Podbanské	Belá	922.72	93.49	1928
5390	Kôprová dolina	Kôprovský p.	989.6	31.24	1940
5380	Tichá dolina	Tichý p.	978.8	57.45	1940
5460	Račkova dolina	Račkov p.	894.41	35.51	1963
5465	Dovalovo	Dovalovec	627.02	21.68	1980
5480	Liptovský Hrádok	Belá	630.44	244.26	1965

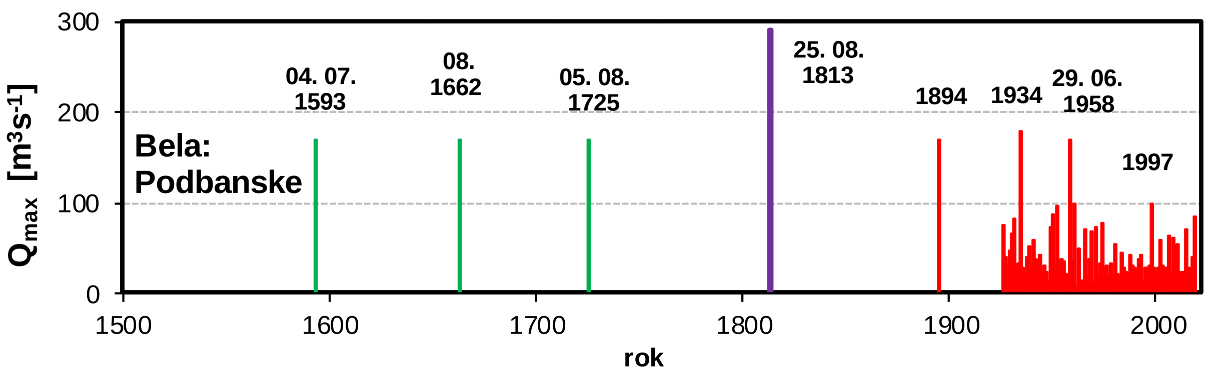


Fig. 3. Maximum annual discharges of the Belá river at station Podbanské during the period (1928–August 2018) (red color) and occurrence of the historical floods (green color).

STUDY AREA

The Morava basin

The Slovak part of the Morava River basin has the area of 2282 km^2 and is situated in the most western part of Slovakia near borders to Czechia and Austria. It is bordered with the Morava River in the west. The northern border of the basin is identical with the state border with Czechia and from the village of Rohatec it continues along the Sudoměřický creek to the White Carpathians mountain ridge. From the peak of Čupec (816 m n. m.) the border turns to south along the Small Carpathians ridge. The southern border forms the water divide with the Danube River basin.

From the geomorphological point of view is the Slovak part of the basin situated on divide of the two main orographic units of the Western Carpathians and of the Western Pannonian basin. The area is mostly lowland, as almost 77.4% of the area is below 300 m a.s.l. The highest point is in the White Carpathians geomorphologic unit in elevation of 816 m a.s.l. and the lowest point is the confluence of the Morava River and the Danube River in elevation of 106 m a.s.l. (Fig. 4).

The lowland part of the basin is covered by fluvial and Eolic sediments. The Small Carpathians Mountains are geologically complex with clays, sandstones, granodiorite, amphibolite and limestones. The forest covers about 38 % of the area (863.82 km^2) with oak, beech, pine and floodplain forest. Most of the area is agriculturally used.

The area belongs to warm and mild warm climatic area. The mean annual air temperature is about 9^{o}C and it is decreasing with elevation. Mean air temperature of January is from -2.0^{o}C in lowland below -3.2^{o}C in the valleys of the hills. The warmest month of July has the mean temperature between 18 to 20^{o}C. The long-term precipitation depth is about 700 mm per year.

The minimum discharge occurs mainly in August and September, when the evaporation is the highest and the maximum discharges occur in February-March due to snowmelt. The length of the main Morava channel is 114 km in the Slovak part (329 km total length). The significant tributaries on the Slovak territory are Myjava, Rudava and Malina (MŽP, 2015).

Fig. 4. Terrain in Slovak part of the Morava River basin and used water gauges

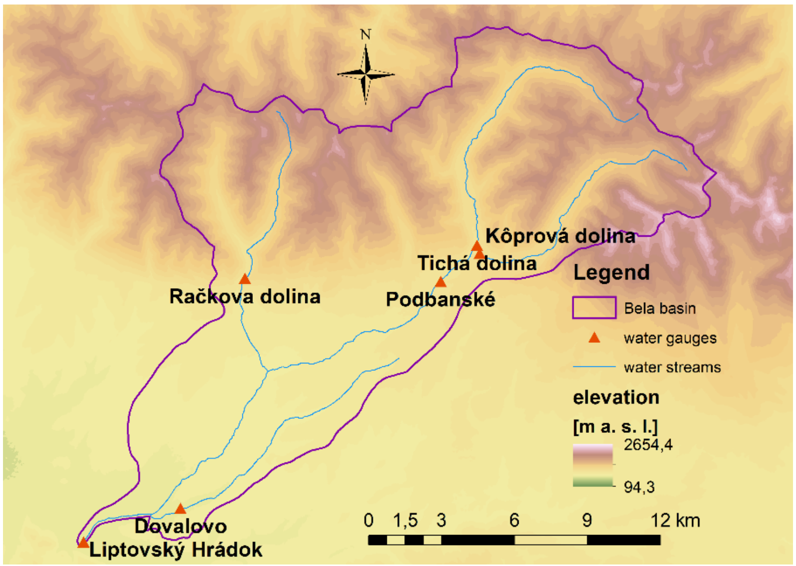


Fig. 5. Terrain in the Belá River basin and used water gauges

The Belá basin

The major stream is the Belá River draining the border area between the Western and Eastern Tatras. It represents the runoff conditions of the highest parts of the Carpathians. The river channel training measures are very limited and the river is meandering and changing its channel after big floods. It originates at the confluence of the Tichý and Kôprovský streams in the elevation of 976.8 m a.s.l. (Pacl, 1959). The confluence with the river Váh is in elevation of 629 m a.s.l. (Fig. 5). The length of the stream is 23.6 km, the basin area to Podbanské is 93.46 km^2 and to the Liptovský Hrádok gauge 244.26 km^2 (Hlubocký, 1974). The mountainous part of the basin is covered by dwarf pine, spruce and meadows and the lower part is agriculturally used.

The climate is continental and influenced by steep slopes and increase of the elevation. It belongs to cold climate zone. The mean annual air temperature in 1931—2000 was in Podbanské 4.8 °C, at Kasprowy peak -0.8°C. The annual precipitation regime is single peak one with minimum in winter (February) and maximum in summer (June to July). The precipitation depth increases with elevation. The annual precipitation depth is between 900 mm at Podbanské to 1800 mm at Kasprowy peak, out of it 500 mm to 1000 mm during summer. Number of days with snowfall is between 57 and 180 days, and the snow cover lasts 120–200 days (Pekárová et al., 2009a).

The Belá basin was included into the international category of „representative basins“ and it was listed in the framework of the International hydrological program of UNESCO (Hlubocký, 1974). Hydrological regime of the Belá River was studied by Pacl (1951, 1959, 1977) or by Pekárová et al. (2009a-b, 2010).

RESULTS AND DISCUSSION

We have used measured data series of maximum annual discharges Q_{max} to estimate the coefficients of LP3 distribution functions in the Morava and Belá River basins. These were recalculated to specific discharge q_{max} to make possible to compare runoff in different basins and to regionalize the results. We have proceeded as follows:

1. we have estimated from the q_{max} series the parameters of LP3 distribution curves (mean X, standard deviation S and skewness coefficient G) separately for each station (Fig. 6, up, Table 2).
2. We have added values of historical floods into the q_{max} series (Fig. 6, down) and we have calculated the historical regional skewness Gr (Table 2).

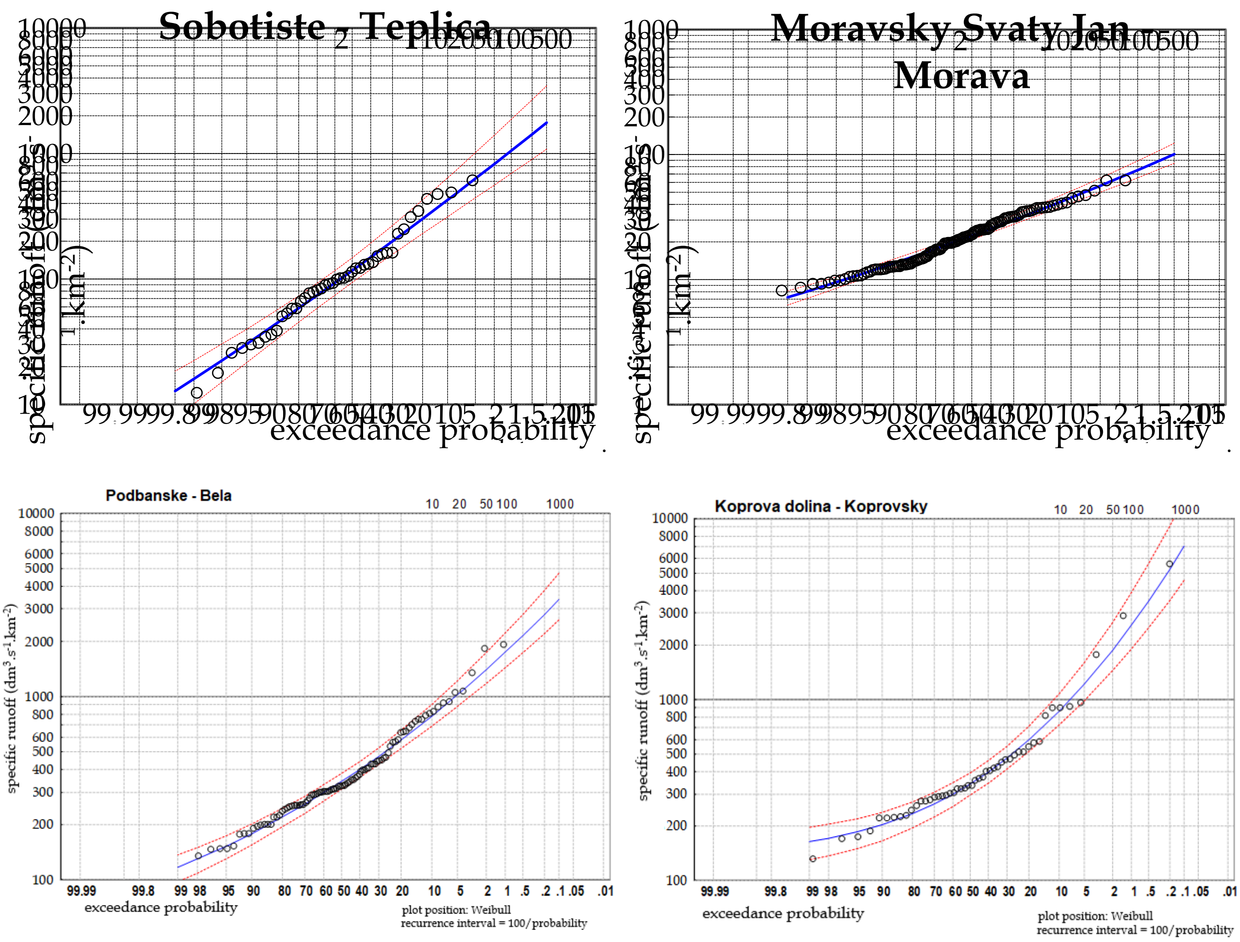


Fig. 6. Examples of the theoretical log Pearson probability exceedance curve type III, of the maximum annual runoff of chosen streams, 5% and 95% confidence intervals

Table 2. Skewness coefficient *G* and regional skewness coefficient *Gr* estimated for gauging stations

ID	water gauge	stream	*G*	*Gr*
5010	Lopašov	Chvojnica	0.17	0.38
5025	Sobotište	Teplica	0.34	
5020	Myjava	Myjava	0.57	
5030	Šaštín-Stráže	Myjava	0.29	
5060	Sološnica	Sološnický p.	0.35	
5070	Studienka	Rudava	-0.36	
5095	Jakubov	Malina	0.52	
5100	Láb	Močiarka	0.35	
5120	Borinka	Stupávka	1.19	
5040	Moravský Svätý Ján	Morava	0.19	0.27
5085	Záhorská Ves	Morava	0.36	
5400	Podbanské	Belá	0.82	0.73
5390	Kôprová dolina	Kôprovský p.	1.23	
5380	Tichá dolina	Tichý p.	1.14	
5460	Račkova dolina	Račkov p.	0.8	
5465	Dovalovo	Dovalovec	0.338	
5480	Liptovský Hrádok	Belá	0.9	

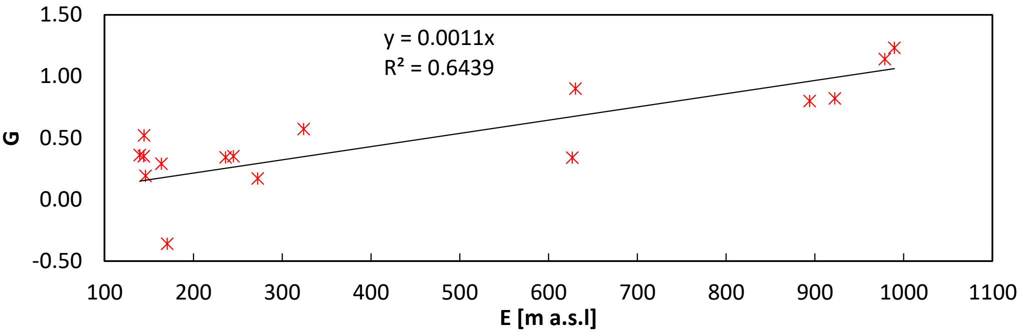
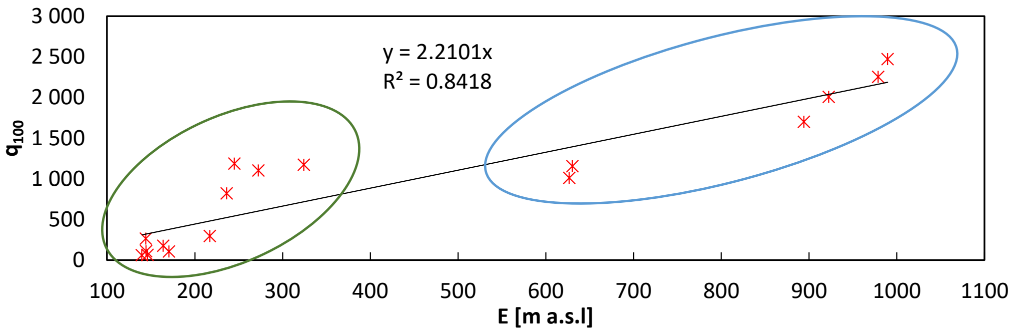


Fig. 7. The relation of the skewness coefficient *G* to elevation *E* of the station.

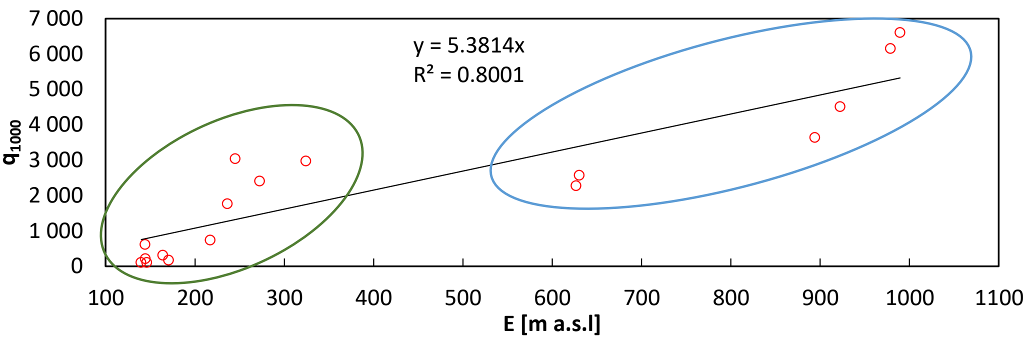
3. Then we have recalculated the parameters of the distribution curves for each station separately including historical floods into account. Applying the regional coefficients, we have estimated the design specific discharge of the q_{max} series listed in Table 3. The values are lying within the 5 and 95% confidence intervals.
4. Finally, we have tested the relation between the skewness coefficient *G* and a set of the different physical-geographical characteristics of the basins. The example of the relation between the skewness coefficient *G* and the elevation of the stations *E* is presented in Fig. 7. The significance of the relation is not very high, but is simple and applicable.

The highest values of specific discharge with the mean return period 1000 years occur in stations of higher elevation and smaller basin area. On the contrary, the smallest values occur in stations of lower elevation and bigger basin area (Fig. 8). Therefore, we have decided to establish the relation of q_{1000} to the elevation *E*. In Figs. 8a-b are depicted the empirical relations between q_{100} and q_{1000} and the elevation in both regions.

In Fig. 9 are the relations displayed for both regions separately for q_{1000}. Using these regional relations, it is possible to estimate the *1000*-year specific discharge from the elevation data in the ungauged profiles (Fig. 10). Water gauges are in the Morava basin at an altitude between 140 and 325 m a. s. l. and in the Bela basin between 627 and 990 m a. s. l. Therefore, for catchment area outside this altitude is not specific value of specific discharge estimated.



a)



b)

Fig. 8. a) The *100*-year, and b) *1000*-year specific discharge [$dm^3s^{-1}km^{-2}$] in the Slovak part of the Morava River basin (green) and in the Belá River basin (blue) in relation to elevation *E*.

Table 3. Estimated *T*-year design specific discharge [$dm^3s^{-1}km^{-2}$], 5% 95% confidence intervals

water gauge **stream**	**Probability** ***T*-year**	**0,05** **20**	**0,02** **50**	**0,01** **100**	**0,005** **200**	**0,002** **500**	**0,001** **1000**
Lopašov **Chvojnica**	***q***	**555**	**837**	**1102**	**1419**	**1931**	**2400**
	q(5)	835	1349	1864	2513	3619	4683
	q(95)	405	584	744	929	1217	1471
Sobotište **Teplica**	***q***	**426**	**631**	**823**	**1053**	**1423**	**1762**
	q(5)	638	1015	1393	1869	2681	3464
	q(95)	313	443	560	694	901	1084
Myjava **Myjava**	***q***	**551**	**860**	**1173**	**1573**	**2273**	**2968**
	q(5)	817	1383	2003	2847	4430	6106
	q(95)	409	606	794	1025	1409	1773
Šaštín-Stráže **Myjava**	***q***	**108**	**144**	**176**	**211**	**163**	**309**
	q(5)	132	182	227	279	359	430
	q(95)	92	120	143	168	206	238
Sološnica **Sološnický p.**	***q***	**535**	**860**	**1188**	**1606**	**2329**	**3038**
	q(5)	836	1458	2137	3056	4760	6534
	q(95)	381	579	770	1001	1384	1743
Studienka **Rudava**	***q***	**70**	**90**	**107**	**124**	**149**	**169**
	q(5)	93	126	153	183	226	263
	q(95)	56	71	82	94	110	122
Jakubov **Malina**	***q***	**65**	**89**	**110**	**135**	**172**	**206**
	q(5)	85	122	156	198	264	325
	q(95)	53	70	85	101	125	146
Láb **Močiarka**	***q***	**132**	**199**	**265**	**345**	**481**	**610**
	q(5)	183	294	409	558	822	1087
	q(95)	103	148	190	240	322	397
Borinka **Stupávka**	***q***	**146**	**220**	**295**	**391**	**560**	**729**
	q(5)	201	328	465	652	1005	1381
	q(95)	115	164	212	271	369	463
Moravský Svätý Ján **Morava**	***q***	**45**	**56**	**65**	**75**	**89**	**101**
	q(5)	51	65	77	89	108	123
	q(95)	41	50	57	65	76	85
Záhorská Ves **Morava**	***q***	**40**	**52**	**61**	**71**	**87**	**100**
	q(5)	51	68	82	99	126	149
	q(95)	34	42	49	56	66	75
Podbanské **Belá**	***q***	**1074**	**1547**	**2008**	**2582**	**3559**	**4506**
	q(5)	1287	1935	2594	3442	4943	6453
	q(95)	925	1290	1635	2051	2739	3386
Kôprová dolina **Kôprovský p.**	***q***	**1189**	**1816**	**2472**	**3342**	**4938**	**6601**
	q(5)	1569	2583	3727	5338	8509	12042
	q(95)	964	1399	1831	2379	3334	4283
Tichá dolina **Tichý p.**	***q***	**1064**	**1643**	**2254**	**3069**	**4574**	**6151**
	q(5)	1425	2381	3469	5014	8082	11529
	q(95)	853	1250	1646	2152	3037	3919
Račkova dolina **Račkov p.**	***q***	**945**	**1333**	**1703**	**2155**	**2911**	**3630**
	q(5)	1193	1777	2366	3119	4440	5758
	q(95)	789	1071	1329	1635	2128	2580
Dovalovo **Dovalovec**	***q***	**530**	**775**	**1013**	**1306**	**1798**	**2267**
	q(5)	758	1199	1657	2258	3336	4432
	q(95)	407	567	715	889	1168	1423
Liptovský Hrádok **Belá**	***q***	**628**	**896**	**1157**	**1481**	**2031**	**2564**
	q(5)	791	1194	1609	2148	3112	4093
	q(95)	525	720	903	1121	1479	1813

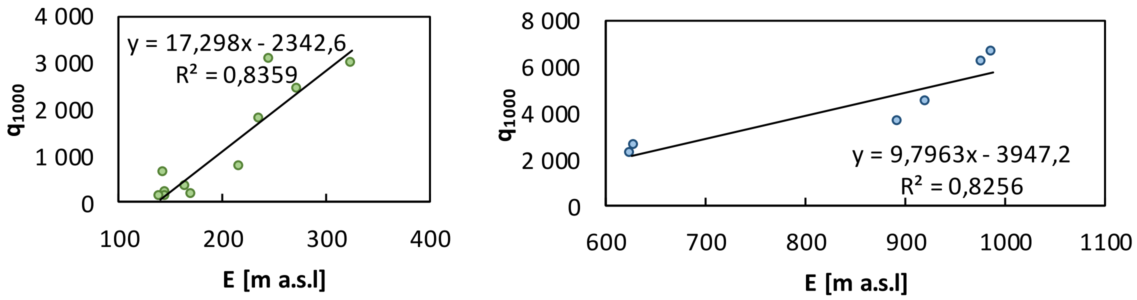
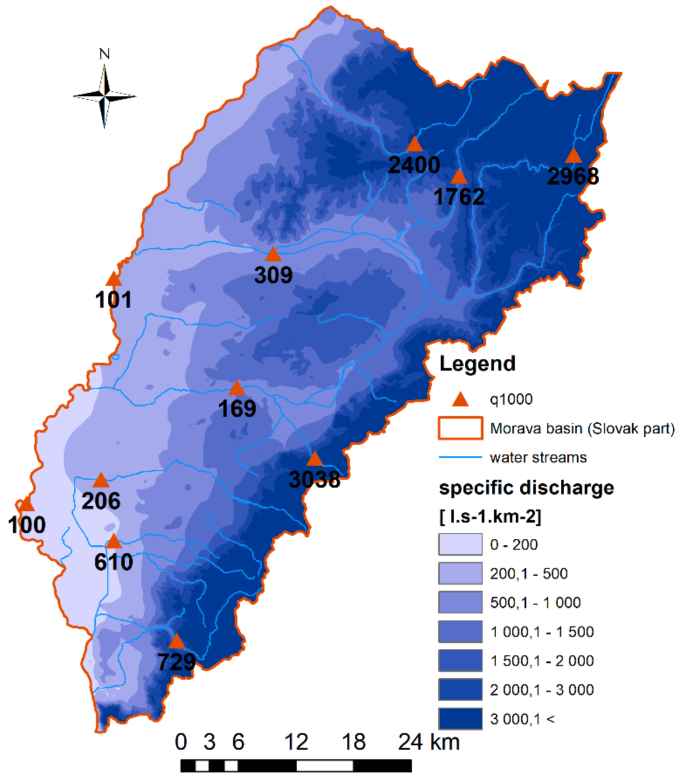


Fig. 9. a) The relation of the *1000*-year specific discharge [dm^{3}s^{-1}km^{-2}] on elevation *E* in the Slovak part of the Morava River basin (left) and in the Belá River basin (right).



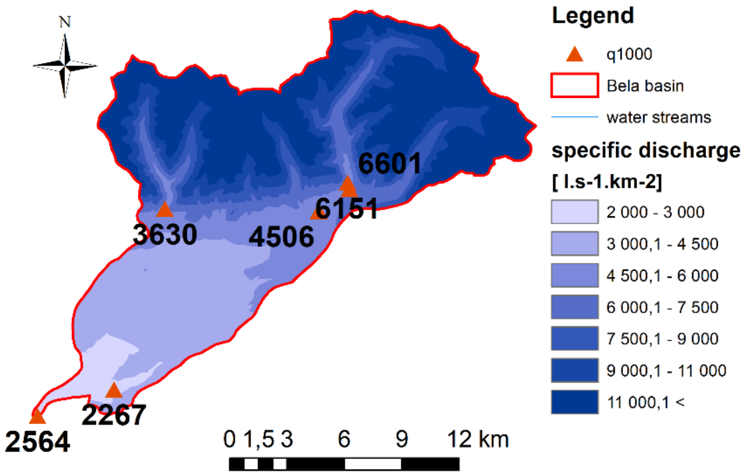


Fig. 10. Map of estimated *1000-year* design specific discharge q_{1000} [dm^{3}s^{-1}km^{-2}] in the Slovak part of the Morava basin (upper) and in the Belá basin (lower).

CONCLUSIONS

In our study we present the results of estimation of the *T*-year specific discharge of the selected streams in the lowland basin of the Morava River and in the mountainous basin of the Belá River. We are testing application of the single probability distribution type (Log-Pearson Type III Distribution) to estimate the peak flow design values. Application of single distribution offers several advantages, e.g.:

1. During re-calculation of the distribution parameters after adding new data into series it is possible to track the changes of the distribution parameters (old results-new results);
2. It is also possible to track the changes of parameters after adding the data on historical floods;
3. LP3 distribution is widely used in many countries as a standard for calculation of the of *T*-year flows, therefore there exist several free available and easy to use EXCEL spreadsheets for estimation of the distribution parameters;
4. It is possible to regionalize the skewness coefficient of the LP3 distribution for different areas of the country or river basin. The usage of the regionalized skewness coefficient improves the estimation of the *T*-year flows in basins with short data series;
5. Application of only one distribution allows estimating easily the 5% and 95% confidence intervals of the design values, what is required nowadays and becomes a standard.

Regional skewness coefficient *Gr* of the Log-Pearson Type III Distribution was estimated to be 0.38 in the Morava basin taking into consideration the selected water gauging stations. The regional skewness coefficient has value of 0.27 for the main stream of the Morava River only. In the Belá River basin the regional skewness coefficient was estimated to be 0.73.

The values in Table 3 and on the Fig. 6 show that the uncertaintity of estimation is high even in case of the *20*-years design flows. For example, the *20*-years design specific discharge can vary between 964 and 1569 $dm^3.s^{-1}.km^{-2}$ with 90 percent probability in the subbasin of the Kôprovský creek in the closing profile of the Kôprovská valley.

Using the regional skewness coefficient has refined the estimation of *T*-year values, but there is still a high uncertainty in estimating design values for very long return periods. The accuracy improvement of the results can be expected after involving other variable physical-geographical properties of the river basins (e.g. forest area, geology, land use, soil types, river basin shape, etc.) into the estimation of the regional coefficients. These aspects will be considered in next steps of the analysis.

Better results were used when estimating the specific discharge using the empirical relation to the elevation. The derived empirical regional relations can be used to estimate the specific discharge of other streams in the region.

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FUZZY LOGIC BASED FLASH FLOOD FORECAST

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ABSTRACT

The flash flood forecasting remains one of the most difficult tasks in the operative hydrology worldwide. The torrential rainfalls bring high uncertainty included in both forecasted and measured part of the input rainfall data. The hydrological models must be capable to deal with such amount of uncertainty. The artificial intelligence methods work on the principles of adaptability and could represent a proper solution. The application of different methods, approaches, hydrological models and usage of various input data is necessary.

The tool for real-time evaluation of the flash flood occurrence was assembled on the bases of the fuzzy logic. The model covers whole area of the Czech Republic and the nearest surroundings. The domain is divided into 3245 small catchments of the average size of 30 km^2. Real flood episodes were used for the calibration and future flood events can be used for recalibration (principle of adaptability). The model consists of two fuzzy inference systems (FIS). The catchment predisposition for the flash flood occurrence is evaluated by the first FIS. The geomorphological characteristics and long-term meteorological statistics serve as the inputs. The second FIS evaluates real-time data. The inputs are: The predisposition for flash flood occurrence (gained from the first FIS), the rainfall intensity, the rainfall duration and the antecedent precipitation index. The meteorological radar measurement and the precipitation nowcasting serve as the precipitation data source. Various precipitation nowcasting methods are considered. The risk of the flash flood occurrence is evaluated for each small catchment every 5 or 10 minutes (the time step depends on the precipitation nowcasting method).

The Fuzzy Flash Flood model is implemented in the Czech Hydrometeorological Institute (CHMI) – Brno Regional Office. The results are available for all forecasters at CHMI via web application for testing. The huge uncertainty inherent in the flash flood forecasting causes that fuzzy model outputs based on different nowcasting methods could vary significantly. The storms development is very dynamic and hydrological forecast could change a lot of every 5 minutes. That is why the fuzzy model estimates are intended to be used by experts only.

The Fuzzy Flash Flood model is an alternative tool for the flash flood forecasting. It can provide the first hints of danger of flash flood occurrence within the whole territory of the Czech Republic. Its main advantage is very fast calculation and possibility of variant approach using various precipitation nowcasting inputs. However, the system produces large number of false alarms, therefore the long-term testing in operation is necessary and the warning releasing rules must be set.

Keywords: Fuzzy Logic, Flash Flood, Operative Hydrology.

INTRODUCTION

The flash flood forecasting has always represented a major challenge for hydrologists. A causal torrential rainfall has substantial dynamics in both space and time and it brings high amount of uncertainty, which we will probably not be able to eliminate sufficiently in the near future. Mentioned uncertainty must be taken into account in the process of forecasting as well as when interpreting the results. The Czech hydrometeorologic institute (CHMI) is the national service for meteorology, hydrology and air quality and ensures the flood forecasting service (FFS) in the Czech Republic. Standard hydrological forecast based on outputs from numerical prediction models is issued for more than one hundred forecasting profiles but in the case of flash floods it is not sufficient and a different approach is needed. A prime product of CHMI for flash flood forecasting is Flash Flood Guidance (Daňhelka et al., 2015) and output from this model is published in CHMI web site. Simultaneously, attention to a development of other tools is being paid. For example, the distributive hydrological models used for flood forecasting on bigger catchments can be applied but it requires very detailed schematization and calculation is time-consuming. Currently this approach is tested only on selected small catchments and it doesn't cover whole area of the Czech Republic (Daňhelka et al., 2015). The artificial intelligence based methods are also tested in the CHMI, the Fuzzy Flash Flood model is introduced in following text. Its advantage consists particularly of very fast calculation, which enables us to evaluate the most up-to-date input data in more variants. Moreover, the adaptability principle becomes more and more important in the current climate change context. The fuzzy model assembly comes from the real flash flood episodes (2009-2019) and the new episodes are being added constantly. The model is so able to reflect possible changes in the rainfall-runoff processes. The difficulty of flash flood forecasting requires the usage of more tools and that is why the variety in the modeling approaches will be always beneficial.

METHODS AND DATA

In general, a process of a hydrological forecast could be divided into the three elementary steps:

1. An input data preparation.
2. A calculation of a hydrological model.
3. A results evaluation and publication.

Let us compare a standard hydrological forecast (it means forecast for a catchment of size of hundreds of square kilometres, usually based on outputs from numerical weather prediction models) and flash flood forecast in each mentioned step.

In the case of a standard hydrological forecast, the first step (input data preparation) enables checking input data both automatically and manually. Time-resolution of input data is usually 1 hour. Measured precipitation ordinarily consists of a merged product calculated as radar estimates combined with rain gauge measurements. More variants of weather forecast could be considered, according available numerical weather prediction (NWP) models. Through the consultation with meteorologists, the most probable future weather development could be determined.

In contrast, a flash flood forecasting requires the most frequent updating as possible (5-10 minutes). A manual checking or editing of input data is unrealistic. The whole process must be fully automated. Time-resolution of input data should be 5-10 minutes. Measured precipitation is being derived from radar measurement and should be significantly under/overestimated. The precipitation forecast comes from the extrapolation of radar echo (nowcasting) and includes a huge amount of uncertainty. For example, extrapolation methods do not involve the life cycle of storm cells. It is possible to consider more variants of precipitation nowcasting methods.

In the second step, a calculation of a hydrological model is carried out. When calculating a standard hydrological forecast, hydrologist’s main work lies in the adaptation of the hydrological model to the current rainfall-runoff situation. Parameters of the hydrological model could be adjusted to achieve the best possible matching of measured and simulated discharges. The estimation of the future discharge development follows.

The flash flood forecasting does not enable any real-time adjustment of the hydrological model especially because of the lack of time and high uncertainties included in the input data. Hydrologists are reliant on the automated results only. The hydrological model can be recalibrated additionally (for example according hit/miss/false analyses). It needs to be pointed out, that flash floods occur randomly and mostly hit an unobserved catchment. That means that there is the lack of relevant data for the calibration of the hydrological model.

There are differences also in the publishing options. Within the FFS provided by CHMI, the standard hydrological forecast is published on the internet and usually it is updated twice a day and during the flood situation, the updates can be done more frequently (every hour if needed). The flood reports with a verbal description of the current state and the further development are issued. The publishing of the flash flood forecast still remains a subject for discussion, in particular because of huge uncertainty of the results and the necessity of more complex interpretation. Currently, the presentation of forecast from the Flash flood guidance model is tested on CHMI website. The outputs from the Fuzzy Flash Flood model are not available for public and are used only internally.

The problem lies in the fact that we probably cannot enhance the accuracy of the input data significantly in the near future. That is the main motivation for using the artificial intelligence methods.

The theory of the fuzzy logic could be found for example in (Jang, 1993). The principles of the Fuzzy model assemblage are described in (Janál, Starý, 2012). In following text, a description of the current version of the Fuzzy model with the emphases on its operation is provided.

The whole area of the Czech Republic and certain surroundings is covered by the model. The area of interest is divided into the small catchments of the size of 30 km^2 on average. There are 3245 small catchments in total and for each the input variables are considered as an average values. Many different structures of the model were tested in the past. The current version consists of two fuzzy interference systems (FIS). The first FIS was developed by dr. Ježik (Ježík, 2015) and it serves to the determination of the predisposition to the occurrence of the flash flood for each mentioned small catchment. Input variables are the catchments characteristics like the area, forest cover, slope, soil type and others. The second FIS forms an operative part of the model and has 4 input variables:

- Potential predisposition to the occurrence of the flash flood (gained from the first FIS)
- Average precipitation intensity
- Duration of the rain
- Antecedent precipitation index (calculated for 14 days)

The values of the first input (Potential predisposition to the occurrence of the flash flood) are calculated in advance by the first FIS for the whole set of the small catchments and they are fixed. These values could be updated by new calculation of the first FIS when the more relevant catchments characteristics are available or in terms of the analyses of the success of the model. The remaining three input variables (a precipitation characteristics) are computed operatively for the whole set of the small catchments in each time step. More variants of the precipitation forecast are considered based on different precipitation nowcasting methods. The time step (updating frequency) of the Fuzzy model is 5 or 10 minutes, according to the used precipitation nowcasting product. The time interval of 5 hours is considered in each time step, 2 hours of history and 3 hours of nowcasting. The detailed description could be found in (Janál, Starý, 2012). Currently, three precipitation nowcasting products are used as inputs for the Fuzzy model (Haiden at al., 2011), (Novák, 2007):

- COTREC (time step 5 minutes)
- CELLTRACK (time step 10 minutes)
- INCA (time step 10 minutes)

Additionally, the Fuzzy model is calculated in the variant when no precipitation nowcasting is taken into account and only measured precipitation is considered. In this variant, the uncertainty of input data is significantly lower, but the time for the warning is reduced.

The antecedent precipitation index is also updated in each time step (moving method).

The output variable of the Fuzzy model is the flash flood endangerment degree and it is determined for each catchment (3245 values in each time step). The modeled catchments are interlinked in the meaning that the endangerment is propagated downstream while it is reduced gradually. The exact time of the culmination is not the subject of the forecast. The interpretation is so, that flash flood could occur in the nearest future (in oncoming hours or minutes). The output variable ranges from 0 to 1, when 0 means no endangerment and 1 means the endangerment of flood with the return period of 100 years or more. This interval is divided into 5 levels represented by different colors, which are used for the operative presentation of the results through the Fuzzy Flash Flood application created by J. Brzezina, see Fig. 1.

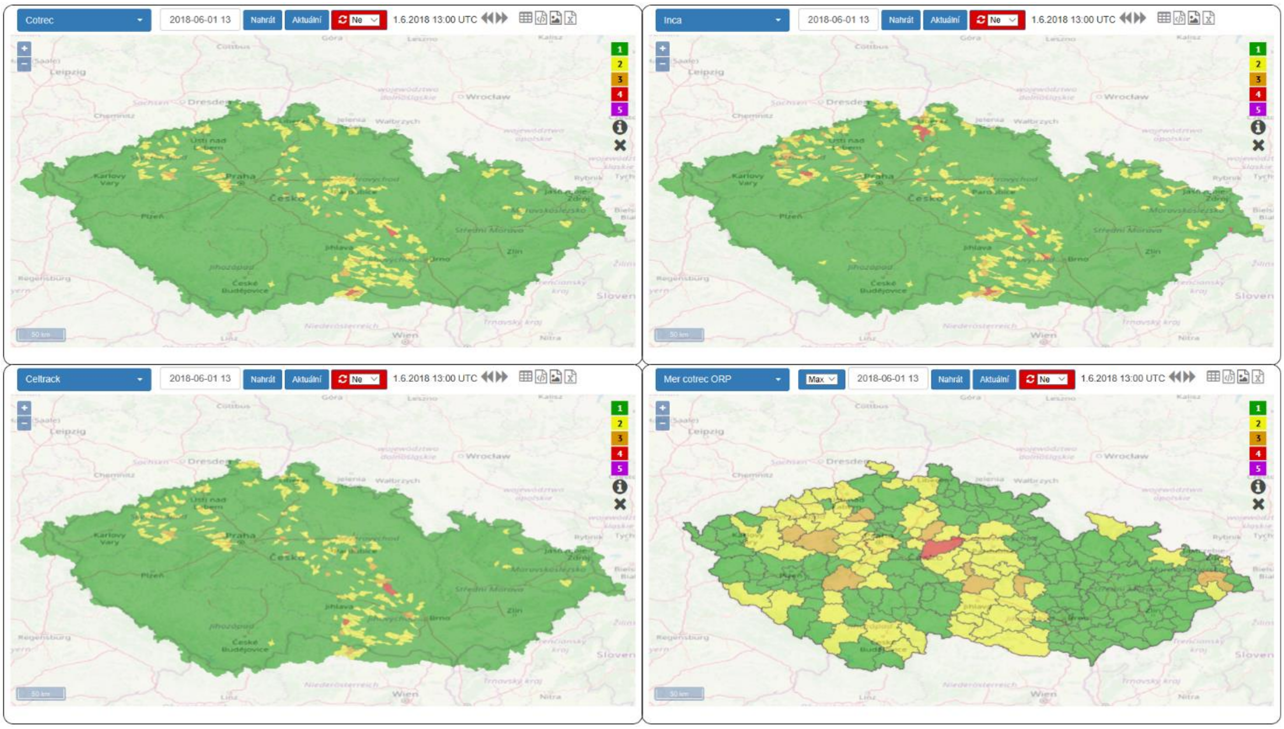

Fig. 3. Fuzzy Flash Flood application

Through the application, the hydrological response based on different precipitation nowcasting methods can be compared in the form of the maps of endangered areas. Hydrologists can get a primary information about oncoming situation almost immediately after data from the meteorological radar are available. It means that the time for warning or some reaction is maximized. An easier interpretation could be achieved by merging the results into the bigger areas, which reflects the areas for standard warnings of CHMI (lower right map on the Fig. 1). All results are stored in relation database and are available for the retrospective analyses.

RESULTS AND DISCUSSION

The fuzzy model is in the testing operation in Brno regional office of CHMI and results are shared with the other offices of CHMI for internal use. Contemporary development is focused mainly on the validation of the model. This part is very demanding because of the character of flash floods. There is often not sufficient feedback and we can hardly detect all events, which have happened. Alongside the local case studies the more robust validation method is being developed. The validation method should be able to evaluate continuous time period and should be automatized. The essential requirement for such method is the reliable source of the impacts caused by the torrential rainfalls. Since CHMI closely cooperates with firefighters, the database of the firefighter actions was used for this purpose. This source of impact data has advantages that it is covering the whole territory of the Czech Republic and the events are localized by GPS coordinates. However, we must be aware of weaknesses of this data source. The time of the firefighter action does not always correspond with the time of flash flood. The reason of firefighter action is described by the specific code, it enables us to select only the situations that concern the flooding, for example the flooded cellars. But not all such events are caused by torrential rainfalls. The cellars could be for example flooded by the water pipe breakdown.

The algorithm of evaluation method was compiled taking into account all mentioned features of the firefighter actions database. Flash flood warnings were evaluated for the same areas as in the case of the standard warnings of CHMI (lower right map on the figure 1) and hit-miss-false statistic was processed. The goal of evaluation was to find an adequate sensitivity of the Fuzzy model. Since the evaluation method is still the subject of the development, the results published in this article cover only short time period from 26th May to 1st June 2018, nevertheless they could illustrate the potentialities of the model. Seven different levels of the model sensitivity were tested, that means that warnings were issued after exceedance of seven different thresholds, whereas the sensitivity of the model was decreasing from the first to the seventh variant.

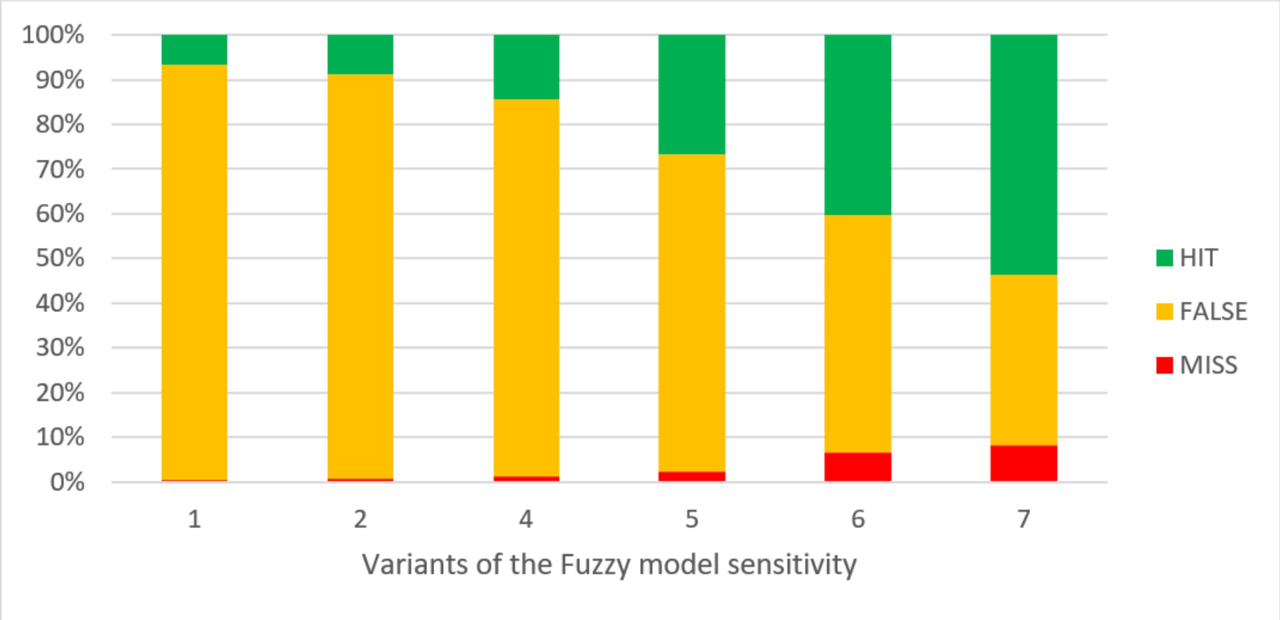

Fig. 2. Hit-miss-false ratio

The hit-miss-false ratio for mentioned seven variants of the model sensitivity is depicted in Fig. 2. The high amount of false alarms will be probably always present because of the high uncertainty of input data but it could be reduced by appropriate setting of the warning threshold. It is up to as to decide which warning threshold is the most suitable for the practice. The high number of the false alarms could lead to the devaluation of the forecast in the eyes of the users. On the other hand, the issuing of the false alarm might not be connected with the same risk as in the case of the missed flood.

CONCLUSIONS

The aspiration for the flash flood forecasting comes from the possibilities that are currently available in CHMI. Fifteen years ago, the flash flood forecast seemed to be almost impossible. The major progress in the meteorological radar measurement and precipitation nowcasting brought certain ways to predict even such fast natural disasters. The successfulness of the forecast is directly dependent on the accuracy of the precipitation estimates. The error of the precipitation measurement during the convective precipitation event could be dozens of percent and the error of the precipitation nowcasting could be even higher. We cannot rely on the specific values of the precipitation inputs since they are “always wrong”. The essence of the flash flood forecast lies in the real-time evaluation of all the data we have. The artificial intelligence methods enable the very fast calculation and the ability to work with the uncertain data.

The question of the form of warning remains open. The publishing of the forecast through the websites might not by sufficient. If we were able to warn the residents of endangered municipality directly, the reaction strategy would have to be clearly specified. In the extreme cases it is not about the flooded cellars but about saving lives. Early warning may provide a few minutes for leaving the zones around watercourses.

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APPLICATION OF RAINFALL-RUNOFF MODEL: CLIMATE CHANGE IMPACTS ON RESERVOIR INFLOW

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ABSTRACT

The impacts of climate change are beginning to be felt in the Czech Republic. In recent years, we were challenging a dry period, which threatens to continue affecting Czech economy, agriculture and personal comfort of local people. The need to adapt to climate change is obvious. The groundwater resources are in continuous decline, consequently, the surface water supplies are increasing in importance. How would the quantity of available water change in the future? How much water would we be able to store within the year to manage it during the dry seasons?

Rainfall-runoff models enable us to simulate future changes in hydrological conditions based on climate projections. One of such tools is Runoff Prophet, the conceptual lumped model being developed at the Institute of Landscape Water Management at Brno University of Technology. It is used to simulate time series of monthly river flow in a catchment outlet without the need to describe the morphological characteristics of the catchment. Runoff Prophet produced good results of calibration and proved its suitability for conceptual hydrological modelling in variable hydrological conditions of the Czech Republic.

The aim of the paper was to assess the possible impact of climate change on future inflow into Vír I. Reservoir, one of the drinking water resources for Brno, a city of 380 000 inhabitants. The recently developed software Runoff Prophet was used to simulate future river flow time series. The model was calibrated on the catchment of gauging station Dalečín on Svratka River as the reservoir inflow. Prognoses of future river flow were performed using climate scenarios prepared by Global Change Research Institute of Czech Academy of Sciences. These scenarios (RCP types) are based on the outcomes from different regional climate models of Euro-CORDEX initiative. Characteristics of possible future air temperature and precipitation in the basin were evaluated in terms of its impact on reservoir management. The results of hydrological modelling gave the perspective of expected changes in Vír I. inflow yield. The options of using Vír I. Reservoir as a drinking water supply for Brno in coming decades were assessed.

Keywords: Runoff Prophet, climate change, rainfall-runoff model, hydrology, water resources

INTRODUCTION

The impacts of climate change are beginning to be felt in the Czech Republic. In future, the remarkable changes in temperature and precipitation are expected to continue (Štěpánek et al. 2016). According to the Czech Hydrometeorological Institute evaluation (Daňhelka et al. 2019), in 2018, our country was still suffering from a dry period, which is lasting since 2014. One of the indicators of drought is a low value of mean annual rainfall in comparison to its long-term average, which is 686 mm in the Czech Republic for the reference period 1981–2010. Year 2018 was evaluated as the most critical one from the dry period with 164 mm mean annual rainfall deficit (24%). Year 2015 was the second driest with 154 mm deficit (22%). Concerning the hydrological impact in the form of low river flows, the situation is getting worse due to long-term accumulation of water deficit from previous years. In year 2019, the drought is expected to continue. For the moment (07 2019), we have 9% deficit with 370 mm of rainfall from beginning of the year, which is not enough to restore balance to the hydrological cycle.

The dry period in the Czech Republic has visible impact on water resources, both surface and underground. Water levels are declining in not only house wells, a boreholes and springs, but in large groundwater resources of drinking water. As the groundwater yield declines, the importance of surface water resources is increasing. Brno, the second biggest city of the Czech Republic with 380 000 inhabitants, has two main sources of drinking water - Březová nad Svitavou spring area (treated groundwater) and Vír I. Reservoir (treated surface water). In 2018 annual report of Brno water and sewage works (Brněnské vodárny a kanalizace, a.s. 2019), we can see that the ratio of drinking water taken from Vír I. increased from 6% to almost 13% since 2014. Therefore, it is appropriate to ask how the quantity of available surface water would change in the future.

From the perspective of climate, we have scenarios of possible future development from different climate models at our disposal. Global Change Research Institute of Czech Academy of Sciences is one of organizations specialized in climate projections for the Czech Republic. For this study, they provided bias corrected scenarios (RCP types) based on outcomes from different regional climate models of Euro-CORDEX initiative.

Based on these climate data, the projections of future hydrological situation can be made. Nevertheless, we have to be able sufficiently describe the rainfall-runoff process in the particular catchment. Rainfall-runoff models are tools enabling simulation of this natural cycle. There are some very complex ones with high demands on quantity of input data and description of catchment characteristics. However, there are also very simple models with empirical or conceptual approach, where the relationship between cause and consequence is searched using calibration datasets of input elements. One of such models is also Runoff Prophet described in Knoppová (2018) and Knoppová & Marton (2019) which was developed at the Institute of Landscape Water Management at Brno University of Technology.

The aim of the paper is to assess the possible impact of climate change on the quantity of water available in Vír I. Reservoir. One of the key factors is the future water yield of the reservoir inflow, which is the Svratka River above the gauging station Dalečín. Software Runoff Prophet was used to simulate its future river flow time series. The model was calibrated on the catchment of gauging station Dalečín and the hydrological projections were made using ensemble of climate scenarios.

We have evaluated the characteristics of projected air temperature and precipitation in terms of its impact on reservoir management. The results of hydrological modelling have given the perspective of expected changes in Vír I. inflow yield. We have assessed the options of using Vír I. Reservoir as a drinking water supply for Brno in coming decades.

METHODS AND DATA

Climatological and Hydrological data

The Czech Hydrometeorological Institute provided processed historical climate and hydrological time series for model calibration. We have been using time series of monthly mean air temperature [˚C], monthly precipitation sum [mm] and mean monthly discharge [m^3/s].

The projected climatological data have been processed at the Global Change Research Institute of Czech Academy of Sciences. The input data have been prepared according to Štěpánek et al. (2009, 2011) and the output scenarios bias corrected by quantile mapping method (Štěpánek et al. 2016). Based on projections of future temperature and precipitation for the Czech Republic, an ensemble of 11 simulation have been prepared. It consists of three RCP scenarios from five climate models (Table 1). The ensemble covers range of possible future climate development. We have been using simulations of daily mean air temperature [˚C] and precipitation sum [mm] time series recalculated to monthly time step.

Table 2. Description of used climate models/scenarios

ID	Climate model name	RCP emission scenarios
M1	ipsl-cm5a-mr_rca4	4.5, 8.5
M2	mohc-hadgem2-es_racmo22e	2.6, 4.5, 8.5
M3	mpi-esm-lr_clm4.8.17	4.5, 8.5
M4	mpi-esm-lr_rca4	4.5, 8.5
M5	ncc-noresm1-m_hirham5	4.5, 8.5

Historical data (climate and hydrological) have been divided into tree datasets - one for calibration (1970–2005) and two for validation of calibrated model (1961–1969 and 2006–2018).

Simulated climatological data consisted of control run of used climate models (1970–2005) and projected scenarios (2006–2099).

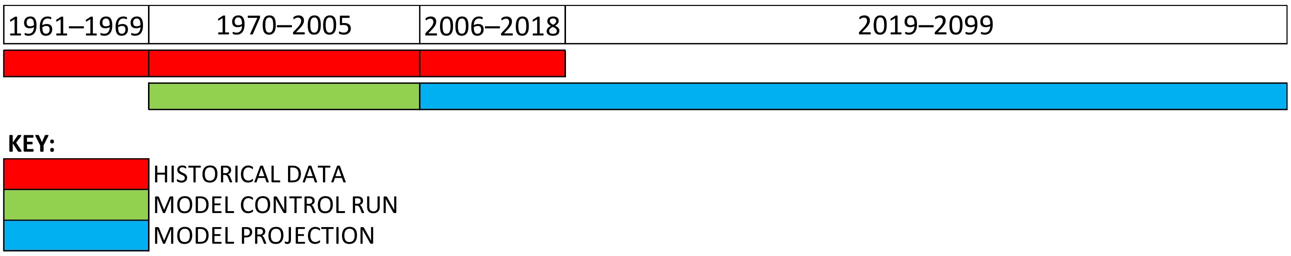

Fig. 4. Scheme of used historical and projected data

To evaluate the results, we have recalculated the data into a difference to its long-term average (reference period 1981–2010). We have used a double moving average MA(5x30) to show the trends in projected climatological and hydrological data. Thus, we have calculated a moving average of order 30, and then applied another moving average of order 5 to the results. We have also used boxplots to show basic statistical characteristics of the ensemble of scenarios. It shows minimum, first quartile Q_{25}, median, mean (cross mark), third quartile Q_{75}, and maximum.

Runoff Prophet

Runoff Prophet is a hydrological model for simulations of river flow in the catchment outlet. It is based on parametrised rainfall-runoff equations described in Wang et al. (2013). For chosen catchment, 37 parameters in equations have to be optimized. Nash-Sutcliffe model efficiency coefficient (NS) is used as the optimization criterion and it also express the model calibration success.

The calculation requires no geographical characteristics of the catchment but its area. Firstly, the model is calibrated and validated using historical climatological and hydrological data. After that, future discharge can be simulated based on projected climatological data.

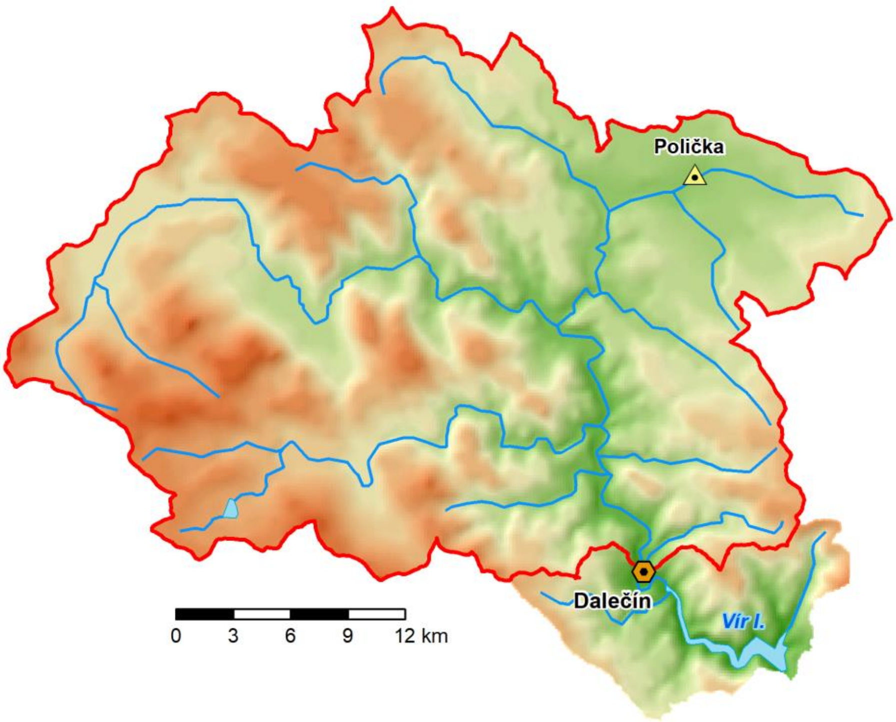

Fig. 2. Study area - Dalečín as the main Vír I. Reservoir inflow

STUDY AREA

Vír I. is an open water reservoir with 56 mil. m^3 of total water storage capacity. Its´ purpose is mainly to secure ecological discharges in Svratka River under the reservoir; it serves as drinking water supply, for hydro power production and as a flood protection. The gauging station Dalečín on Svratka River represents the reservoir inflow. It´s basin occupies an area of 366.94 km^2. After previous evaluation, we have chosen climate station Polička as a representative one for the catchment. Thus, the rainfall-runoff process in the catchment has been described by time series of temperature and precipitation in Polička and discharge in Dalečín.

RESULTS AND DISCUSSION

Model calibration and validation

Success of model calibration and validation has been quantified by the value of NS and the difference in observed and simulated mean yearly discharge (MQ). We have calibrated the model on 36 years of historical data (1970–2005). Resulting NS has been 0.69 that signifies good efficiency of hydrological model according to Moriasi et al. (2007). Mean difference in MQ has been -2.79%. Calibrated model has been validated on two datasets: 1961–1969 (A) and 2006–2018 (B). Dataset A has had very pleasing results. Dataset B, nevertheless, has had worse result - satisfactory model efficiency with NS < 0.65 and MQ considerably undervalued (-8.17%).

We have assumed that the rainfall-runoff process in the period B was affected by the drought. Therefore, we have split dataset B into two parts – B1 (2006–2013) and B2 (2014–2018). The results have confirmed our assumption. Model has had good results on B1. Within the dry period B2, Runoff Prophet has underestimated MQ by almost 19% and the value of NS was unsatisfactory.

Table 2. Results of model calibration and validation

	Calibration	**Validation**			
		A	**B**	**B1**	**B2**
Nash-Sutcliffe [-]	0.690	0.657	0.624	0.668	0.068
Mean difference in MQ [%]	-2.79	-0.13	-8.17	-1.54	-18.77

Projected changes in temperature and precipitation

All climate scenarios from the ensemble show increasing trend in projected mean temperature (Fig. 3). When we look at the historical data (red line), we can see that it is in the upper part of the model ensemble. It could indicate that we would stay in the upper, i.e. warmer part also in the future.

The precipitation sum has slightly increasing trend in projected data. In late 50´s, all the ensemble members are above the reference long-term average. Until beginning of the dry period (2014), the historical data are in the upper part of the ensemble. Since then, the precipitation sum is on rapid decline.

In addition to the continuous trends, we have evaluated the modelled data in three consecutive 30-year periods: 1981–2010 (present), 2011–2040 (near future) and 2041–2070 (distant future). Fig. 5 shows basic statistical characteristics of temperature and precipitation ensemble in these periods. In the distant future, the median mean temperature is 1.6˚C above the long-term average. If the temperature growth continued in current trend, it will more likely move towards the maximum projected value - increase of 2.8˚C.

Concerning the precipitation ensemble, we can see that in the distant future the variance of scenarios is markedly smaller than in the near future. The median precipitation sum in distant future is 5% higher than the long-term average. We have to consider that the simulations slightly underestimated the present mean sum of yearly precipitation (96% of long-term average). Thus, we can assume that it has underestimated precipitation also in the future and the resulting sum could be even higher.

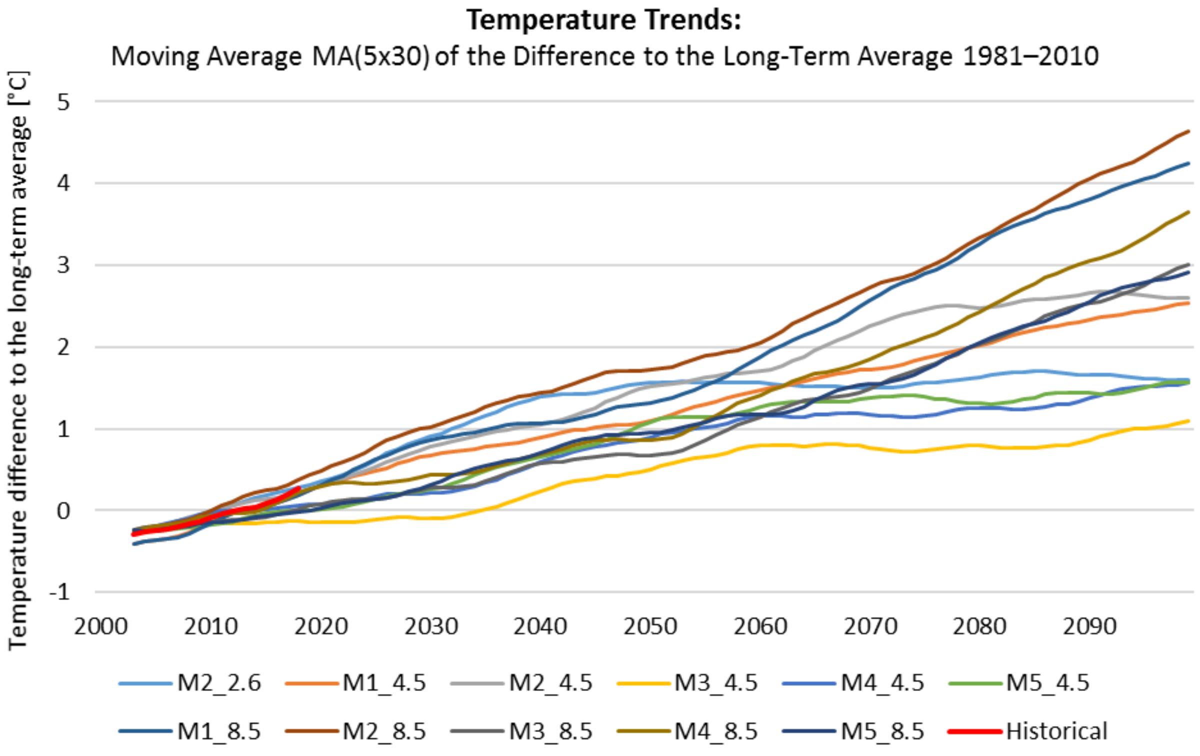

Fig. 3. Temperature trends

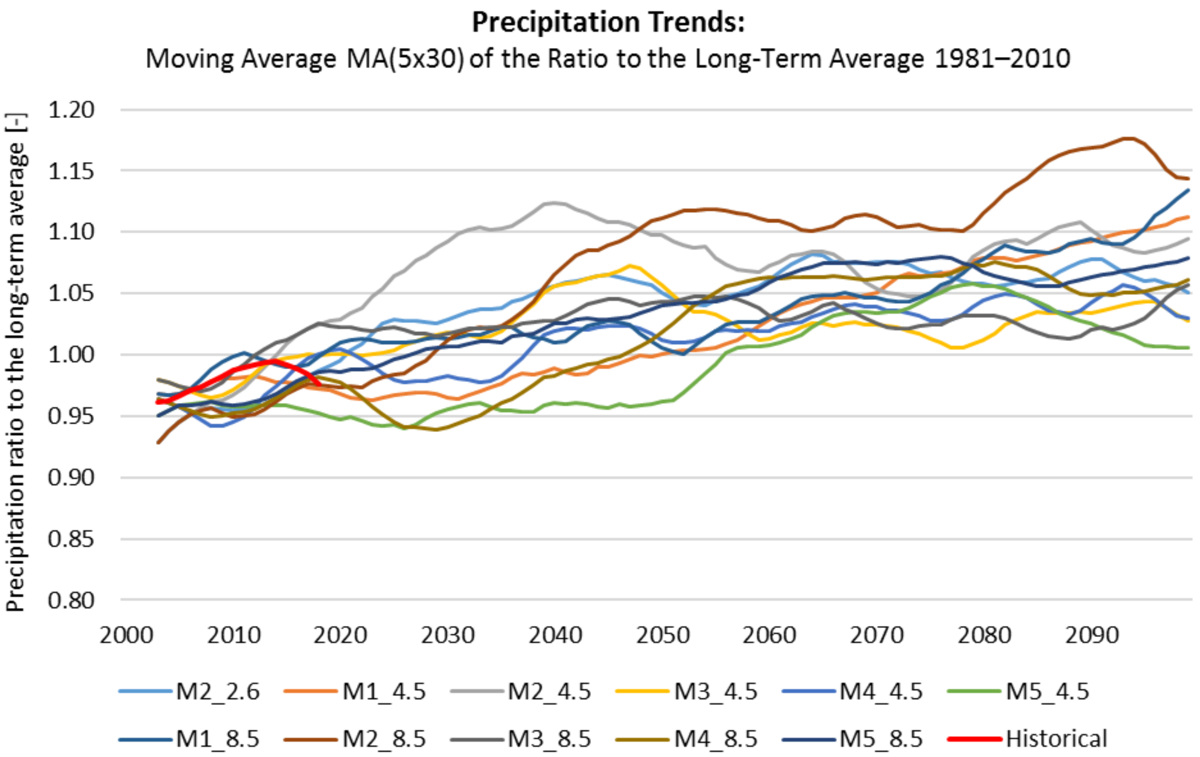

Fig. 4. Precipitation trends

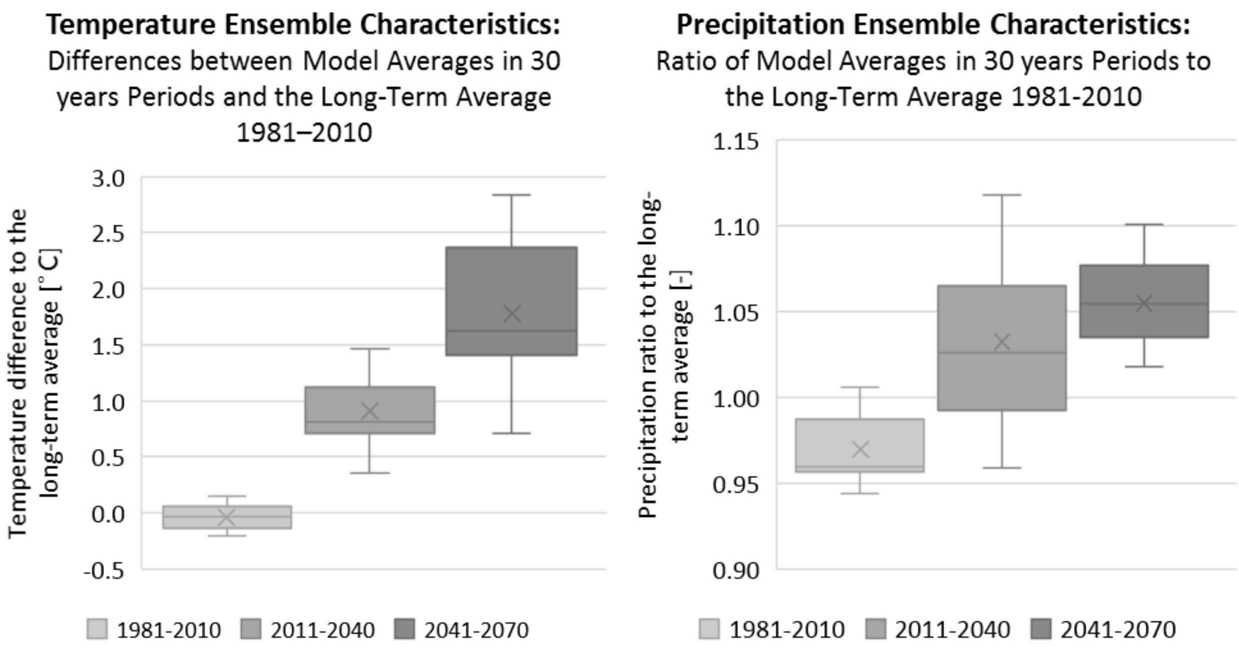

Fig. 5. Statistical characteristics of temperature and precipitation ensemble

Projected changes in the reservoir inflow

Most scenarios from the ensemble have slightly decreasing trend in projected mean discharge, but they are rather diverse. In historical data, we can see sharp decrease since 2014.

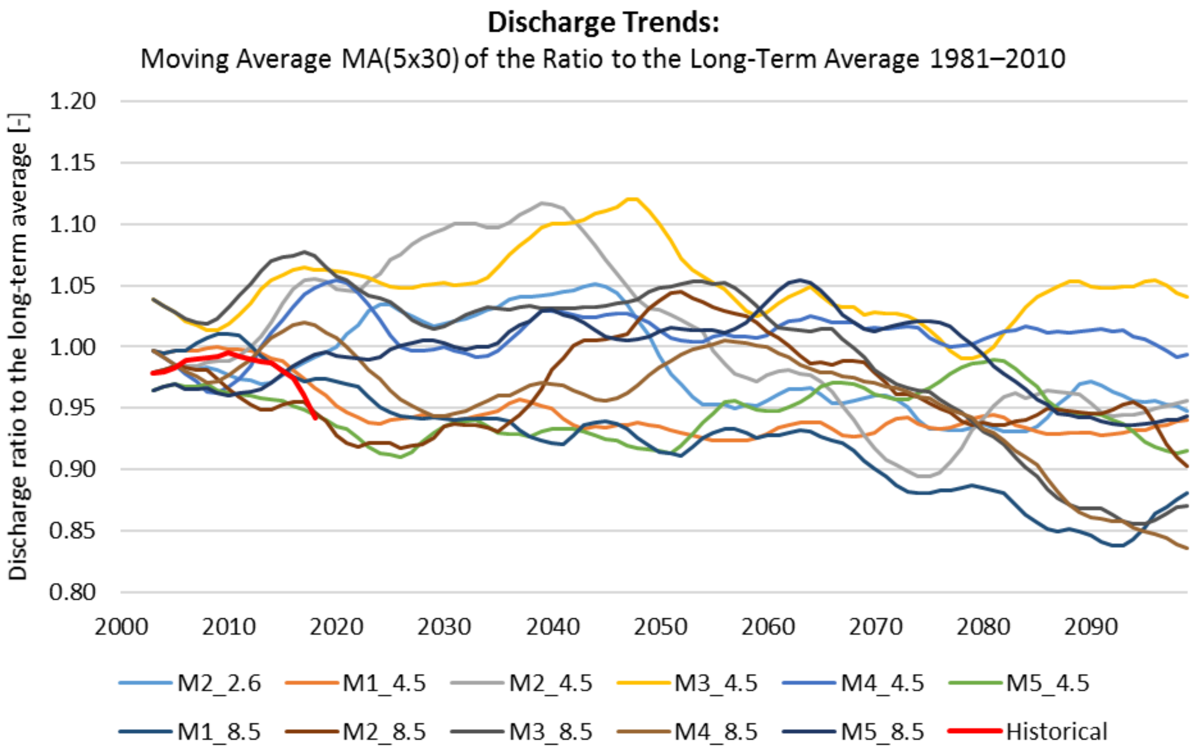

Fig. 6. Discharge trends

As with climatological projections, we have evaluated the statistical characteristics of the ensemble in three consecutive 30-year periods. However, the results have shown that for the discharge evaluation, 30-year periods are insufficient. Therefore, we have examined also 20-year consecutive periods (Fig. 7).

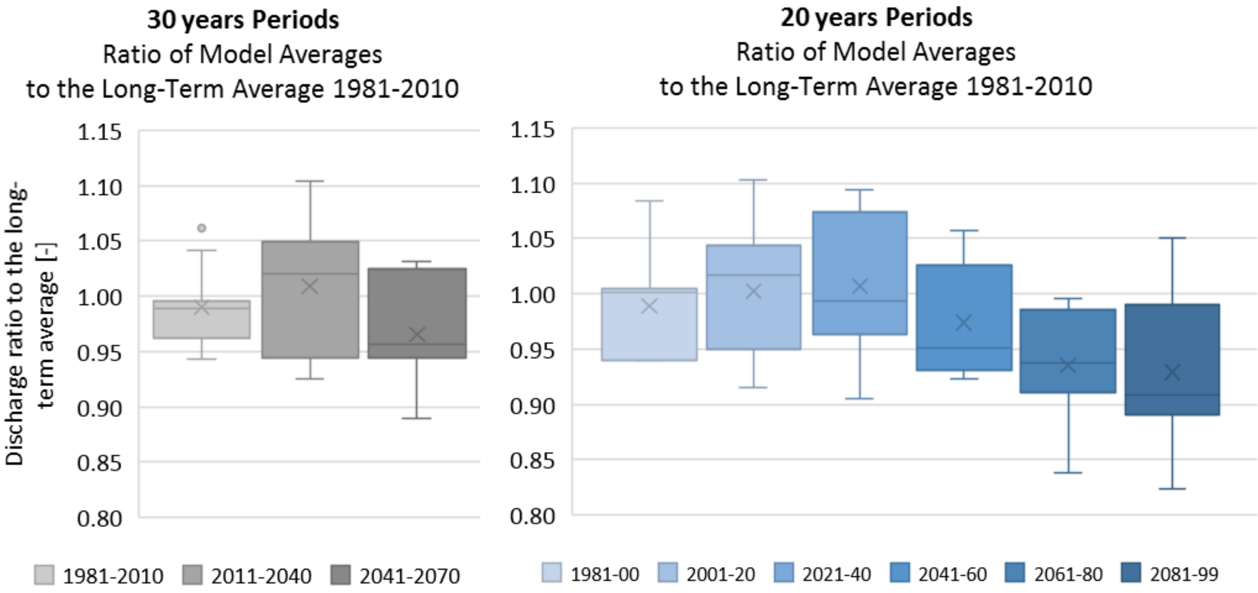

Fig. 7. Statistical characteristics of discharge ensemble – 20 and 30-year periods

In 30-year periods boxplot, we can see that the discharge modelled for presence slightly underestimate the reality (median = 99% of the long-term average). Distant future has mean discharges from 89% to 103% of the long-term average. However, more than 25% of ensemble is still above the long-term average. Thus, it is hard to say if the future discharge would be higher or lower then today.

In 20-year periods boxplot, from 2021–2040 the median discharge visibly decreases. From 2061, more than 75% of the scenarios are under the long-term average. Based on these results, we can say that the mean yearly discharges in 2061–2099 will be more likely lower than the long-term average.

CONCLUSIONS

As the results have demonstrated, mean temperature will increase in the basin of Dalečín. According to the current trends, until 2070 it could be between 1.6°C to 2.8°C above the long-term average. The yearly precipitation sum will have slightly increasing trend in the range of several percent. Based on used climate scenarios, mean yearly discharge in Svratka River should remain in current state until 2030´s. Since then, the yield of the Vír I. Reservoir inflow will decline. Until 2099, the ensemble shows median discharge 9% down from the long-term average.

Simulated changes in the reservoir inflow are not very high. However, there are some facts that should not be overlooked. The current dry period (2014–now) do not fit very well into the modelled ensemble. In precipitation, we have recorded a sharp change in the long-term increasing trend. The current low values of mean discharge are even beyond the simulated ensemble. Thus, the presented results are valid unless the dry period is only a rare extremity. Unless the discharge decline could be much worse. Furthermore, the rising temperature would mean greater evaporation from open water bodies. It could also negatively influence the water quality and thus its treatability.

According to our results, the amount of drinking water in Vír I. Reservoir will decrease in the future. If the yield of Březová groundwater resource would continue to decline, Brno city should rethink its drinking water management.

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APPLICATION OF THE «CLIMATE-RUNOFF» MODEL TO THE ASSESSMENT OF THE DUNABE RIVER BASIN WATER RESOURCES IN THE XXI CENTURY ACCORDING TO THE CLIMATE SCENARIOS (A1B)

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ABSTRACT

The results of calculations of possible state of water resources within The Danube River in the XXI century were shown. This estimation was based on the model «climate-runoff», developed in Odessa State Environmental University. As the input to model data of climate scenario A1B (model REMO) were used. Average long-term annual flow values using meteorological data (air temperature and precipitation) from the scenario for different climatic periods of XXI century were calculated. 32 points (grid nodes) which were uniformly distributed over the catchment area of The Danube River were studied. Projection of changes in water resources was given by comparing the calculation results in the past (before 1989) and in the future (1990-2030, 2031-2070, 2071-2100).

The major trends in climatic factors of the flow formation and water resources were established. It is shown that the climatic conditions in the XXI century on the Danube River catchment is unfavorable for the formation of runoff. The positive component of the water balance (precipitation) remains unchanged and the negative component (evaporation) increases. Isolines of norms of climatic annual flow within the whole basin were constructed. It is established that by 2030 a significant reduction of water resources will not occur; during the 2031-2070 diminution will be 17,9%; during the 2071-2100 – 22,0%.

Thus, in the XXI century, changes in the water resources of the Danube will not be destructive and irreversible.

Keywords: water resources, climate change scenarios, the model «climate-runoff»', forecast of Danube water resources change

INTRODUCTION

Water resources are the most valuable natural resource. It is determine the success of economic and social development of the countries. The task of assessing of climate change effects, especially in terms of redistribution of water resources in time and in space, is especially problematic [20]. The river flow is formed, first of all, by climatic factors that determine its zoning. Recently, in the world there is an increase in the number of dangerous hydrological phenomena – catastrophic floods and the reduction of water resources of vast territories [18]. Climate change affects not only quantitative but also qualitative characteristics of river runoff [24]. It requires adaptation measures for all sectors of the economy, population and ecosystems [27]. Ukraine belongs to the countries of the Danube basin [31]. It is located in the mouth of the river and uses significant amounts of water for economic and drinking needs [4]. Prospects for changing the state of the Danube water resources should determine the water strategy of our country in the Northwest part of the Black Sea in the XXI century [14].

The purpose of the work is the forecast of future changes in water resources in the Danube basin based on global scenario data. The object of the study is the water resources of the Danube River. The subject is the quantitative characteristics of the annual runoff of this river, obtained by the «climate-runoff» model [28], using the meteorological data of the A1B climate scenario.

The peculiarity of the study is that the runoff of the Danube River at its mouth is determined by the hydrometeorological processes of its formation zone, which is located in the mountainous parts of the basin. Thus, determining the state of the Danube water resources by meteorological data requires, first of all, the study of climatic factors.

Content of the work is in line with the European Union Strategy for the Danube Region, approved by the EU Council on 24 June 2011, the work of the Coordination Center related to the participation of Ukraine in the implementation of the European Union Strategy for the Danube Region (21 September 2011), the Danube Transnational Program 2014-2020.

LITERATURE REVIEW

Most of the joint international scientific research on Danube water resources relates to their quantitative assessments. Usually they are performed on the basis of observation data [31-33] with the assessment of the natural conditions of the runoff formation and the levels of water management in time and space (mainly along the length of the river). Calculations of the state of the water resources under the scenarios of climate change were carried out by Ukrainian scientists for the part of the Danube basin, which is located in the Ukrainian Carpathians [9, 15]. To calculate the changes in water resources of the transboundary influx of the Danube, the development of scientists from neighboring countries [25] was used. In 1994-1997 the Slovak Republic participated in the second round of the American Research Program, which was conducted with the participation of the American Department of Environmental Protection. From CSMT, Slovakia received five general circulation models, three of which were selected for regionalization (CCCM, GISS, GFDL).

The results of calculations obtained in the Odessa State Environmental University (OSEU) for the territory of Transcarpathia according to the projected scenario data adapted for Slovakia and Ukraine, showed, basically, their satisfactory compliance. The exception was the GISS scenario. According to it in Ukrainian scientists the increase of precipitation will occur 1,06 times (in case of doubling of CO_2 concentration), and according to Slovak scientists - in 1,14 times. As a result of calculations under the GISS scenario, according to Ukrainian scientists, water resources are reduced by 25-31 %, and according to Slovak scientists - by 1-6 % [13]. This discrepancy was due to the insufficient resolution of the CCCM, GISS, and GFDL scenarios that were developed at the end of the last century.

Investigation of the impact of changes in the Danube water resources as a result of global warming on the hydrological, hydrochemical and hydroecological state of the Northwest of the Black Sea is being carried in OSEU. It was done within the framework of the research work «Investigation of the influence of climatic fluctuations on the hydrological and hydrochemical regimes of the Northwest of the Black Sea» in 2010-2011 on order of the Ministry of Education of Ukraine.

Annual runoff calculations were performed using data from global warming scenarios. It was established that while simultaneously doubling the CO_2 concentration in the atmosphere Danube water resources would decrease by 30-42% under the CCCM and GISS scenarios and by 30-37% under the GFDL and UKMO.

It was determined that with the gradual increase of carbon dioxide concentration in the non-stationary GFDL scenario in 2000-2010, the reduction of water resources of the Danube River became 8%, and according to observation data for the period 2000 - 2004 – 1 %. It was found that under this scenario the reduction of water resources in the Danube River will pass a critical limit of 50 % by 2080 [12, 14].

In these calculations, data from the forecast of changes in climatic factors in different climatic zones of Ukraine were used [21]. For the transition from the conditions of the steppe zone (the mouth part in Ukraine) to other climatic zones of the Danube gradients of changes of precipitation and air temperatures with height were established. Modern scenarios of climate change, including A1B, describe the study area in more detail and are available in electronic resources [8]. This made it possible to estimate changes in the water resources of the Danube River with greater accuracy.

METHODS AND DATA

The Danube River belongs to the Black Sea basins and is the largest river in Central and Southeastern Europe. The total catchment area is 817000 km^2, and the length is 2857 km. The Danube River crosses various landscape zones with a pronounced diversity of natural conditions. Most of the Danube river basin is in the mixed forest zone, the bottom reaches the forest-steppe and steppe zones. The orographically, the watershed of the Danube River is very heterogeneous and includes both mountainous and plain areas (Table 1). According to the data [26], the difference between the highest and lowest points of relief is 3651 m. Mountain areas with a height of more than 500 m include 31% of the total catchment area.

Table 1. Distribution of the catchment area of the Danube River in high altitudes

Altitude zone, m	Average height of altitude zone, m	Area of high-altitude zone, %
<100	50	18
100-500	150	51
501-1000	750	23
1001-2000	1500	6,5
>2000	2500	1,5

According to the complex of physico-geographical and geological features, the Danube River is divided into three parts: Upper, Middle, and Lower Danube [31, 32] (Fig. 1). Such a distribution is confirmed by the results of factor analysis [16, 22], which we used to estimate the synchronization of annual precipitation variations (Fig. 2).

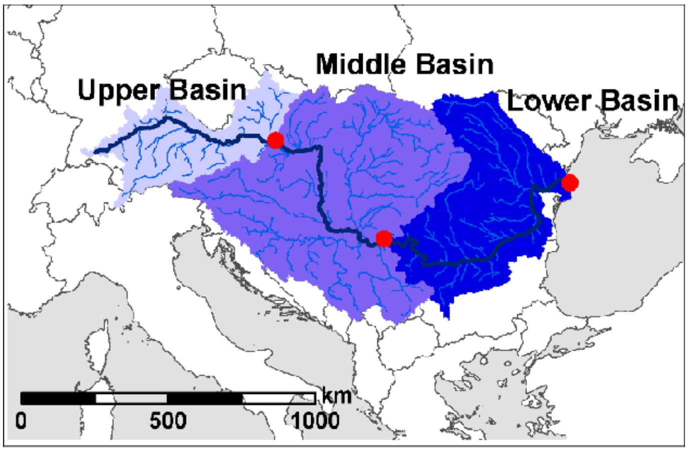

Fig. 1. Main parts of the Danube river basin [27]

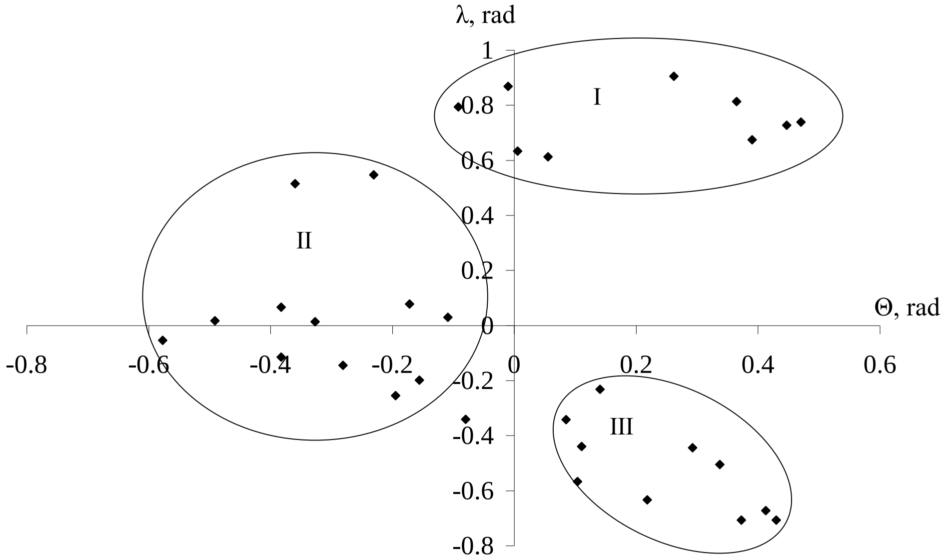

Fig. 2. Allocation of groups with synchronous quantities of precipitation based on three

factors (I - the region of the Supreme Danube, II - the region of the Middle Danube, III - the Lower Danube area)

Most often, in the assessment of the impact of climate change on water resources of territories with a not dense network of hydrometeorological observations, balance models are used.

To be more precise, it is models of water and water-thermal balance, which combine both the water balance of the catchment and the thermal balance of the underlying surface. The fact is that the equations of water and heat balances contain a common component - evaporation from the surface of the land. This allows the use of heat balance components to calculate evaporation.

In Odessa State Environmental University over the past three decades for assessment of water resources of Ukraine using meteorological data model «climate-runoff» was used. It was developed by prof. E.D. Gopchenko and prof. N.S. Loboda [5]. The development of such a model was relevant in the second half of the twentieth century because of the lack of data of runoff observations in both natural and disturbed water management. Since the 1980s, relevance, theoretical and practical significance of the model has increased as a result of the addition of climate change [6]. The model has been calibrated and verified on the materials of river flow of different geographical zones of Ukraine. It is sensitive to modern changes of climatic factors. This model allows to estimate with satisfactory accuracy the zonal runoff and influence of the underlying surface, including water management transformations [11]. The developed method of calculating the characteristics of annual runoff has become a component of the State Building Norms of the Republic of Moldova [17] and is included in the new edition of the State Building Norms of Ukraine [7].

The «climate-runoff» model consists of two parts. The first part allows estimation of natural annual runoff on the basis of meteorological data, the second - the estimation of domestic (transformed by water management) runoff. At the entrance to the first part of the model meteorological data are used, in the second - the natural (undisturbed water management) annual runoff and quantitative indicators of water management transformations.

To estimate the changes in water resources at the Danube catchment area, the first part of the model was used. The theoretical basis of it is the equation of water-heat balance of the catchment area. For a long period, it looks like

$$\overline{Y}_K^{'} = \overline{X}^{'} - \overline{E}_m^{'}\left[1+\left(\frac{\overline{X}^{'}}{\overline{E}_m^{'}}\right)^{-n}\right]^{-\frac{1}{n}} , \qquad \textbf{(1)}$$

where $\overline{Y}_K'$ is the average long-term value of annual climatic runoff in terms of climate change, mm; $\overline{E}_m^{'}$- average long-term value of the maximum possible evaporation in the terms of climate change, mm; $\overline{X}^{'}$ - the average long-term value of annual precipitation in terms of climate change, mm.

It is established that the norms of annual climatic runoff correspond to the norms of zonal runoff of rivers in natural conditions of its formation [10]. The accuracy of determining the statistical parameters of annual runoff using the «climate-runoff» model is within the accuracy of calculations (±10,0% for the average long-term value of annual runoff). The structure of the water-heat balance equation (1) allows it to be used to calculate runoff with meteorological data of climate scenarios.

The study used the international ENSEMBLES project database, which can be accessed on the Internet at http://ensemblesrt3.dmi.dk. The A1B scenario (REMO model) was chosen for the calculations, which is characterized by the highest correspondence of observed and simulated meteorological series for the retrospective period in Europe.

The A1B climate change scenario is implemented in the REMO regional climate model developed at the Max Planck Institute for Meteorology in Hamburg, Germany. REMO integrates the former numerical EUROPA-MODEL weather forecast model for the calculation of thermodynamic characteristics and the ECHAM5 global climate model unit [29].

For the study of changes in the main climatic factors of runoff and water resources formation within the Danube catchment area 32 points were considered. It is point-nodes of the 25 km grid of scenario data with different physical and geographical conditions.

To estimate changes in the basic hydrometeorological characteristics (average values of annual precipitation, maximum possible evaporation, climatic runoff), a comparison of the calculated values obtained for different climatic periods in the 21st century was performed. Periods 1990-2030, 2031-2070, 2071-2100 were compared with relevant characteristics of the base period (1951-1989), in which the manifestation of changes in air temperatures was not yet statistically significant in either Ukraine or Europe [3, 23].

Trends in meteorological fluctuations were detected by meteorological stations located at the Danube catchment area in different parts of it. The type of trend equations and correlation coefficients were determined on the basis of regression analysis [30].

RESULTS AND DISCUSSION

The analysis of time series of the annual air temperature (scenario A1B) showed the existence of trends to their growth for all 32 weather stations. For example, at the point corresponding to the meteorological station Innsbruck, the conditional mathematical expectation of annual air temperatures will increase from 2.3 °C in 1951 to 6.9 °C at the end of the XXI century (Fig. 3), in Belgrade - from 12.0 °C to 16,5 ºC, and in the Danube Delta (Izmail) this characteristic will increase from 11,8 ºC to 16,3 ºC. By the end of the XXI century, as compared with the middle of the last century (1951), the annual air temperature increase would be on average about 4.0 ºC. And compared to 1989 (year with a statistically significant increase of air temperature in Ukraine) will be 3-3,5 ºC.

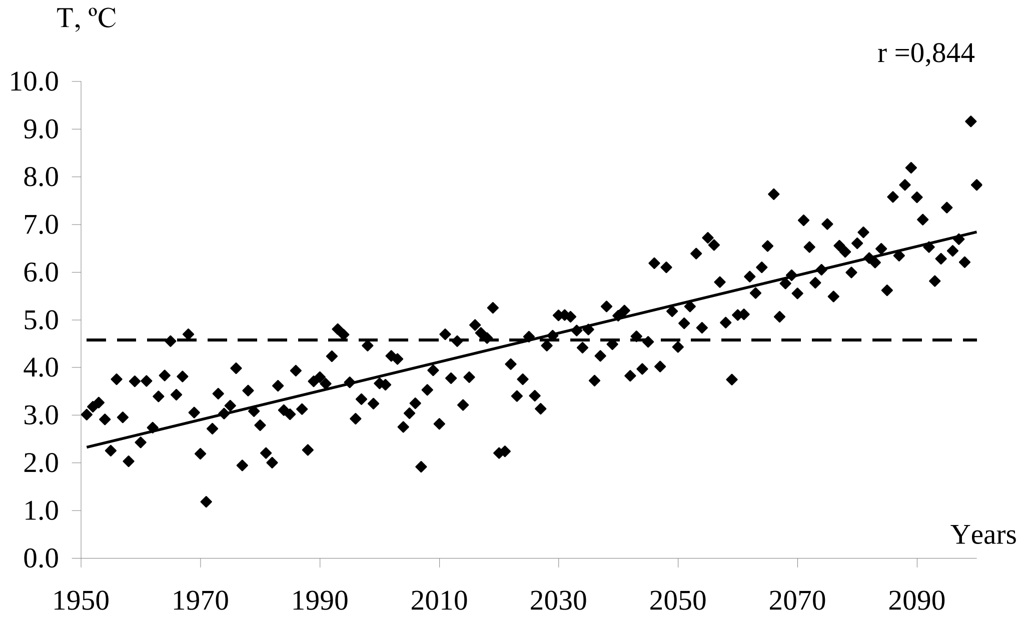

Fig. 3. Time series of the annual air temperature, scenario A1B, Innsbruck (---- average long-term value, —— trend line)

It has been established that average temperatures of warm (IV-X) and cold (XI-III) periods will also increase in all studied meteorological stations. The increase in the air temperatures of the cold period in the upper Danube will occur not so intensively, as at the mouth. However, the transition of the average temperatures of the cold period from the negative values to positive in the 30 years of the XXI century (Fig. 4) is well marked. This transition during the cold period means changing the conditions of the formation of the spring runoff. The contribution of thawed water to the formation of the runoff will decrease, and the role of rain floods and underground river recharge will increase.

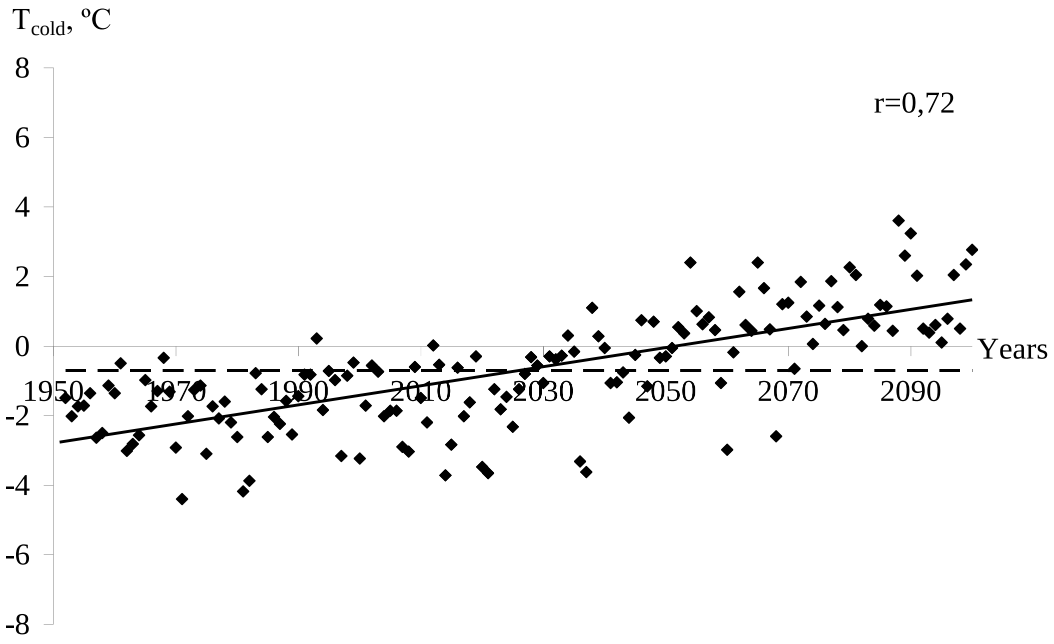

Fig. 4. Time series of the air temperature of the cold (XI-III) period, Murau, 1951-2100 (---- average long-term value, —— trend line)

An analysis of the time series of annual precipitation amounts as well as precipitation amounts of warm and cold periods showed that it was not possible to detect statistically significant trends in their fluctuations during the period 1951-2100 on all 32 stations (Fig. 5).

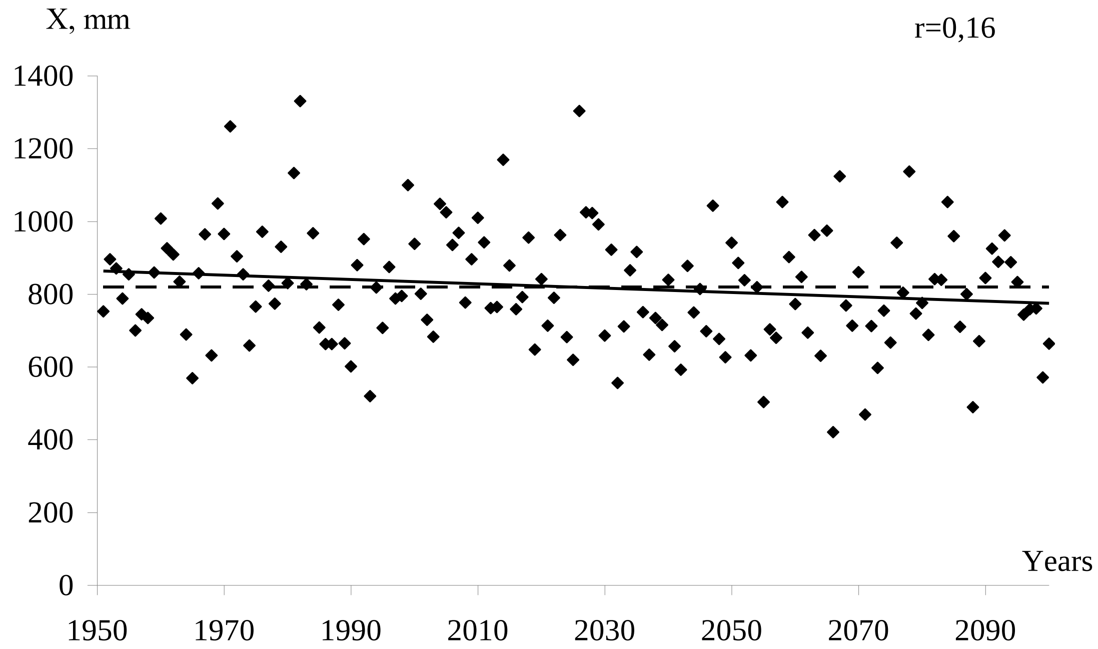

Fig. 5. Time series of the annual precipitation, scenario A1B, Bihac (---- average long-term value, —— trend line)

The results of the study of the trend existence in the fluctuations of climatic factors correspond to those obtained by the authors for the Northwest Black Sea: air temperatures are projected to increase at the background of almost unchanged precipitations [2, 3]. Such climatic conditions are unfavorable for the formation of runoff, since the growth of air temperatures leads to an increase in evaporation from the surface of the land.

Comparison of the average long-term precipitation before and after 1989 showed that during the period 1990-2030 the amount of precipitation at individual points-meteorological stations will grow and decrease. Compared with the scenario data until 1989, these changes will be within ± 10 %. The average relative deviation of the average values $\overline{X}$ for the estimated climatic period (1990-2030) from the corresponding value for the basic climatic period (1951-1989) will be ± 2,7 %. During the estimated period 2031-2070, changes in the humidity resources compared with the base period will be ± 4,0 %, and in the period 2071-2100 - ± 4,2 %.

The maximum possible evaporation (heat equivalent) will increase throughout the catchment area by increasing air temperatures. Compared to the base climate period (1951-1989), the increase of $\overline{E}_m$ will be + 6,9 % in 1990-2030; 22,4 % - in 2031-2070; 39,9 % - in 2071-2100.

The peculiarity of the «climate-runoff» model is that the meteorological data are calculated at points that correspond to the position of the grid stations. An analysis of the climate runoff values $\overline{Y}_K$ for each point showed that during the 1990-2030 the largest changes of $\overline{Y}_K$ would not exceed «minus» 15 %. The average relative deviation of the compared values would be ±11,2 %. Destructive effects of global warming under the A1B scenario will start from 2030. From this year the increasing of air temperatures will become more intense. In 2031-2070, averaged reduction in annual climate runoff will reach «minus» 32 %, and in 2071-2100 - «minus» 40 %.

However, simply averaging the climate runoff values for each point-node does not give a complete picture of the average long-term runoff from the Danube catchment. The weight coefitient of each point may be different. To identify possible changes in the Danube water resources in the 21st century, maps of isolines of the annual climate runoff norms were constructed for each of the calculated climatic periods. An average annual value of annual runoff from the catchment was also established by the method of «weighing» by area [19]. This average long-term annual runoff of the Danube River for the basic climatic period (1951-1989) is 246 mm, which corresponds to the actual data [1,31]. The differences are within ± 5.0 %. The distribution of the isolines of the annual climate runoff norms is in accordance with the developed maps of the runoff norms of the annual runoff given in professional editions [32].

According to the A1B scenario, the water resources of the Danube catchment area will decrease over time (Table 2).

Table 2. Changes of average long-term annual climatic runoff of Danube River, determined by weighing in different time intervals (at comparison with the data before 1989)

Characteristic	The climate period			
	1951-1989	1990-2030	2031-2070	2071-2100
Average long-term values of annual climatic runoff $\overline{Y}_K$, mm	246	231	202	192
Changes of $\overline{Y}_K$ in comparison to the baseline climatic period 1951-1989, %		-6.1%	-17.9%	-22.0%

A more complete picture of the change in the Danube water resources is given by the isolines of relative deviations δ

$$\delta = \frac{\overline{Y_K}' - \overline{Y_K}}{\overline{Y_K}}, \qquad \textbf{(2)}$$

where $\overline{Y_K}'$ is the average annual value of annual climatic runoff, calculated according to scenario data, mm; $\overline{Y_K}$ - the average annual value of the annual climatic runoff, calculated for the basic climatic period.

The isolines maps were constructed. According to them the decrease in the annual climatic runoff is well traced in the direction from northwest and north to south (Fig. 6, Fig. 7).

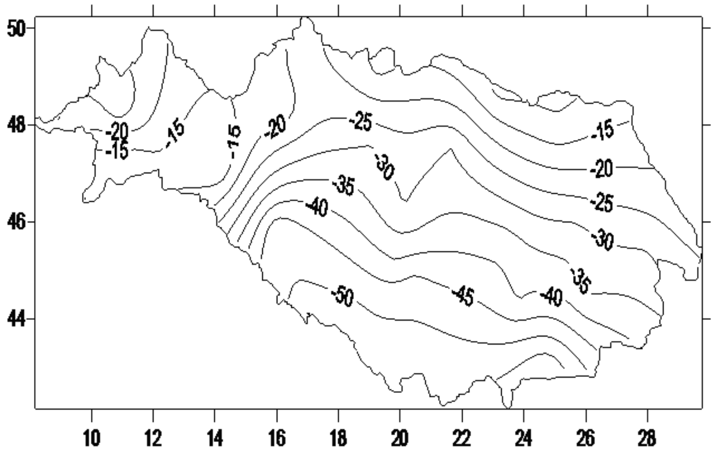

Fig. 6. Spatial distribution of relative deviations (%) of annual climate runoff in the Danube basin according to the A1B scenario (REMO model) for the period 2031-2070 compared to 1989

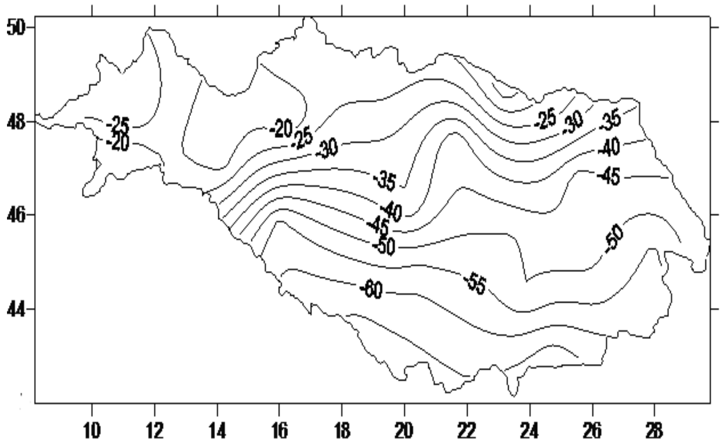

Fig. 7. Spatial distribution of relative deviations (%) of annual climate runoff in the Danube basin according to the A1B scenario (REMO model) for the period 2071-2100 compared to 1989

In the period 2031-2070, the interval of changes is within the «minus» 15-20% in the northwest and north to «minus» 50% in the south. In the period 2071-2100, the decrease in annual climate runoff is 20-25% in the north and northwest (if compared to the base period) and reaches 70% in the south. The obtained results of the calculations of water resources by the «climate-runoff» model make it possible to conclude that a significant reduction of water resources of the Danube River will occur after 2030. The least affected by climate change will be the areas of the sufficient humidity. The plains and the southern part of the Danube catchment, which belong to the area of insufficient moisture, will be the most hit.

CONCLUSIONS

The climatic conditions of the 21st century by the A1B scenario at the Danube catchment are unfavorable for runoff formation. The positive component of the water balance (precipitation) remains unchanged and the negative component (evaporation) increases. The water resources of the area will decrease under such climatic conditions.

Changes in water resources will occur in different parts of the Danube catchment area. They will be the smallest in the northwest and north of the catchment area and will increase in the southeast. In the period 2031-2070, the reduction of water resources by the A1B scenario will reach 50 % in the south, and in the period 2071-2100 – 70 %.

The total annual runoff from the catchment of the Danube River was determined by «weighing» the values of runoff in areas by parts. It was established that the river water resources will decrease very gradually: in the period 1990-2030 – by 6,1 % (decreasing will not be statistically significant), in the period 2031-2070 – by 17,9 %, in the period 2071-2100 – by 22,0 %. This result is ensured by the high water content of the Danube mountainous zones, which are the areas of runoff formation. In mountainous areas that climate change will be least affected.

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HYDROLOGICAL DROUGHT AND FIRE RELATIONSHIP

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ABSTRACT

Drought can be defined in meteorological terms or in relative terms with respect to hydrology and ecosystems. Meteorological drought is not a necessary or a sufficient condition for fire, because fires burn during conditions of normal seasonal aridity. Drought occurs without wildfires in the absence of ignitions. However, when drought occurs, both live and dead fuels can dry out and become more flammable. Hydrologic drought as natural event is the result of long-lasting rainfall in the catchment area leading to the gradual depletion of water resources in the river network and the occurrence of a drought. Typically, hydrological drought is recorded as a river runoff below acceptable critical value.

The authors explore the relationship between hydrological drought and forest fires. They present projections of fire-related drought indicators: the hydrologic indicator 7Q10 (the lowest 7-day average flow that occurs on average once every 10 years). The implementation of the hydrological drought as an approach for fire risk assessment has just started in Bulgaria. For this purpose, the assessment of the feasibility of using the hydrological 7Q10 drought index as a fire hazard indicator in real time is based on archive information on the variation of hydrological characteristics in the river network before and during an actual fire in an accepted pilot catchment.

The Hydrologic Index 7Q10 for the pilot catchment of the Struma River was determined according to the rules for the last 15 years (2003-2017) using the daily water flows from all hydrometric stations

The results of the presented study confirm the possibility of using the hydrological 7Q10 drought index to assess the risk of real-time fires by information on runoff from operational hydrological stations. One of the largest fires in the Struma River in 2017 occurred in an area identified as a fire on a highly hazard area according to the hydrological drought index 7Q10.

Keywords: hydrology, drought, fires, indexes

INTRODUCTION

The historical relationships between drought and wildfire are well documented in many countries, with forest fire occurrence and area clearly increasing in response to drought. There is also evidence that drought interacts with other controls (forest productivity, topography, fire weather, management activities) to affect fire intensity, severity, extent, and frequency (Littell et al. 2006, 2010, 2011, 2016).

Meteorological drought is a period of significant deficiency of rainfalls or even a prolonged lack thereof. This deficiency is closely linked to a number of more factors, such as high temperature and high-speed winds, which inevitably increase the total evaporation. The meteorological drought occurs when rainfall cannot compensate for the physical evaporation and transpiration of plants, and falls below a certain level, depending on climatic and regional characteristics. Meteorological drought analysis refers to monthly and annual time series of rainfall, on the basis of which the corresponding exceeding thresholds (Adler and et al. 2015).

Hydrological drought, characterized by reduced volume of lakes, reduced groundwater levels and reduced river runoff may occur over a period of one or several consecutive years, often affecting large areas. Climate variations are the main natural physical determinant of its degree of manifestation but human activity also influences (Smakhtin, 2001).

Hydrological drought is a rare hydro-climatic phenomenon, with a negative frequency deviation in the amount of water fed by rainfall, compared to the average multiannual value considered as "normal". When hydrological drought occurs, the result of its occurrence is felt in much wider territories in terms of space and time, and usually affects users in the lower parts of the studied river basins. According to many accepted definitions, the spatial and temporal variation of hydrological drought is expressed by the shortage of groundwater and surface water. Hydrological drought can be defined by the following characteristics: absence of rainfall and reduced humidity; the abnormal deficit in reference statistics (average and normal for the climate) and the continued manifestation of this deficit (Adler and et al. 2015).

Meteorological drought is not a necessary or sufficient condition for fire because fires burn during conditions of normal seasonal aridity. Both fire and hydrologic drought occur with some lag after meteorological drought begins. Such relationships could be useful, because fire forecasts based on the same mechanisms could be built from the substantial infrastructure and capacity for forecasting hydrologic drought. Index that can be used to define drought may at least determine the ability to detect mechanisms by which hydrological affects wildfire. The hydrologic indicator 7Q10 (the lowest 7-day average flow that occurs on average once every 10 years) is a fire-related drought indicated invented and implemented in US to predict fires in forest national parks and is based on the water balance deficit in the water system critical for fire occurrence. (Littell et al. 2016).

METHODS AND DATA (STUDY AREA)

According to the definition drought indicator 7Q10 is the lowest average discharge over a period of one week with a recurrence interval of 10 years. Since the value of number of years for the 7Q10 is 10 years, there is only a 10% probability that there will be a lower flow in any given year. There is a 90 % probability that the flow will be greater than the 7Q10 value. The relationships between fire occurrence of wildfires and the above drought indicator related to the water balance deficit and streamflow is proven in many ecosystems is US (Littell et. al. 2006, 2010, 2011, 2016).

The drought indicator 7Q10 is implementing in Bulgaria now. The very good result of this indicator appliance, as a fire predictor, is demonstrated in the present material. The indicator was applied and successfully validated during the real and very severe wildfire in Kresna Gorge on 24-29 August 2018.

The drying indicator 7Q10 is a very strict index where the probability of occurrence of wildfire is already a reality. The water deficit in the ecosystem has reached a threshold where the presence of ignition factors and materials that can burn makes the fires an imminent danger. Notwithstanding the usefulness of such an indicator, we also need other drought indicators, which would have warned us earlier about the approach of fire conditions without this danger being necessarily imminent.

Such an index is the Standardized Runoff Index (SRI), implemented in the operational practice of the institute. The standardized runoff index is a tool suitable for characterizing hydrological drought relative to a river runoff. It is a standardized assessment of the outflow, allowing its values to be taken outside the normal range. It is similar to the Standardized Precipitation Index (SPI), based on the same basis as the river runoff basis that is appropriate for the river runoff. The index SRI can serve to identify past droughts as well as future droughts. For the diagnosis of the phenomenon drought can be associated with thresholds as follows: extremely wet SRI > 1.65; very wet 1.65; SRI 1.28; moderately wet 1.28; SRI 0.84; near normal 0.84; SRI - 0.84; moderate drought - 0.84, SRI - 1.28; severe drought - 1.28; SRI - 1.65 and extreme drought SRI < - 1.65. The last ones values can be used to identify areas of high and very high risk of fires.

The Kresna Gorge is a forest National Park located in the Struma river catchment with a significant Mediterranean climate influence and hot dry summers. The Struma River is among the biggest rivers flowing both in Bulgaria and Greece. The upper and the middle streams are situated on the Bulgarian territory. On the Greek territory, the river Struma inflows into the Mediterranean Sea at open large valley. The watershed area till the boundary is 1097 km2; average altitude is 900 m – Fig.1 *a*. The climate is a mixture between the European continental and Mediterranean. The climate of the northern part of the basin is of continental type and gradually moves to the Mediterranean type towards the southern part of the catchment area. Annual precipitation amounts vary between 500 mm for the plains and 1200 mm for the plains high mountain parts of the catchment area. The monthly precipitation amounts are relatively evenly distributed, with a maximum at the end of spring due to the influence of the continental climate in the northern part and another maximum at the beginning of winter which is more pronounced in the southern part of the catchment area. During the summer heats there are periods with significant droughts. The heats and dry winds flow easily into the area near Kresna Gorge thanks to the topography - a "funnel" open to the sea.

The climatic and topographical features of the area make comparatively frequent forest fires during the hot summer months. Examples of registered fires close to the towns last years were registered by the municipalities and fire protection services. The main parts of registered wildfires are in the middle and lower Bulgarian part of the watershed – Fig.1 *b*. The map shows only the recent fires because the registration of the wildfires has started only recently. The big fires in past exist only in the human memories. Anyway, the map shows that the fires are not rare events in the Struma region.

National Institute of Meteorology and Hydrology is a State scientific institution responsible for both monitoring, collection and interpretation of the hydrological information in Bulgaria. The total number of gauging stations in the Struma watersheds is 28. The operative stations among them are 11 and all of them automatic. The information from the operative is obtained every day and is available online openly. The non-operative stations are 17; the information is collected less frequently from recorders and is not available online. The usage of non-operative stations during the fire time required additional mobilization and observations. That is possible because these stations have a designated observer who, in extreme conditions (for example fires), can transmit information in real time. Information of the all gauging stations is used in the investigation – Fig. 1 *c*.

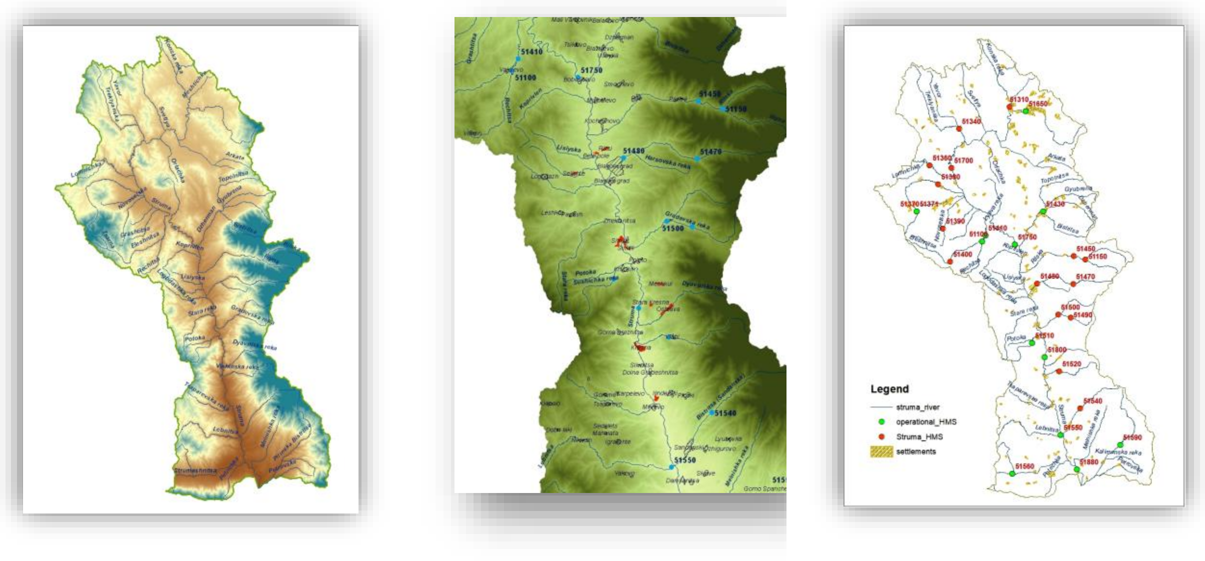

Fig.1. *a* – topography map of the Struma watershed /Bulgarian part/; *b* – map of registered fires last years; 1 *c* – map with gauging stations on the territory of the Struma watershed

The basic idea behind the usage of different drought indicators for fire protection is extremely simple but effective. Having the values of these indicators expressed as water discharge (m^3/s) at some gauging station and knowing the corresponding water levels we quickly can assess the risk of fire occurrence in the nearby area. If the values of the passing flows (or their respective water levels) are close to the value of 7Q10 or less then the danger of fire is imminent.

The SRI index can be used only for preliminary assessment of the deteriorating water conditions that could make possible occurrence of fires in the future. However, as part of NIMH operational practice, it can be used successfully without additional activities as a first warning of a looming fire hazard. The NIMH's website periodically publishes monthly maps showing in colors from blue to red different watersheds indicating various drought conditions at the moment.

The use of both indicators is discussed below in the case of a real large wildfire at Kresna Gorge.

RESULTS AND DISCUSSION

The Hydrologic Index 7Q10 for the pilot catchment of the Struma River was determined according to the rules for the last 15 years (2003-2017) using the daily water flows from all hydrometric stations. The specified index 7Q10 is considered to be the minimum flow runoff value in the rivers below which fire conditions are generated. The values for the hydrological indicator 7Q10 are calculated for all gauging stations in the Struma watershed in (m^3/s) and the areas with equal values of this indicator are determined after interpolations. On the Fig. 2 are visualized, using different green colors, the spatial distribution of the indicator 7Q10 and the gauging stations divided into operative and non-operative.

In the period 24-29.08.2017 in the area east of the Kresna Gorge in the valley of the Struma River happened one of the biggest fires for 2017, which affects 16,000 decares. The big fire has spread into forest areas, as well on significant grass and shrub barren areas. The fire occurred in the grassy heathlands south of the Mechkulska River and quickly spread to the south, reaching the villages of Stara Kresna, Oshtava and Vlahi. The protected area in the gorge is also partially affected. On the map below is shown the burned area during the fire with red color - Fig. 3.

Years after the fire broke out near Stara Kresna village the eco-catastrophe over the gorge not completely overcome leaving destroy pine forests and burned houses. Shortly before 2 pm on August 24 a fire broke out. The smoke pillar was visible from Blagoevgrad and Sandanski towns (mote the 40 km), the fire reached Vlachy village, Kresna municipality was extinguished. The headquarters headed by Interior Minister was closed on 29 August. In the fire that passed through the villages of Oshtava and Stara Kresna, 10 houses were burned, two of them inhabited. Fortunately, there were no human casualties. It has been identified as one of the largest eco-catastrophes in the country in the last 20 years. The logging of the burned wood is over recently, only the stumps of the cut pines, as well as the stones cracked by the fire, protrude from the burnt earth. And trees that are not fit for felling, “jutting” out into the sky, as “signposts” to a destroyed and living eco-system.

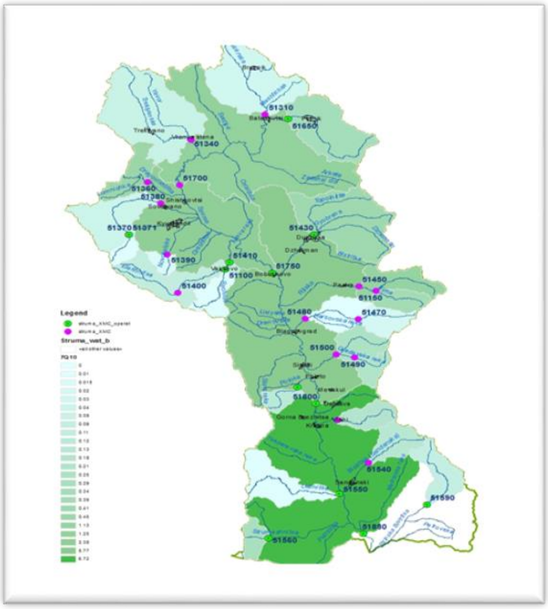

Fig. 2. - The spatial distribution of the indicator 7Q10

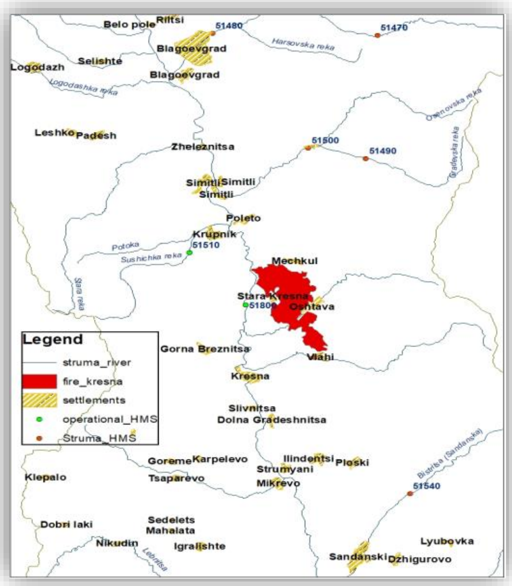

Fig. 3. - The burned area during the fire

The wildfire event in August 2017 lasts six days. For each day between 24 and 28 August are determined the running daily flows at any gauging stations. They are compared to the previously calculated values for the indicator 7Q10 in (m^3/s). As result six maps are prepared, day by day, of fire risk zones with running water <7Q10 for where areas in fire risk are colored in light brown and the zone in non-fire risk in blue – Fig. 4. Obviously, the whole area above or close to the fire is in area in fire-risk all the time. The burned fireplace is located just at the end of the risky zone where the risky factors are more concentrated. They are result not only of the local factors as flammable materials but the impact of the whole severe drought above on the water conditions at the fireplace.

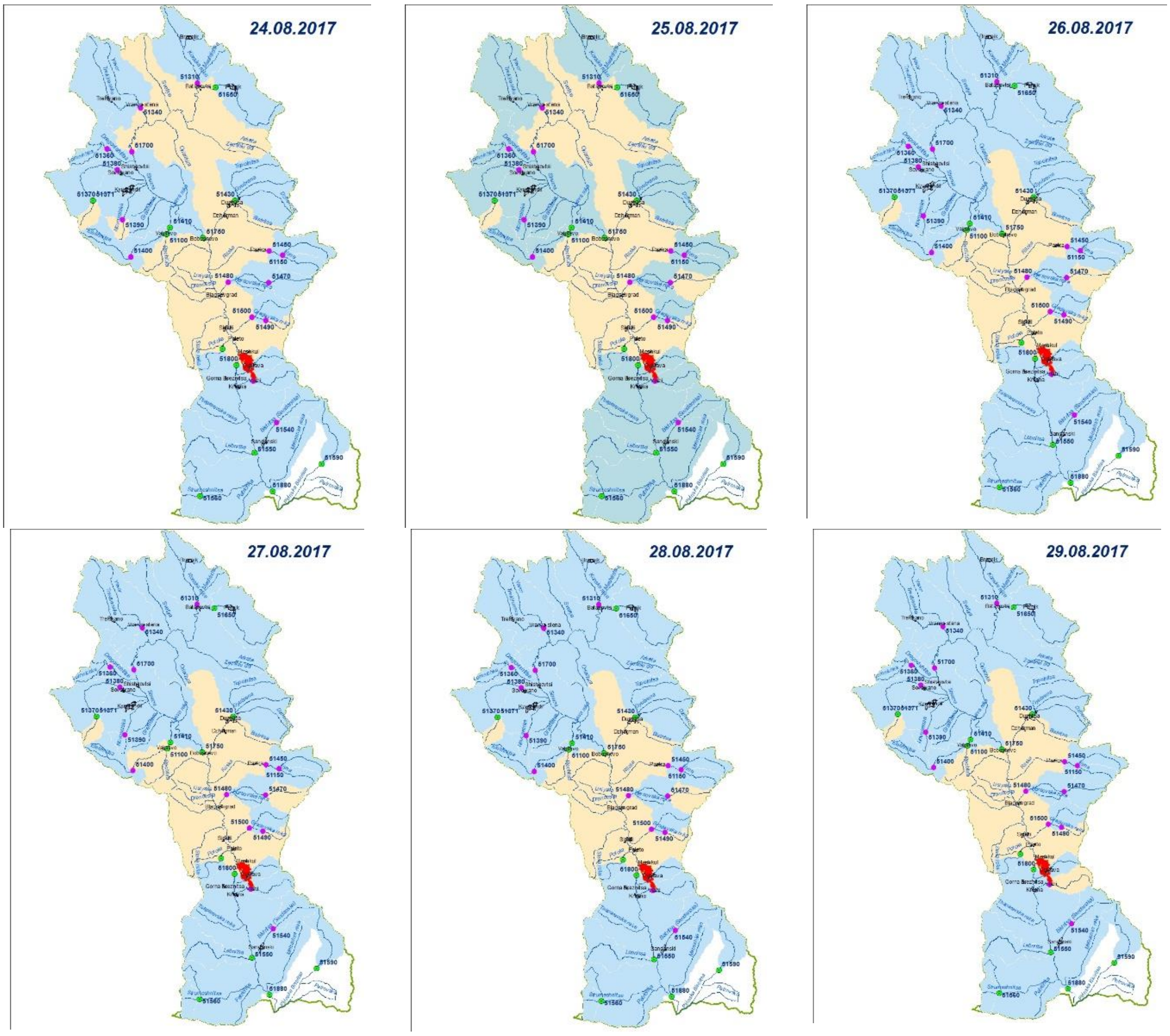

Fig. 4. Risk zones with running water <7Q10 for the period 24-29.2017 (day by day)

Photos of the Kresna Gorge fire in August 2017

In the area of the wildfire exists a gauging station Kresnensko hanche (N 51800), opened in 1950 and working continuously until nowadays. Comparing calculated 7Q10 and measured flow values during the real demonstrates in a categorical way that daily flows consistently decrease as they approach the moment of fire, but the flows fall below the 7Q10 indicator value entirely around the time of the fire event - Fig. 5. This is indisputable evidence of the relationship between the minimum water quantity and the relevant significant water deficit in the ecosystem determined by the above indicator and the actual risk of fires in the presence of such conditions on land. Some daily flow values at the Kresnensko hanche station compared to the calculated 7Q10 indicator in (m^3/s) for the critical period of the fire in August 2017 are shown in the Table 1.

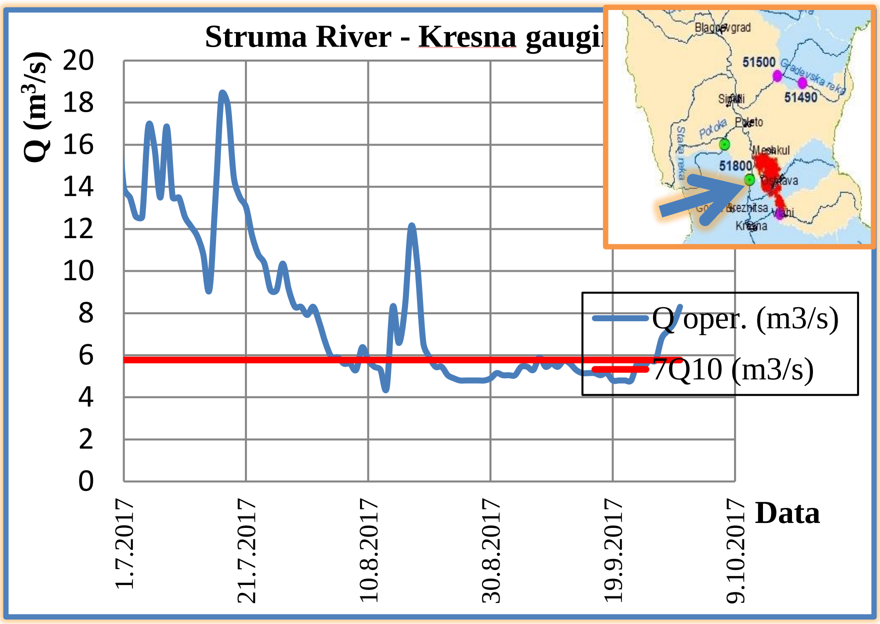

Fig. 5. Juxtaposition of calculated 7Q10 and daily flow values during the real fire

Table 1. Daily flows at the Kresnensko hanche station compared to 7Q10 value in (m^3/s)

23.8.2017	24.8.2017	25.8.2017	26.8.2017	27.8.2017	28.8.2017	29.8.2017	7Q10
Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)
5.05	4.90	4.80	4.80	4.80	4.80	4.80	5.77

The results of the presented study confirm the possibility of using the hydrological 7Q10 drought index to assess the risk of real-time fires by information on runoff from operational hydrological stations. One of the largest fires in the Struma River in 2017 occurred in an area identifies as a fire highly hazard area according to the hydrological drought index 7Q10.

The indicator 7Q10 surely defines imperatively the real fire risk. But we need some other more indexes (or characteristic flows) which will extend the boundary for the preliminary warning for fires. We need not just a red warning flash where the danger is immediate or even factual. We need a less severe drought indicator to sharpen our attention before the risk of fires is so great. The above mentioned Standardized Runoff Index (SRI) is suitable for these purposes. There are many indices relevant to drought assessment. The Standardized Runoff Index has the advantage of being widely known, comparable and easy to calculate. It expresses the standardized assessment of the dispersion of the outflow relative to the mean over a period of time (McKee et al., 1993, Shukla, Wood, 2008). The index calculation is performed on the basis of river outflow data transformed by standard normal distribution over a specified time step.

Available and reliable information is available to determine this indicator. However, it must be emphasized that SRI is not directly related to fires and the conditions for their occurrence but to the overall conditions of the drought. Its use for the purpose of forecasting and fire alarm to the relevant services and/or population is unjustified. The index SRI can serve professionals and scientists in their operational practice as a preliminary indicator.

Different durations (e.g., 1-month, 9-month) and different spatial aggregations of the index can be calculated depending on source data resolution and desired application. Definition of new severity thresholds based on the probability of exceeding an observed runoff value, which will have an associated SRI value. These values, quoted above, determine the different drought conditions following: extreme drought - runoff value exceeded 95 % of the time, corresponds to SRI = - 1.65, severe drought - runoff value exceeded 90 % of the time, corresponds to SRI = - 1.28, mild drought runoff value exceeded 80 % of the time, corresponds to SRI = - 0.84. On the Table 2 "Standardized Runoff Index for Struma basin 2017" in different colors from red till yellow are indicated the different stages of drought condition at different gauging stationc and their adjacent areas month by month. The light or deep green and blue colors indicate the different wet conditions according to the same index. Obviously where the color is red at this station and in this month the drought conditions are worsening and we must keep in mind the reduced water content in the ecosystem and the already registered water deficit. This deterioration of water resources and water scarcity is not yet a sufficient cause for fire alarms, but it is a cause for caution.

The Table 2 is very indicative with its color images for the period during which fires can be expected. Although it is only for one year demonstration - the year of the fire study 2017, it is extremely clear to see the summer months in which this phenomenon can be expected in the Struma watershed, as well as the periods where the probability is insignificant. However, the high water content in the springtime almost eliminates the possibility of wildfires. A multiannual analysis may also outline the most endangered areas around gauging stations with higher wildfire probability from hydrological point of view.

Table 2. Standardized Runoff Index for Struma basin 2017 for all hydrometric stations

Year	Struma River - HMS																										
2017	51310	51340	51360	51370	51380	51390	51100	51400	51410	51510	51550	51560	51430	51150	51450	51470	51480	51490	51500	51520	51540	51590	51650	51700	51750	51800	51880
1	4	3	4	2	4	3	4	3	3	3	4	4	4	3	3	3	3	4	3	3	4	4	4	4	3	3	3
2	5	4	4	4	4	2	4	4	4	4	4	4	4	3	3	4	4	4	4	2	4	4	4	4	4	4	4
3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	5	4	4	4	4	4
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
5	4	4	4	4	4	4	4	4	4	4	4	4	5	5	7	6	6	4	5	6	4	4	5	4	4	4	4
6	4	4	4	4	4	4	4	4	4	4	4	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
7	3	4	4	3	4	2	3	4	2	4	4	3	4	4	4	4	4	2	3	4	4	3	3	3	3	3	2
8	2	3	3	3	2	2	2	2	1	2	2	2	3	4	4	2	1	1	2	3	3	3	4	3	1	2	1
9	2	3	3	4	2	2	2	2	1	2	3	2	3	4	3	1	1	2	3	3	4	3	2	3	2	2	1
10	3	3	3	3	3	2	2	3	2	3	3	2	4	4	3	3	3	3	4	4	4	4	3	3	3	2	2
11	4	3	3	4	4	4	2	3	3	3	4	4	4	4	3	4	4	3	4	4	4	4	3	3	3	3	4
12	5	4	4	7	7	5	4	7	6	4	4	4	5	4	4	4	4	4	4	5	7	6	6	5	5	4	4

Finally, back to the fire in August 2017. On the maps below Fig. 6 – there is a very clear and simple visualization of the positive warning effect using the Standardized Runoff Index (SRI). On the maps the two neighboring watersheds - Struma and Mesta (smaller one) are presented. The assessment using indicator SRI is very rough been calculated and spread all over the whole watersheds. But any way in July we have assessed a severe drought in the Struma watershed (in orange warning color on the map) and wet conditions in the near Mesta catchment. In August we have already extreme drought in the Struma watershed (in red warning color on the map) and real wildfire events. At the same time the conditions in the Mesta catchment are only worsening (in yellow) been away from risky fire conditions and without any fire registered in this month.

Drought is a natural event that, unlike floods, does not occur in a sudden burst but gradually happens. This length of the process allows sufficient time before the conditions for fires to be prepared for such possible development using more general drought indexes as the Standardized Runoff Index. Reporting of extreme drought in an area, of course, does not necessarily imply the occurrence of fires when the water conditions deteriorate additionally. But a warning of such potential danger is certainly useful. In Bulgaria there is not experience in the usage of hydrological approaches and indices for wildfire predictions but only for meteorological ones. But the link between wildfires and the water deficit in the river basins is obvious and that attitude will alter.

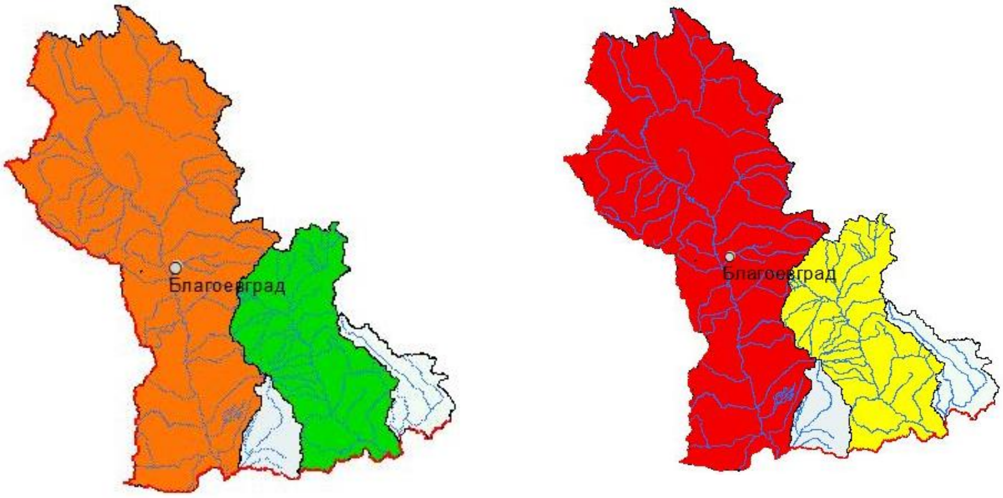

Fig. 6. The Standardized Runoff Index for Struma basin compare to the nearby Mesta basin - July (left map) and August (right map) 2017

The observed and expected impacts of climate change indicate the increase in the observed annual temperature and decrease in precipitation over the territory of the country the coming decades. Such development is unfavorable in terms of the frequency and magnitude of extreme droughts in the future and their relation to fires. This additionally makes the issue of fire prediction and preventive measures even more relevant, including the use of various approaches such as the hydrological drought indicators.

CONCLUSIONS

Combating extreme droughts and the resulting wildfires has always been a problem in Bulgaria with serious economic consequences. There are numerous meteorological indicators that take into account droughts and their relation to fires. However, there are only few hydrological indicators determining the risk of fires provided that the hydrological drought determines conditions suitable for this phenomenon.

The presented material deals with hydrological indicators assessing droughts and the relationship with fires as a means of forecasting. Particular attention is paid to the indicator 7Q10 which quality as a fire predictor is demonstrated, by the example of a real fire in Bulgaria. The use of hydrological indicators is applied for the first time to assess wildfire risks in Bulgaria. Further verification of the indicators is considered at other parts on the territory of Bulgaria and consequently implementation of this approach into the operational activities of the National Institute of Meteorology and Hydrology. From the operational point of view minimal additional organizational work is required. Hydro-observers are appointed in all hydrometric stations in Bulgaria. It is sufficient, when a critical water level corresponding to a water flow Q10 is approaching or reaching, the observer to inform the operational hydrologists in the institute. That is a reason for wildfire warning in the area around the gauging station.

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DEVELOPMENT OF STREAMFLOW DROUGHT INDICES IN THE MORAVA RIVER BASIN

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ABSTRACT

The territory of Czechia currently suffers from a long-lasting drought period which has been a subject of many studies, including the hydrological ones. Previous works indicated that the basin of the Morava River, a left-hand tributary of the Danube, is very prone to the occurrence of dry spells. It also applies to the development of various hydrological time series that often show decreases in the amount of available water. The purpose of this contribution is to extend the results of studies performed earlier and, using the most updated daily time series of discharge, to look at the situation of the so-called streamflow drought within the basin. 46 water-gauging stations representing the rivers of diverse catchment size were selected where no or a very weak anthropogenic influences are expected and the stability and sensitivity of profiles allow for the proper measurement of low flows. The selected series had to cover the most current period 1981-2018 but they could be much longer, which was considered beneficial for the next determination of the development direction. Various series of drought indices were derived from the original discharge series. Specifically, 7-, 15- and 30-day low flows together with deficit volumes and their durations were tested for trends using the modifications of the Mann–Kendall test that account for short-term and long-term persistence. In order to better reflect the drivers of streamflow drought, the indices were considered for summer and winter seasons separately as well. The places with the situation critical to the future water resources management were highlighted where substantial changes in river regime occur probably due to climate factors. Finally, the current drought episode that started in 2014 was put into a wider context, making use of the information obtained by the analyses.

Keywords: climate change, nonstationarity, stochastic processes, statistical hydrology, Moravia

INTRODUCTION

The current long-lasting drought period in Czechia has steered the attention of the public and many scientists to the question whether climate change is responsible for the origin of such a situation. Indeed, according to Šercl *et al.* (2019), the beginning of the period dates back to the winter 2013/2014 which was characterized by less amount of snow cover and higher air temperature. During the next months, the combination of prevailing lack of precipitation and above-normal air temperature did not help overcome the adverse conditions where even groundwater recharge was lowered, which, in turn, influenced also the amount of water in rivers, and the phenomenon known as streamflow drought developed. The water deficit has not been compensated even though some of the next winters were again rich in snow. Despite the presence of several water reservoirs in Czechia, some parts of it have suffered from the water shortage affecting various sectors of economy including agriculture and water supply (e.g., Ledvinka, 2015*a*), which, incidentally, was the main impulse to establish interministerial bodies addressing the issues connected with drought, and to financially support those who combat the drought, either actively in the field or from a scientific point of view. Several papers have been published, various seminars, workshops or meetings have been organized (e.g., CHMI, 2018a, 2019), the development of a new online system aimed at the prediction of drought occurrence has been initialized (Vizina *et al.*, 2018), and reports summarizing meteorological and hydrological conditions have been made publicly available, either for the entire territory of Czechia (Daňhelka *et al.*, 2015; Daňhelka and Kubát, 2019) or its specific regions (CHMI, 2018b). Everybody agrees that, so far, the worst effects have been observed in eastern Bohemia in the basin of the Elbe River above the confluence with the Vltava River, and in the Morava River basin. The years 2015 and 2018, to which one can add also the year 2016 (eastern Bohemia), have been considered the driest in these parts of Czechia during the entire episode. Climatologists hypothesize that there have been some changes in the circulation patterns over Central Europe and that the frequency of individual mechanisms resulting in the occurrence of rain and snow in Czechia have been changing, influencing the water cycle as well (Šercl *et al.*, 2019).

Bearing in mind the above-mentioned facts, the purpose of this contribution was to take advantage of

1) the existence of the list of a number of water-gauging stations from Czechia that have been recently assessed so as to find out how they behave during low flows from the perspective of the sensitivity and stability of their profiles, as well as from the perspective of possible anthropogenic impacts (Šercl *et al.*, 2016),
2) the accessibility of log time series of discharge in a daily time step at the Czech Hydrometeorological Institute (CHMI), many of which cover the periods longer than the current 30-year Czech hydrological reference period 1981–2010

and, using the combination of the above information, to perform an analysis that would substantially contribute to the knowledge of the changing water cycle in Czechia. Since the basin of the Morava River, a left-hand tributary of the Danube, has been highlighted as one of the most problematic, the study stared here, trying to answer the question whether the drought-related indices derived from the mean daily discharges (QD) of selected water-gauging stations reveal any temporal trends defined as gradual (monotonic) changes in terms of hypothesis testing which, moreover, takes into account the effects of short-term persistence (STP) or long-term persistence (LTP), both possibly present in the available time series.

The study further describes the methodology, explains what streamflow drought-related indices were subjected to it, then discusses the results and, finally, concludes with the recommendations.

DATA AND METHODS

The primary effort was to avoid the anthropogenic impacts on the discharge and to study mainly the natural forces influencing the fluctuation of water table in rivers, of which the climate itself has likely one of the most important roles (if we assume channel hydraulics stable, or if its changes are correctly captured by rating curves converting water level to discharge). Therefore, only water-gauging stations where no or weak anthropogenic influences are expected according to the investigation of Šercl *et al.* (2016) were further considered. Because streamflow drought-related indices had to be subjected to the analyses, we looked also at the suitability of the stations from the perspective of the stability and the sensitivity of the profiles during low flows (Šercl *et al.*, 2016). Furthermore, criteria applied that the time series of QD, from which we wanted to derive the series of indices, should cover the period from 1 November 1980 to 31 December 2015 and, according to the general rules for the inclusion of the stations in the reference network (Whitfield *et al.*, 2012), that their observations should continue (i.e., records ended on 31 December 2018 in this case). Measurement interruption was allowed only before 1 November 1980. This was because the current Czech hydrological reference period starting just on 1 November 1980 and ending on 31 October 2010 was considered the common period that should be investigated across all stations. The compromise between the criteria finally resulted in the selection of 46 water-gauging stations representing the Morava River and its tributaries. Their location is shown in Fig. 1 where their database numbers are provided as well. Figure 2, on the other hand, depicts the detail of the Morava River basin together with the names of the 46 stations. Basic morphometric characteristics of the subbasins delineated by the stations are given in Table A.1 in Appendix. For instance, the catchment size ranged from 4.17 km^2 (station 374000) to 9144.83 km^2 (station 421500) with a median value of about 150 km^2.

The lengths of the individual basic QD discharge series are shown in Fig. 3 where the missing values are mapped for the hydrological years used in Czechia. From Fig. 3 it is apparent that the lengths differed before the analyses. The longest, and uninterrupted, QD series starts on 1 November 1911 and continues until today (station 355000). The beginning of the shortest QD series represents the day of 1 November 1979 (station 441500). The longest segments without missing values were further sought, which was done using the ‘na.contiguous()’ function implemented in R statistical software. However, before doing this, some of the QD values for station 429500 had to be guessed. For now, we did not want to devote our analyses completely to the phenomenon known in statistics as imputation, but, exactly for this station, the process could not be circumvented since there were missing values affecting about two months in one of the recent hydrological years 2017.

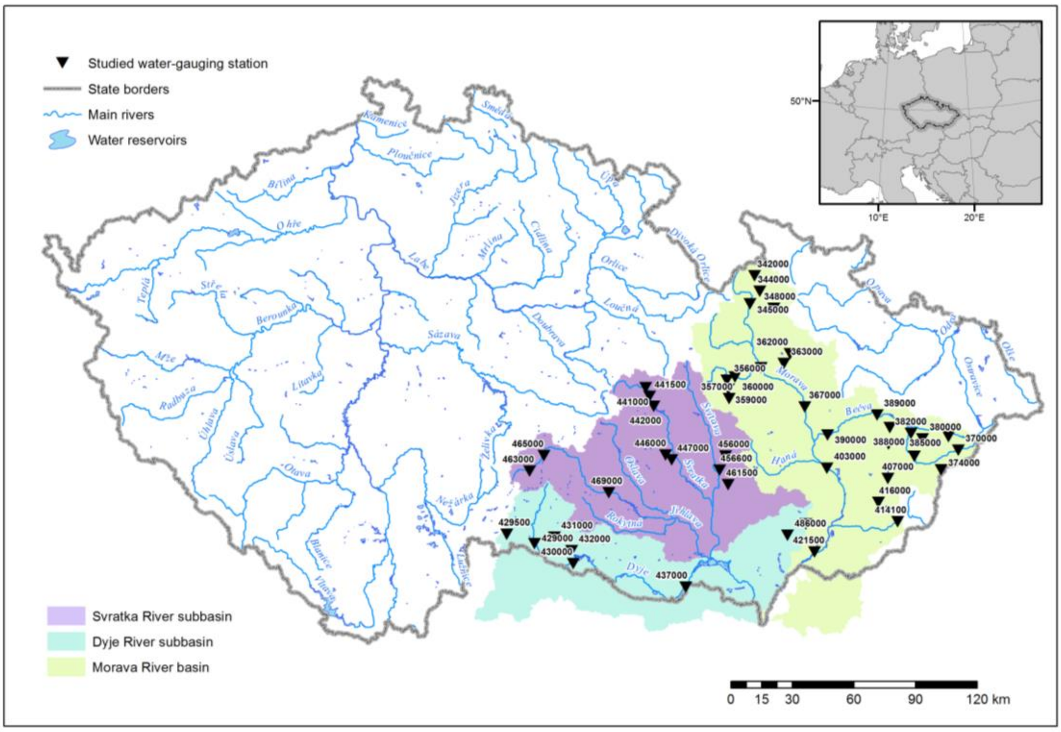

Fig. 5. Location of 46 selected water-gauging stations within the territory of Czechia and their database numbers

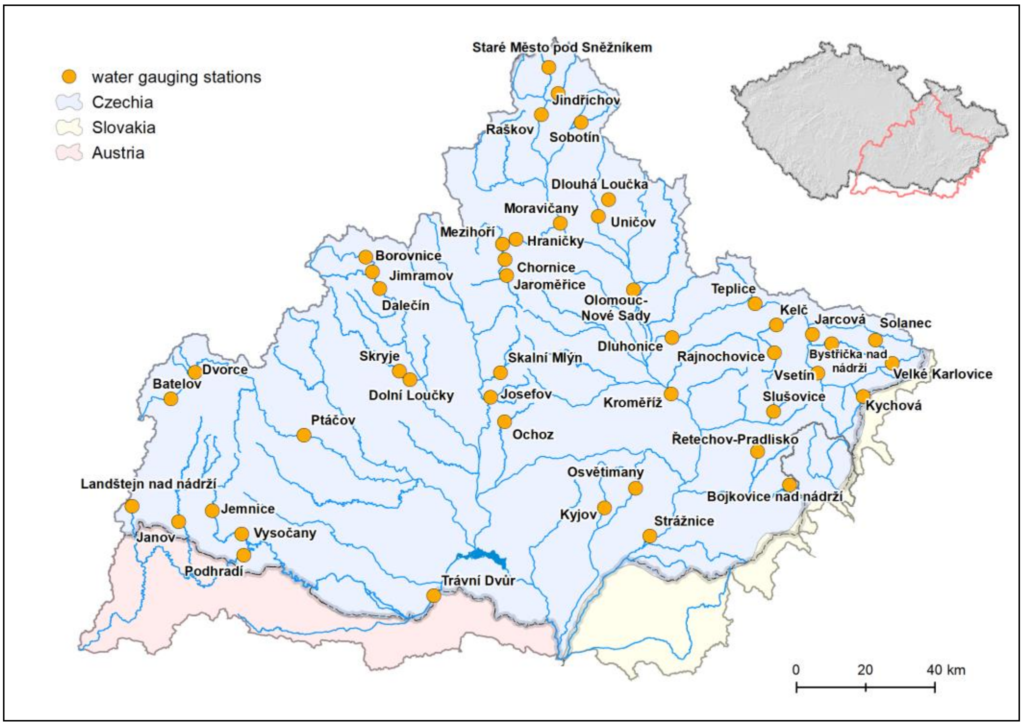

Fig. 2. A closer look at the study area of the Morava River basin and the 46 investigated water-gauging stations together with their names

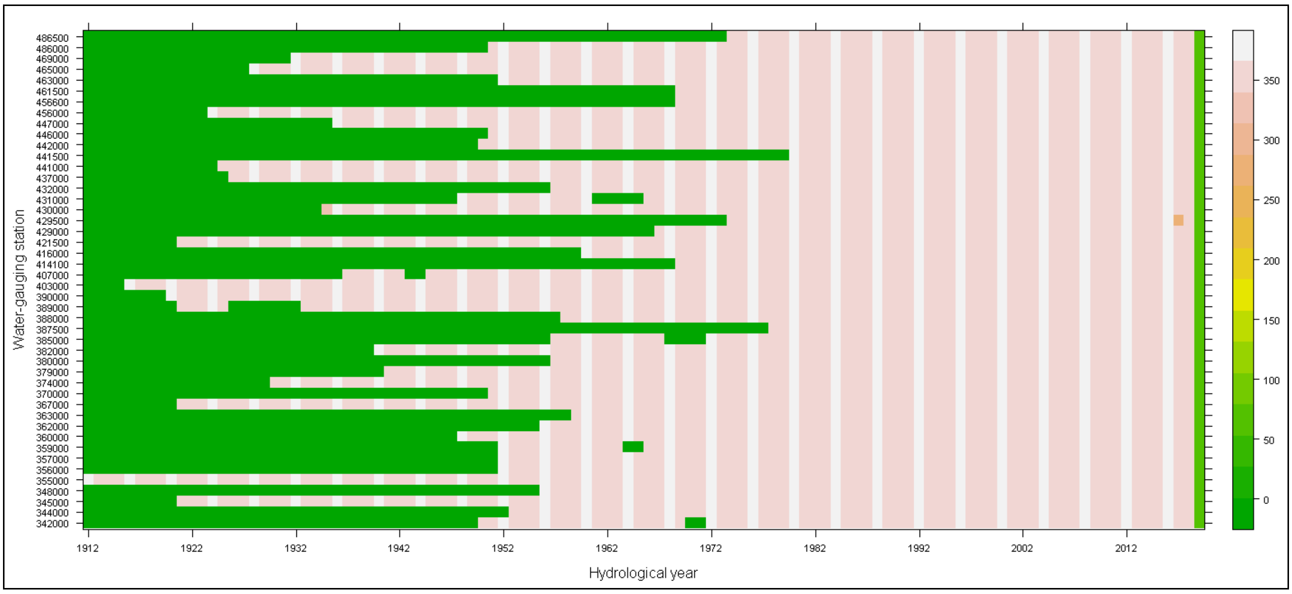

Fig. 3. Numbers of available mean daily discharge values at the 46 selected water-gauging stations in each hydrological year (previous November – actual October) of the period from 1 November 1911 to 31 December 2018. The leap years naturally manifest themselves as lighter stripes. The green stripe at the end of the plot means that there were only the first two months available for the hydrological year 2019.

Data imputation was performed by the function 'na_kalman()' which is part of the R package 'imputeTS' (see Moritz and Bartz-Beielstein, 2017, and the references therein). The structural model whose parameters were estimated by a maximum likelihood technique was then used for the estimation of a few missing QD values in 2017. Subsequent visual inspection of the time series plot (not shown) confirmed the validity of the model and the 'na.contiguous()' function could be then applied here as well. The other missing values were not estimated and addressing this issue was postponed to some of the future studies.

In the next step, two time periods were chosen:

1) the current Czech hydrological reference period 1981–2010 because we were curious about its representativeness, especially in relation to the recent dry episode having been experienced in Czechia, and
2) the longest period obtained by the R 'na.contiguous()' function that can be guessed from Fig. 3. Here, the beginnings of the QD series could naturally differ, but the ends were always 31 Decembers 2018.

Note, however, that for the purpose of analysing streamflow drought-related indices, we set up a different start of the hydrological year. According to the recommendations in Fiala *et al.* (2010) and after the visual inspection of polar plots constructed separately for the reference period and the longest periods that show the typical timing of the occurrence of a low flow in the year (Fig. 4), we selected 1 April where, after spring snowmelt, the probability of the low-flow occurrence should be very low. The new hydrological years were then denoted according to the calendar years which shared the majority of the months. In order not to mix the natural processes that lead to the generation of droughts, the hydrological years were divided into the summer season (April–November) and to the winter season (December–March), similarly as in Fiala *et al.* (2010) or Ledvinka (2015a).

The division was made especially due to the planned analysis of low flows representing the minima for each season separately. Specifically, the series of following indices were derived from the QD series for each year of the longest periods and the reference period, respectively:

- Q_{min7S} representing the summer 7-day low flow and Q_{min7W} representing the winter 7-day low flow,

- $Q_{\min15S}$ representing the summer 15-day low flow and $Q_{\min15W}$ representing the winter 15-day low flow,
- $Q_{\min30S}$ representing the summer 30-day low flow and $Q_{\min30W}$ representing the winter 30-day low flow.

Fig. 4. Polar plots showing (by black dots) the timing of occurrences of standardized annual (either summer or winter minimum) 7-day, 15-day and 30-day low flows altogether in each hydrological year of the reference period (left) and each possible hydrological year of the longest periods (right) for all 46 investigated stations. The standardization was carried out for each station separately so that the maximum low flow over all years equals 1.

When selecting and defining these indices, we were inspired by the work of Khaliq *et al.* (2008), and party by the work of Fiala *et al.* (2010) who analysed only the seasonal 7-day low flows to which they added also the annual (mixed) 7-day low flows. First, the original QD series were filtered by respective moving averages (of window widths equal to 7, 15 and 30 days) and, then, their minima were extracted from the filtered series for each season. To accomplish this objective, we used the function 'MAM()' implemented in the 'lfstat' R package (Koffler *et al.*, 2016) whose goal is to follow the methodology presented in the WMO manual (Gustard *et al.*, 2008). However, the function had to be slightly modified so as to obtain also the Julian days corresponding to the first occurrences of the minima falling to the seasons, which allowed us to create Fig. 4. For the seasons where the filtered series were not complete (due to the use of centred moving averages), we did not extract any minima and, consequently, these seasons were not subjected to trend analyses. Further information about this type of indices coming from the QD series can, for instance, be found in Tallaksen and van Lanen (2004) or Tokarczyk (2013).

The second group of streamflow drought-related indices derived from the QD series used here were the so-called deficit volumes that, basically, represent the amount of water needed to be added to the stream so as to reach again a threshold that has not been equalled or exceeded for some time period. This time period is a typical accompanying variable of deficit volumes and is called the drought duration. The method through which the deficit volumes are calculated is called the threshold level method (TLM) which is an analogy of the peak-over-threshold (POT) method used for floods. Because, in the case of drought, one is interested in the opposite extreme, the TLM is sometimes called the pit-under-threshold (PUT) method (Gottschalk *et al.*, 2013), or it has even other names in hydrology (Önöz and Bayazit, 2002). When looking for the missing amounts of water at our stations, we again employed the R package 'lfstat' (Koffler *et al.*, 2016) and its function 'find_droughts()' where, in order to be as close as possible to reality and after gaining some experience in Czechia (e.g., Vlnas and Fiala, 2010), the 95th percentile of the flow duration curve (FDC) was set as the threshold that, moreover, was allowed to shift according to the months. This means that non-constant (seasonal) thresholds were set, even though Czech national standards consider only constant thresholds (COSMT, 2014). It is worth noting that only the thresholds defined for the reference period ensuring comparability of the results were used. Furthermore, since there may be some minor exceedances of the thresholds but, in fact, they should be part of longer drought periods, the so-called pooling techniques are very important here. For this purpose, we selected the sequent peak algorithm (SPA; see, e.g., Tallaksen *et al.*, 1997; Tallaksen and van Lanen, 2004; Tokarczyk, 2013; Baran-Gurgul, 2018). Using the 'summary()' function applied to the object created by the function 'find_droughts()', we further left out the drought episodes with the duration less than 7 days and the deficit volumes with the magnitude lower than 0.5% of the maximum found for the station.

Finally, inspired by the paper of Hisdal *et al.* (2001), and setting zeroes for years with no drought episode, we got the time series of maximum and total deficit volumes and drought durations, both for the reference period and the longest possible periods for all the 46 water-gauging stations. Similar to the work of Ledvinka (2015b), we focused only on the summer season which, however, lasted until November. Namely, we obtained the series of the following indices (always for the 95th percentile of the FDC valid for the reference period):

- SSV_{95} representing the summer sums of deficit volumes,
- SSD_{95} representing the summer sums of drought durations,
- SMV_{95} representing the summer maxima of deficit volumes,
- SMD_{95} representing the summer maxima of drought durations that did not necessarily correspond to their deficit volume counterparts.

The last step was the trend analysis itself. Current studies indicate that there is a need to discriminate between STP and LTP before the application of a trend test because the original versions of the trend tests were designed for the data that are independent of each other, which, often, is not true in time series analysis in hydrology (Kundzewicz and Robson, 2000). This applies also to widely used nonparametric tests in hydrology such as the Mann–Kendall (MK) test that we wanted to employ. Therefore, we used the R package 'HKprocess' (Tyralis and Koutsoyiannis, 2011; Tyralis, 2016) and its function 'MannKendallLTP()' that, according to Hamed (2008), first checks whether the Hurst exponent, an important indicator of LTP, is significant. Depending on the results, we switched between the *p*-value accounting for LTP implemented in the R function 'MannKendallLTP()' or for STP (or white noise) in terms of the function 'mmky1lag()' which is part of the 'modifiedmk' R package (Patakamuri and O'Brien, 2019) and employs the MK test modification of Yue and Wang (2004). The direction of a significant trend (either at the 0.05 or 0.1 level of significance) was determined based on the Sen slope estimator (Sen, 1968) or the Kendall correlation coefficient measuring the dependence of a variable of interest on time (Kendall, 1970).

RESULTS AND DISCUSSION

A lot of results were obtained that were summarized in maps. The maps show that there are only very few significant changes in drought-related characteristics derived from the series of QD representing the Morava River basin, which corroborates the previous outcomes presented for the entire territory of Czechia (Fiala *et al.*, 2010; Vlnas and Fiala, 2010; Ledvinka, 2015a, 2015b). It must be mentioned here that, apart from STP, we considered LTP as well, and exactly this might have caused the lowering of the number of expected trends (e.g., Cohn and Lins, 2005; Hamed, 2008). Notwithstanding, some trends can be observed that, moreover, cluster in typical regions. However, due to space limits, we decided to present only the most important maps here.

In the case of the longest periods the series SMD_{95} reveal very strong upward trends in the catchments of the rivers Branná (station Jindřichov), Fryšávka (station Jirmanov), Říčka (station Ochoz) and Juhyně (station Rajnochovice). The station Rajnochovice on the Juhyně shows an increase also in the series of SMV_{95} (see Fig. 5) and SSV_{95}, which means that there must be groundwater resources drops as well. Otherwise, the groundwater would refill the surface waters on the northern slopes of the Hostýn Hills. Similar situation can be found in the catchment of the Fryšávka River which is a right-hand tributary of the Svratka River. The increasing trends at the Ochoz water-gauging station are interesting as well. Namely, the station is located below karstic springs. Here, one can observe an increasing trend in all the variables connected with the deficit volumes. From the perspective of the reference period 1981–2010, the station Bystřička nad nádrží (Bystřice River) unveils increasing trends in both deficit volumes and their durations, no matter when it comes to the summer maxima or sums. This can be valuable knowledge for water managers who manipulate the outflow from the reservoir Bystřička, as this situation may be repeated in the future.

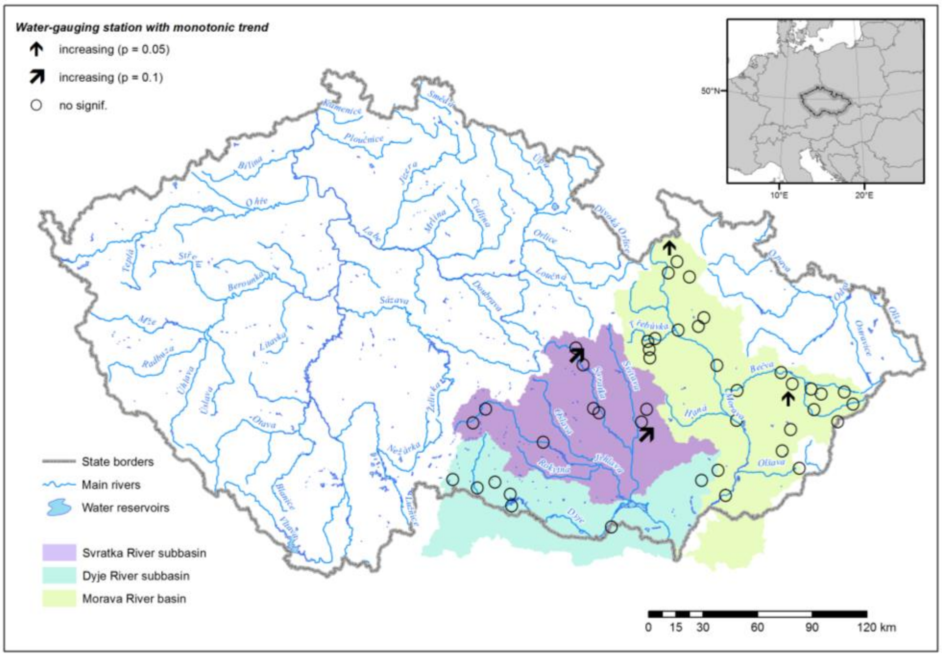

Fig. 5. Trends in the series of summer maxima of deficit volume for the longest periods

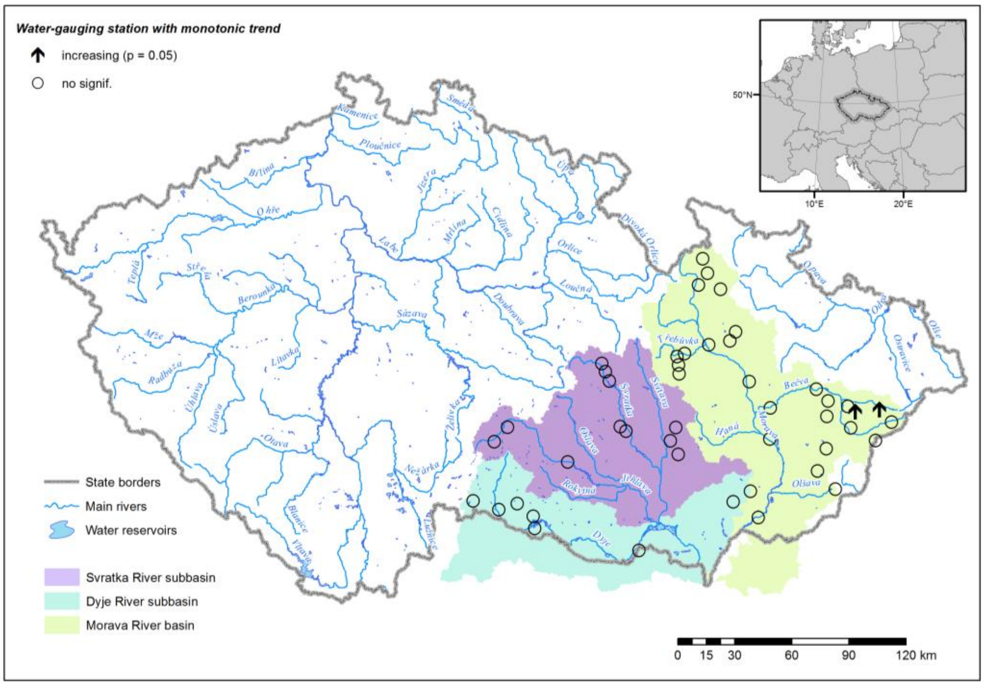

Fig. 6. Trends in the series of summer sums of drought duration for the reference period

After the analyses of summer (April–November) minima, and taking into account the longest periods, trends in the series of Q_{min7S} must be stressed that point to the decreases in water levels of streams draining the karst (see stations Ochoz and Josefov in Fig. 7). The spatial pattern of deficit volumes is somewhat inherited here as well. Namely, the station Rajnochovice on the Juhyně can be mentioned as an example. There are also subbasins of the Morava River basin where the same directions of trends occur regardless of the length of the smoothing window applied to the series of QD. The indices Q_{min7S}, Q_{min15S} and Q_{min30S} reveal substantial decreases at stations Sobotín (Merta River), Dlouhá Loučka (Loučka River), above-mentioned Ochoz, Josefov and Rajnochovice, Solanec (Hutisko Brook), and Bojkovice nad nádrží (Kolelač Brook). Regarding the reference period and the summer season, the Bystřička nad nádrží water-gauging station should be highlighted where the shift to the lower values of filtered QD series has been recorded for all the three indices corresponding to discharge minima. It seems that there is a good consistency between deficit volumes and minima, and, without a doubt, water manages should be aware of this behaviour of the Bystřice River above the water reservoir. When looking only at wider smoothing windows, namely at the series of Q_{min15S} and Q_{min30S} (Fig. 8), the station Řetechov-Pradlisko indicates drops in the water levels of the Ludkovice Brook.

On the contrary, the winter season (December–March) shows also the opposite directions of the development of discharge minima. Nevertheless, for the longest periods, it is true that we have observed prevailing downward trends, namely for the station Josefov (Křtiny Brook) where this pattern is supported by all the indices Q_{min7W}, Q_{min15W} and Q_{min30W}. However, when looking at the minima represented by Q_{min7W} (Fig. 9) and Q_{min15W}, upward trends are apparent at the Skryje water-gauging station (Bobrůvka River), indicating that the winter seasons may be characterized rather by rising discharge here, which is especially contradictory to the situation in summer 2018 with, historically, the lowest discharge values in this catchment. Of course, the very dry period 2014–2018 can be visible only using the longest periods analysed here and the information what happens before the summer low flows occur is more than valuable. The phenomenon of larger discharge minima in winters that do not correspond to the tendencies occurring in summers may be attributed to the changes relating to the snow cover, likely triggered by a warming climate (Jenicek *et al.*, 2016). The rising low flows at the Kychová station (i.e. the smallest catchment of the Kychová River with relatively long QD series; see Fig. 9) should definitely be studied from this point of view as well.

Having merely the data from the reference period would force us to conclude that, at a number of water-gauging stations in the Morava River basin, rather mitigation of winter low flows occurred until 2010. For all the indices Q_{min7W}, Q_{min15W} and Q_{min30W}, it happened in the Upper Morava River basin and in the Lower Bečva River basin – stations Staré Město pod Sněžníkem and Dlouhá Loučka for the Morava and Teplice and Dluhonice for the Bečva, respectively. Nevertheless, most increasing trends can be found for the case corresponding to the monthly width of the smoothing windows (i.e., for Q_{min30W}; see Fig. 10).

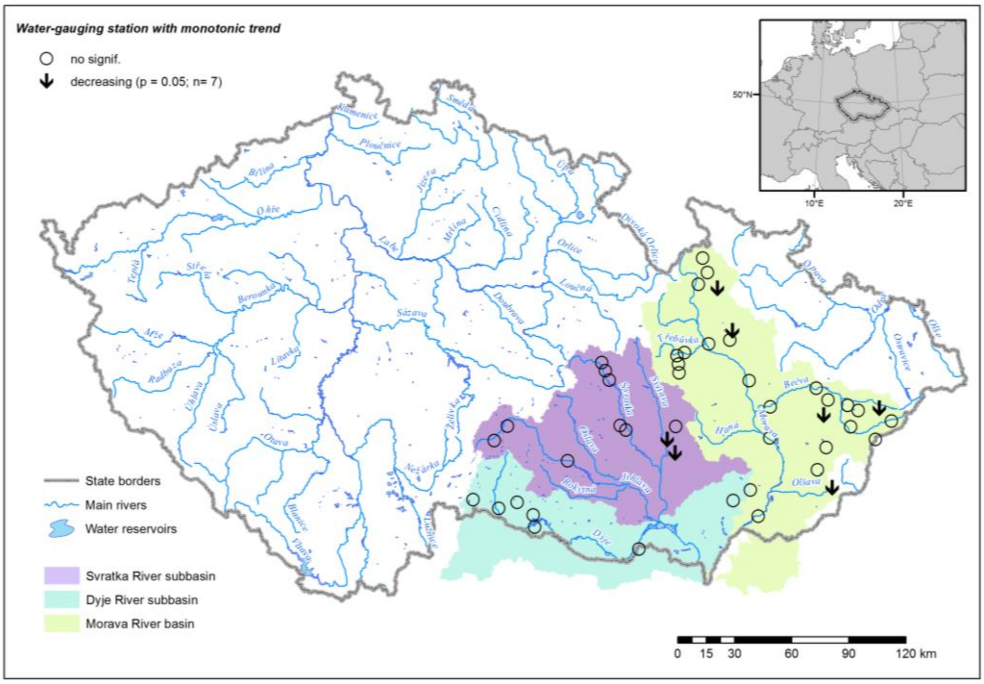

Fig. 7. Trends in the series of summer 7-day low flows for the longest periods

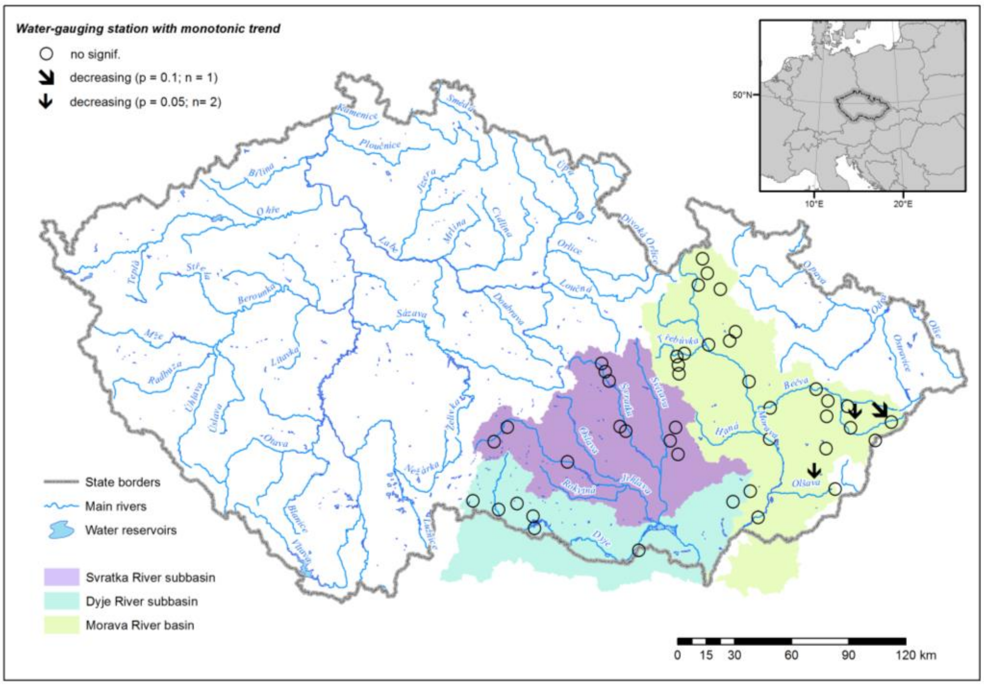

Fig. 8. Trends in the series of summer 30-day low flows for the reference period

At first glance, a compensation process occurring in winters might come across one's mind. However, before suggesting this, it would be necessary to know what happens now with snow in winters. During higher air temperatures, snow and ice may melt earlier than in the past, and the ratio of liquid precipitation to water stored in snow and ice probably rises. This all may cause the precipitation water to join the runoff much faster in current winters, which, on the other hand, does not necessarily mean that the overall water balance changes as well. Rather, the seasonal course changes in accordance with the behaviour of snow cover, which may have crucial effects on the occurrence of summer low flows (Jenicek and Ledvinka, 2019). Therefore, the pattern of increasing winter low flows (northern slopes of the Hostýn Hills, upper basins of the Jihlava River, the Morava River, the Svratka River, and eastern slopes of the Drahany Highlands), should be considered with caution.

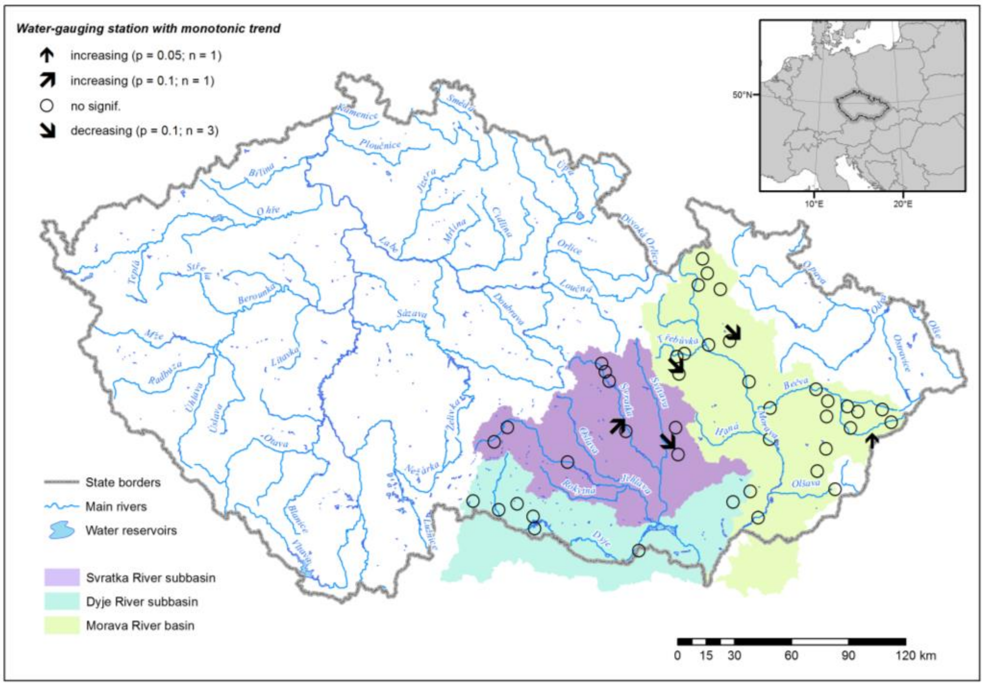

Fig. 9. Trends in the series of winter 7-day low flows for the longest periods

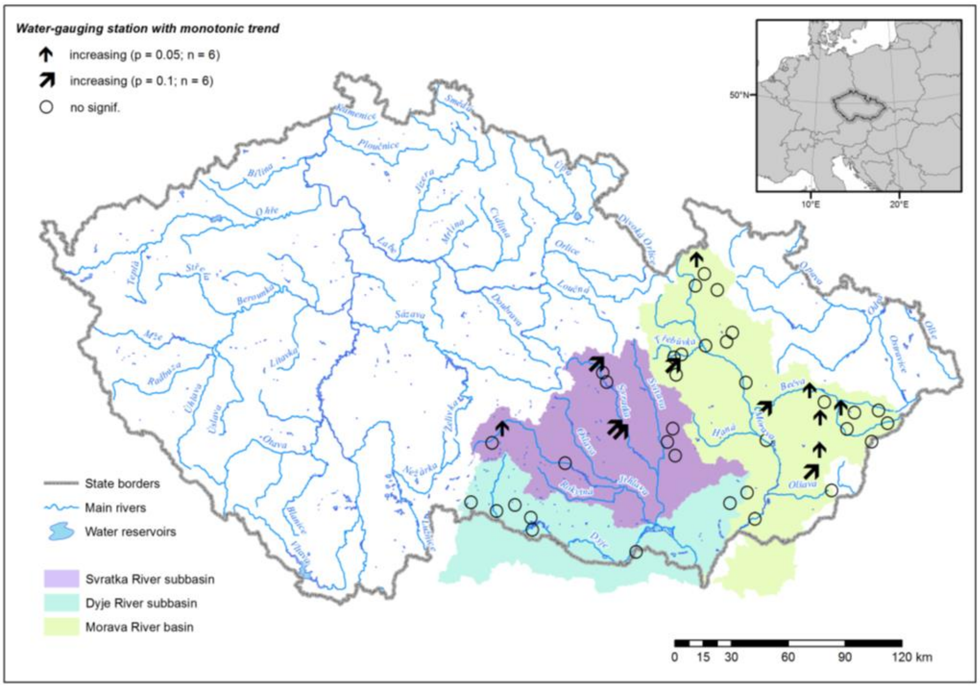

Fig. 10. Trends in the series of winter 30-day low flows for the reference period

CONCLUSIONS AND RECOMMENDATIONS

In this study, trends in streamflow drought-related indices were sought using the hypothesis tests that account for STP or LTP, namely the modifications of the MK test that have been developed in hydrology. The basin of the Morava River, and specifically the series of QD from 46 selected water-gauging stations were investigated, either for the case of the Czech reference hydrological period or the longest periods allowed by the lengths of the QD series. The analyses were done separately for the summer seasons (April–November) and winter seasons (December–March). The results show that, although the basin currently suffers from a long-lasting drought episode, there are almost no significant trends in the indices including the 7-, 15- and 30-day low flows or the deficit volumes and the drought durations. If some, one can observe rather increases in summer deficit volumes, which corresponds to the decreases in summer low flows, especially in the karst areas. On the other hand, winter low flows indicate that the Morava River basins experiences some changes in snow cover, likely due to a warming climate. It is apparent that, now, the snow cover melts earlier (or the ratio of liquid precipitation is getting higher) in winters, which causes the winter low flows to rise at some places. However, we assume that these rising low flows do not compensate the water deficits occurring in summers. Rather, they indicate the shifts in seasonal course that may have an adverse influence on the summer discharge (Jenicek and Ledvinka, 2019).

Regarding the reference period, some decreases in water resources above the Bystřička water reservoir were detected that water managers should take into account in the future. However, we are aware of the fact that a 30-year period is relatively short for the estimation of the Hurst exponent, an important characteristic indicating LTP (Montanari, 2003), and the results of the subsequent trend analyses may be somewhat biased. Therefore, we recommend that the longest periods should be analyses in the future. Looking at the lengths of the available discharge series (Fig. 3), one should also pay more attention to the missing values that could be filled in based on a rigorous imputation technique (e.g., Moritz and Bartz-Beielstein, 2017). One could also look at the frequency of the occurrence of dry episodes within each year in a similar way to Hisdal *et al.* (2001). Last but not least, we suggest studying physical-geographical characteristics of the catchments (such as those in Table A.1) so as to better understand the clustering of detected trends. Other types of changes in the series of the indices (i.e., different from gradual or monotonic ones) should be investigated as well.

ACKNOWLEDGEMENTS

The authors would like to thank especially to the team of Petr Šercl from the Surface Water Department of the Czech Hydrometeorological institute who carried out the investigation of the Czech water-gauging stations and highlighted those suitable for low-flows studies, which substantially helped us select the 46 stations for the Morava River basin.

APPENDIX

Table A.3. Basic morphometric characteristics of 46 selected subbasins of the Morava River basin delineated by the water-gauging stations for which the streamflow drought-related indices were computed

Station (ID)	River	Area [km^2]	Max. elevation [m a.s.l.]	Outlet elevation [m a.s.l.]	Mean elevation [m a.s.l.]	Mean slope [%]	Basin shape
Staré Město pod Sněžníkem (342000)	Vrbno Brook (Telčava)	21.94	1123	521	802	26	0.19
Jindřichov (344000)	Branná	90.31	1422	448	789	24	0.18
Raškov (345000)	Morava	349.79	1423	364	744	23	0.33
Sobotín (348000)	Merta	66.56	1385	405	759	30	0.34
Moravičany (355000)	Morava	1561.19	1491	244	553	18	0.25
Mezihoří (356000)	Třebůvka	177.44	661	306	428	12	0.23

Station (ID)	River	Area [km^2]	Max. elevation [m a.s.l.]	Outlet elevation [m a.s.l.]	Mean elevation [m a.s.l.]	Mean slope [%]	Basin shape
Jaroměřice (357000)	Úsobrnka	41.10	677	365	548	14	0.18
Chornice (359000)	Jevíčka	179.73	677	319	464	12	0.34
Hraničky (360000)	Třebůvka	426.17	677	308	462	13	0.39
Dlouhá Loučka (362000)	Loučka (Oslava)	80.79	809	261	558	20	0.19
Uničov (363000)	Oskava	256.25	956	235	484	16	0.30
Olomouc-Nové Sady (367000)	Morava	3323.58	1491	202	479	14	0.23
Velké Karlovice (370000)	Vsetínská Bečva	68.50	1023	506	730	30	0.37
Kychová (374000)	Kychovka	4.17	919	557	709	30	0.55
Vsetín (379000)	Vsetínská Bečva	505.81	1023	338	589	27	0.26
Bystřička nad nádrží (380000)	Bystřice	57.43	910	390	638	27	0.23
Jarcová (382000)	Vsetínská Bečva	723.87	1023	296	564	26	0.20
Solanec (385000)	Hutisko Brook (Leští Brook)	10.39	907	484	697	31	0.30
Rajnochovice (387500)	Juhyně	20.31	753	421	577	24	0.16
Kelč (388000)	Juhyně	86.12	864	297	474	17	0.10
Teplice (389000)	Bečva	1275.32	1205	242	518	22	0.17
Dluhonice (390000)	Bečva	1592.84	1205	235	513	19	0.11
Kroměříž (403000)	Morava	7013.27	1491	185	430	13	0.28
Slušovice (407000)	Všemínka	21.22	623	271	410	21	0.20
Bojkovice nad nádrží (414100)	Kolelač	9.76	574	323	405	12	0.48
Řetechov-Pradlisko (416000)	Ludkovice Brook	8.45	671	333	463	20	0.25
Strážnice (421500)	Morava	9144.83	1491	164	401	13	0.19
Janov (429000)	Moravian Dyje	517.96	836	442	564	8	0.22
Landštejn nad nádrží (429500)	Pstruhovec	6.36	722	577	655	11	0.33
Podhradí (430000)	Dyje	1755.49	836	349	558	-	-
Jemnice (431000)	Želetavka	145.69	702	438	539	7	0.17
Vysočany (432000)	Želetavka	368.71	702	411	522	6	0.13
Trávní Dvůr (437000)	Dyje	3535.06	836	159	458	-	-
Borovnice (441000)	Svratka	127.97	830	516	680	10	0.10
Jimramov (441500)	Fryšávka	65.93	829	500	694	10	0.11
Dalečín (442000)	Svratka	366.94	830	471	652	11	0.14
Skryje (446000)	Bobrůvka (Loučka)	222.01	821	311	560	10	0.07
Dolní Loučky (447000)	Bobrůvka (Loučka)	385.65	821	310	553	10	0.10
Skalní Mlýn (456000)	Punkva	154.17	735	344	577	9	0.13
Josefov (456600)	Křtiny Brook	66.03	600	288	498	12	0.10
Ochoz (461500)	Říčka	46.72	542	303	447	15	0.21
Batelov (463000)	Jihlava	73.48	788	543	636	7	0.25
Dvorce (465000)	Jihlava	307.35	791	502	620	8	0.24
Ptáčov (469000)	Jihlava	962.71	791	386	580	9	0.10
Kyjov (486000)	Kyjovka	117.49	564	188	332	16	0.07
Osvětimany (486500)	Hruškovice	9.54	552	268	392	18	0.19

Note: Hyphens indicate that, currently, the characteristics could not be computed easily because parts of the subbasins lie in the territory of Austria for which we did not have any digital elevation models at hand. Basin shape ranges from (stretched basins) to 1 (circular-shaped basins).

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TIME SERIES ANALYSIS AND FORECAST ESTIMATES OF THE MEAN ANNUAL WATER RUNOFF OF RIVERS IN OF THE PRUT AND SIRET BASINS (WITHIN UKRAINE)

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ABSTRACT

The systematization, generalization, estimation of the variability of time series of the mean annual water runoff of rivers in of the Prut and Siret basins has been carried out, and its cyclic structure has been revealed. For this purpose, a database of average annual discharges water with 12 of hydrological observing stations on the rivers in of the Prut and Siret basins from the beginning of observations to 2015 have been created. Number of years under observation by the annual runoff values for river Prut near city of Chernivtsi is 121. Their representativeness and homogeneity for practical calculations has been evaluated. To identify and formalize the cyclic structure of time series of the mean annual water runoff of rivers in of the Prut and Siret basins used the methods of mathematical statistics and theory of random functions: a function of mathematical expected value; a function of dispersion values or standard deviation; probability distribution function; autocorrelation function. Also have been involved different of the standard mathematical criteria (criteria homogeneity, criteria of the series and of the longest series), integral curves of the differences. As a result, the structure of cyclic oscillations is revealed of the mean annual water runoff of rivers in the Prut and Siret basins and that is what made it possible to provide forecast estimates until 2050.

Keywords: rivers of Prut and Siret basin (within Ukraine); mean annual runoff; multi-annual variability, cyclicity in the fluctuations runoff.

INTRODUCTION

The main aims of study are calculations of hydropower potential of small mountain and foothill rivers in Prut and Siret river basin (within the Ukraine) in wet years and dry years phases. Knowledge of the cyclicity features in the fluctuations of river runoff, duration and character of the change of the periods of the wet years and dry years in river basins, and especially their prediction provides invaluable assistance in the planning and sound management of the water resources, improving the operational efficiency of the hydropower, reclamation and other water facilities.

It is necessary to stress the particular importance of analyzing the temporal variability of Ukrainian Carpathians river runoff Prut and Siret basins. Firstly, they are the wettest rivers of Ukraine, and secondly, the frequent floods, both in warm and cold periods of the year qualify this territory as one of the most flood hazard regions of Europe by the intensity of their development and the simultaneous spread over the territory.

Based on the identified stochastic patterns in fluctuations in multi-annual mean of river runoff in Prut and Siret river basins (within Ukraine), according to observation data, were found theirs forecast estimates for the near future are found.

DATA AND METHODS

A base of average annual discharges water with 12 of hydrological observing stations on the rivers in of the Prut and Siret basins from the beginning of observations to 2015 have been created. At 83% of gauging stations have periods of observation ≥ 50 years (Table 1).

Fluctuations of mean annual runoff water of rivers are treated as a random process with discrete-time $t \epsilon T$ (random sequence). In particular, the value $t = 1, 2...N$ can be attributed to the available number of observations for N years; values $t = N+1, N+2...$ refer to the following periods of time, and the value $t = N-1, N-2...$- to the previous periods. In order to describe the process fluctuations of mean annual runoff water used the range of functions, the most important of which are: a function of mathematical expected value; a function of dispersion values or standard deviation;

probability distribution function; autocorrelation function. Also have been involved different of the standard mathematical criteria (criteria homogeneity, criteria of the series and of the longest series), integral curves of the differences etc.

Table 1. Hydrological observing stations in the Prut and Siret basins, multi-annual mean runoff data and representativeness of its determination

River	hydrometric station	Catchment area km^2	Mean elevation of catchment area, m a.s.l.	Multi-annual mean		Variation coefficient	Number of years under observation	Relative value of mean standard deviation , %
				Discharge, $m^3 \cdot s^{-1}$	Specific discharge, $dm^3 \cdot s^{-1} \cdot km^{-2}$			
The Prut and Siret basins								
Prut	Vorokhta	48,3	1500	1,99	41,1	0,27	38	4,6
	Tatariv	366	1200	7,76	21,2	0,26	56	3,6
	Yaremche	597	960	12,4	20,8	0,28	66	3,5
	Chernivtsi	6890	450	73,0	10,6	0,29	121	3,5
Kamyanka	Dora	18,1		0,37	19,5	0,38	67	4,7
Chornyava	Lyubkivtsi	333		1,60	4,80	0,42	31	7,9
Bilyi Cheremosh	Yablunytsia	552	1200	9,77	17,1	0,38	58	5,1
Chornyi Cheremosh	Verkhovyna	657	1200	14,1	21,5	0,37	58	5,0
Cheremosh	Usteriky	1500	1100	27,9	18,6	0,25	58	3,4
Iltsya	Iltsi	86,1		1,67	19,4	0,29	57	4,0
Putyla	Putyla	181	960	2,57	14,2	0,34	51	4,9
Siret	Storozhynets	672	590	6,65	9,90	0,39	63	5,0

RESULTS AND DISCUSSION

The greatest success in the study of temporal runoff fluctuations can be achieved if one considers the long time series of hydrological characteristics in large scale (Lukyanets et al., 2015), i.e. the water runoff of large basins which are not significantly affected by the random factors and local conditions.

For the establishment of the patterns of long-term fluctuations of in the Prut and Siret basins rivers' runoff and given the above circumstances, were investigated the average annual runoff values for river Prut near city of Chernivtsi (F = 27,540 km^2, 1895-2015). Number of years under observation by the annual runoff values for river Prut near city of Chernivtsi is 121 (Fig. 1).

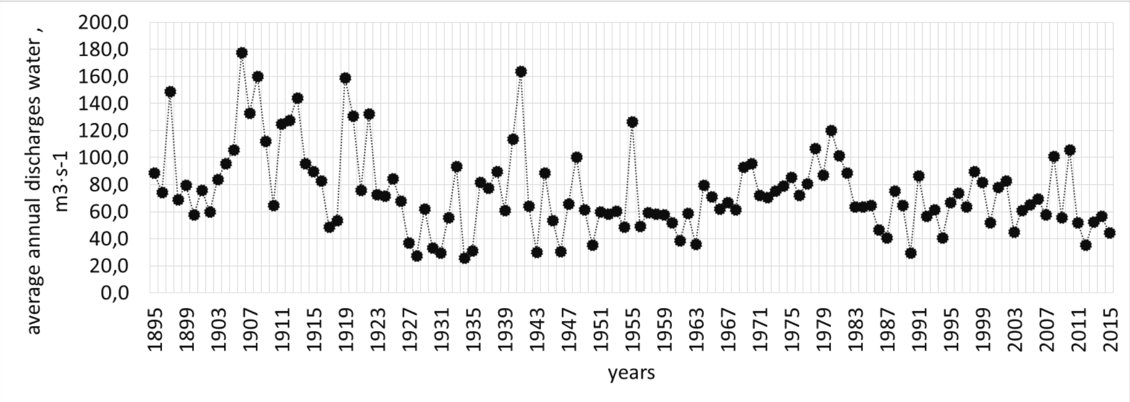

Fig. 1. Long-term fluctuations in average annual water runoff of river Prut – a city of Chernivtsy

Quantitative assessment of intra-series homogeneity of the average annual water discharges for river Prut – city of Chernivtsi (Table 2) is performed by generalized standard parametric criteria: Student - to test the significance of the mean values (statistics t) and Fisher - to check the relation of variances (statistics F). As to the non-parametric criteria, one of the most stringent criteria is used-Wilcoxon--Mann-Whitney criterion (statistics of the number of inversions U).

Table 2. Results of test for homogeneity of average annual water runoff of Prut River (Significance level of 2α = 5 %)

Homogeneity criteria	Statistics value		Results of hypothesis test
	empirical	theoretical	
Student's, statistics *t*	1,95	[-1,98,+1,98]	homogenous
Fisher's, statistics *F*	2,33	[+1,+1,61]	heterogeneous
Wilcoxon-Mann-Whitney *U*	2434	[1719, 2571]	homogenous

As you can see (Table 2), the hypotheses of the Student's t and Wilcoxon-Mann-Whitney criteria about homogeneity of the average annual runoff series in the studied basin at a significance level of 2α=5% are not rejected. Only the hypothesis of series homogeneity for a relation of variance with F statistics at significance level of 2α=5 % is rejected, i.e. difference of the empirical data with the null hypothesis is statistically significant.

The apparatus of the random process theory is applied in the hydrological studies for the description of the time sequences, which examines patterns of random phenomena in the dynamics of their development.

The cyclic fluctuations (cyclicity) means the variability of time series values that have varying degree of regularity, subject to the existence of mathematical expectations of the parameters of these fluctuations.

The way to identify tendencies of the grouping of years with relatively large and small runoff values which the presence of cyclical trend is a graphical analysis integral curves of the differences St:

$$St = \frac{\sum_{i=1}^{n}(k_i - 1)}{Cv} \qquad (1)$$

Where: modular factor k_i is the ratio of $Q_i/\bar{Q}$ ($\bar{Q}$ – the arithmetic mean of the whole series $Q_1, Q_2, ...Q_n$

Cv – variation coefficient of the series members.

For the analysis of long-term fluctuations, build (Fig. 2) integral curves of the differences of average annual water discharges of rivers in the Prut and Siret basins.

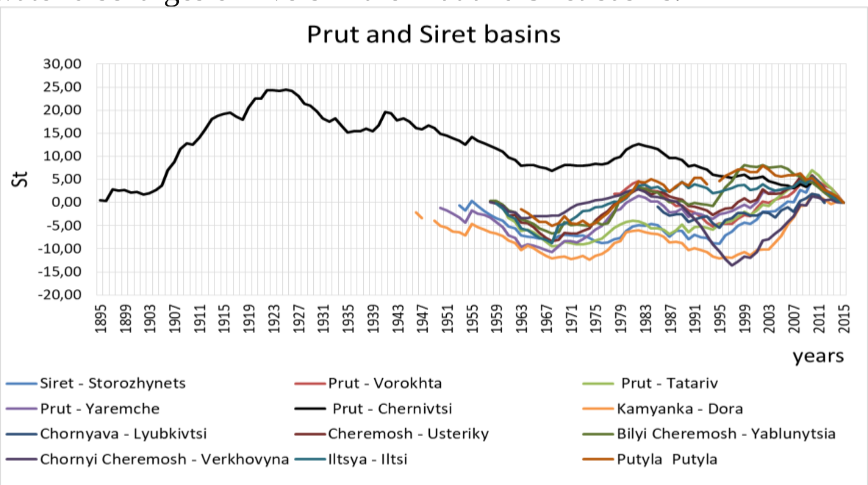

Fig. 2. Integral curves of the differences of multi-annual mean annual water discharges of the rivers in Prut and Siret basins

Positive increasing of function St (a wet phase) on average means the increase of water runoff. Negative decreasing of function St (a dry phase) characterizes the average reduction of water runoff.

The statistical reliability of the existence of such wet and dry phases, and therefore a breach of stationary conditions can be checked by means of criteria of the series and of the longest series (Obodovskyi et al., 2017), as well autocorrelation function.

Criteria of the series revealed a statistically significant tendency to frequent changes in dry and wet values of water runoff.

Analysis of the sequence of the groups demonstrated that the longest length relates to the series consisting of elements of dry groups and for river Prut – a city of Chernivtsi is 8 yare (from 1956 to 1963). Theoretically proved that the grouping of low-water years for the studied rivers in the Prut and Siret basins can be 10 ± 2 years.

In order to formalize the long-term fluctuations of annual water runoff of in the Prut and Siret basins rivers' runoff as cyclical fluctuations with groups of years of high and low values (dry and wet phases) and evaluate their quantitative parameters (duration, intensity), the autocorrelation analysis of time series of average annual water for river Prut – city of Chernivtsy was appropriate and made (Fig. 3). The application of this method is based on the acceptance of the hypothesis of stationary processes that cause fluctuations in the studied values.

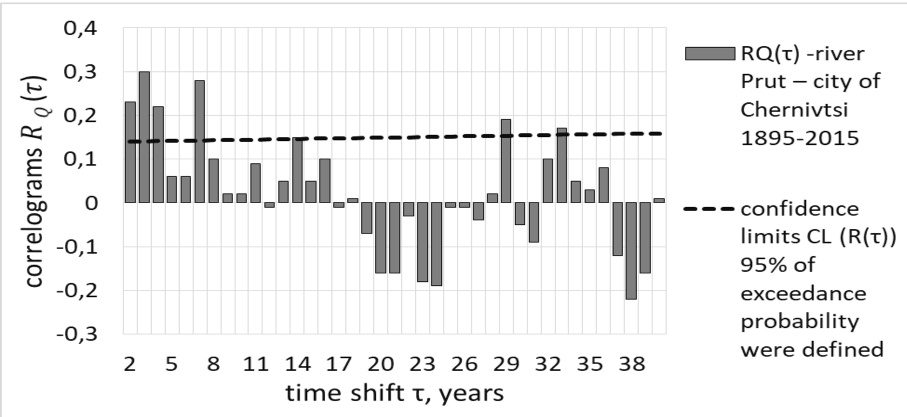

Fig. 3. Correlogram of time sequences of average annual water consumption for river Prut – city of Chernivtsy

Autocorrelation function characterizes the closeness of the relationship between the members of the time sequence of annual water runoff $Q(t)$. The function $R_Q(\tau)$ is a sequence of linear correlation coefficients calculated with different distances between sections (or shift values) of the average annual water discharges on the time axis data (Lukianets et al., 2015, Lukianets, 2017).

In practice of the hydrological calculations, the following restrictions are assigned for shift τ: $\tau = 1/3 \cdot n$. The scope of shift values is taken from τ = 2 to τ = 40, given the length of observations n for studied sequences of average annual water discharges (for river Prut – city of Chernivtsy – 121 years) (Fig. 3).

To assess the statistical significance of defined ordinates of the autocorrelation function the confidence limits $CL(R_Q(\tau))$ 95% of exceedance probability were defined (Table 3).

Table 3. Confidence limits $CL(R_Q(\tau))$ 95% of probability of exceedance of the autocorrelation functions of average annual water runoff for river Prut – city of Chernivtsy

River - hydrological station	$CL(R_Q(\tau))$ 95%	
	Lower limit	Upper limit
river Prut – city of Chernivtsy	0,14	0,16

Fig. 3 shows the evaluation of cyclicity in the form of cycle duration (number of years) that exceed confidence limits of 95% probability of exceedance or close to them.

It is believed that these estimates represent through the frequency of average annual water discharges the natural fluctuations in water content of studied river basins. The presence of distinct cyclicity of the autocorrelation functions indicates that the structure of time series has stochastic dependency between their elements and real continuous cyclical fluctuations which are not accidental in terms of their origin.

When reviewing the estimates of cycles, it is revealed that in the basins of Prut and Siret the cycles with a duration of 2-4, 7, 14 and 29, 33 years dominate. The first of them relate to the rain floods in the Carpathian Mountains, which form the internal peaks in basic cycle (or phases of water content). Basic cyclicity of 29 years is a repeatability in this cycle of years groups with high and low water content (dry and wet phases).

For the forecast estimates of water runoff fluctuations the water content phases were allocated in the runoff series of river Prut – city of Chernivtsy, given the basic cycle frequency (29 ± 2 years), defined duration of low-water phases (10 ± 2 years) (Table 4, Fig. 4).

Table 4. Average water discharges for a period of water content phases and forecast estimates of the runoff for the period until 2050

Period (years)	phase water content ↑ - wet, ↓ - dry	Number of years in phase	Period average water content discharges ($m^3 \cdot s^{-1}$) river Prut – city of Chernivtsy, *F*=6890 km^2,
1883-1898	↑	15	
1899-1911	↓	13	
1912-1927	↑	16	93
1928-1939	↓	12	56
1940-1955	↑	16	73
1956-1964	↓	9	54
1965-1981	↑	17	83
1982-1992	↓	11	62
1993-2009	↑	16	69
The forecast values with standard deviations in phase water content ($m^3 \cdot s^{-1}$)			
2010-2020÷21	↓	11÷12	57±4
2021-2037÷38	↑	16÷17	80±9
2038-2048÷49	↓	11÷12	57±4

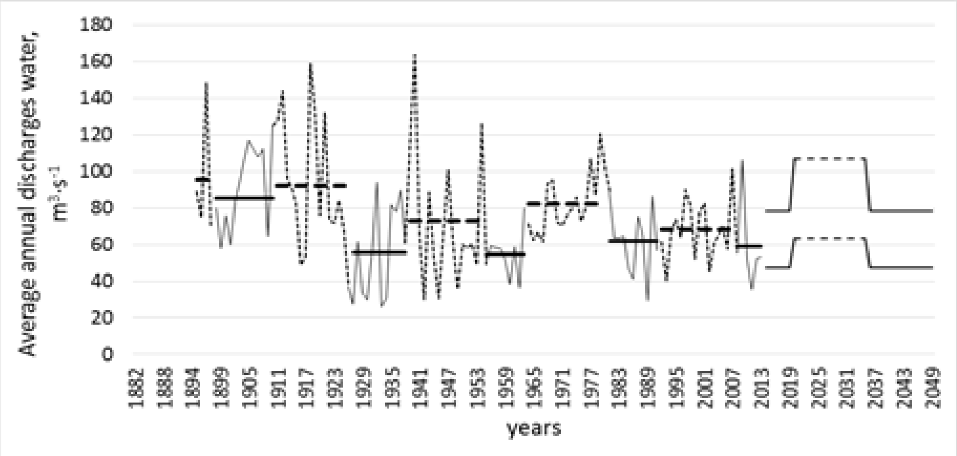

Fig. 4. Fluctuations in water content and their forecast estimates for of river Prut

As the calculations demonstrated there is a clear cyclical variability for all rivers in the Prut and Siret basins, which is well evident in Fig. 5, which demonstrates the ratio of multi-annual mean discharges of rivers for Prut and Siret basins and their values in the periods of dry and wet phases.

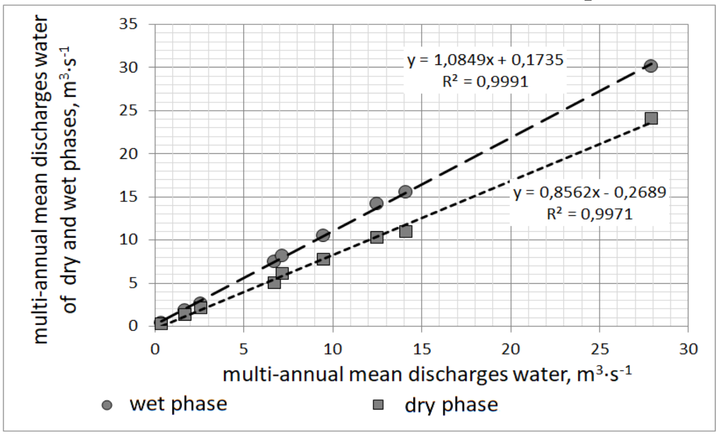

Fig. 5. Ratio between multi-annual mean discharges water and multi-annual mean discharges water of dry and wet phases of the rivers Prut and Siret

Probable errors in determining multi-annual mean discharges water of dry and wet phases of the rivers Prut and Siret are generalized (Table 5). They are presented as a percentage and determined by the ratio of values of average water discharges in the corresponding water-content phase.

Table 5. Probable deviation of calculated values of average water runoff in dry and wet phases

River basins	Probable deviation of calculated values of average water runoff, %	
	wet phase	dry phase
river Prut and Siret	± 11	± 7

High availability of the proposed equations and significance of built relationships (approximation of all reaches R^2 = 0,99) enabled to generalize for rivers of basins of Siret and Prut probable average water discharges which can be expected in the dry and wet phases of the cycle, depending of their multi-annual mean discharges water values (Table 6).

Table 6. The generalized ratio of average water discharges of the rivers of basins Prut and Siret in periods of dry and wet phases

Longstanding average water discharges, $m^3 \cdot s^{-1}$	water content		Difference in the phases of water content, $m^3 \cdot s^{-1}$	Longstanding average water discharges, $m^3 \cdot s^{-1}$	water content		Difference in the phases of water content, $m^3 \cdot s^{-1}$
	wet phase, $m^3 \cdot s^{-1}$	dry phase, $m^3 \cdot s^{-1}$			wet phase, $m^3 \cdot s^{-1}$	dry phase, $m^3 \cdot s^{-1}$	
0,5	0,72	0,16	0,56	22,0	24,04	18,57	5,47
1,0	1,26	0,59	0,67	24,0	26,21	20,28	5,93
2,0	2,34	1,44	0,90	26,0	28,38	21,99	6,39
3,0	3,43	2,30	1,13	28,0	30,55	23,70	6,85
4,0	4,51	3,16	1,36	30,0	32,72	25,42	7,30
5,0	5,60	4,01	1,59	32,0	34,89	27,13	7,76
6,0	6,68	4,87	1,81	34,0	37,06	28,84	8,22
7,0	7,77	5,72	2,04	36,0	39,23	30,55	8,68
8,0	8,85	6,58	2,27	38,0	41,40	32,27	9,13
9,0	9,94	7,44	2,50	40,0	43,57	33,98	9,59
10,0	11,02	8,29	2,73	42,0	45,74	35,69	10,05
12,0	13,19	10,01	3,19	44,0	47,91	37,40	10,51
14,0	15,36	11,72	3,64	46,0	50,08	39,12	10,96
16,0	17,53	13,43	4,10	48,0	52,25	40,83	11,42
18,0	19,70	15,14	4,56	50,0	54,42	42,54	11,88
20,0	21,87	16,86	5,02				

CONCLUSIONS

Time series of average annual water runoff for basins of Prut and Siret rivers were estimated with the use of mathematical tools. The methodological framework of which is based on a statistical means of summarizing, systemization of the input data, evaluation methods of time random sets of the runoff characteristics, methods of analysis of the time series variability and the manifestation of their structure.

High reliability of the cycles with periods of 29 ± 2 years demonstrates a stable frequency of wet phases (17 ± 2 years) and dry phases (10 ± 2 years). That is to say, the features found in the structure of the time series of average annual runoff of the rivers of basins Prut and Siret can be qualified as cyclical. That is what made it possible to provide prediction estimates of the water content for the rivers of basins Prut and Siret. Until 2020-21, the dry phase will continue, and then the wet phase with the duration of 16-17 years can be expected and from 2037-38 the dry phase will again continue until 2048-49.

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ASSESSMENT HARMONIZATION PROBLEMS OF THE LONG RETURN PERIOD FLOODS ON THE DANUBE RIVER

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ABSTRACT

One of the basic problems of the flood hydrology was (and still is) the solution of the relationship between peak discharges of the flood waves and probability of their return period. The assessment of the design values along the Danube channel is more complicated due to application of different estimation methods of design values in particular countries downstream the Danube. Therefore, it is necessary to commence the harmonization of the flood design values assessment methods. All methods of estimating floods with a very long return period are associated with great uncertainties. Determining of the specific value of the *500*- or *1000*-year floods for engineering practice is extremely complex. Nowadays hydrologists are required to determine not only the specific design value of the flood, but it is also necessary to specify confidence intervals in which the flow of a given *100*-, *500*-, or *1000*-year flood may occur with probability, for example, 90%.

The assessment of the design values Q_{max} can be done by several methods. In this study we have applied the statistical methods based on the assessment of the distribution function of measured time series of the maximum annual discharge. In order to apply regionalization methods for the estimation of the distribution function in this study we used only one distribution - the Pearson Type III distribution with logarithmic transformation of the data (log Pearson Type III distribution - LP3 distribution). To estimate regional skew coefficient for the Danube River we use 20 Q_{max} measured time series from water gauges along the Danube River from Germany to Ukraine. We firstly analyzed the occurrence of historic floods in several stations along the Danube River. Then we search relationship between the parameter of skewness of the log Pearson type III distribution function and runoff depth, altitude, or basin area in all 20 water gauge. Skewness coefficients of the LP3 distribution in the stations along the Danube River vary between –0.4 and 0.86.

Keywords: floods, design values, Danube River, LP3 distribution, regionalization

INTRODUCTION

Under the present and foreseeable human activities to a sustainable development of the industry, agriculture, energy and water supply the demands of the hydrological synthetic characteristics of the flow regime are continuously increasing (Stănescu, 2004). One of the basic problems of the flood hydrology was (and still is) the solution of the relationship between peak discharges of the flood waves and probability of their return period. Importance of extrapolation derived from these variables (so called frequency curve) is especially necessary for proposal of water management and flood control plans. Directive 2007/60/ EC of the European Parliament of 23 October 2007 concerning the assessment and management of flood risks requires member States to draw up flood hazard maps of floods with very long return periods T (*500* to *1000* years).

The main steps of the statistical processing are the following:

1) Selection of the time series of the maximum discharges:

a) the maximum annual discharges Q_{max}, or

b) the maximum discharges exceeding a certain threshold value.

A big problem of the **hydrological regionalization** refers to the manner in which the transfer of data to the ungauged basins or to deficient data sites is carried out. There are two main procedures to perform this transfer: the first one consists in finding out some relationships aiming to the spatial interpolation of the principal statistics of the probability curves. The second procedure tries to eliminate the shortcoming of the first one. This consists in finding out several statistical distribution curves of standardised annual maximum discharge. Standardisation is achieved by dividing the maximum annual discharges by their average magnitude Q. These standardised (or dimensionless) curves are often called growth curves (Stănescu, 2004).

All methods of estimating floods with a very long return period are associated with great uncertainties. Determining the specific value of a *500*- or *1000*-year flood for engineering practice is extremely complex. Nowadays hydrologists are required to determine not only the specific design value of the flood, but it is also necessary to specify confidence intervals in which the flow of a given *100*-, *500*-, or *1000*-year flood may occur with probability, for example, 90%. Estimation of the uncertainty at the design discharges was investigated for example by Szolgay et al. (2003), Merz et al. (2004), or Rogger et al. (2012). It is generally known, that the extrapolation of the data is very sensitive not only to the length of the data series, but also to the **inclusion of the historic extremes to data series**. The correct estimations of potential culminations of floods require the inclusion of the longest data series of observations, as well as the inclusion of historic pre-instrumental data to statistically analysed data series (Lauda et al., 1908; Kresser, 1957; Merz and Blöschl 2008a,b; Elleder 2010; Gaal et al., 2010; Elleder et al., 2013; Kjeldsen et al., 2014). Brazdil et al. (2006) studied historic hydrological materials in order to estimate floods threat in Europe.

Except the mentioned factors the estimation of the *T*-year discharges is finally influenced by used type of the theoretical probability distribution function. The choice of the type of the theoretical probability distribution function should relatively accurately represent uncertainty and variability of the hydrological problem. Application and choice of a particular probability distribution function, method of the parameter estimation as well as choice of the analyzed period depend on the calculation method commonly used in a particular country. For large international basins such as the Danube River basin, it is necessary to synchronize the methodology and to prepare common procedures for determining flood hazard. Investigation of the history of extreme flood event frequency, severity and duration provides a greater understanding of the region’s extreme event characteristics and the probability of recurrence at various levels of severity. This type of information is beneficial in the development of extreme response and mitigation strategies and preparedness plans.

The aim of the paper is to propose unified methodology to estimate the design values of flood discharges in stations along the Danube River. Here we present the results of the estimation of the Q_{max} discharge series distribution function using log Pearson Type III distribution (LP3) with inclusion of the historical floods into data series. We focused on estimation of the relationship between the skew coefficient of the log Pearson type III distribution function and runoff depth on the base of data from 20 water gauges along the Danube River.

METHODS

As it was mentioned, for the estimation of the Q_{max} discharge series distribution function we used the log Pearson Type III distribution. The Pearson Type III, or Gamma, distribution is used to calculate the frequency of maxima events when the distribution of all events (both big and small) is log-normally distributed. In hydrologic applications, the log-normal distribution has been found to reasonably describe such variables as the depth of precipitation of individual storms and annual peak discharges Griffis and Stendinger (2007 and 2009). Today, the application of LP3 distribution to quantify the recurrence interval of large peak annual discharges is recommended by the U.S. Interagency Advisory Committee on Water Data ("Guidelines for Determining Flood Flow Frequency", Bulletin 17B of the Hydrology Committee, U.S. Geological Survey, Reston, VA). It is the default distribution used by the U.S. Geological Survey for flood studies (Koutsoyiannis, 2008).
Pilon and Adamowski (1993) developed the Log Likelihood function of LP3 and estimated its parameters. Cheng et al. (2007) presented a frequency factor based method in hydrological frequency analysis for random generation of five distributions (normal, lognormal, extreme value type 1, Pearson Type III and log-Pearson Type III). He used LP3 distribution in flood frequency analysis too. Some authors (Stedinger and Griffis 2008) preferred the Generalized Extreme Value distribution (GEV). Comparison of several types of distributions (GEV, LP3 and Gumbel) for estimating *T*-year discharges presented Millington et al. (2011). Authors did not prefer any distribution as better and they suggested other researches in this problem.

Stănescu (2004) used for the extrapolation of the regional curves in Danube Basin the Pearson III curves. Using one type of distribution also allows to estimate the value of the *T*-year maximum discharges in parts of the river without observations, only on the basis of long-term average of maximum annual discharge and distribution parameters from the neighbouring gauging stations.

In this study, to estimate the distribution parameters, the method described in Bulletin17B was used. Bulletin 17B was issued in USA in 1981, and re-issued with minor corrections in 1982 in the Centre for Research in Water Resources of the University of Texas at Austin (IACWD, 1982). Bulletin 17B provided revised procedures for weighting station skew values with results from a generalized skew study, detecting and treating outliers, making two station comparisons, and computing confidence limits about a frequency curve. Bulletin 17B is based on Bulletins 15, 17, 17A (http://acwi.gov/hydrology/ Frequency/minutes/index.html). (Design flood estimation procedures in the United States have traditionally focused on two primary methods: frequency analysis of peak flows for floodplain management and levee design; and deterministic – Probable Maximum Flood estimates – for design of dams and nuclear facilities.)

The log-Pearson Type III distribution is a three-parameter Gamma distribution with a logarithmic transform of the variable. It is widely used for flood analyses because the data quite frequently fit the assumed annual maximum discharge series. The probability density function of the Pearson Type III distribution is of the form:

$$f(x|\tau,\alpha,\beta) = \frac{\left(\frac{x-\tau}{\beta}\right)^{\alpha-1} exp\left(-\frac{x-\tau}{\beta}\right)}{|\beta|\Gamma(\alpha)} \tag{1}$$

with $\frac{x-\tau}{\beta} \geq 0$, where τ, α, β are parameters:

τ – is the location parameter;

α – is the shape parameter;

β – is the scale parameter;

$\Gamma(\alpha)$ is the Gamma function given by:

$$\Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} exp(-t)dt. \tag{2}$$

Random variable X follows log-Pearson type III distribution if random variable $Y = lnX$ or $Y = logX$ follows the Pearson type III distribution. Log-normal distribution is a special case of the log-Pearson type III distribution when skew coefficient of logarithmic data is equal to zero.

The distribution is fit by computing the base 10 logarithms of the discharge, *Q*, at a selected exceedance probability, *p*, using the following equation:

$$logQ = \bar{X} + KS \tag{3}$$

where:

$\bar{X}$ is the mean,

S is the standard deviation, and

K is a factor of the skew coefficient at selected exceedance probability.

The formulas for these parameters are provided below.

Mean $$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i. \tag{4}$$

Standard Deviation $$S = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \bar{X})^2}. \tag{5}$$

Skew Coefficient $$G = \frac{n}{(n-1)(n-2)S^3}\sum_{i=1}^{n}(X_i - \bar{X})^3. \tag{6}$$

Probability estimates are made using plotting positions. A basic plotting position formula for symmetrical distributions is (Stedinger et al., 1993, p. 18.24)

$$p_i = \frac{i-a}{n+1-2a}, \qquad (7)$$

where p_i is the exceedance probability of flood observations Q_i ranked from largest (i = 1) to smallest (i = n), and a is a plotting position parameter, $(0 \leq a \leq 0.5)$.

The method of moments uses the logarithms of flood flows to estimate the distribution parameters. The first three sample moments are used to estimate the LP3 parameters. These include the mean ($\hat{\mu}$), standard deviation ($\hat{\sigma}$), and skewness coefficient ($\hat{\gamma}$).
In the case where only systematic data are available, with no historical information, the mean, standard deviation and skewness coefficient of station data may be computed using the following equations:

$$\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad (8)$$

$$\hat{\sigma} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \hat{\mu})^2} \qquad (9)$$

$$\hat{\gamma} = \frac{n}{(n-1)(n-2)\hat{\sigma}^3}\sum_{i=1}^{n}(X_i - \hat{\mu})^3. \qquad (10)$$

where *n* is the number of flood observations and (ˆ) represents a sample estimate.

Historical floods

Historical flood peaks reflect the frequency of large floods and thus should be incorporated into flood frequency analysis. They can also be used to judge the adequacy of estimated flood frequency relationships. For this latter purpose, appropriate plotting positions or estimates of the average exceedance probabilities associated with the historical peaks and the remainder of the data are desired. Hirsch and Stedinger (1987) and Hirsch (1987) provide an algorithm for assigning plotting positions to censored data, such as historical floods.

Weighted Skew Coefficient

There is relatively large uncertainty in the site sample skewness coefficient (third moment) because it is sensitive to extreme events in modest length records (Griffis and Stedinger, 2007a). The station skew coefficient and regional skew coefficient can be combined to form a better estimate of skew for a given watershed. Under the assumption that the regional skew coefficient is unbiased and independent of the station skew, the mean-square errors (MSEs) of the station skew and the regional skew can be used to estimate a weighted skew coefficient.

If the regional and station skews differ by more than 0.5, a careful examination of the data and the flood-producing characteristics of the watershed should be made. Possibly greater weight may be given to the station skew, depending on record length, the largest floods within the gauging record and watershed, and watershed characteristics. Large deviations between the regional skew and station skew may indicate that the flood frequency characteristics of the watershed of interest are different from those used to develop the regional skew estimate. It is thought that station skew is a function of rainfall skew, channel storage, and basin storage. There is considerable variability of response among different basins with similar observable characteristics, in addition to the random sampling variability in estimating skew from a short record. It is considered reasonable to give greater weight to the station skew, after due consideration of the data and flood-producing characteristics of the basin.

Uniform technique for determining flood discharge frequencies

We added the historic floods to the measured series of Q_{max}, and we recalculated the parameters of the distribution curves for individual stations having included the historic floods.

The Frequency curve spreadsheet version 3.06 (Dan Moor, August 2014) was used to estimate the parameters of distribution functions and to calculate the design values.

Q_{max} series conditions

Among the basic assumptions for application of the frequency analysis of the maximum annual discharge belong the following conditions:

- Maximum annual discharges must be independent and stochastic;
- Processes influencing the runoff process are stationary with respect to time (homogeneity of the series);
- Statistical characteristics of the measured data series (series of maximum annual discharge) represent the past, presence and future, as well.

DANUBE BASIN DESCRIPTION

The Danube River with a total length of 2857 km and a long term daily mean discharge of about 6500 m^3s^{-1} is listed as the second biggest river in Europe. In terms of length it is listed as the 21st biggest river in the world, in terms of drainage area it ranks as 25th with a drainage area of 817,000 km^2. The Danube basin extends from the central Europe to the Black Sea. The extreme points of the basin are 8º 09′ and 29º 45′ of the Eastern longitude, and 42º 05′ and 50º 15′ of the Northern latitude (Stancik & Jovanovic, 1988). More recent estimation of the Danube basin area was done by the International Commission on Protection of the Danube River (ICPDR, 2005) which calculated the areas using GIS on the basis of the Danube River Basin District overview map. According to the estimation of the ICPDR the total area of the Danube river basin is 801,463 km^2 (Fig. 2).

Nineteen countries share the Danube basin, though two thirds of the catchment lies within five countries (Romania, Hungary, Serbia, Austria and Germany). The Danube River originates in the Schwarzwald (Black Forest) mountains in Bavaria in Germany. It has its sources outside the Alps in an old mountainous massif. The Breg, which is the longer of the two streams that form the river Danube, begins at only 1,078 m above sea level, 100 m from the European Water Divide. In the case of the Danube River Basin, its landscape geomorphology is characterised by a diversity of morphological patterns and the river channel itself can be divided into 6 sections (Fig. 1) according to the river slope (Lászlóffy, 1965). The main tributaries of the Danube River are shown in Fig. 2.

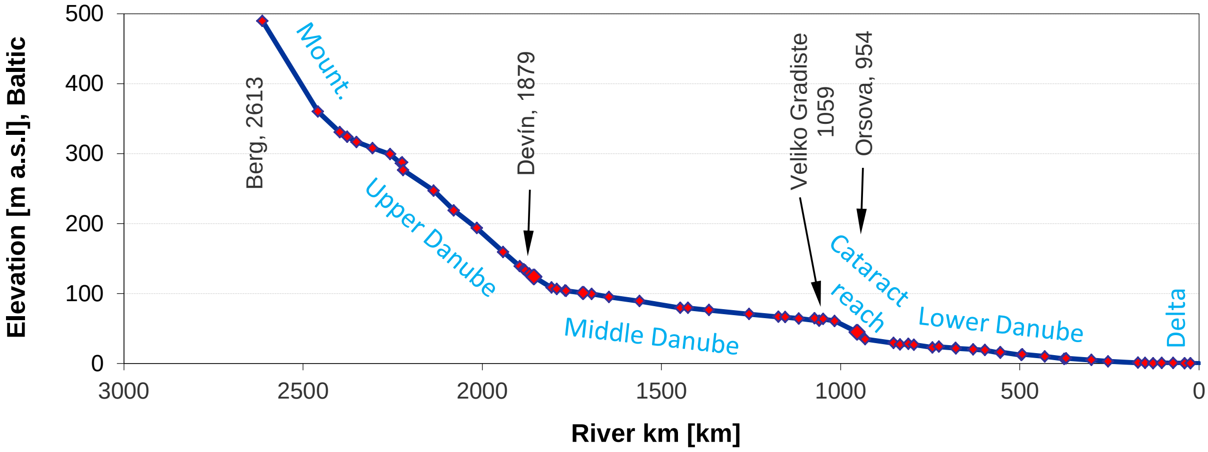


Fig. 1. The Danube River sections.

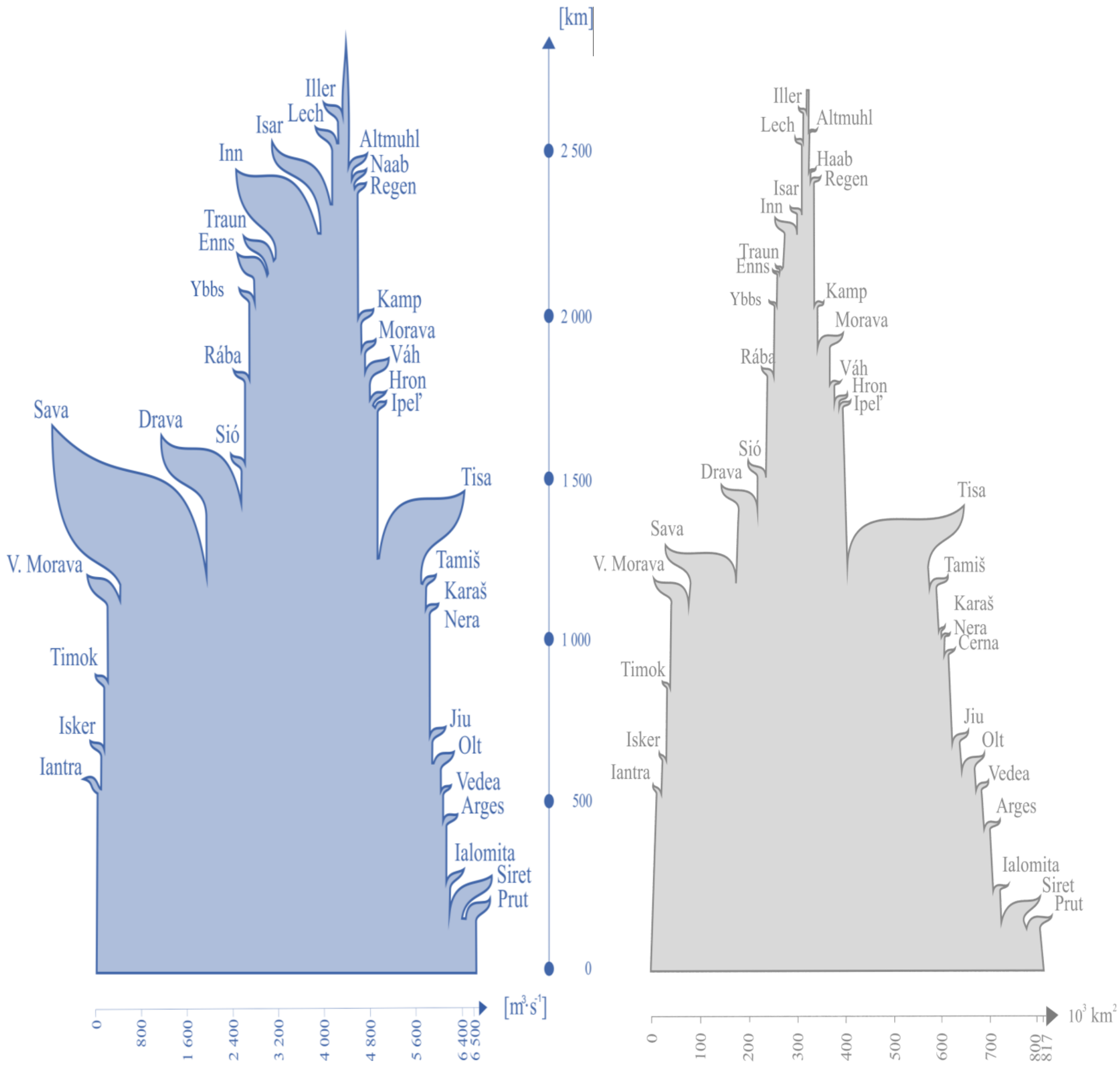


Fig. 2. The Danube and its tributaries, discharge, and area scheme.

DATA DESCRIPTION

Flooding is the most common natural disaster in the Danube River basin and, in terms of economic damage, the most costly one. In case of the Danube River from Achleiten downstream the duration of the floods is longer than one day. Therefore, the flood peak discharges differ very rarely from the mean daily discharges of the day when the flood peak did occur. In Fig. 3 there are presented examples of the maximum annual discharges in the upper (Hofkirchen gauge), in the middle (Bratislava gauge) and lower Danube (Orsova/Turnu Severin gauge, and Reni gauge) from 95 to 170 years.

It is interesting that similar maximum discharges as in the last period did occur also at the end of the 19th century in both stations. Very significant floods occurred on the lower Danube in 2006 (peak discharge 15,900 m^3s^{-1} at Ceatal Izmail), and on the upper Danube in 2013 (peak discharge 10,640 m^3s^{-1} at Bratislava and 9,460 m^3s^{-1} at Budapest).

To estimate regional skew coefficient of the LP3 distribution for Danube River we use 20 Q_{max} measured time series from water gauges along the Danube River from Germany to Ukraine (Fig. 4). Basic statistical characteristics of the stations are presented in Table 1.

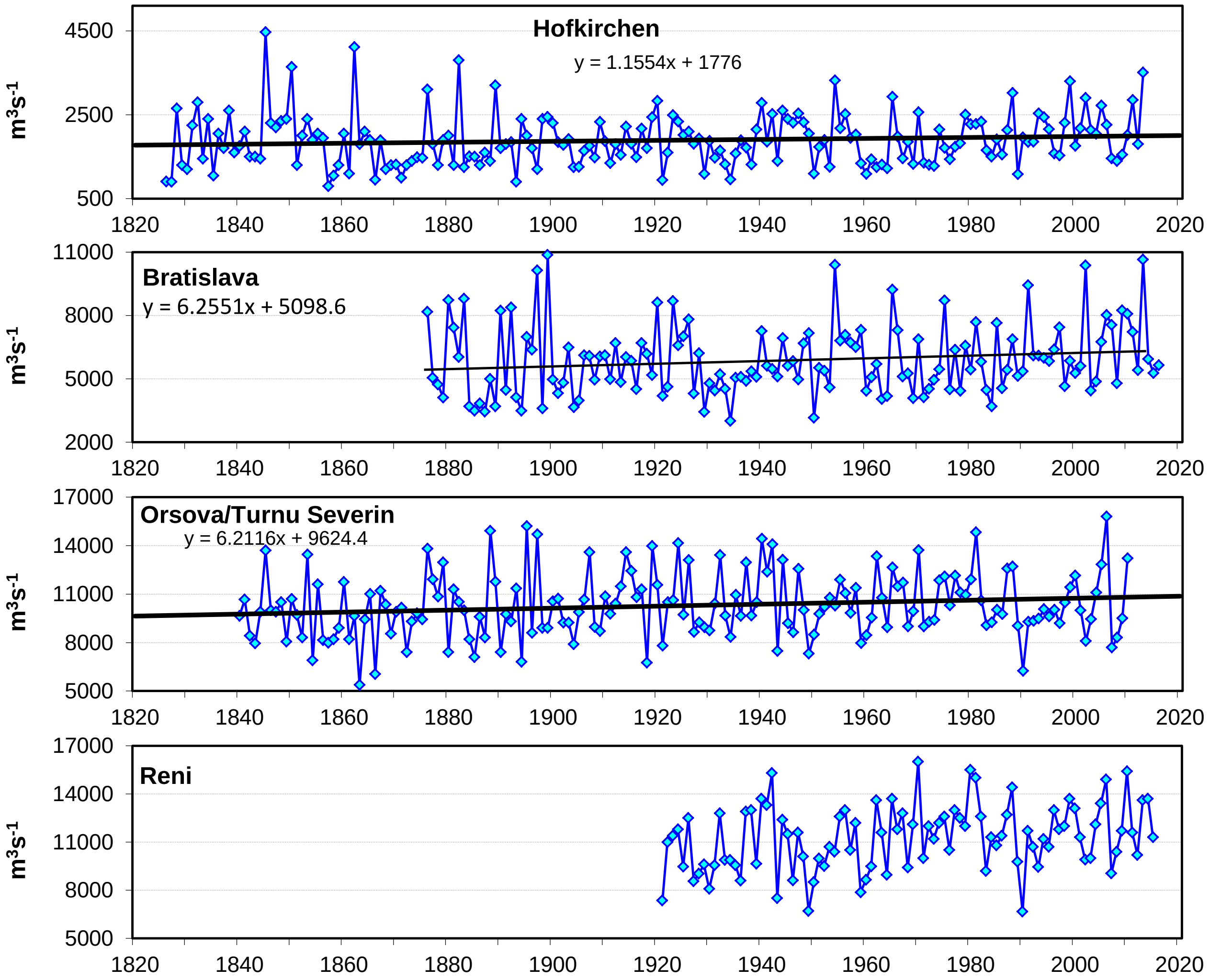


Fig. 3. The maximum annual discharges series.

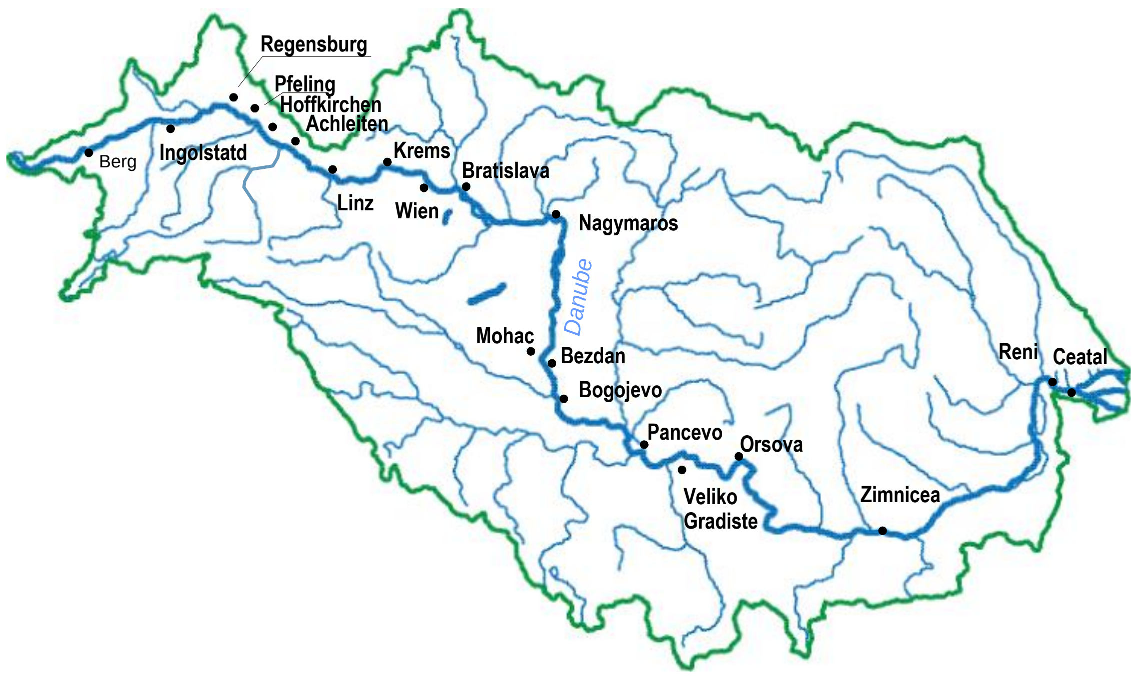


Fig. 4. Scheme of the Danube River basin and water gauging stations along the Danube River.

Table 1. List of the gauging stations along the Danube River and Q_{amax} – long-term average of the maximum annual discharge

No.	River km	Gauge	Period	Country	Area [km^2]	Elevation [m a.s.l.]	Mean *Qmax* [m^{3}s^{-1}]	Gw skew hist.
1	2613	Berg	1930–2007	GE	4047	489.48	204	-0.29
2	2458.3	Ingolstadt	1940–2007	GE	20001	359.97	1110	0.57
3	2376.1	Regensburg-Schwabelweis	1924–2007	GE	35399	324.06	1532	0.26
4	2300	Pfelling	1926–2007	GE	37757	307.73	1516	0.20
5	2256.9	Hofkirchen	1826–2013	GE	47496	299.17	1896	0.56
6	2150	Achleiten	1901–2007	GE	76653	287.27	4146	0.86
7	2135.2	Linz*	1821–2013	AT	79490	247.06	3670	0.60
8	2002.7	Stein-Krems (Kienstock)	1828–2006	AT	96045	193.32	5372	0.59
9	1934.1	Wien-Nussdorf*	1828–2006	AT	101731	157.0	5301	0.58
10	1868.8	Devin/Bratislava*	1876–2013	SK	131338	132.86	5884	0.24
11	1694.6	Nagymaros	1893–2007	HU	183534	99.37	5598	0.11
12	1446.8	Mohács	1930–2007	HU	209064	79.19	5063	0.04
13	1425.5	Bezdan	1940–2006	SR	210250	79.29	4974	0.30
14	1367.4	Bogojevo	1940–2006	SR	251593	76.11	5675	0.19
15	1153.3	Pancevo	1940–2006	SR	525009	65.98	10147	0.15
16	1060	Veliko Gradiste	1931–2007	SR	570375	60.83	10529	0.02
17	955	Orsova-Turnu Severin	1840–2006	RO	576232	44.76	10295	-0.19
18	554	Zimnicea	1931–2010	RO	658400	16.06	11087	-0.09
19	132	Reni	1921–2010	UKR	805700	0.2	11217	-0.40
20	72	Ceatal Izmail*	1931–2010	RO	807000	0.1	11173	0.02

*T-year discharges were estimated both including extreme historical data as well as excluding historical data from 1501, 1787 and 1897

RESULTS AND DISCUSSION

Estimation of the design values of the Q_{max} discharges along the Danube River

In this paragraph the design values for 20 gauge station along the Danube River were calculated. The Frequency curve spreadsheet version 3.06 (Dan Moor, August 2014) was used to estimate the parameters of distribution functions and to calculate the design values.

In the first step, we estimated the LP3 distribution function parameters (mean *Q*, standard deviation S, and station skewness coefficient *G*), for each of the stations separately and computed Q_{max} design values. In the case of gauges with historic floods, we added historic floods into the measured Q_{max} series (see Fig. 5), and recalculated the parameters of the distribution curves for individual stations having included the historic floods. The inclusion of the historical floods to calculation procedure has increased the skew coefficient G_h by 0.2 in average. The example for Danube: Bratislava station is presented in Fig. 6 *a, b*. Design values are sorted in Tables 2 *a, b*.

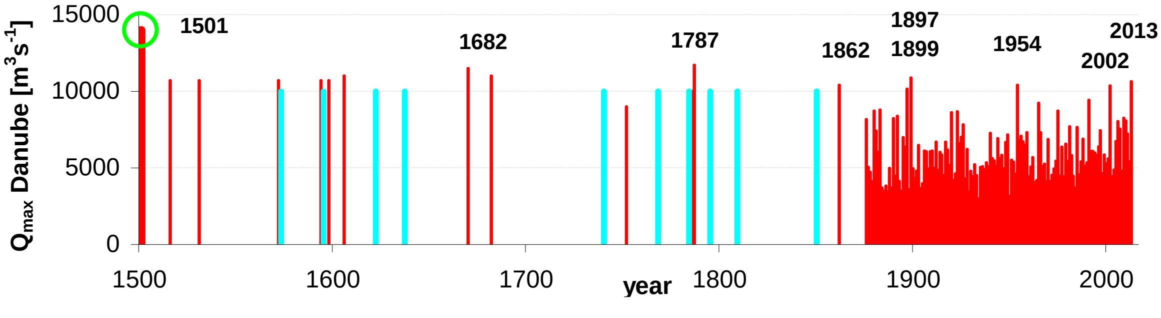
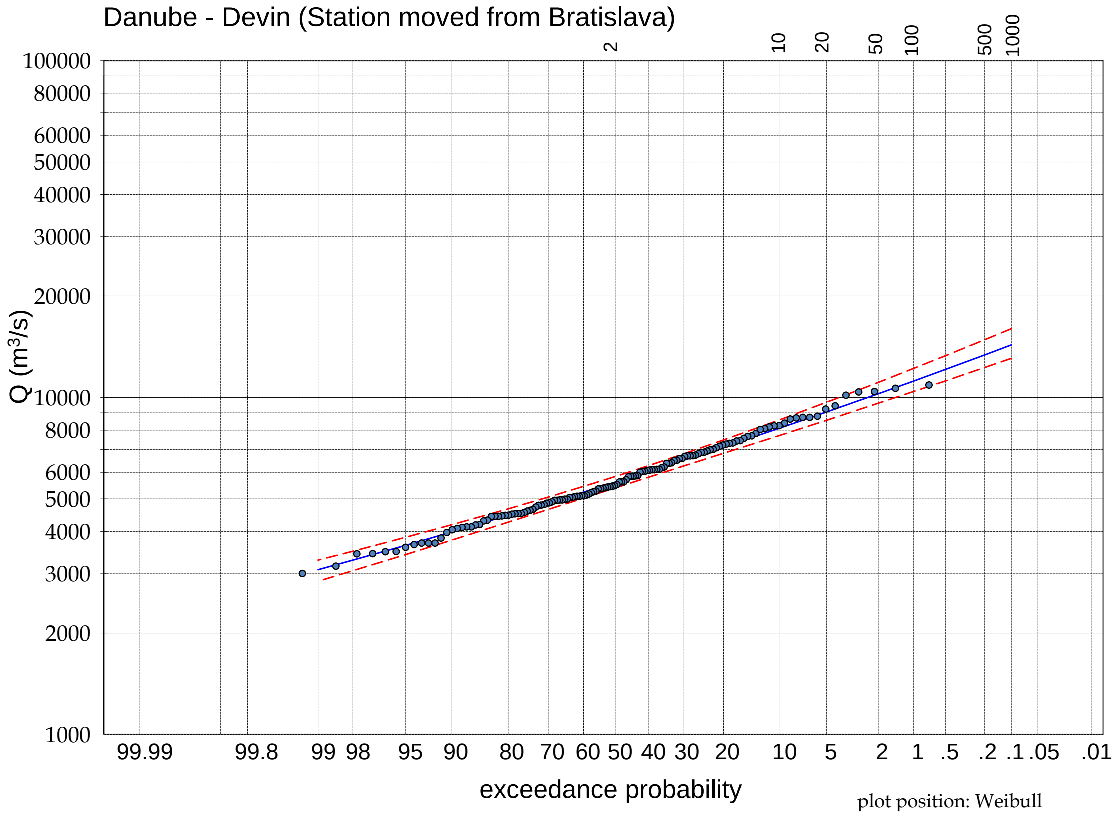
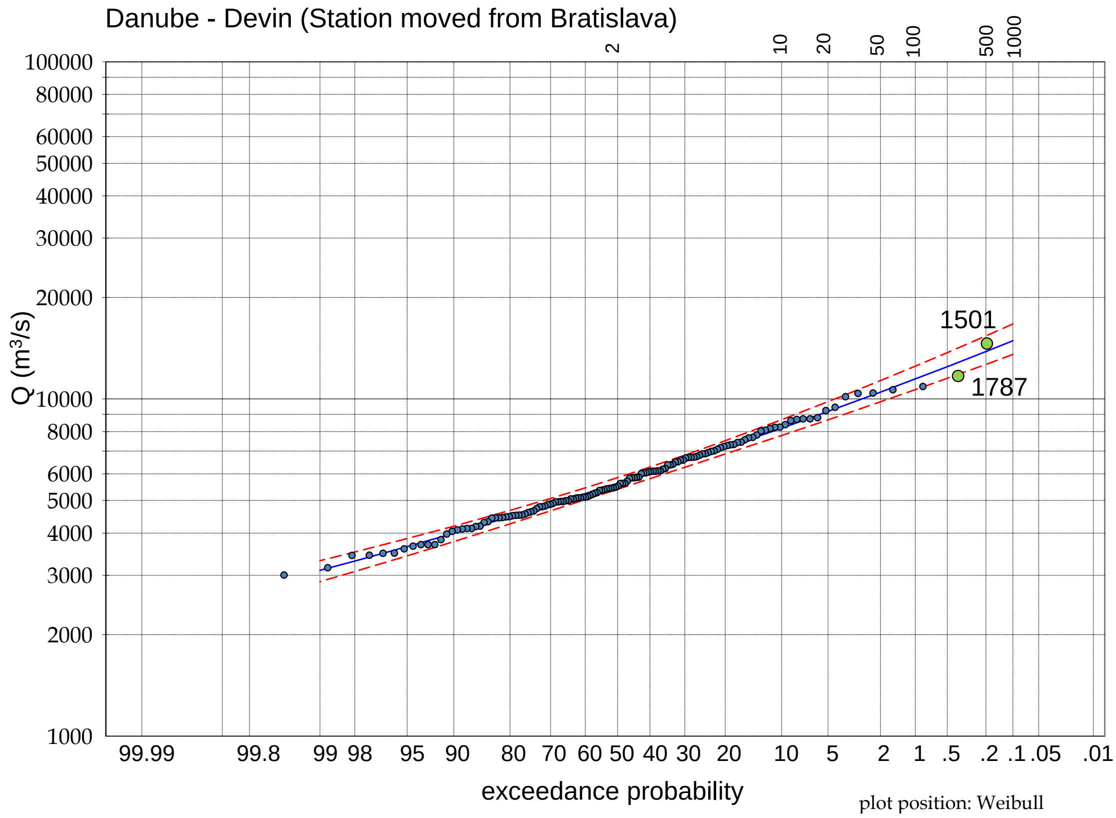


Fig. 5. Historical Danube River floods in river section Devín–Bratislava since 1500 up to 1876 (red columns - summer floods, blue columns - winter floods); since 1876- the observed annual peaks Q_{max} at the Bratislava water gauge.



a)



b)

Fig. 6. Example of the computations output for the Danube at Bratislava/Devín station a) without historical data; b) with two historical data. Distribution curve with confidence limits, design values.

Tables 2a. Design values of selected *T*-year annual maximum discharges along the Danube River

River km	Station/*T*-year	*5*	*10*	*50*	*100*	*200*	*500*	*1000*
2613	Berg	272	324	432	476	518	573	613
2458.3	Ingolstadt	1327	1526	2002	2222	2453	2779	3043
2376.1	Regensburg-Schwabelweis	1902	2125	2530	2675	2809	2969	3081
2300	Pfelling	1888	2144	2649	2846	3034	3273	3447
2256.9	Hofkirchen	2334	2765	3840	4353	4905	5701	6359
2150	Achleiten	4839	5512	7155	7925	8744	9913	10869
2135.2	Linz	4641	5455	7352	8205	9092	10323	11304
2002.7	Stein-Krems (Kienstock)	6439	7397	9605	10592	11613	13028	14154
1934.1	Wien-Nussdorf	6345	7187	9046	9847	10658	11756	12610
1868.8	Devin/Bratislava	7129	8116	10273	11192	12119	13365	14328
1694.6	Nagymaros	6629	7325	8712	9257	9783	10457	10955
1446.8	Mohács	5958	6548	7708	8157	8589	9138	9541
1425.5	Bezdan	5807	6452	7847	8437	9029	9823	10435
1367.4	Bogojevo	6632	7334	8810	9418	10020	10815	11418
1153.3	Pancevo	11602	12611	14661	15483	16285	17326	18105
1060	Veliko Gradiste	12095	13128	15167	15962	16728	17708	18430
955	Orsova-Turnu Severin	11914	12901	14754	15445	16094	16901	17481
554	Zimnicea	12737	13776	15769	16528	17248	18155	18815
132	Reni	12963	13918	15596	16183	16715	17352	17793
72	Ceatal Izmail	12699	13677	15492	16161	16785	17557	18108
2b	**With historic maxima**							
River km	Station/*T*-year	*5*	*10*	*50*	*100*	*200*	*500*	*1000*
2376.1	Regensburg-Schwabelweis*	1966	2298	3065	3407	3761	4249	4637
2300	Pfelling*	1964	2306	3089	3437	3795	4289	4680
2256.9	Hofkirchen*	2334	2765	3840	4353	4905	5701	6359
2150	Achleiten*	4995	5776	7748	8701	9730	11226	12472
2135.2	Linz*	4563	5453	7717	8818	10014	11758	13218
2002.7	Stein-Krems (Kienstock)*	6482	7535	10096	11295	12569	14384	15869
1934.1	Wien-Nussdorf*	6371	7329	9623	10682	11798	13374	14652
1868.8	Devin/Bratislava*	7166	8194	10479	11469	12476	13842	14909
1694.6	Nagymaros*	6671	7431	9020	9671	10314	11159	11799
132	Reni	12963	13918	15596	16183	16715	17352	17793
72	Ceatal Izmail*	12743	13830	15973	16808	17612	18640	19397

* With estimated historical maxima

Regionalization of the skew coefficients *G* for the stations along the Danube River

Firstly, the evaluation of several hydrological characteristics were analysed along the Danube River. In Fig. 7 left there are presented course Q_T design values along the Danube. Development of the coefficients $k=Q_T/Q_a$, (Q_a is long term mean discharge) is presented in Fig. 7 right.

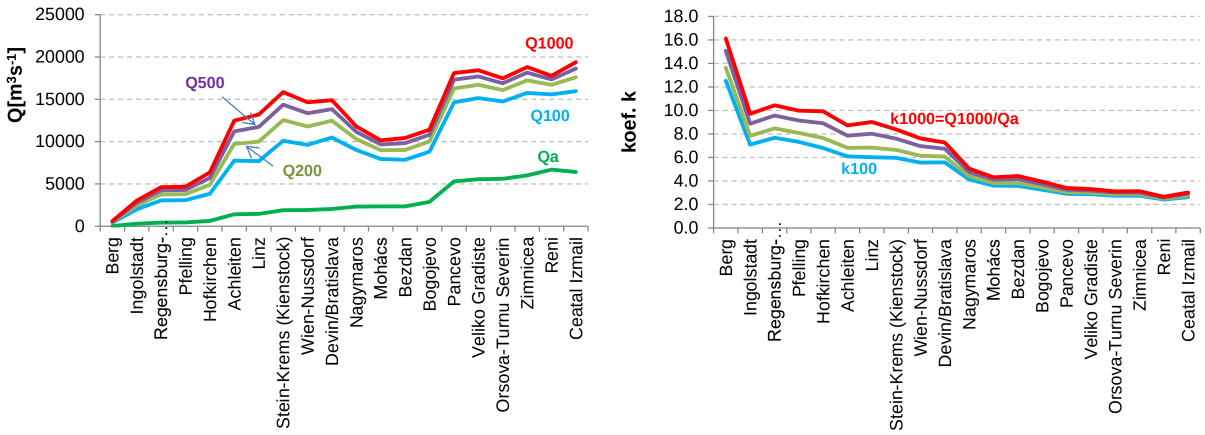


Fig. 7. Course of Q_{1000}, Q_{500}, Q_{200}, Q_{100} design discharges, and Q_a (left); course of coefficient k_{1000}, k_{500}, k_{200}, k_{100} (right) in stations along the Danube River.

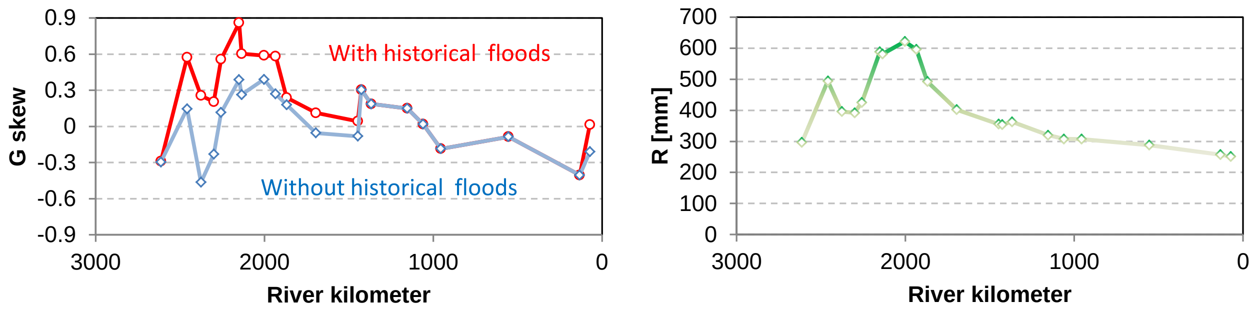


Fig. 8. Course of skew coefficients *G* and G_h (left) and course of runoff depth (right) along the Danube River.

The *1000*-year discharge is 16-times higher than the mean annual discharge at station Berg, while only 7-times higher at station Bratislava, and only 3-times higher at station Reni.

From the Fig. 8 it follows, that the skew coefficients *G* and G_h have the similar course as long term runoff depth at the analysed stations. Therefore, the following two best fitted relationships between the historical skew coefficient G_h and the runoff depth at the station were estimated:

$$G_h = 1.03437*\ln(R) - 5.95 \qquad (11)$$

$r^2 = 0.788$;

$$G_h = 10.00246*R - 0.778 \qquad (12)$$

$r^2 = 0.769$;

where: *R* – long-term average annual runoff depth in mm (from 240mm to 640mm).

Finally, we propose to use the regional skew coefficient *Gr* calculated according to linear relationship (12) to estimate the *T*-year discharges in all stations on the Danube River.

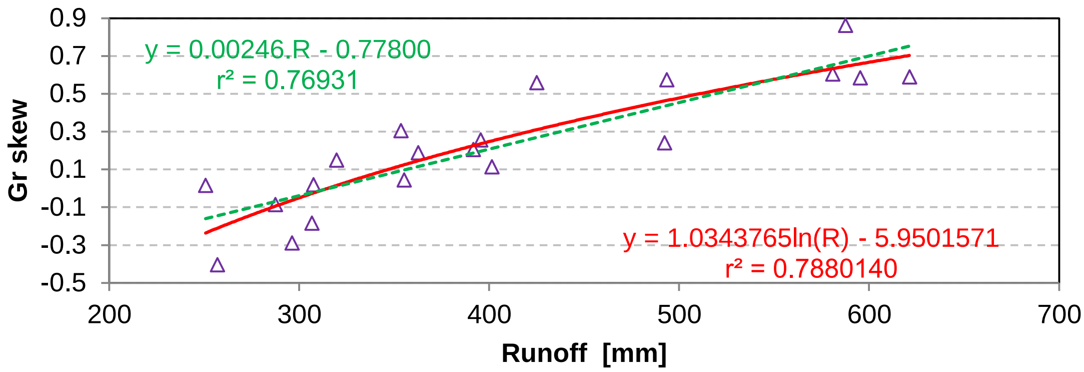


Fig. 9. Dependence of regional skew coefficient G_r on the runoff depth *R*, Danube River

CONCLUSION

With the increase of population – and with the development of civilization in general – an increase of vulnerability of the society is closely connected. It concerns also the threats by high floods as well as by incidents of long periods of droughts.

The territory of the Danube River is one of the most flood-endangered regions in Europe. Therefore, there is a strong need to have complete and exhausting information on the flood regime in order to be able to generalize such information on the basis of long-term observations from the whole Danube territory.

In estimating the extreme floods design values, we test the use of only one type of peak probability distribution, namely the log-Pearson type III distribution (LP3). This type of distribution is flexible and possible to reach extreme values according to coefficient of skewness (*G*). Coefficient of skewness calculated from measured data influences the shape of frequency curve. Steep slopes in catchments, low infiltrated areas, quick propagation of flood waves and one or more extremely high peak flows indicate high positive values of skewness (*G*). On the other hand flat slopes, high infiltrated areas and runoff from catchment regulated by lakes and wetlands indicate negative values of skewness.

In the case of gauges with historic floods, we added historic floods into the measured Q_{max} series, and recalculated the parameters of the LP3 distribution curves for individual stations having included the historic floods. The inclusion of the historical floods to calculation procedure has increased the skew coefficient G to G_h by 0.2 in average. Historic coefficients of skewness (G_h) of the LP3 distribution curves are in a range from –0.404 to 0.861 along the Danube River.

For stations along the Danube River, we propose to apply the regional skew coefficient G_r, estimated according to relation (12). Using one type of distribution gives us a chance to generalize its skewness coefficients. Then we are able to estimate *T*-year discharges at gauges with short period of observations, and even between two observing gauges.

The calculated *1000*-year discharge is 16-times higher than the mean annual discharge at station Berg, while only 7-times higher at station Bratislava, and only 3-times higher at station Reni.

The estimation of *T*-year discharges is never-ending process. Urbanization, channel regulation, flood protection construction and many other interventions, can change maximum discharges and negatively influence the application of frequency analysis. The future prediction of peak annual discharges is based on historical records. Land use changes and massive regulations of river beds can interrupt a stationarity of hydrological time series. Selected statistical variables (mean, median, skew, variation) have to be estimated appropriately from all the observing data. If anything will be changed in a catchment, it is necessary to recalculate distribution curves and define new *T*-year discharges in particular stations.

ACKNOWLEDGEMENTS

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ESTIMATION OF THE FLOOD MAXIMUM VOLUMES FOR VARIOUS DURATIONS OF THE RIVER RUNOFF AND THEIR MUTUAL DEPENDANCES: A CASE STUDY ON HRON RIVER IN SLOVAKIA

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ABSTRACT

This work deals with the determination of the annual maximum discharge volumes on the Hron River for the runoff time duration t = 2, 5, 10, and 20 days. The series of 84 years (1931–2015) mean daily discharges of the Hron River at Banská Bystrica station was used as input data to calculate the maximum annual volumes of runoff of the Hron River. Subsequently, the theoretical curves of exceedance of the maximal discharge volumes were determined by the LogPearson distribution of the Type III. This type of probability distribution is used to estimate maximum (extreme) values across a range of natural processes. The results of the estimated T-year volumes by using PL III distribution were compared to other types of theoretical distribution functions used in hydrological extreme analyses in Slovakia (Gamma, Log-normal, etc.). The second part of our work was focused on the bivariate modelling of the relationship between T-year maximum volumes with different duration and peak discharges. In the case of modelling without evaluating this mutual dependence of the flood wave characteristics, they may be overestimated (in the case of the negative dependence) or underestimated (in the case of the positive dependence). The Archimedean class of copula functions was used as mathematical tool for the dependence modelling. The LP III distribution was used as marginal probability distribution function. Subsequently joint and conditional return periods of the T-year maximum annual flows and T-year maximum volumes with different time duration were calculated. The first one defines joint return periods as: the return periods using one random variable equaling or exceeding a certain magnitude and/or using another random variable equaling or exceeding another certain magnitude. The second one is conditional return periods for one random variable, given that another random variable equals or exceeds a specific magnitude.

Keywords: Hron River, maximum runoff volume, peak discharge, probability distribution, T-year volume, copula function.

INTRODUCTION

Solution of some water management tasks requires not only knowing maximum discharge but also the shape of the flood wave or at least its volume. The volume of the flood waves and its importance is evaluated rarely. In the study of the flood wave parameters the attention is usually given to the culmination or maximum water level. The significance of the flood wave volume as an important hydrological characteristic was evident, e.g. during the flood in 1965 on the Danube river, when the protective dams ruptured due to the occurrence of extremely long, high levels of flood water.

One of the first hydrologist who to deal with the theoretical processing of flood volumes in Slovakia was Bratranek (1937). In the first case, he processed the volumes of all major floods above the selected limits of discharges using the return period curve. T-year volumes determined from the extrapolated return period curve. In the second case author T-year volumes determined from generalized results of wave processing. The disadvantage of this method was that the derived formula could not be used for volumes with less probability of discharge exceedance than is return period of 20 years. Zatkalik (1970) dealt with the calculation of the maximum volumes of the Danube River waves. The author takes in calculating of the maximum volumes procedure into account the duration of the flood wave in days. The study, analysis and estimation of the flood wave volumes corresponding to the maximum design discharge with a return period of T on Danube River in Slovakia was reported in last years in e.g. Mitková et al., 2002; Halmová et al. 2008; Szolgay et al. 2012 or Pekarova et al. 2018.

From foreign authors the determination of maximum volumes was, for example, addressed by Beard (1956). The author used the theoretical curves of exceedance to calculate the annual maximum volumes of the different probability taking also into account the duration of the flood wave. The mathematical expressions for probability distribution of runoff volume and the maximum discharge from the selected basin derived Guo and Adams (1998). The modelling of flood flows and flood wave volumes using special statistical methods has also been addressed by Mediero et al. (2010). The hydrological model and formula for determining the hypothetical flood wave volume in non-gauged basins for the area of Upper Vistula River was presented by Gądek and Bodziony (2015).

In addition to the estimation of the N-year maximum flood wave volumes there is also a need to model the development of two risk hydrological factors that are dependent on each other. In the case of modelling without evaluating this mutual dependence of the flood wave characteristics, they may be overestimate (in the case of negative dependence) or underestimate (in case of positive dependence). The traditional approaches to analysing dependencies between variables, such as flood discharge and volume, can be described by the classical class of two-dimensional distributions. Such a class can be considered two-dimensional copula functions. Many hydrologists analysed mutual dependence between the components of the hydrological cycle to identify the flood-generating processes using the copula functions (Ashkar and Rousselle, 1982; Salvadori and De Michele, 2004; Sraj et al., 2014; Brunner et al., 2016; Stamatatou et al., 2018 and etc.). In Slovak conditions, Gaal et al. (2010); Bačová and Halmová (2014); Szolgay et al. (2016); or Kohnova et al. (2016), dealt with the modelling of multidimensional time series in the field of natural sciences, especially the relation of maximum discharges, volume and eventually the duration of flood waves. The correlation dependencies between the individual elements of the flood waves were also analysed by Bezak et al. (2015) or Papaioannou et al., (2016) and etc.

This paper is focused on determination of maximum volumes of given duration of runoff (2, 5, 10 and 20 days) on the Hron River at Banská Bystrica during the period of 1931–2015. Subsequently, the theoretical curves of exceedance of the maximum discharge volumes Vtmax will be determined by the selected probability distributions and the T-year maximum annual volumes was estimated. At the end of the article an analysis and statistical evaluation of the mutual dependence and occurrence of maximum discharges and volumes with different time duration using the copula functions will be estimated. Results of the analysis will be discussed and presented in figures and tables.

METHODS AND DATA (STUDY AREA)

Determination of annual maximum volumes of a given duration

The series of mean daily discharges (1931–2015) of the Hron River at Banská Bystrica station was used as input data. Maximum volumes with time durations t (2, 5, 10 and 20 days) of the wave was determined. If the wave duration was less than 20 days the steady discharges were included into the analysis. Figure 1 presents example of the determination of maximum volumes with given durations. In case of the flood in 1974 and t=5 days the fifth 5-daily move averages were calculated around the culmination. Consequently, only one maximum value was included into the statistical data set for analysis (Fig. 1).

Estimation of the T-year maximum annual volumes for different durations of the runoff on the Hron River at Banská Bystrica (1931–2015)

In our analysis we use one type of the theoretical probability distribution the Log-Pearson distribution type III (LP III). The advantage of this particular technique is that extrapolation can be made of the values for events with return periods well beyond the observed flood events. This theoretical distribution belongs to the family of Pearson distributions, so called three parametric Gamma distributions, with logarithmic transformation of the data. Its parameters are median μ, variation $\sigma 2$ and asymmetry γ. In many countries is LP III distribution used as a first chose for flood. Parameters can be determined by several methods e.g.: LGMO – method of logarithmic moments, RLMO – method of real moments or MXM – method of mixed moments.

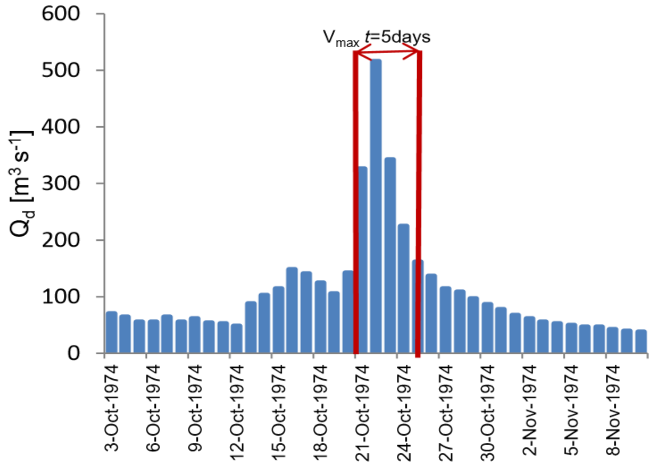


Fig. 1. A scheme for determining of the maximum flood wave volume on Hron River: Banská Bystrica for flood in 1974 for t=5 days.

The cumulative distribution function and probability distribution function according Hosking and Wallis (1997) are defined as:
If $\gamma \neq 0$ let $\alpha = 4/\gamma^2$ and $\xi = \mu - 2\sigma/\gamma$

If $\gamma > 0$ then:

$$F(x) = G(\alpha, \frac{x-\xi}{\beta})/\Gamma(\alpha), \qquad (1)$$

$$f(x) = \frac{(x-\xi)^{\alpha-1} e^{-(x-\xi)/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \qquad (2)$$

If $\gamma < 0$ then

$$F(x) = 1 - G(\alpha, \frac{\xi-x}{\beta})/\Gamma(\alpha) \qquad (3)$$

$$f(x) = \frac{(\xi-x)^{\alpha-1} e^{-(\xi-x)/\beta}}{\beta^{\alpha}\Gamma(\alpha)} \qquad (4)$$

where: μ - location parameter; σ - scale parameter; γ - shape parameter; Γ – Gamma function. In the world literature, there are a number of scientific papers dealing with the selection and testing of the suitability of theoretical probability distributions in estimating the maximum values of hydrological characteristics. Therefore, we compared the LP III distribution with the theoretical probability distributions that were (and still are) most widely used hydrological practice in Slovakia: Gamma distribution and Log-normal distribution. To verify the accuracy of theoretical distributions, we used a non-parametric Kolmogorov-Smirnov goodness of fit test for the significance level α = 0.05.

Analysis of the dependence between maximum annual volumes with different duration and maximum annual discharges on the Hron River at Banská Bystrica by copula functions

Joint distribution function –copula functions

Copula functions were used as mathematical tool for determining a joint cumulative distribution of two dependent variables. We used the Archimedean class of copula functions. Among existing types of copulas, the Archimedean one is the very popular class used in hydrological application. This class of copulas is popular in empirical applications for flexibility, easy construction and includes a whole suite of closed-form copulas that covers a wide range of dependency structures, including comprehensive and non-comprehensive copulas, radial symmetry and asymmetry, and asymptotic tail dependence and independence. The Clayton, Gumbel-Hougaard and Frank copulas were selected for this study (Table 1). The copula parameter θ was estimated using a mathematical relationship between the Kendall`s coefficient of rank correlation and the generating function φ(t) (Nelsen, 2006).

Table 1. Probability functions, parameter space, generating function and relationship of nonparametric dependence measure with association parameter for the most frequently used Archimedean copulas.

Copula function	C (u, v, θ)	parameter θ	Kendall's τ	Generator φ(t)
Clayton	$(u^{-\theta}+v^{-\theta}-1)^{-1/\theta}$	$[-1,\infty)/\{0\}$	$\frac{\theta}{\theta+2}$	$\frac{1}{\theta}(t^{-\theta}-1)$
Gumbel-Hougaard	$\exp\left[-((-\ln u)^{\theta}+(-\ln v)^{\theta})^{1/\theta}\right]$	$[1,\infty)$	$\frac{\theta-1}{\theta}$	$(-\ln t)^{\theta}$
Frank	$-\frac{1}{\theta}\ln[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{(e^{-\theta}-1)}]$	$(-\infty,\infty)/\{0\}$	$1+\frac{4}{\theta}[D_1(\theta^{*})-1]$	$-\ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$

Joint and conditional return period.

In hydrological frequency analysis the return period of the hydrological variable that occurs once in a year, we can define as:

$$T=\frac{1}{(1-F(x))} \qquad (5)$$

where, T is return period in years and F(x) is univariate cumulative distribution function.

In multivariate statistical analysis, we can determine the return period of the phenomenon in two ways. The first is a joint return period and second, is a conditional return period.

Joint return period for two variables defined more authors (Shiau, 2003; Salvadori and De Michele, 2004) and it can be written in the form:

$$T_{x,y}^{and}=\frac{1}{(1-F(x)-F(y)+H(x,y))} \qquad (6)$$

or

$$T_{x,y}^{or}=\frac{1}{(1-H(x,y))} \qquad (7)$$

Equation (6) represents joint return period of X≥ x and Y≥ y. Equation (7) represents joint return period of X≥ x or Y≥ y. These relationships indicate, that different combinations of the numbers x and y, can take same return period (equation 8). H(x, y) is the joint cumulative distribution function (can be expressed as copula function).

$$T_{x,y}^{or}\le min[T_x,T_y]\le max[T_x,T_y]\le T_{x,y}^{and} \qquad (8)$$

Conditional return period for X given Y≥y may be expressed as:

$$T_{(x|Y\ge y)}=\frac{1}{(1-F(x))*(1-F(x)-F(y)+H(x,y))} \qquad (9)$$

where x and y are random variables and H(x, y) is the joint cumulative distribution function. An equivalent formula for conditional return period of Y given X≥x can be obtained.

RESULTS AND DISCUSSION

Hron River basin and input data

The Hron River is the second longest Slovak river. It measures 298 km and flows only through the territory of Slovakia and flows into the Danube above Štúrovo. Hron springs in Horehronské podolí, in contact with Low Tatras and Spiš-Gemer karst. Hron after Banská Bystrica drains the drainage area of 1 766.48 km². The long-term mean daily discharge during 1931–2015 amounted to 25.9 m^3s^{-1} in Banská Bystrica. The maximum discharge during the analysed period at the station Banská Bystrica was 560 m^3s^{-1} (October, 1974). The probabilities of exceedance curve of the maximum annual discharges according to LP III probability distribution is shown in Figure 2. The course of the maximum annual discharges and their long-term trend is shown in Figure 3a. The annual maximum discharges show a slightly decreasing trend. Deviations from the long-term mean annual discharges in the analysed period show the occurrence of three dry periods 1941–1945, 1985–1991 and 2003–2007 (Figure 3 b). The years from 1951 to 1956 we can refer as a longer wet period and two highest discharges during the whole period were recorded in 1960 and 1974 (Figure 3 b). Scenarios of changes in selected components of the hydrosphere and biosphere in the Hron River basin are described in Pekarova and Szolgay (2005). In terms of 2 to 10 days maximum volumes, the flood in 1974 was the largest flood during the period of 1932–2015. The maximum number of maximum annual discharges was occurred in April and mean time duration of the waves was 20 days.

The time course of the selected maximum runoff volumes on the Hron River at Banská Bystrica for the runoff times duration t= 2, 5, 10 and 20 days is shown in Figure 4. a-d and show a slightly decreasing linear trend.

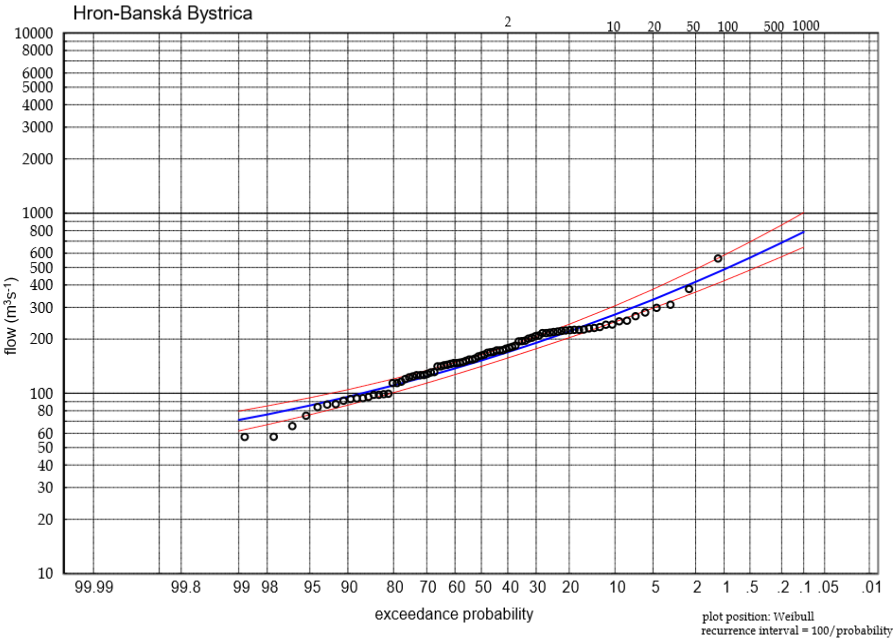
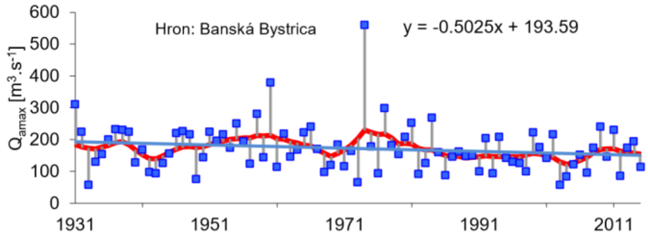
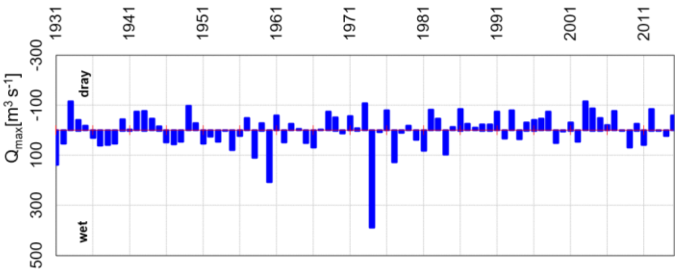


Fig. 2. The exceedance probability curve of the annual peak discharges of the Hron River: Banská Bystrica during the period of 1931–2015 (Log-Pearson III distribution).

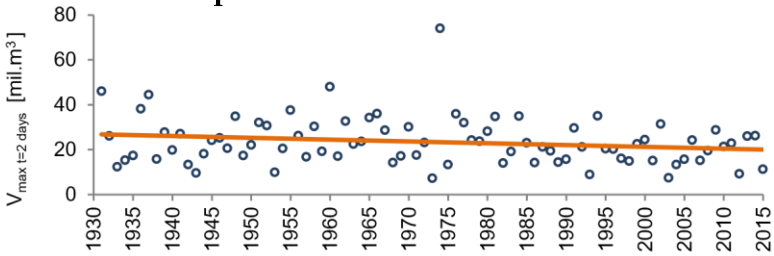


a)

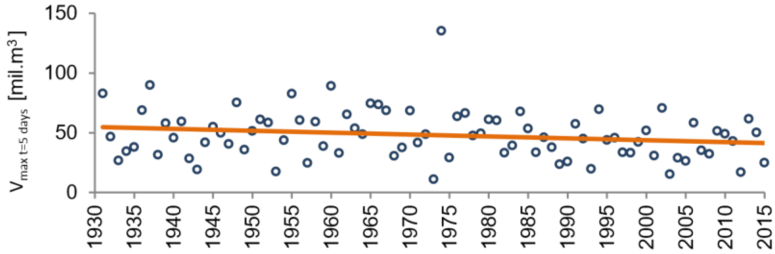


b)

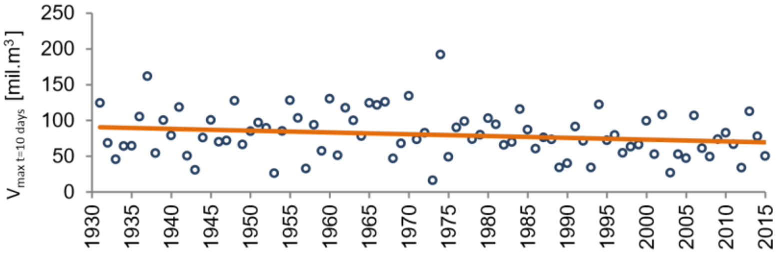
Fig. 3. a) Maximum annual discharges of Hron River: Banská Bystrica, their linear trend and 5-year moving trend and b) deviation from long-term mean annual discharge during the period of 1931–2015.



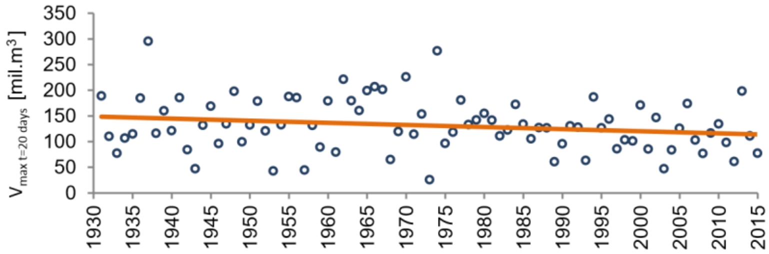
a)



b)



c)



d)

Fig.4. a)-d) Flood wave annual maximum volumes for various flood duration of the Hron River: Banská Bystrica during the period of 1931–2015.

Return period of the maximum volumes for different runoff duration on the Hron River at Banská Bystrica

The series of V_{tmax} has been arranged descending separately for runoff durations, and for individual members of the series have been attributed probability of exceedance.

The calculation of the theoretical maximum volume overrun curve was done using LP III theoretical probability distribution. Subsequently, the calculated T-year maximum volumes V_{tmax} were estimated for given discharge values. The relationship between the probability of exceedance a certain value in any year and its average return period is (Szolgay, 1994):

$$p = 1 - e-1/T \qquad (10)$$

If $N \geq 10$ than

$$p = 1/T. \qquad (11)$$

Figure 5 shows the exceeding probabilities of the maximum annual volumes for different values of the flood wave duration t = 2, 5, 10 and 20 days on the Hron River at Banská Bystrica. Estimated values of T-year maximum annual runoff volumes for given duration according selected LP III, Gamma and Log-normal distributions are listed in table 1. Kolmogorov-Smirnov test shoved that we cannot reject hypothesis that selected theoretical probability distributions fit well the observed data at 5% significance. Results shoved relatively small differences between estimated values of Tyear maximum volumes when comparing the individual types of theoretical probability distributions used in hydrological analyses of extremes in Slovakia. The Gamma theoretical probability distribution reached the lowest values of estimated T-year maximum volumes Vtmax, especially for volumes with high return periods (Table 2).

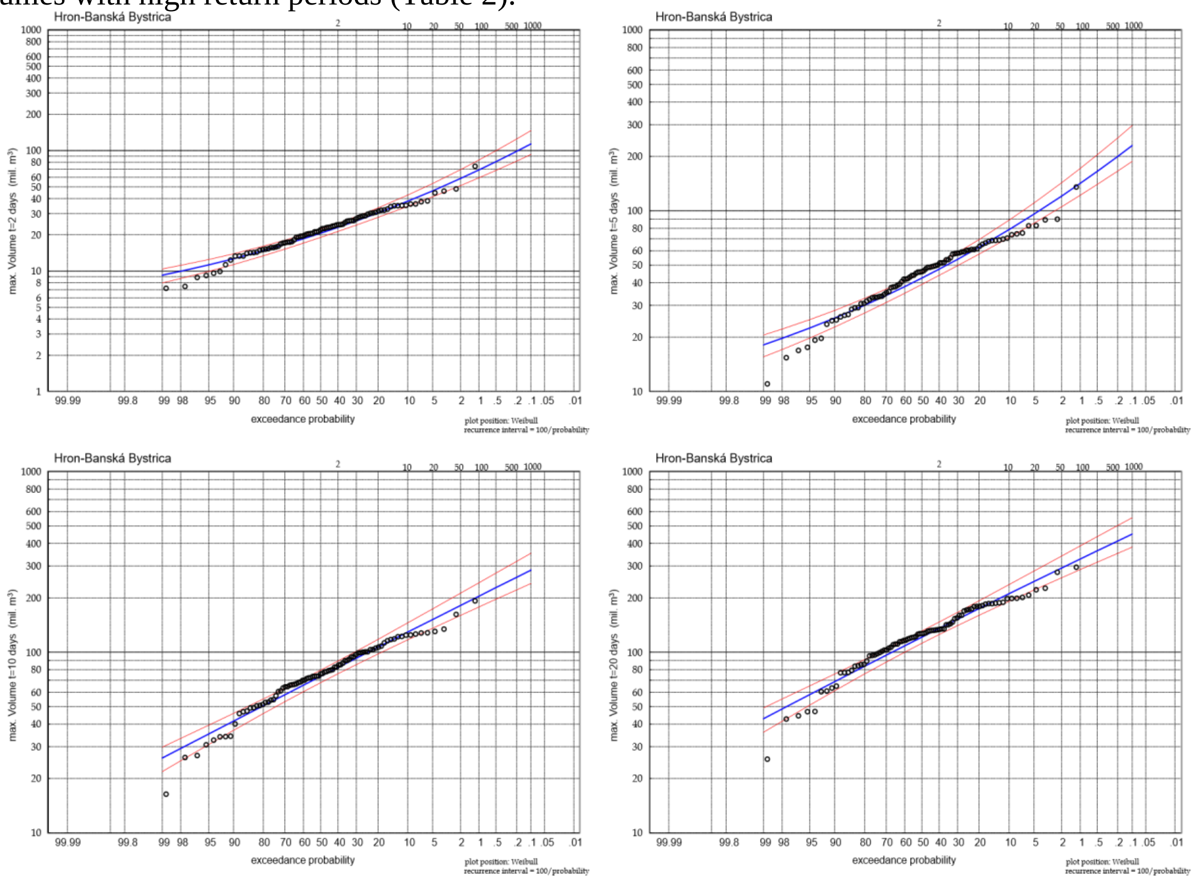


Fig. 5 Exceedance probabilities of maximum flow volume V_{tma}x of the Hron River: Banská Bystrica (1931–2015) for different values runoff duration.

Table 2. T-year maximum discharges Q_{max} [m^3s^{-1}] and T-year runoff volumes V_{tmax} [mil. m^3], Hron: Banská Bystrica, period of 1931-2015.

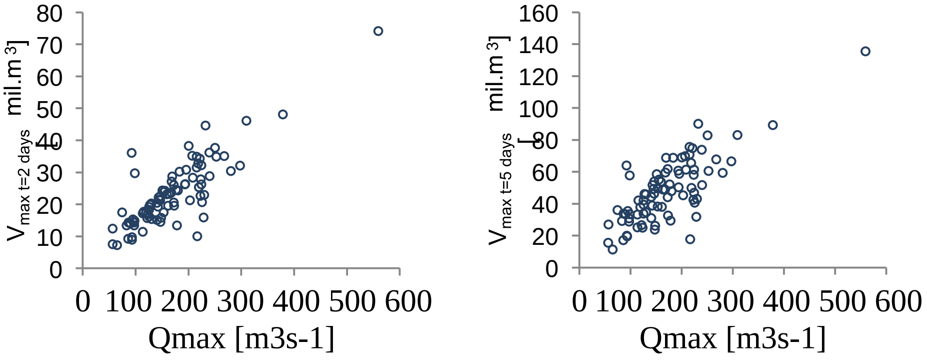
N ○[roky]	2	5	10	50	100	200	500	1000
P [%]	39	18	9.5	2	1	0.5	0.2	0.1
Q_{max} [m^3s-1]	169	221	274	416	487	567	685	787
			Log-Pearson II					
$V_{tmax=2\ dni}$ [mil. m^3]	23.0	30.4	38.0	58.6	69.1	80.9	98.5	113.6
$V_{tmax=5\ dní}$ [mil. m^3]	47.5	62.9	78.7	120.7	141.9	165.2	200.0	229.6
$V_{tmax=10\ dní}$ [mil. m^3]	82.2	106.6	129.4	181.4	204.3	227.8	259.8	284.8
$V_{tmax=20\ dní}$ [mil. m^3]	135.4	174.6	210.9	292.5	328.0	364.0	412.6	450.4
			Log-normal					
$V_{tmax=2\ dni}$ [mil. m^3]	24.1	31.7	37.7	51.9	58.4	65.0	74.1	81.2
$V_{tmax=5\ dní}$ [mil. m^3]	49.5	5.6	78.1	108.4	122.2	136.4	155.9	171.1
$Vt_{max=10\ dní}$ [mil. m^3]	82.2	109.6	130.7	181.4	204.6	228.3	260.9	286.4
$V_{tmax=20\ dní}$ [mil. m^3]	135.4	178.7	209.5	288.0	323.9	360.5	410.6	449.8
			Gamma					
$V_{tmax=2\ dni}$ [mil. m^3]	24.4	31.9	37.4	49.1	53.9	58.5	64.4	68.8
$V_{tmax=5\ dní}$ [mil. m^3]	50.7	65.4	75.8	98.0	107.0	115.7	126.8	135.0
$V_{tmax=10\ dní}$ [mil. m^3]	84.6	107.3	124.6	159.1	173.0	186.9	204.2	216.9
$V_{tmax=20\ dní}$ [mil. m^3]	138.8	175.8	201.9	256.8	279.1	300.5	327.8	347.8

Bivariate analysis of the dependence between maximum annual volumes with different runoff duration and maximum annual discharges using copula functions

Using copulas that combine one-dimensional marginal distributions of random variables with their associated distribution, we tried to process and analyse the interdependence structure of the variables Q_{max} and V_{tmax}. Calculated values of the Spearman ρ and Kendall's τ correlation coefficients are listed in table 3. The dependences between variables Q_{max} and V_{tmax} for t = 2, 5, 10 and 20 days are presented in figure 6. The LP III distribution was used as marginal distribution. Archimedean copula functions (Clayton, Gumbel-Hougaard and Frank) were used in our analysis.

Table 3. Values of the Spearman ρ and Kendall's τ of the selected combination of Q_{max} and V_{tmax} on Hron River: Banská Bystrica (1931–2015)

	$Q_{max\text{-}Vtmax=2dni}$	$Q_{max\text{-}Vtmax=5dní}$	$Q_{max\text{-}Vtmax=10dní}$	$Q_{max\text{-}\ Vtmax=20dní}$
Spearman ρ	0.76	0.69	0.63	0.611
Kendall's τ	0.62	0.52	0.46	0.46



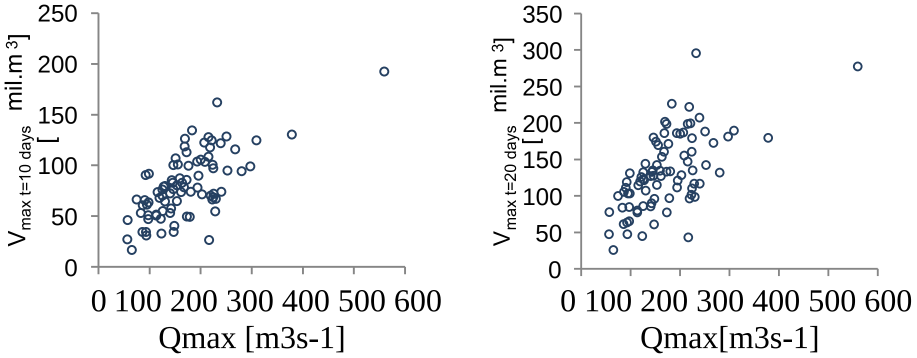


Fig. 6. Relationships between annual peak discharges Q_{max} and maximum wave volumes V_{tmax} of the Hron River: Banská Bystrica (1931–2015) for selected runoff duration t= 2, 5, 10 and 20 days

The copula parameters were calculated based on the relationship with the Kendall correlation coefficient. The Kolmogorov-Smirnov goodness-of-fit test was used to evaluate the accuracy of the parametric copula functions. Subsequently, some statistical criterions were also used (MAE, RMSE). Copula parameters for selected combination of the variables and results of the Kolmogorov-Smirnov goodness-of fit test are listed in Table 4. The results showed that all three tested Archimedean copulas achieved relatively equal estimation errors. The lowest error estimation values reached the probability calculated using Gumbel-Hougaard copula function. From a visual comparison of empirical and parametric copulas, it was also evident that the low correlation between the variables had reached a higher match between the theoretic and empirical copula function (Figure 7). Figure 8 shows simulation of 1000 pairs of variables Q_{max} and V_{tmax} calculated by Gumbel-Hougaard copula function.

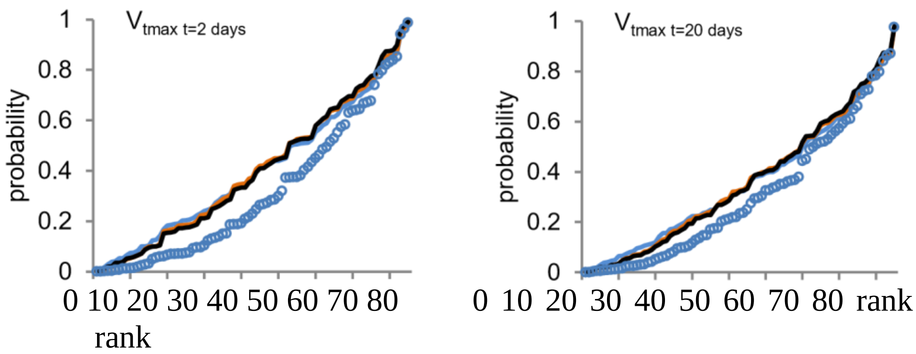


Fig. 7 Comparison of the empirical and selected parametric copula functions (Clayton, Gumbel-Hougaard Frank) of the Hron River: Banská Bystrica (1931–2015) for Q_{max} and V_{tmax} for selected runoff duration t=2 and t=20 days.

Table 4. Values of the copula parameters (C - Clayton, G-H - Gumbel-Hougaard, F – Frank) and p-values of the Kolmogorov-Smirnov test

	Q_{max} - $V_{tmax=2d}$	Q_{max} - $V_{tmax=5d}$	Q_{max} - $V_{tmax=10d}$	Q_{max} - $V_{tmax=20d}$
C	3.24	2.20	1.70	1.67
G-H	2.62	2.10	1.85	1.83
F	8.6	6.2	5..1	5
p-value KS (C)	0.098	0.098	0.142	0.270
p-value KS (GH)	0.142	0.270	0.199	0.275
p-value KS (F)	0.067	0.140	0.142	0.270

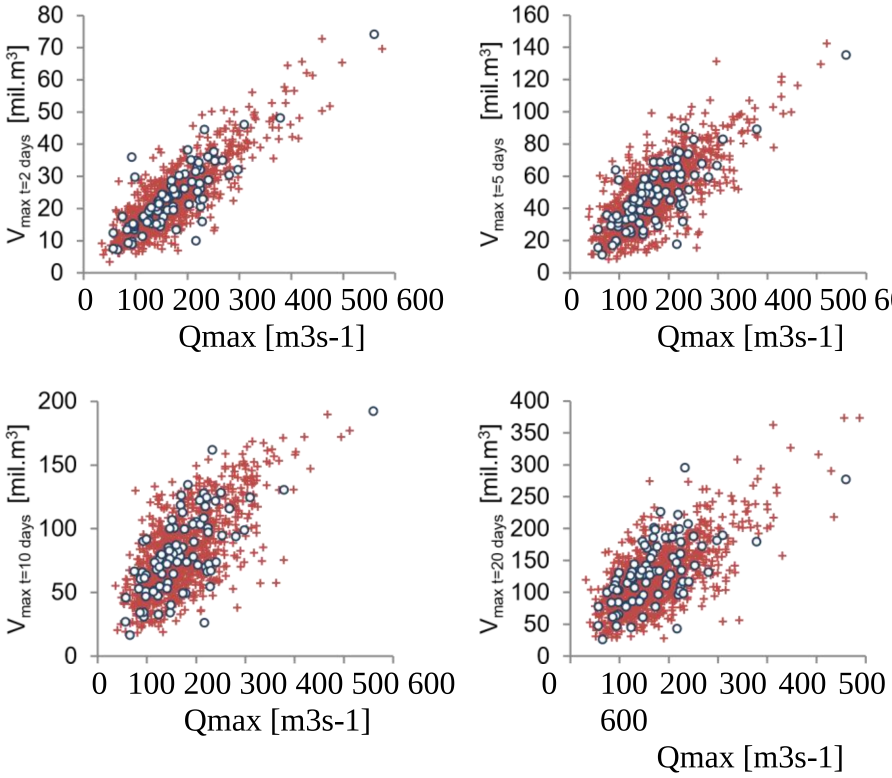


Fig. 8. Simulation of 1000 of the Q_{max} and V_{tmax} pairs using the selected Gumbel-Hougaard copula function on the Hron River: Banská Bystrica (1931–2015).

Examples of the joint and conditional return periods of the T-year maximum discharges and T-year maximum volumes for duration of the runoff t=2 and 20 days for Hron River at Banská Bystrica (1931–205) using the Gumbel-Hougaard copula function are listed in Table 5 and Table 6.

Table 5. Joint and conditional return period for maximum discharges Q_{max} [m^3s^{-1}] and T-year runoff volumes V_{tmax} = 2 days [mil.m^3] on Hron River: Banská Bystrica for the period of 1931- 2015

T [year]	P [%]	Q_{max} [m^3s^{-1}]	$V_{tmax=2d}$ [mil. m^3]	F_{Qmax}	$F_{Vtmax = 2 d}$	CG-H	T^{or} [year]	T^{and} [year]	$T_{V/Q}$ [year]
2	39	169	23	0.61	0.61	0.5252	3	2	8
5	18	221	30	0.82	0.82	0.7722	8	4	42
10	9.5	274	38	0.905	0.905	0.8781	15	8	155
50	2	416	59	0.98	0.98	0.9740	71	38	3566
100	1	487	69	0.99	0.99	0.9870	143	77	14304

Table 6. Joint and conditional return period for maximum discharges Q_{max} [m^3 s^{-1}] and T-year runoff volumes V_{tmax}=20 days [mil.m^3] on Hron River: Banská Bystrica for the period of 1931-2015

T [year]	P [%]	Q_{max} [m^3s^{-1}]	$V_{tmax=20d}$ [mil. m^3]	F_{Qmax}	$F_{Vtmax = 20 d}$	CG-H	T^{or} [year]	T^{and} [year]	$T_{V/Q}$ [year]
2	39	169	135.38	0.61	0.61	0.4858	4	2	10
5	18	221	174.65	0.82	0.82	0.7484	9	4	51
10	9.5	274	210.90	0.905	0.905	0.8643	18	7	194
50	2	416	292.53	0.98	0.98	0.9709	92	34	4577
100	1	487	327.96	0.99	0.99	0.9854	184	69	18420

CONCLUSIONS

The first part of the paper deals with the determination of the annual maximum discharge volumes on the Hron River for the duration of 2, 5, 10 and 20 days (V_{tmax}). The series of 84 years (1931–2015) mean daily discharges were analyzed. The empirical probability distribution of the data was compared with the theoretical Log-Pearson probability distribution. Subsequently, the maximum volumes with different duration were estimated by Log-Pearson distribution type III (LP III). The results of comparison with two other theoretical distribution types used in Slovakia: Lognormal and Gamma probability distribution showed:

- The high sensitivity of the LPIII distribution to extremes of the dataset. We can say that this probability distribution is appropriate for design hydrological values with higher values of the return period.
- Relatively small differences in the values of estimated T-year maximum volumes in compared types of theoretical probability distributions used in hydrological analyses of extremes in the Slovakia.
- The lowest values of estimated T-year volumes of a given duration, achieved Gamma theoretical probability distribution, especially for volumes with high repeat times.

In interpreting the results, it should be kept in mind that T-year maximum discharges related to the length of the analysed data set, and therefore estimated values with very high return periods are extrapolated values. Each statistical method includes some uncertainty that may be caused by the method but also the data may be affected by certain measurement error.

The second part of our paper was focused on bivariate analysis of the relationship between T-year maximum volumes with different duration and annual maximum discharges by three Archimedean copula functions (Clayton, Gumbel-Hougaard and Frank). The LP III distribution was used as marginal probability distribution function. The results of this analysis showed:

- From a visual comparison of the empirical and parametric copula functions, was evident that if correlation between variables is lower, than the match between the theoretical and the empirical copulas were better.
- The difference between selected theoretical copulas was not significant, but GumbelHougaard copula was the most suitable for maintaining and monitoring the interdependence of the variables.
- Subsequently joint and conditional return periods of the T-year maximum annual flows and T-year volumes with different time duration on the Hron River, were calculated. The first one defines joint return periods as: the return periods using one random variable equaling or exceeding a certain magnitude and/or using another random variable equaling or exceeding another certain magnitude. The second one is conditional return periods for one random variable, given that another random variable equals or exceeds a specific magnitude.

The results obtained from the bivariate as well as multidimensional analysis of the variables, which characterize the hydrological waves (flow, volume, time) can contribute to more reliable assessment of flood risks. Hence, they give an overview of the flood event as a whole and might be practically used in water management and in the design of flood protective systems.

ACKNOWLEDGMENT(S)

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MAXIMUM RIVERS RUNOFF IN THE BASIN OF TYSA AND PRUT WITHIN UKRAINE

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ABSTRACT

Research focuses on the objective assessment of maximum river runoff and its multi-annual variability in the basin of Tysa and Prut within Ukraine. For this purpose, a database of maximum river water runoff (the highest daily values per year and the largest for one of the terms of daily measurement periods) from 36 measuring stations were created. The series were formed from the beginning of observations until 2015 and in most of them, the length is 50-70 years. Their representativeness for practical calculations has been evaluated. The main statistical parameters of the maximum runoff are determined – normals of water discharge and maximum specific discharges, coefficients of variation and skewness. A comparison was made between the maximum daily runoff values and their corresponding peak maxima. This is especially important for mountain rivers to calculate and predict dangerous peaks maxima on rivers. The multi-annual variability of the maximum runoff of rivers was examined by integral curves of differences, autocorrelation, and spectral functions. The result revealed the structure of cyclical fluctuations and an assessment of trends in the current period.

Keywords: basin of the rivers Tysa and Prut; maximum runoff of the rivers; multi-annual variability; statistical parameters and distribution functions.

INTRODUCTION

The rivers Tysa and Prut belong to the Danube basin and within the boundaries of Ukraine originate in the mountains of the Carpathians. Rain and snow-rain floods are typical for rivers in their basins (Grebin et al. 2013). Often those floods acquire the character of dangerous phenomena with devastating consequences. The characteristic of such an extreme hydrological phenomenon is the maximum runoff of rivers, which serves as a measure of danger for the population and the economy. It has usually expressed as the largest discharge, volume or depth of runoff for the flood wave this year. The maximum discharge can be the largest mean daily discharge, the largest in the observation term (taken in one of the terms of the daily measurement periods) or instantaneous (absolute daily maximum).

METHODS AND DATA (STUDY AREA)

Aim of the research is to estimate the maximum runoff of rivers in the basins of Tysa and Prut and its multi-annual variability. A base of average annual and maximum discharges – largest daily mean values and the largest in the observation term, with 36 gauging stations on the rivers from the beginning of observations to 2015, have been created. At 8% of the gauging stations, the observation period is ≥ 70 years, 81% – 50-70 years, so 89% of gauging stations have periods of observation ≥ 50 years, and only 11% - ≤ 50 years (Table 1).

The criterion for the sufficiency of the available observation periods and the accuracy of determining the average maximum runoff of rivers is the ratio – the relative value of the standard deviation σ_n (1) that should not exceed 20 %. According to Table 1, such excesses are available. In the Prut and Siret basins, this is observed only on the river Cherniava – Lubkivtsi, whose period of hydrometric observations is just 28 years (Lukianets, Moskalenko 2019).

In current research were used methods of mathematical statistics processing of random variables and random functions, as well as statistical analysis of relations between hydrological variables. Practical value is determined by the further development of studies of maximum runoff of the rivers of the Carpathian Mountains and their generalization according to modern observation data

Table 4. Data about the period of hydrometric observations, the sizes of catchment areas and the relative squared errors in determining the maximum annual runoff of the rivers of the Tisza, Prut and Siret basins within Ukraine (according to hydrometric observations: from the beginning to 2015 inclusive)

River basin	Ranges		
	number of years of the observations	catchment areas F, km^2	relative quadratic error in the determination of long-term values of maximum annual water runoff σ_n, %
Danube river basin			
rivers in the basin of Tysa	53 ÷ 70	25.4 ÷ 9140	4.6 ÷ 11.7
rivers in the basin of Prut and Siret	28 ÷ 71	18.1 ÷ 6890	7.6 ÷ 20.8

RESULTS AND DISCUSSION

Explored basins within Ukraine locate on different slopes of the Carpathian Mountains: rivers of Tysa basin – on the southwest slopes, rivers of Prut basin– on the northeastern slopes. This causes certain features of physical and geographical factors in the formation of highs on the rivers in the basins of Tysa and Prut. Ranges of catchment basins of investigated rivers are in the Tysa basin F=25,4 – 9140 km^2, in the Prut basin – F=18,1 - 6890 km^2 (Table 1).

The average maximum runoff of rivers in the observation term in the multi-annual period varies– 17,1-1873 m^3·s^{-1} in the Tysa basin, and 15,7 – 1133 m^3·s^{-1} in the Prut basin. Accordingly, maximum specific discharges runoffs are 90,6 – 1886 and 71,8 – 867 dm^3·s^{-1}·km^{-2} (Table 2).

Absolutes instantaneous of the maximum runoff during observation in the Tysa basin recorded on the river Turia – Turia Polyana (F = 98,6 km^2) – 6298 dm^3·s^{-1}·km^{-2}, in the Prut basin on the river Kamianka – Dora (F = 18,1 km^2) – 4790 dm^3·s^{-1}·km^{-2} (Table 3).

Table 2. The ranges maximum discharge of water of the Tisza, Prut and Siret rivers within Ukraine and the parameters of their variability according to hydrometric observations (from their beginning to 2015 inclusive)

River basin	Ranges		
	the maximum for year discharge of water $\bar{Q}_{макс}$, m^3·s^{-1}	variation coefficient C_V	skewness coefficient C_S
Danube river basin			
rivers in the basin of Tysa	17.1÷1873	0.37-0,89	0.22-5.49
rivers in the basin of Prut and Siret	15.7÷1133	0.54-1.1	1.49-3.37

Table 3. The ranges of long-term values of maximum drainage modules for rivers of the Tisza, Prut and Siret basins within Ukraine and their maximum values for the period of hydrometric observations (from their beginning to 2015 inclusive)

River basin	The range of long-term values of average maximum specific discharges runoff $\bar{M}_{макс}$, dm^3·s^{-1}·km^{-2}	Instantaneous of the maximum runoff during observation, dm^3·s^{-1}·km^{-2}
Danube river basin		
rivers in the basin of Tysa	90.6-1886	6298 (r. Turya – Turya Polyana)
rivers in the basin of Prut and Siret	71.8-867.4	4790 (r. Kamianka – Dora)

The coefficients of variation in the Tysa basin are smaller (0,37–0,89) than in the Prut basin (0,54–1,1). Skewness coefficients have positive values that vary in wide range from 0,2 to 5,5 (Table 2). On small rivers, there are significant differences between the maximum daily average values and peak highs values, but with increasing river length, those differences are less.

The ratio between the maximum daily average values and peak highs values on rivers is very important in the development of methods of calculation and prediction of flood peaks. Such ratios are shown in the example of the Tysa River basin. Fig. 1-2 shows the dependencies between the maximum daily average and peak highs values of water flow of the Tysa River and the Latorica River that have several hydrological posts characterizing different conditions of river water flow (Table 4).

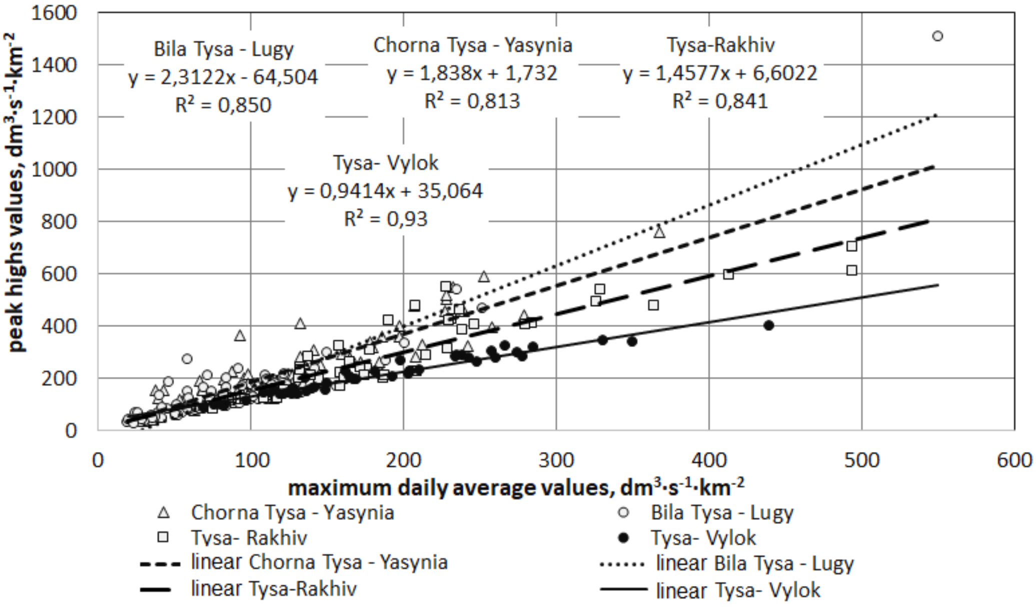

Fig. 6. The ratio between the maximum daily average values and peak highs values of specific discharges runoff of the Tysa River according to observations at the hydrological posts of Yasynia, Lugy, Rakhiv and Vylok

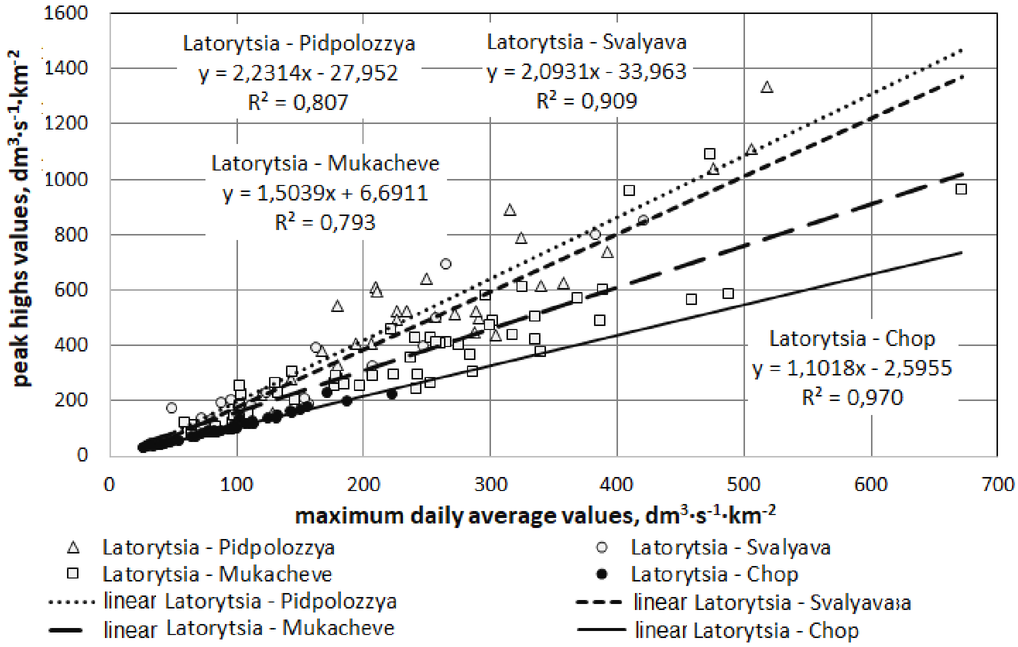

Fig. 2. The ratio between the maximum daily average values and peak highs values of specific discharges runoff of the Latorica River according to observations at the hydrological posts of Pidpolozzya, Svalyava, Mukacheve and Chop

Analyzing Fig. 1-2 and similar dependencies on the rivers of the Prut and Siret basins, it can be stated that for mountain rivers the maximums exceed the daily average values by 1,7 – 2,2 times, in the foothills – by 1,3-1,6 times, and with access to the plain – 1,0-1,2 times.

Table 4. The weighted mean rivers fall and their basin areas in the Tysa River basin.

River Post	Basin area, km^2	Weighted mean river fall, ‰
Chorna Tysa – Yasynia	194	15.7
Bila Tysa – Lugy	189	26.3
Tysa – Rakhiv	1070	9.1
Tysa – Vylok	9140	2.9
Latorytsia – Pidpolozzya	324	12.3
Latorytsia – Svalyava	680	7.4
Latorytsia – Mukacheve	1360	4.5
Latorytsia – Chop	2870	1.9

Naturally, on the rivers of the Tysa, Prut and Siret basins, at the same value of maximum daily average discharge of water, the maximum value in the observation term, in the warm period is higher than in the cold. For mountain rivers this difference can be from 10 % to 30 %, for the plain rivers it is insignificant (Grebin et al. 2013**)**.

Comparative analysis of maximum and average annual runoff of water in discharges has shown that first one is on 9-16 times bigger than average (Lukianets 2017; Lukianets, Moskalenko 2019).

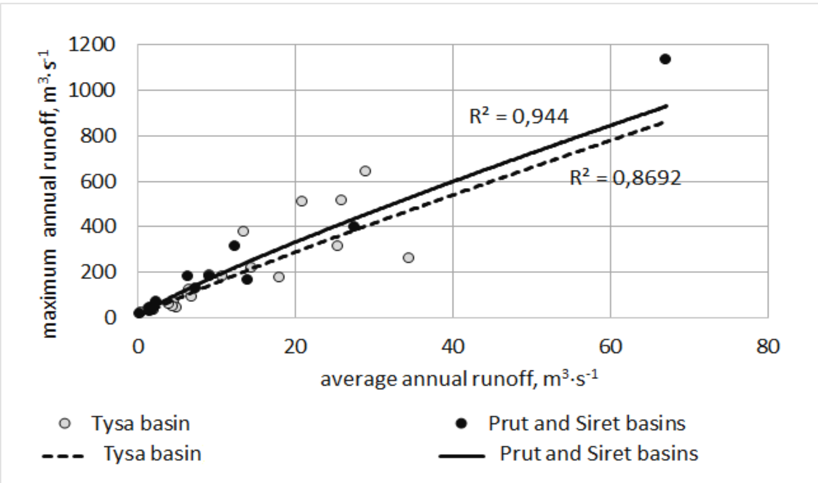

Fig. 3. Comparative analysis of maximum and average annual runoff of the rivers in the basins of Tysa, Prut and Siret

Integral curves of differences, autocorrelation and spectral functions were used to study the multi-annual variability of the maximum runoff of rivers (Fig. 4-6, Table 5-6).

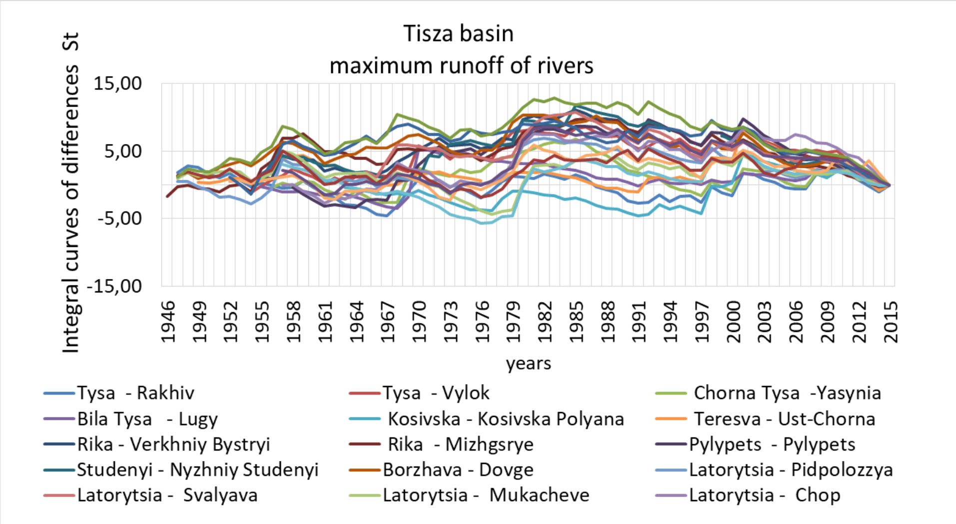

Fig. 4 Integral curves of differences maximum per year runoff of rivers Tysa basin within Ukraine

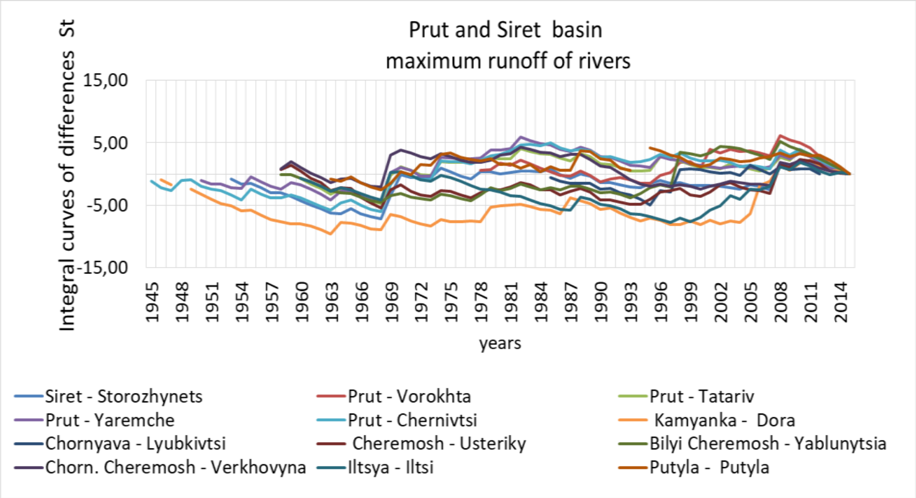

Fig. 5 Integral curves of differences maximum per year runoff of rivers Prut and Siret basin within Ukraine

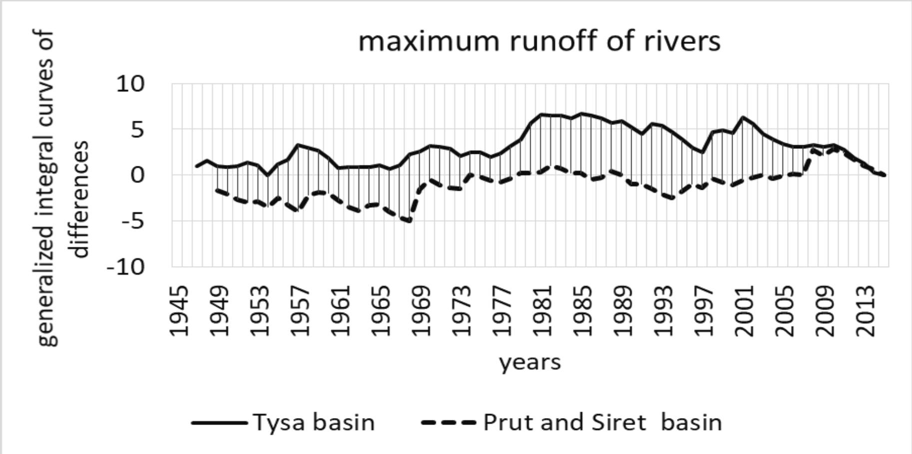

Fig. 6 Summary integral curves of differences maximum per year runoff of rivers Tysa, Prut and Siret basins within Ukraine

Table 5. Generalized data on the duration of cycles in time series of characteristics of water runoff on the rivers of the Tysa, Prut and Siret basins within Ukraine by autocorrelation and spectral analysis

River – section	Duration of cycles (number of years)			
	average annual water runoff	water runoff (warm period)	water runoff (cold period)	maximum per year water runoff
Tysa -Vylok	4, 30	3-5	6-8	7, 14-15
Prut - Chernivtsi	3-5, 7, 14	4, 7	3-4, 7 29-31	5-7, 26

Table 6. The closeness of the relationship between time series of water runoff characteristics of adjacent river basins of the Ukrainian Carpathians Tysa -Vylok↔ Prut – Chernivtsi

River – section	Average annual water discharge	Average water discharge (warm period)	Average water discharge (cold period)	maximum discharge of water
	Correlation coefficients *r*			
Tysa-Vylok ↔ Prut- Chernivtsi	0.62	0.72	0.46	0.05

Their analysis showed that cyclic components are present (5-7, 14, 15 and 26 years), in the current period there is a tendency to decrease the maximum (Lukyanets, Kaminska 2015; Lukianets 2017; Lukianets, Obodovskyi 2015). If the connection between the average annual discharges of the Tysa and Prut rivers is rather tight (the correlation coefficient is 0,62), then it is absent for the highs due to the difference in the orography, climatic conditions, and, as a matter of fact, the genesis of floods. Within the basin of the Prut and Siret rivers, particularly intense rainfall is observed in the summer at the time of cold fronts moving from the northwest and north. The Tysa basin is characterized by both rain and mixed floods in the cold period.

CONCLUSIONS

The average maximum runoff of rivers in the observation term in the multi-annual period varies– 17,1-1873 $m^3 \cdot s^{-1}$ in the Tysa basin, and 15,7 – 1133 $m^3 \cdot s^{-1}$ in the Prut basin. Accordingly, maximum specific discharges runoffs are 90,6 – 1886 and 71,8 – 867 $dm^3 \cdot s^{-1} \cdot km^{-2}$. Absolutes instantaneous of the maximum runoff during observation in the Tysa basin recorded on the river Turia – Turia Polyana (F = 98,6 km^2) – 6298 $dm^3 \cdot s^{-1} \cdot km^{-2}$, in the Prut basin on the river Kamianka – Dora (F = 18,1 km^2) – 4790 $dm^3 \cdot s^{-1} \cdot km^{-2}$. The coefficients of variation in the Tysa basin are smaller (0,37–0,89) than in the Prut basin (0,54–1,1). Skewness coefficients have positive values that vary in wide range from 0,2 to 5.

For mountain rivers in the Tysa basin and in the Prut basin the maximums exceed the daily average values by 1,7 – 2,2 times, in the foothills – by 1,3-1,6 times, and with access to the plain – 1,0-1,2 times.

Generalized data on the duration of cycles in time series of characteristics of water runoff on the rivers of the Tysa, Prut and Siret basins within Ukraine by autocorrelation and spectral analysis, showed that there is a periodicity of 5-7, 14, 15 and 26 years in the structure of cyclic oscillations of maximum runoff. The oscillation periods do not coincide in the studied basins. If average annual water runoff of the Tisza and Prut rivers has a strong connection, in maximum runoff it is not recorded. In the current period, there is a tendency to decrease the maximum.

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THE WMO PROJECT ON CATALOGING HAZARDOUS HYDROMETEOROLOGICAL EVENTS: LESSONS LEARNED BY UKRAINE

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ABSTRACT

The article deals with the results of research which was carried out by the Ukrainian Hydrometeorological Institute and the Ukrainian Hydrometeorological Center in the framework of the WMO Project "Cataloging Hazardous Hydrometeorological Events". The cataloging methodology was elaborated by WMO experts and is based on a standardized procedure for identification and description of natural disasters caused by hazardous hydrometeorological events, beginning from a time of creation of warning of dangerous event and up to ending of estimation of damages caused by this event. A description of dangerous hydrometeorological events as well as an assessment of losses caused by these events, were recorded in the agreed EXCEL table format with standard definitions of event types. The filled tables were sent to the European Regional Climate Center (ERCC), which operates under the German Weather Service. The terms of the Project stipulate that the ERCC ensures a full methodological and technical coordination of the Project implementation, including an integration of data received from countries, their consolidation into a regional database and an integration of many events in one regional event that corresponds to their origin. The implementation of the Project first phase was completed in December 2018. During the second Project phase (January- May 2019) an analysis of results was carried out. The experience gained from the Project implementation, was used to create " the WMO methodology for cataloging hazardous weather, climate, water and space weather events" that was presented for consideration at the 18th World Meteorological Congress in June 2019. The Congress adopted the cataloging methodology and recommended to implement this methodology on an operational basis in the hydrometeorological services. The participation of the Hydrometeorological Service of Ukraine in the Project should be considered as very useful. The Ukrainian side got the opportunity: to get acquainted with an international experience in the field of standardization of description of negative influence of extreme hydrometeorological phenomena; to compare the state of affairs in this area of activity in the Hydrometeorological Service of Ukraine and in relevant services of European countries; to bring the contribution in international efforts aimed at reducing the risks of natural disasters. The obtained results showed an importance of reviewing a number of standards and other regulations which are currently used in organizations of the Hydrometeorological Service. The researches in this area is currently being carried out by the Ukrainian Hydrometeorological Institute.

INTRODUCTION

At present, the natural disasters are adverse factors that hold back a socio-economic development of society even in the developed countries. Among the natural disasters, the most prevalent, in particular in Ukraine, are those caused by factors of hydrometeorological origin. A number of natural disasters associated with extreme hydrometeorological events has increased significantly over the past decades. Thus, according to the UN Natural Disaster Risk Reduction Bureau, for the period from 1995 to 2015, about 606,000 people were killed by natural disasters due to extreme hydrometeorological events, and about 4.1 billion people lost their property. The economic losses are amounted about $ 1.9 trillion *(Natural Disasters in 2017…, 2018).*

The investments in the measures of reducing risks of adverse effects of natural disasters save lives and prevent economic losses. Over the world, it is recognized that disaster risk reduction activities should be a part of balanced development of society. The UN has adopted a series of documents defining "The International Strategy for Disaster Reduction", approved by resolution 56/195 of the UN General Assembly. The Disaster Risk Reduction Program has become one of the priority areas of UN activities. The basis of this Program is the principle of transition from a liquidation of disaster consequences to creating effective tools for their early warning, that is, concentrating efforts and resources on preventing new risks, reducing existing ones, and strengthening a society's resilience to these risks.

Regarding successful implementation of the UN Disaster Risk Reduction Program, the national hydrometeorological services play one of the key roles, as they send the information, forecasts and warnings which are the core segment of the Early Disaster Warning System. A coordination of participation of the national hydrometeorological services in international efforts to reduce a risk of natural disasters is one of priority directions of the work of the World Meteorological Organization (WMO).

The 17th World Meteorological Congress (2015) emphasized the need for systematic characterization and cataloguing of extreme weather and climate events in a form that allows data on losses and damage to be cross-referenced to the phenomena, and adopted Resolution 9 to "…standardize weather, water, climate, space weather and other related environmental hazard and risk information and to develop identifiers for cataloguing extreme weather, water and climate events" *(WMO publication,No 1157, 2015).*

In a pursuance of the Congress resolution the approach for cataloging hydrometeorological events (having a potential to be associated with high impacts in terms of losses and damages) was developed at the International Workshop on Cataloging and Monitoring Information on Extreme Weather, Water and Climate Events which was held at WMO in November 2017 *(WMO Publication, 2017).* In fact, this approach has allowed to standardyze whole process of identification, description in space and time of extreme hydrometeorological events with an assessment of damages caused by these events.

In February 2018, the 17th Session of the WMO Regional Association VI (Europe) took the decision "...to test the proposed approach for cataloging high impact events, involving a standard topology of high impact event types and the assignment of universal unique identifier (UUID), as a mean of tracing events and enabling them to be systematically linked to associated data on loss and damage such as is being routinely collected by relevant authorities, and that the test phase should start in 2018 and continue over a sufficient period to deliver results and recommendations relevant for operationalization of the approach the 18th Session of the World Meteorological Congress in 2019".

In July 2018, at the Headquarters of the German Weather Service, the working meeting of experts from the hydrometeorological services of 13 European countries, as well as representatives of the WMO Secretariat was hold. During the meeting "The Guide on Test Phase on Cataloguing Hydro-Meteorological Events Having High Impact Potential" was considered and agreed upon. It was decided to conduct the test phase in two stages: the first stage covered the period from September to December 2018, the second one - from January to May 2019. The overall coordination of this work was entrusted to the WMO Secretariat, and the methodological and technical support - to the European Regional Climate Center, which operates under the German Weather Service.

The purpose of the article is to present the main tasks, organizational principles, methodological approaches, and some results of the test phase of cataloging hydrometeorological events with high potential of influence, with an emphasis on the analysis of peculiarities associated with conducting this work in Ukraine.

METHODS AND DATA (STUDY AREA)

The issue of creation of unified approaches to describe the extreme hydrometeorological events and disasters related to them is highlighted in a number of national and international regulatory documents *(Guide on Forecasting and Warning…,2003; Heat waves and Health…, 2015; Hydrology of Land. Term and Definitions…,1997; Meteorology. Terms and Definitions…, 1997)*. These documents are different by approaches used for identification of dangerous events, for definition of quantitative indicators that can cause natural disasters, as well as for ways of collection of data of damages. This WMO Project can be considered as the first attempt to develop and implement in the international practice the standardized approach to describe extreme hydrometeorological events having high impact potential.

Project participants agreed that the test phase for cataloging of high impact events should be based on the following principles, which were elaborated by WMO experts *(International Workshop on Cataloguing…,2017*): a) preserving the right of each country to state how they choose to record and warn for hazards; b) do not categorize hazards or events into groups (e.g. meteorological, hydrological, climate); c) initially we restrict to hydrometeorological hazards; d) do not quantify and qualify hazard definition or express its severity (e.g. extreme, heavy, high); e) align to emerging the Common Alerting Protocol (CAP2.0) for warnings to avoid duplication, confusion and misinterpretation.

The CAP2.0 Protocol is the simple but universal format for exchanging alerts on all types of emergencies, and for warning the population about them by using all communication means *(Guidelines for Implementation of Common Alerting Protocol…, 2013).*

The methodology of cataloging natural disasters of hydrometeorological origin is schematically illustrated by the figure, which presents the key indicators that are used to describe the events, as well as the parameters that are the subjects of description.

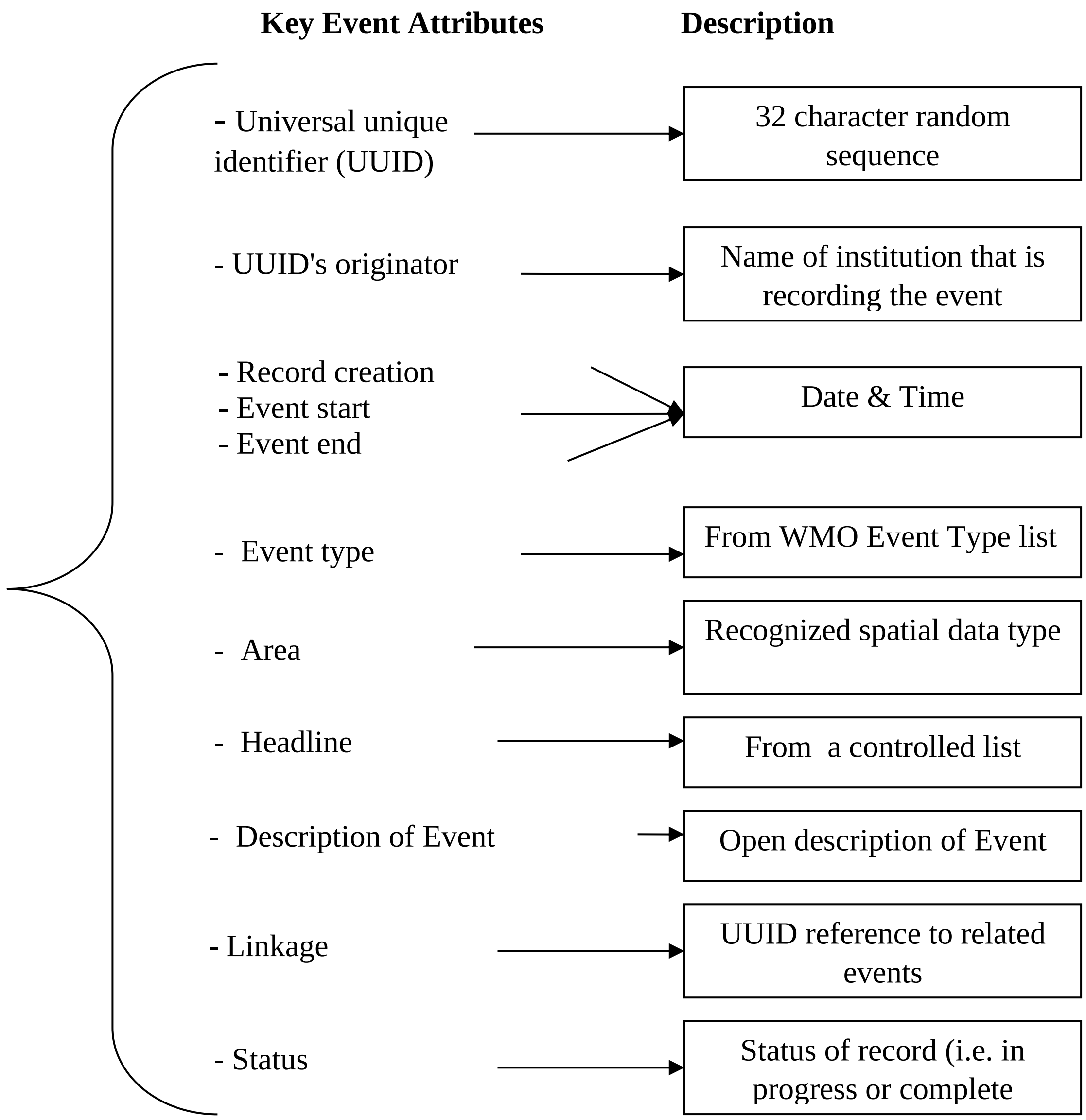

Fig. 1. Structure of recording the extreme hydrometeorological events
(International Workshop on Cataloguing….,2017)

The certain list of extreme hydrometeorological events was included in works during the test phase *(International Workshop on Cataloguing…,2017).* The hydrometeorological events that have a high probability of formation in Ukraine are included into this study (Table 1). The hydrometeorological events have been divided into three groups: systemic, primary and those that are directly subject to be described.

Table 1. Types of extreme hydrometeorological events, which have been the subject of cataloging

System	*Primary*	*Event headline*
Cyclonic Anti-cyclonic Convective	Rain	Heavy rain, extreme precipitation, hoar frost, landslide
	Snow	Snowstorm, avalanche
	Температура	Heat wave, cold wave
	Wind	Strong wind, hurricane, squall
	Drought	Hydrological drought, meteorological drought
	Flood	Flash flood, river flood, ice and debris-jam flood, rain flood, snowmelt flood, thaw - rain flood
	Marine waves	Sea storm, storm surges

The experts from the Ukrainian Hydrometeorological Institute (UHMI) and the Ukrainian Hydrometeorological Center (UHMC) took part in the Project implementation. The study has been carried out on the basis of agreed procedure for identification and registration in an appropriate format of data on extreme hydrometeorological events which are classified according to the classification adopted in Ukraine as "dangerous" (they are designated orange color) and "extremely dangerous" (red color).

RESULTS AND DISCUSSION

Cataloging procedure

When, according to a forecast of the Ukrainian Hydrometeorological Centre a formation of a "dangerous" or an "extremely dangerous" hydrometeorological event has been expected in Ukraine, a hydrometeorological warning has been placed on the UHMC site (https://meteo.gov.ua). The date and time of warning placement on the site have been considered as a beginning of the cataloging work. The information related to a description of hydrometeorological event, actions of the Hydrometeorological Service to prevent their negative consequences, as well as the information about losses incurred by these events, have been recorded in an agreed EXCEL table format with standard definitions of types of events.

We will consider the procedure of filling the table on the example of recording the information about the extreme hydrometeorological event (rain flood), which was observed in Ukraine in May 2019 (Table 2). In this example, in order to simplify the materials presentation, the table has been filled in the WORD format.

Table 2. Example of recording the information about the extreme hydrometeorological event (rain flood), which was observed in Ukraine in May 2019

NN	Key events attributes	Description
1.	Universal unique identifier (UUID)	23ba20e5-fbd5-4522-8651-4c4c18739ebb
2.	Date and time of creation of warning	20/05/2019; 06 hours 00 min (UTC)

NN	Key events attributes	Description
3.	Name of institution that records the event	Ukrainian Hydrometeorological Centre
4.	Date and time of event start	21.05.2019; 00 hours 00 min (UTC)
5.	Date and time of event end	27.05.2019; 00 hours 00 min (UTC)
6.	Event type (primary)	Flood
7.	Event type (system)	Cyclonic
8.	Area	Rivers of Dniester, Tysa, Uzh, Latoritsa river basins within Lviv, Ivano-Frankivsk and Trans-Carpathians administrative districts (oblast)
9.	Event headline	Rain flood
10.	Event description	As a result of the heavy rains which are expected in the Carpathian river basins on May 21-23, 2019, a high flood will be formed on the rivers Dniester, Tisza, Uzh, Latoritsa and their tributaries. Raising water levels up to 2-2.5 meters and up to 4.0 – 5.0 meters on river sections with protection embankments are expected
11.	Linkage to related events	Mudflow, Landslide
12.	Record status	Completed
13.	Information on actual parameters of extreme hydrometeorological event and accounted losses related to it	Maximum flood levels exceeded their average values for long-term period of observation, but they were below their maximum historical values. The amplitude of lifting of water levels was 1.5-2 m, and on river sections with protection embankments - 4.5-4.9 m. In many places there was flooding of floodplains of rivers. In the Transcarpathian region the following losses were registered: 241 farmsteads (including 23 residential buildings), 1835 hectares of agricultural land, 170 hectares of pastures were flooded; 1 bridge was destroyed; 15 bridges were damaged; about 1000 meters of protection embankments were destroyed. the following socio-economic losses were recorded in the Ivano-Frankivsk region: two people died; 177 farmsteads in 16 settlements were flooded.

Row 1. The 32 character random sequence of UUID, which is formed for each individual hydrometeorological event, was determined automatically using a software placed on the site: https://www.uuidgenerator.net.

The row 2. Warning of the threat of extreme hydrometeorological event was created on 20 of May, 2019 at 06 hours 00 minutes UTC, where UTC means "coordinated universal time" used by all hydrometeorological services over the world for time-coordinated observations.

The row 3 contains the name of hydrometeorological organization that created the warning, namely, the Ukrainian Hyrodrometeorological Center.

The rows 4 and 5 contain information about the expected date and time of event start, and about the actual date and time of event end.

The rows 6 and 7. Types of events were determined based on the data given in Table 1. In our case, the "primary" extreme hydrometeorological event is a flood that was formed under an action of the "system" hydrometeorological event - the cyclone.

The row 8. The area of the hydrometeorological event covers the territory of Dniester, Tysa, Uzh, Latoritsa river basins within Lviv, Ivano-Frankivsk and Trans-Carpathians administrative districts (oblasts).

The row 9 contains the name of the hydrometeorological event to be described, in our case, "rain flood", that is, the flood which is caused by heavy rainfall.

The row 10 contains the description of quantitative characteristics of hydrometeorological event.

The row 11 contains information on the presence of a linkage between the described extreme hydrometeorological event and another dangerous event. In our case the heavy rain flood caused landslides and mudflows.

The row 12 presents the status of recording the hydrometeorological event, namely, recording was completed or it is continued. In our case, recording was completed.

The row 13 contains information on actual quantitative characteristics of hydrometeorological event that were recorded in points of hydrometeorological measurements, as well as information on losses caused by this event. Losses data were received from territorial divisions of the State Service of Ukraine for Emergency.

When filling the table 2, paid a lot of attention to the quality control of the data that was entered into the database. The primary control was carried out directly in the Ukrainian Hydrometeorological Centre. The Ukrainian Hydrometeorological Institute has performed the scientific analysis of materials. After the final checking and agreement of data, these table has been sent to the European Regional Climate Center.

The terms of the project stipulate that the ERCC ensures full methodological and technical coordination of project implementation, including the integration of data received from countries, its consolidation into a regional database and the integration of many phenomena in one regional phenomenon that corresponds to their origin. The information generalized on regional level has been posted on the German Weather Service website, that is enable all interested institutions to use it in hydrometeorological and climatic studies.

The implementation of the first Project phase was completed in December 2018. The second phase has been carried out during January-May 2019. During this phase, the analysis of obtained results was carried out. The main focus will be on how the proposed methodological and organizational approaches allow standardizing the process of describing natural disasters of hydrometeorological origin at national and international levels. The general results of test phase implementation test phase can be found in a report prepared by the group of authors from German Weather Service.

The experience gained as a result of the Project carrying out, was used to create "The WMO methodology for cataloging hazardous weather, climate, water and space weather events" that was presented for consideration and approval by the 18th World Meteorological Congress in June 2019.

The Congress's decisions and recommendations on this issue were reflected in the resolution 5.1/1 (Cg-18). In particular, the Congress:

-"…*convinced* that a standard methodology for cataloging hazardous hydrometeorological events, including internationally agreed definitions and accounting practices, is essential for many disaster risk management (DRM) applications";

-"…*agrees* that the proposed methodology will fill a major gap in the standardization of data collection and use of information on weather, water, climate and space weather events and their recording and archiving in interoperable databases";

-"…*adopts* the cataloging methodology hereafter referred to as "WMO Cataloging of Hazardous Events" (WMO-CHE);

- '…*requests* the technical commissions and other bodies, in collaboration with the Regional Associations, relevant partner organizations and entities, to: 1) establish an implementation plan for developing globally agreed standards and procedures for identifying and cataloging hazardous weather, climate, water and space weather events…; 2) set up a mechanism for the coordination of the implementation of this methodology on an operational basis".

Lessons and experience learned by Ukraine from participation in the Project

First of all, the participation of hydrometeorological organizations in Ukraine in the Project should be considered as very useful. The Ukrainian side got the opportunity: 1) to get acquainted with an international experience in the field of standardization of description of negative influence of extreme hydrometeorological events; 2) to compare the state of affairs in this area of activity in the Hydrometeorological Service of Ukraine and in relevant services of European countries; c) to bring the contribution in international efforts aimed at reducing the risks of natural disasters

Concerning organizational issues related to the implementation of this work, it should be noted that the Hydrometeorological Service of Ukraine have a certain advantage over the Services of many European countries. In Ukraine, the meteorological and hydrological services are united in the join state institution, while in many European countries meteorological and hydrological services work as separate institutions. In Ukraine, this state of affairs facilitates a collection and processing of information, as well as forecasting, as often extreme meteorological events cause a formation of extreme hydrological events.

In general, the level of cooperation between the Hydrometeorological Service of Ukraine and the State Service of Ukraine for Emergencies (SES) should be recognized as sufficiently effective. The SES is authorized by the Government of Ukraine to implement the national policy in the sphere of protection of population and territories from the negative impact of natural and man-made disasters. In particular, the SES coordinates, at the national level, the organizational and methodological issues of accounting for losses incurred by sectors of economy and the population by natural disasters.

On the other hand, there were problems in assessing the damages from natural disasters. In many European countries there is a mechanism for quantification of losses which are expressed in a monetary form. In Ukraine receiving such information from local authorities requires a considerable efforts and time. Often, the received data "to put it mildly" cannot be considered as reliable, but there is no a possibility to check them. This complicates not only a determination of losses, but also an evaluation of effectiveness of activity of the Hydrometeorological Service to prevent dangerous hydrometeorological events.

There are a number of methodological problematic issues that reflect the current level of scientific, methodological and technological developments of the Hydrometeorological Service of Ukraine. In number of cases standards on terms and definitions in the field of hydrometeorology developed earlier in Ukraine do not conform to the WMO technical documents that have been adopted in recent years. The national regulatory documents on an organization of observation, forecasting and prevention of extreme hydrometeorological phenomena are different from similar documents of foreign hydrometeorological services in terms of determining quantitative indicators of dangerous values of extreme hydrometeorological phenomena.

The presence in the hydrometeorological services of many European countries of advanced models of hydrometeorological forecasting and powerful computing equipments required for complex model calculations allows them to predict and prevent dangerous hydrometeorological phenomena with greater details in space and time.

However, there are also differences in approaches to a description of extreme hydrometeorological phenomena, as well as to a collection of information on damages and losses between the European Hydrometeorological Services, especially when the meteorological and hydrological activities are provided by different institutions.

Finally, it should be noted that the English translation of Ukrainian geographic names and names of administrative districts should be corrected in tabular and cartographic formats used to form databases on the cataloging of hazardous hydrometeorological events.

The above-mentioned problematic issues caused some difficulties in creating a standardized procedure for cataloging of hazardous extreme hydrometeorological phenomena. Therefore, in decisions of the18th World Meteorological Congress it is envisaged, to develop (based on the proposed methodology) an implementation plan for developing globally agreed harmonized standards and procedures for identifying and cataloging of hazardous hydrometeorological events.

CONCLUSIONS

The participation of organizations of the Hydrometeorological Service of Ukraine in the WMO project on cataloging hazardous hydrometeorological events allowed them: 1) to gain a new knowledges and experience as well as make a contribution in developing the international standardization in the field of hydrometeorological activity; 2) to bring a contribution in international efforts, aimed at reducing the risks of natural disasters. The international guidelines for cataloging hazards hydrometeorological events will become one of the key tools for disaster risk management and protection. In addition, the data of the international catalog of natural disasters of hydrometeorological origin will be used in studies of climate change and a relation of these changes with hazardous hydrometeorological events. The obtained results showed the importance of reviewing a number of standards and other normative documents that are currently used in organizations of the Hydrometeorological Service of Ukraine. The researches in this area is currently being carried out by the Ukrainian Hydrometeorological Institute within the framework of the study "The development of Standards and Other Regulatory Documents in the Field of Hydrometeorological Activity".

Also, the implementation plan of developing and introducing the methodology for cataloging hazardous hydrometeorological events in the organizations of the Hydrometeorological Service of Ukraine has been prepared.

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ANALYSIS OF LOW-FLOW CONDITIONS IN A HETEROGENEOUS KARST CATCHMENT AS A BASIS FOR FUTURE PLANNING OF WATER RESOURCE MANAGEMENT

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ABSTRACT

Understanding and prediction of low-flow conditions are fundamental for efficient water resources planning and management as well as for identification of water-related environmental problems. This is problematic especially in view of water use in economic sectors (e.g., tourism) where water-use peaks usually coincide with low-flow conditions in the summer time. In our study, we evaluated various low-flow characteristics at 11 water stations in the non-homogenous Ljubljanica river catchment in Slovenia. Approximately 90% of the catchment is covered by karst with a diverse subsurface, consisting of numerous karst caves. The streams in the remaining part of the catchment have mainly torrential characteristics.

Based on daily discharge data we calculated and analysed values of 5 low-flow indices. In addition, by analysing hydrograph recession curves, recession constants were determined to assess the catchment's responsiveness to the absence of precipitation. By using various calculation criteria we analysed the influence of individual criteria on the values of low-flow recession constants. Recession curves are widely used in different fields of hydrology, for example in hydrological models, baseflow studies, for low-flow forecasting, and in assessing groundwater storages which are crucial in view of assessing water availability for planning water resources management.

Moreover, in the study we also investigated the possible impact of projected climate change (scenario RCP4.5) on low-flow conditions in two sub-catchments of the Ljubljanica river catchment. For the evaluation we used the lumped conceptual hydrological model implemented in the R package airGR. For periods 2011-2040, 2041-2070, and 2071-2100 low-flow conditions were evaluated based on flow duration curves compared with the 1981-2010 period. The lowest discharges at all water stations in the Ljubljanica river catchment occur mostly during the summer months. Our results for the future show that we can expect a decrease of the lowest low-flows in the first two 30-year periods, while in the last one low-flows could increase by approx. 15%. However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

This study demonstrates that evaluation of several low-flow characteristics is needed for a comprehensive and holistic overview of low-flow dynamics. In non-homogeneous catchments with a high karstic influence, the hydrogeological conditions of rivers should also be taken into account in order to adequately interpret the results of low-flow analyses. This proved to be important even in case of neighbouring water stations.

Keywords: low-flow analysis, low-flow indices, Ljubljanica River catchment, climate change, heterogeneous karst catchment

INTRODUCTION

For efficient water resources management and planning, understanding and prediction of low-flow conditions is needed. This is fundamental for identification of water-related environmental problems too, since in many cases, the low-flow season coincides with the high-demand season for water use (e.g. in tourism). According to the World Meteorological Organization (WMO, 1974), "low-flow is flow of water in a stream during prolonged dry weather". As the definition was not quite clear, therefore, Smakthin (2001) added an important complement to the definition that low flows are seasonal phenomena and an integral part of all streams.

In the literature, one can find many different methods and indices, by which low-flow characteristics can be described. For example, for estimating the contribution of stored water in the catchment to the surface stream water, baseflow index (Gustard et al., 1992), different mean annual minima, and hydrograph recession analyses are widely used. Flow-duration curves contain information on how much of the time over a certain period individual flow is exceeded. In the review paper of Tallaksen (1995), baseflow recession analysis is discussed in detail. Laaha and Blöschl (2006) did a regionalization of low flows in Austria based on different seasonality indices. A comprehensive overview about low-flow hydrology, including different indices and methods, can be found in Smakthin (2001) and WMO (2008). Based on the Manual of Low Flow Estimation and Prediction (WMO, 2008) package *lfstat* (Koffler et al., 2016) included in R (R Core Team, 2018) software was also prepared. The package was used also in our study for calculation of low-flow indices.

In this paper, we present some of the calculated low-flow indices in the Ljubljanica river catchment. More specifically, BFI, Q50, Q90, ratio Q90/Q50, and recession constants. A more detailed discussion is devoted to recession constants, which are often used in hydrological modeling and consequently in planning measures for efficient water resources management. Moreover, we included in this paper the results of investigating the influence of projected climate scenario RCP 4.5 (one of the most optimistic scenarios about greenhouse gas emissions) on low flows in the future at two stations in the considered Ljubljanica river catchment.

STUDY AREA AND DATA

In our study, we evaluated various low-flow characteristics at 11 water stations in the non-homogenous Ljubljanica river catchment in Slovenia (Fig. 1). Approximately 90% of the catchment is covered by karst with a diverse subsurface, consisting of numerous karst caves. The streams in the remaining part of the catchment have mainly torrential characteristics and are located in the north-western part of the catchment. Hydrogeological properties of the catchment are in detail discussed in Kogovšek (2001, 2004).

The catchment's altitude varies between 300 and 1800 m a.s.l. Consequently, annual rainfall is between 1400 mm and more than 2000 mm. The lowest (1400-1600 mm) is at Ljubljana Marshes) while more than 2000 mm can be expected in the Snežnik karst plateau in the southern part of the catchment.

Fig. 1. Study area with locations (green dots) of water stations under consideration in the Ljubljanica river catchment

Analyses of low-flow indices were made based on the daily discharge data series (ARSO, 2018) at 11 water stations in the Ljubljanica river catchment (Fig. 1). In the catchment, there were more water stations operating at the time, however, we included in the analyses only those, where the length of the available data was more than 25 years, and where there were no major gaps in data (i.e. for more than 5 consecutive years).

METHODS

In this paper, we present 5 low-flow indices, which were evaluated in our study: baseflow index, Q50 and Q90, which are flows exceeded 50% and 90% of the time, respectively, ratio Q90/Q50, and recession constant.

With baseflow index (BFI), which is defined as the ratio between the baseflow volume and the total flow volume and is one of the most frequently used indices, the proportion of the total flow that comes from stored sources of the catchment (e.g., groundwater, lakes) can be expressed (Gustard et al., 1992; Smakhtin, 2001). When the duration of low-flows is of interest, flow duration curves (FDC) contain information on how much time over a certain period the individual flow/discharge is exceeded. In low-flow analyses, Q95, Q90, and Q70 are the most frequently used. However, ratios Q90/Q50 are sometimes more informative and contain similar information as BFI (Caissie and Robichaud, 2009).

The recession constant was evaluated by using the *lfstat* package. In the past many methods for its evaluation were developed. We used MRC (master recession curve) and IRS (individual regression segment) methods and different calculation criteria to assess the influence of calculation criteria on the results of recession constants. When calculating the recession constant, either by the MRC or IRS method, one has to define the following calculation criteria: length of the segment (days), and the period for which the discharge threshold is calculated, from which onwards the recession curves are taken into account. We made 24 calculations of recession constants for each of the stations: using 4, 5, 6 and 7 days as the segment lengths, calculating threshold Q70 for the whole data set, by months and by seasons, and for 2 different methods (Fig. 2). The seasons were defined as follows: the time from 1 April to 30 November was defined as summer, and the time from 1 December to 31 March was defined as winter. The influence of the selected computational criteria on the values of recession constants was investigated by using the paired *t*-test. In the *t*-test the mean values of two dependent samples were compared. This is reasonable, since we have calculations with the same input data, but with one criterion changed (e.g., the influence of the calculation method). A two-sided test with level of significance $\alpha=0.05$ was used. When analyzing the influence of method selection (i.e. MRC or IRS) one test was made (1 combination), while when analyzing the influence of the segment length we made 6 tests (6 combinations), and to analyze the influence of the time period for which the threshold for recession analysis Q70 was calculated, we did 3 tests (3 combinations). Since the Ljubljanica river catchment is highly non-homogenous, one can expect that this will be reflected also in the recession constants. Therefore, the results of different stations are not comparable, and tests were made for each of the 10 stations separately. The Mali Otok station was excluded from the analysis because the sample of the calculated recession constants was too small for an objective interpretation of *t*-test's results. A description of the tested criteria and the methodology for investigating their influence on the results of recession constants can be found in Sapač et al. (2019b).

All the indices mentioned above, including the methodologies, are in detail described in Smakthin (2001), WMO (2008), and Koffler et al. (2016).

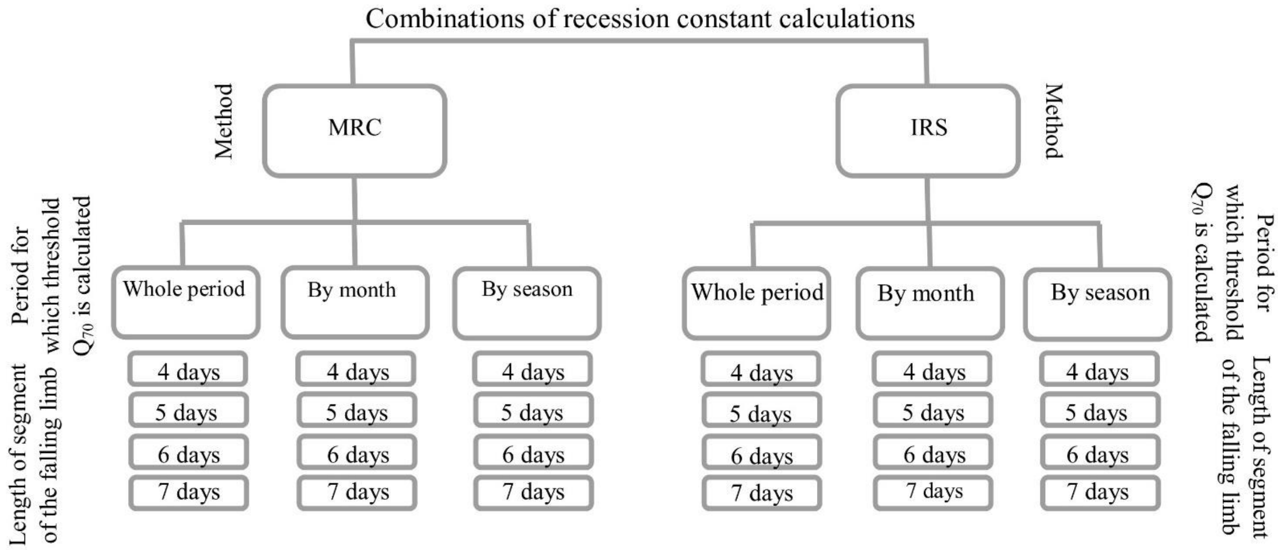

Fig. 2. Scheme of combinations of recession constant calculation for 1 station. For 1 station 24 different recession constants were obtained (adopted by Sapač et al., 2019*b*).

In addition to the current picture of low flows, we were also interested in the future flow situation in relation to the projected climate scenarios. We took into account scenario RCP 4.5, which is one of the most optimistic climatic scenarios.

The catchments of the Ljubljanica river upstream to the Vrhnika water station and the Nanoščica river (Mali Otok water station) have been further investigated in view of the effects of climate change on low flows in the future. Lumped conceptual model GR6J (Pushpalatha et al., 2011) was used at Nanoščica river, while at the Ljubljanica river the CemaNeigeGR6J model (Valéry et al., 2014a; Valéry et al., 2014b) was used for the investigation. CemaNeigeGR6J in comparison with the GR6J model includes also a snow module and two additional parameters. In both models the input data are rainfall and evapotranspiration. However, in the CemaNeige model additional required data are the air temperature and the catchment hypsometric curve. To run the models we used the airGR package (Coron et al., 2017; Coron et al., 2018) in the R software (R Core Team, 2018).

For the selected RCP 4.5 scenario we analyzed 5 combinations of global climate models (GCM) and regional climate models (RCM) which were after some bias corrections to model data used for investigating the influences of the projected climate scenario on precipitation, air temperature, and evapotranspiration in Slovenia (ARSO, 2017; Bertalanič et al., 2018). The projected situation suggests a decrease of summer precipitation and therefore longer and more frequent droughts. On the other hand, in autumn one can expect an increase of precipitation and therefore more frequent flood events. To confirm these assumptions, we performed hydrological modeling. More details about the models, data, and methodology used can be found in Sapač et al. (2019a).

The results of the influence of the projected climate change on flows at two stations in the Ljubljanica river catchment will be presented by flow duration curves. To more clearly present how the flows are expected to change in the future, we will plot flow-duration curves for the next three 30-year periods (2011-2040, 2041-2070, 2071-2100) as a percentage of the reference flow duration curve (1981-2010). Therefore, for each Q in the flow duration curve, one can see if it is expected to be higher or lower than in the reference period.

RESULTS AND DISCUSSION

Table 1 presentes the results of all low-flow indices included in this study. Based on BFI values one can notice that the highest contribution of water from delayed sources (e.g. groundwater) to the surface water is in case of Malni and Bistra, where BFI is 0.85 and 0.91, respectively. This is confirmed also by the Q90/Q50 ratio. The highest the ratio the greater the contribution from the groundwater and other sources of stored water in the catchment. At both stations, Malni and Bistra, the Q90/Q50 ratio is 0.43. On the other hand, the smallest contribution from delayed sources to the surface water is observed at Mali Otok, according to BFI 0.22, and ratio Q90/Q50 0.07. A relatively high ratio Q90/Q50 is observed also on torrential rivers Gradaščica and Šujica, 0.43 and 0.40, respectively.

In the last column of

Table 1, the average values of recession constants, calculated using 24 calculation criteria, are reported. The results of recession constants confirm the results of the BFI and Q90/Q50 ratio. The hydrograph recession limb is falling the slowest at the Malenščica (Malni) and Bistra (Bistra) rivers with average recession constants of 26 and 27 days, whereas the fastest declining of the falling limb is observed at the Mali Otok and Cerknica water stations with average recession constants of 3.8 and 4.7 days, respectively. At other stations under consideration, average recession constants are between 9.7 and 15.8 days.

Table 1. Low-flow indices for water stations in the Ljubljanica river catchment. The recession constant is reported as the average value of the results obtained by using various calculation criteria

River and water station name	Water station code	BFI	Q50 [m^3/s]	Q90 [m^3/s]	Q90/Q50	Recession constant (average) [days]
Ljubljanica, Vrhnika	5030	0.55	14.3	3.24	0.23	10.2
Ljubljanica, Moste	5080	0.56	37.4	11.20	0.30	12.1
Ljubljanica, Verd	5240	0.67	5.34	1.48	0.28	12.7
Bistra, Bistra	5270	0.85	7.54	3.21	0.43	27.0
Borovniščica, Borovnica	5330	0.47	0.59	0.19	0.32	10.7
Gradaščica, Dvor	5500	0.5	1.37	0.59	0.43	15.8
Šujica, Razori	5540	0.47	0.82	0.33	0.40	9.7
Cerkniščica, Cerknica	5770	0.41	0.61	0.16	0.26	4.7
Nanoščica, Mali Otok	5840	0.22	0.44	0.03	0.07	3.8
Unica, Hasberg	5880	0.63	13.6	2.87	0.21	12.3
Malenščica, Malni	5910	0.91	6.97	3.03	0.43	26.0

Unica and Malenščica rivers are geographically relatively close. However, low-flow indices show that their hydrogeological properties, which influence the amount of water in the stream, are significantly different. Therefore, to adequately interpret the results of low-flow analyses, the hydrogeological conditions of rivers should also be taken into account.

In Table 2 all the 24 recession constants calculated for each individual water station are presented. The minimum values for each station are highlighted in green color, while maximum values are marked with yellow color. the minimum values were at 8 out of 11 stations calculated while using the MRC method, a segment length of 4 days and where Q70 as a threshold for the recession analysis was calculated for the entire period of data. At the Dvor water station it was similar. However, Q70 was calculated separately for each season (1 April-30 November, 1 December-31 March). At water stations Malni and Bistra, which were based on low-flow indices recognized as stations with the largest contribution of groundwater, the minimum value was obtained with the MRC method, Q70 calculated for the entire period of data, and with the segment length of 5 days.

Regarding the maximum values of the recession constants, one can notice that the combination of criteria is not as uniform as for minimum values. However, the segment length is 6 or 7 days (with the exception of Malni station), in all cases (with the exception of Mali Otok) calculated with the IRS method. The period of Q70 calculations varies from one station to another.

Since we obtained 24 recession constants for each station (with the exception of Mali Otok, where some values could not be obtained), we wanted to know if there are any statistically significant differences between the values. Three calculation criteria were investigated: the method of calculation, the segment length of the falling limb, and the period for which Q70 as a threshold for recession analysis is calculated. By using a dependent two-tailed *t*-test (α=0.05) it was found that at all 10 stations there is a statistically significant difference between the values calculated by the MRC and IRS methods. More specifically, the recession constants calculated by the IRS method are on average by 3.1 day higher than those calculated by the MRC method.

Table 2. Recession constants calculated for all 24 combination of criteria for 11 stations in the Ljubljanica river catchment. Combination of criteria in the first column is interpreted as follows: the first part represents the method (MRC or IRS), the second part represents the segment length in days (4, 5, 6, and 7), and the third part is the period for which the Q70 threshold is calculated (E = entire period of data, M = monthly, S = seasonally).

Combination of criteria	Water station										
	5030	5078	5240	5270	5330	5500	5540	5770	5840	5880	5910
	Vrhnika	Moste	Verd	Bistra	Borovnica	Dvor	Razori	Cerknica	Mali Otok	Hasberg	Malni
MRC_4_E	7.1	8.7	8.7	20.6	6.5	10.2	5.6	2.2	2.3	10.5	19.4
MRC_4_M	9.3	11.1	11.0	25.9	7.9	11.0	6.9	3.2	4.0	11.0	28.1
MRC_4_S	8.9	10.3	10.2	22.6	7.6	8.5	8.1	2.4	3.5	11.2	21.4
IRS_4_E	10.0	12.1	12.5	29.0	10.7	14.5	8.5	4.6	3.4	12.6	24.3
IRS_4_M	9.3	13.2	14.2	30.2	10.2	16.1	9.3	5.4	NA*	12.8	36.7
IRS_4_S	10.7	12.8	13.9	29.9	11.5	15.5	9.8	4.8	3.6	12.8	27.5
MRC_5_E	7.7	9.6	9.1	20.2	8.0	11.8	8.3	3.5	2.5	10.9	19.0
MRC_5_M	9.6	11.6	12.0	27.7	9.1	12.4	7.4	5.3	4.5	11.3	28.3
MRC_5_S	9.7	11.1	10.7	23.6	9.3	9.1	8.9	3.6	3.8	11.6	21.9
IRS_5_E	9.9	13.1	12.8	28.2	13.1	16.8	10.9	5.6	3.4	12.6	22.7
IRS_5_M	11.7	13.0	15.2	31.1	11.7	18.8	10.4	6.7	4.5	13.0	35.8
IRS_5_S	11.1	13.3	14.4	29.6	12.9	19.3	10.1	5.5	4.1	13.2	27.4
MRC_6_E	8.8	10.4	10.9	21.3	8.0	14.4	9.3	3.9	2.9	11.2	19.5
MRC_6_M	10.1	11.8	13.0	28.4	9.2	16.0	6.6	4.8	4.7	11.8	29.1
MRC_6_S	10.2	11.9	12.0	24.9	10.2	9.2	9.7	3.5	4.9	12.1	22.4
IRS_6_E	10.4	13.8	13.4	28.5	14.0	18.2	12.4	6.5	3.5	12.8	22.6
IRS_6_M	12.0	13.4	15.2	31.2	11.5	19.8	11.0	6.4	4.6	13.6	35.7
IRS_6_S	11.6	14.1	14.2	30.3	13.6	21.6	11.6	5.7	4.2	13.6	27.4
MRC_7_E	9.6	10.7	11.3	21.1	12.6	16.6	11.4	3.7	3.0	11.8	20.6
MRC_7_M	9.9	12.3	13.3	29.5	8.9	19.3	9.8	3.7	4.2	12.0	28.5
MRC_7_S	10.9	11.4	12.9	25.4	10.5	18.3	9.2	3.3	3.6	12.2	22.7
IRS_7_E	11.0	13.9	13.8	27.4	15.7	20.3	12.9	7.2	NA*	13.3	23.5
IRS_7_M	12.3	13.6	15.1	32.2	10.5	21.3	12.2	6.1	4.1	13.7	33.6
IRS_7_S	11.9	13.9	15.0	29.6	13.6	21.3	11.6	5.4	NA*	13.7	26.8
σ_x [days]	1.3	1.5	1.9	3.6	2.3	4.1	1.9	1.4	0.7	1.0	5.2
σ_x [%]	13	12	15	13	22	26	19	29	18	8	20

* the calculation of the recession constant value was not successful | Minimum value | Maximum value

Results of the influence of the segment length on the value of the recession constant are not as uniform as in the case of the calculation method. Where in the *t*-test the recession constants calculated with the segment length of 4 days were used, the differences are statistically significant at

7 or 8 of a total 10 stations. This suggests that the segment length 4 days has the highest impact on the value of the recession constant. However, one should note that this does not mean that results are not appropriate or correct.

When we look at the same results from a station's point of view, we see that at station Malni there is no statistically significant difference between the pairs of the recession constant in any combination, while in the case of the Bistra station it is only one combination where a statistically significant difference was noticed (5 and 6 days). We could conclude that at stations with a greater contribution of the groundwater and other sources to the streamflow, the segment length of the falling limb has a smaller influence on the recession constant value. To exclude characteristics of the catchment, which are reflected in the value of the recession constant, we additionally investigated the influence of the segment length on the value of the recession constant. Firstly, for each of the 24 combinations, the average value of 10 stations was calculated. Secondly, we calculated the differences between the average values of 12 pairs which differed only in the type of the method. We obtained 4×3 values which vary according to the segment length (4, 5, 6, and 7 days). Finally, we calculated 4 average values, based on which the smallest difference was found in the case of the segment length of 7 days (the average of differences 2.6 days).

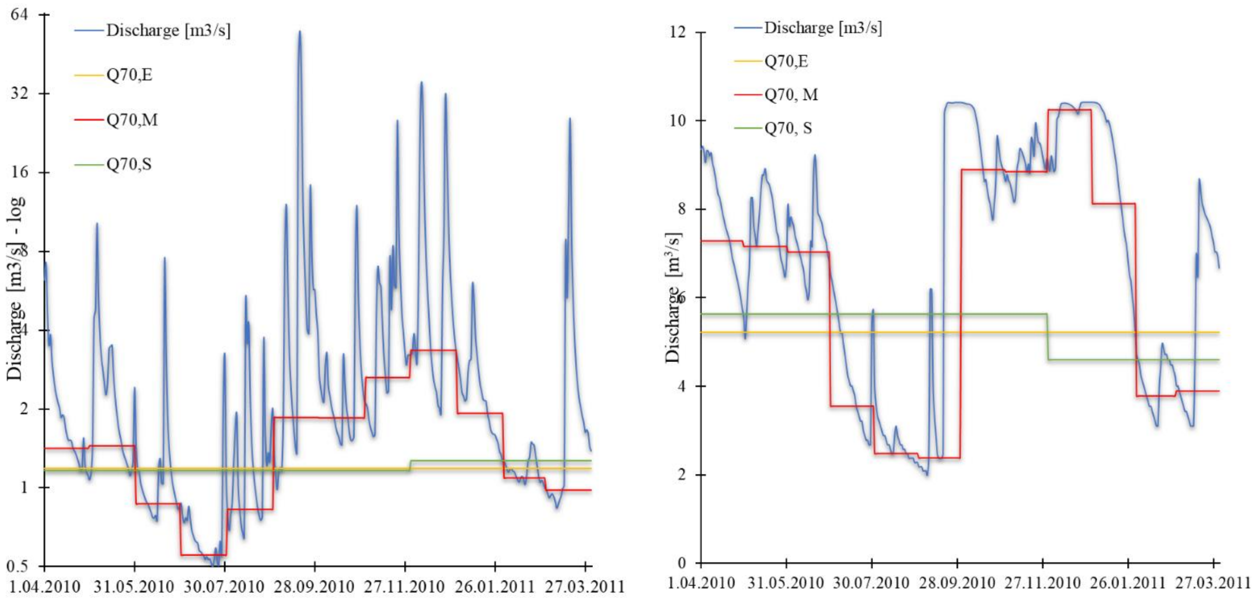

Fig. 3. Discharge at Dvor (left) and Malni (right) water stations between 1 April 2010 and 31 March 2011 with Q70 calculated for the entire period of data (yellow line), monthly (red line), and seasonally (green line). Please note that the plot for Dvor (left) is in the logarithmic scale

When analyzing the influence of the tested period to calculate the threshold for the start of the recession analysis (in our case Q70), we performed three *t*-tests for each station (i.e. monthly vs. seasonal, monthly vs. entire period, and seasonal vs. entire period). It was found that the Razori station is the only one where the impact of the selection of the period on the result of the recession constant is not statistically significant. The opposite (i.e. test showing statistically significant differences for all three combinations of criteria) was found at stations Verd, Bistra, Hasberg, and Malni. This suggests that the selection of the period for calculating Q70 as a threshold influences the result of the recession constant. At Vrhnika and Moste, a statistically significant difference was found for the following combinations: the entire period of data vs. monthly, and the entire period of data vs. seasonal. The opposite was found for stations Borovnica and Cerknica. At Dvor station on the torrential Gradaščica river, a statistically significant difference was found when testing pairs with Q70 calculated with the entire period of data and monthly calculated Q70.

Additionally, the influence of the selected period for calculating Q70 was investigated also by the graphical representation of a 1-year hydrograph of two randomly selected stations. Stations with different hydrogeological characteristics were selected, i.e. Malni (5910) and Dvor (5500), and the hydrographs between 1 April 2010 and 31 March 2011 were plotted (Fig. 3). One should note that the results of the *t*-test are not directly comparable with the 1-year hydrograph. However, the graphical representation helped us interpret why there are some differences or similarities between the stations and what influences the results. On the plots (Fig. 3) hydrographs for Dvor (left) and Malni (right) are presented with a blue line, while Q70 is presented by yellow, red, and green lines, calculated for the entire period of data (1 year), monthly, and seasonally, respectively. While Q70 values, calculated for the entire period and seasonally, do not differ much, there is a greater variability within the monthly calculated Q70. Since Q70 represents the beginning of the recession curve from where on it is included in the recession analysis, in the case of Malni in some months (autumn, spring) we actually did not analyze low flows. On the annual basis, monthly-calculated Q70 in the autumn months represents high flows. This is not the case for the Dvor water station. The reason could be attributed to the torrential characteristic of the Gradaščica river. At this river, the high range between low and high flows is typical. Moreover, due to the quick response of the Gradaščica catchment, the hydrograph decreases and increases rapidly (Fig. 3, left). For these selected periods and water stations, we recalculated the recession constants by using all combinations of criteria. We found that at the Malni station, the average value of recession constants where Q70 was calculated monthly is much higher than in the case where Q70 was calculated seasonally and for the entire period of data. For Dvor, the differences between the obtained recession constants are not significant. More about the methodology and results can be found in Sapač et al. (2019*b*).

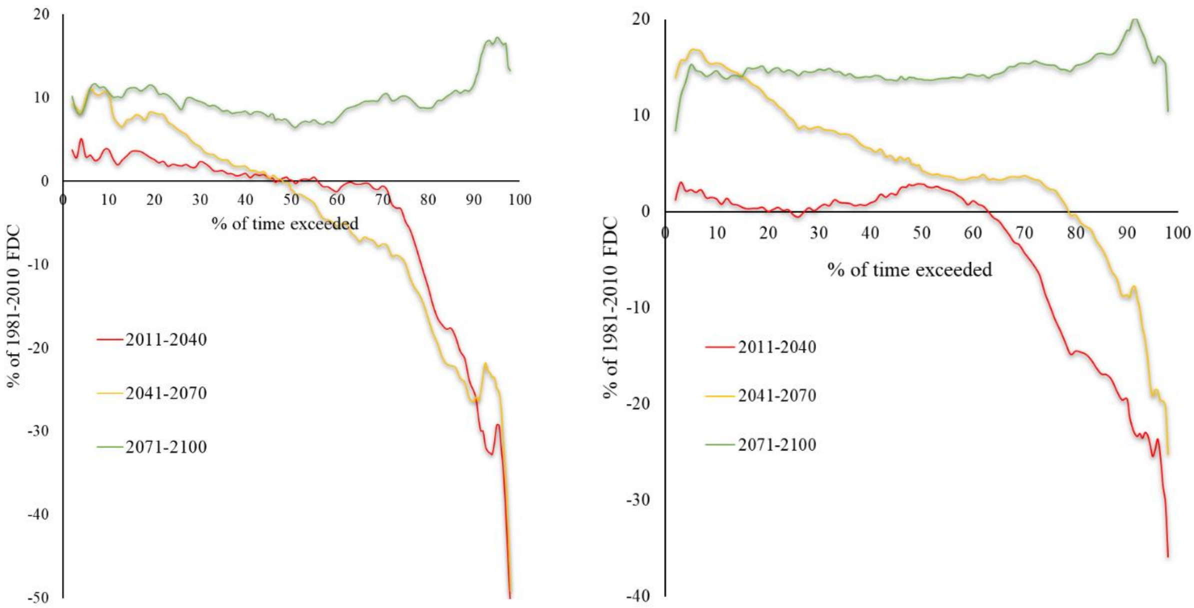

Fig. 4. Flow duration curves (Q2–Q98) for three future periods as percentage of the reference flow duration curve (1981-2010) for two investigated stations: the Nanoščica river (left), and the Ljubljanica river at Vrhnika (right)

In the third part of this study we investigated how low-flows under the projected climate scenario RCP 4.5 will change in the future. For stations at the Nanoščica (Mali Otok) and Ljubljanica (Vrhnika) rivers we obtained 5 data sets with daily discharges (5 simulations). Later on, the discharge data sets were sorted from the highest to the smallest. For each time step, the median value was calculated. Based on the data set of median values, flow duration curves were constructed. Fig. 4 shows flow duration curves for three future periods (2011-2040, 2041-2070, 2071-2100) as a percentage of the reference flow direction curve (1981-2010) (Sapač et al., 2019a). Regarding the low flows, one can notice that in the first two periods (2011-2040 and 2041-2070) flows that are exceeded by more than 60% of the time are expected to be lower in comparison with the reference period. In case of the smaller sub-catchment of the Nanoščica river, the decline of Q90 is expected to be by approx. 25% lower in the periods 2011-2040 and 2041-2070. However, in the third period 2071-2100 the whole flow duration curve is above zero, which means that all flows including high flows are expected to increase. A similar situation can be expected also in the larger sub-catchment of the Ljubljanica river (Vrhnika station), where in the first two periods there are expectations of lowering the low-flows, whereas in the period 2071-2100 all flows (Q2-Q98) are expected to be higher by 10 to 20% compared with the reference period. However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

CONCLUSIONS

This paper is divided into three major sections: (1) calculation and analysis of low-flow indices in the non-homogenous Ljubljanica river catchment with daily discharge data, (2) a detailed analysis of recession constant results and investigation how calculation criteria influence the value of the recession constant, and (3) investigation of the moderately optimistic scenario RCP 4.5 on the low flows at two stations in the Ljubljanica river catchment.

In the first part we calculated 5 low-flow indices for 11 water stations in the Ljubljanica river catchment. Indices show that the largest contribution from the groundwater (and other sources of stored water in the catchment) to the stream is at Malni and Bistra stations. On the other hand, the smallest contribution was found for the Mali Otok water station.

As part of this study we investigated the influence of the calculation criteria on the values of recession constants. We were not looking for the answer as to which combination gives the best results, but rather which criteria under consideration influence the recession constant the most. Analysis has shown that when investigating the influence of the method on the recession constant, at all stations statistically a significant difference was found. The IRS method gives on average by 3.1 days higher results than the MRC method. On the other hand, the influence of other two criteria is not so uniform and the differences between the results vary from one station to another. However, at rivers with a high BFI, the influence of the segment length on the recession constant is smaller (Sapač et al., 2019b).

Although some methods for the recession analysis were considered subjective in the past, Lamb and Beven (1997) think that subjectivity is not necessarily a weakness. Experts who know a catchment very well are able to judge the quality and relevance of the data, which are later used for the recession analysis. The same is true for the assessment of the analysis results. This is suggested also with the findings in our study. For example, the threshold for the recession analysis should be in our case selected for each water station individually. Moreover, the periods with the highest evapotranspiration usually coincide with the periods of low flows – and it is precisely for these periods that we want to determine catchment characteristics and connection with the water storage in the catchment (Tallaksen, 1991; Demuth and Schreiber, 1994).

The third part of this study was to investigate how the projected climate change will influence the low flows in the future, more specifically in three 30-year periods 2011-2040, 2041-2070, and 2071-2100. Construction of the relative flow duration curves (flow duration curves as the percentage of the reference flow duration curve for the period 1981-2010) suggests that in the first two 30-year periods we can expect even lower low flows. However, in the third period 2071-2100 one could expect that low flows will be higher than in the reference period by approx. 15% (Sapač et al., 2019a). However, the uncertainty/variability of the results is very high and as such should be taken into account when interpreting and using the results.

The study demonstrates that evaluation of several low-flow characteristics is needed for a comprehensive and holistic overview of low-flow dynamics. In non-homogeneous catchments with a high karstic influence, the hydrogeological conditions of rivers should also be taken into account in order to adequately interpret the results of low-flow analyses. This proved to be important even in the case of neighboring water stations.

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LOWLAND RUNOFF SURVEY AND MODELING FOR DECISION SUPPORT IN MANAGEMENT OF THE TRANSBOUNDARY PALIC-LUDAS CATCHMENT AREA

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ABSTRACT

Palic and Ludas lakes are located in the northern part of Vojvodina, Serbia near the town of Subotica, just a few kilometers south of the Hungarian border. While Palic lake has a long history as a tourist attraction and a nice recreational setting, Ludas lake and the surrounding steppe plains are habitats of international importance and protected by the Ramsar convention on wetlands. The lakes are connected through the Palic-Ludas canal. Thus Ludas lake is fed partially from Palic lake, but also supplied by the Körös river. The majority of the catchment area of the Körös river is in Hungary, this way the water supply problems related to the lakes are transboundary. The lake system is also drained by the Körös, which finally enters the Tisza river.

Water quality problems and water quantity decrease are both identified and are escalating threatening factors at the lake system in the past decades. Several studies have been carried out in the past about the possible reasons and solutions. The authors have studied the previously published results and have been participating in a cross-border co-operation project funded by the IPA, in frame of which a comprehensive survey and measurement program has been carried out in order to develop, among others, a rainfall-runoff model of the catchment for the investigation of water supply scenarios of the lake system in order to substantiate a monitoring network and program for the sustainable management of the lakes.

In our article we introduce the area, the problem, the field surveying and measurement methodologies and results, the modeling process and the model itself, concluding transboundary responsibility for water supply to the lake system, with a possible complex connection to one of Hungary's major water management issues.

INTRODUCTION

The management of water resources across boundaries, whether sub-national or international, is one of the most difficult challenges facing water managers today. The upstream exploitation or diversion of groundwater or rivers can have devastating consequences for those living downstream, and transboundary rivers can provide a source of conflict between nations or states, particularly where water resources are scarce. Similarly, water based-pollution can spread across borders and create disputes and a need for sound governance (Earle, 2013).

In our article we are discussing a case of a transboundary small catchment in which the majority of the problems can largely be attributed to the water management issues in the upstream country, Hungary.

METHODS AND DATA (STUDY AREA)

Ludas Lake is Pannonia Plain Lake located 4km from Palic town. It is a shallow, natural aeolian lake created million years ago. Ludas Lake Special Nature Reserve was included in the list of Wetlands of International Importance by the Ramsar Convention in 1977. In 1989, the lake and its surroundings were designated as an Important Bird Area. The surface of protected zone covers 2.002 ha. Ludas Lake is hydraulically connected to the Palic Lake by Palic-Ludas Channel, and it is the recipient Palic Lake water (Fig. 1) (Radic et al., 2013). Palic Lake is also the recipient of the outflow from the Subotica WWTP (Horvat et al., 2019). Thus Ludas lake is fed partially from Palic lake, but also supplied by the Körös river. The majority of the catchment area of the Körös river is in Hungary, this way the water supply problems related to the lakes are transboundary. The lake system is also drained by the Körös, which finally enters the Tisza river.

The transboundary Palic-Ludas catchment is home to multiple aquatic habitats. The state of these habitats is governed by the water regime and water quality of the Palic and Ludas lakes. Therefore, the development of a sustainable water resources management policy on this catchment is of great importance.

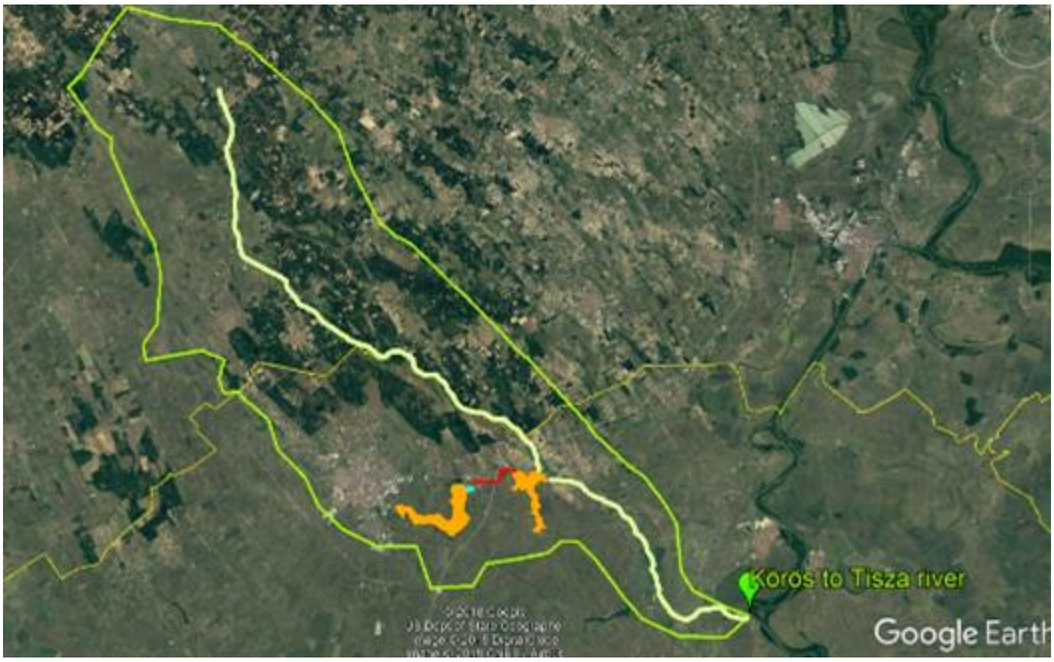

Fig. 1. Overview map of the transboundary catchment area (yellow: Körös-ér channel, red: Palic-Ludas channel, orange: Palic and Ludas lakes)

In frame of a recent Hungarian-Serbian IPA CBC project HUSRB/1602/12/0014 „Sustainable wetland management of the transboundary Palic-Ludas catchment area" / „A határon átnyúló Palics-Ludas vízgyűjtő terület fenntartható vízgazdálkodása" (SWeM-PaL) we have collected historical data and surveyed the missing ones in order to be able to set up a model and help suggest possible improvement solutions as regards to the water quantity and quality of the two lakes, which have deteriorated significantly in the past decades.

The on-site measurements were done with standard surveying equipment (RTK GPS, SonarMite M8 ultrasonic depth meter, standard leveler and static GPS measurements).

The cross-sections and the longitudinal profile of the Hungarian part of the Körös river, as well as the delineation of the Hungarian part of the catchment area were provided by the Lower Tisza district Water Authority (hq: Szeged).

In order to get to a better understanding of the water regime of the area, we also executed discharge measurements, because there is only one permanent gauging station in the whole system, and it is on the Körös river in the Hungarian part.

The equipment used in discharge measurements were an OTT C2 type propeller current meter and an ADCP RiverPro/RioPro.

We used all the obtained data in our modeling tasks described hereafter, for which we applied commercial software (AutoDESK/AutoCAD, ArcGIS and HEC-RAS 1D and 2D by the US Army Corps of Engineers).

RESULTS AND DISCUSSION

During the modeling, the 1D hydrodynamic model of the Körös-ér inlet channel, the 2D hydrodynamic model of Lake-Ludas were established using geodetic measurements, and the direct catchment area of Körös-ér basin was determined based on the available satellite digital terrain models.

One-dimensional hydrodynamic model

As a first step, the runoff model of the Körös-ér and its surroundings was prepared. From this, it is possible to determine the possible amount of water that would load the canal if the field assembly and run-off did not suffer any obstructions. Subsequently, a one-dimensional hydrodynamic model of the Hungary-Serbia section of the Körös-ér was created. During modeling, roughness factors corresponding to the field conditions and the riverbed conditions experienced during the survey were taken into account. According to the data of the water level and discharge sensor station in the Hungarian section of the Körös-ér, the highest discharge in the last 5 years was 1.1 m^3.

The primary purpose of the 1D model is to determine the drainage capacity of the canal, and to investigate the water levels associated with 1.1 m^3 discharge in critical cross sections.

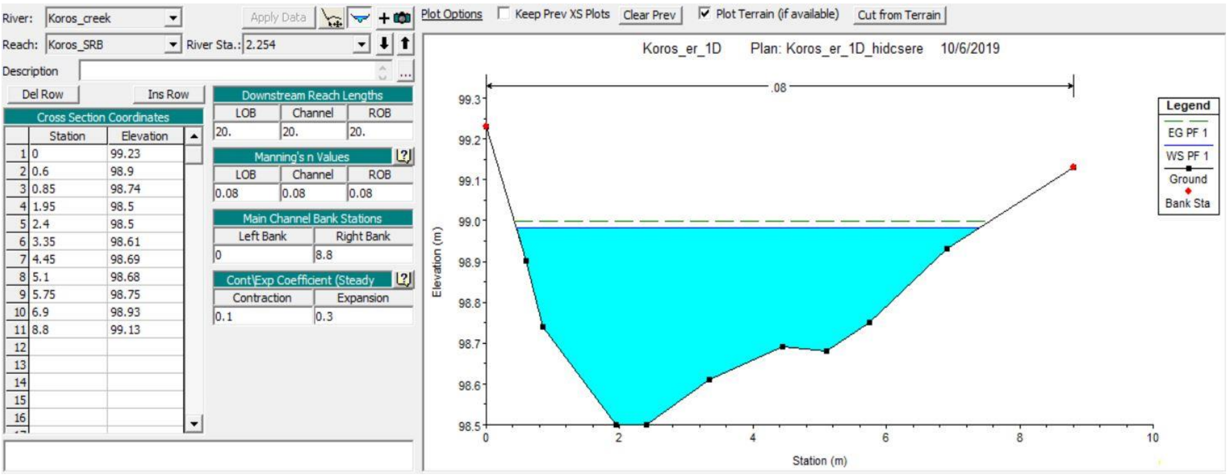

Fig. 2. Körös-ér cross-section - [2+254 rkm]

Based on the results of the model run (Fig. 2), the discharge capacity of the sections is adequate. The second purpose of the run is to determine the maximum discharge capacity of the canal.

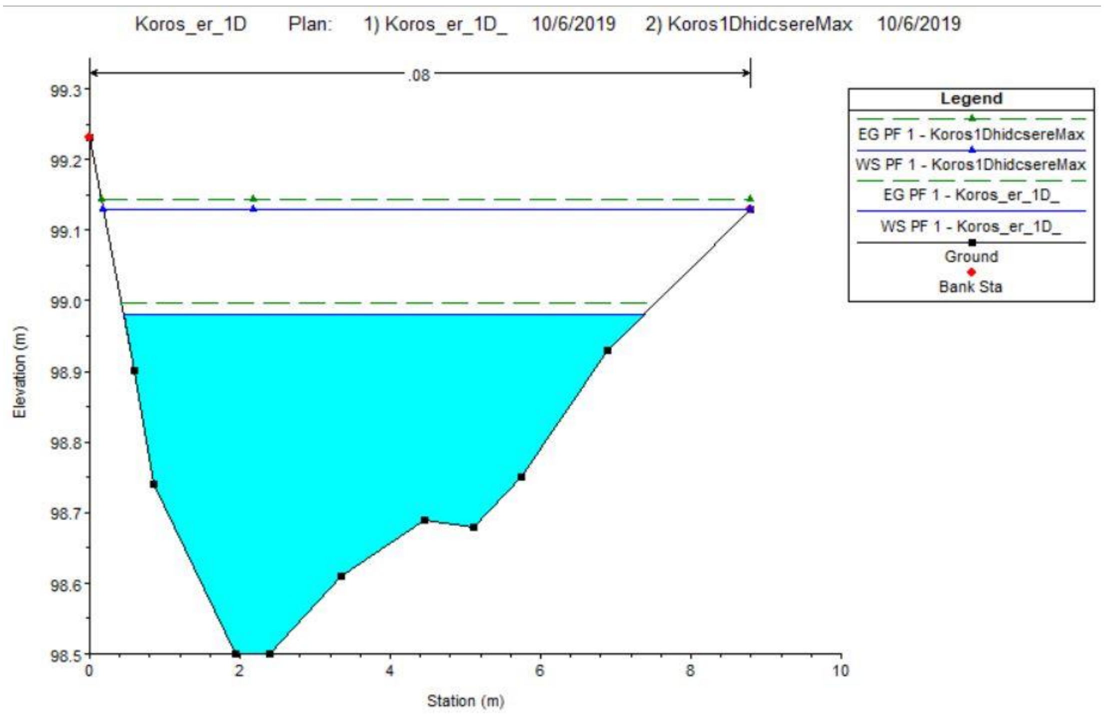

Fig. 3. Körös-ér cross-section - maximum discharge capacity - [2+254 rkm]

Based on the results, the cross sections are capable of draining an additional 500 l/s of water, totaling 1.6 m^3/s – (Fig. 3). Difference in free water surface between observed discharge and maximum possible discharge is 14 cm.

Two-dimensional hydrodynamic model - Lake-Ludas

During the two-dimensional modeling of Lake Ludas, the riverbed survey data made in the summer of 2018 and 2019 were used. In the course of the study, we analyzed the effects of the discharges of the Körös-ér and the inlet of Lake-Palic on the flow conditions of Lake Ludas. The geometry underlying the model was processed in Civil 3D. The digital terrain model built from the data was exported in TIF format with a grid size of 1x1 m.

During the model construction we used the 0.631 m^3/s water discharge of the Lake-Palic connection canal and the 1.1 m^3/s water discharge of Körös-ér as the upper boundary condition. For lower boundary condition we used the Lake-Ludas threshold level.

Geometry has been taken into account when considering the condition of the lake at the time of bathymetry, especially the reed areas influencing the roughness coefficients. The SENTINEL-2 satellite photo taken at the time of the bathymetry was used to determine the roughness coefficients accurately (Fig. 4).

The satellite photo has been used to separate the open water surface and the reed surface using ArcGIS-ArcMAP. In the course of the operation, we used image classification, whereby a training sample was used to create pattern recognition that distinguishes the open water surface and the reed-covered areas with high accuracy compared to the image resolution.

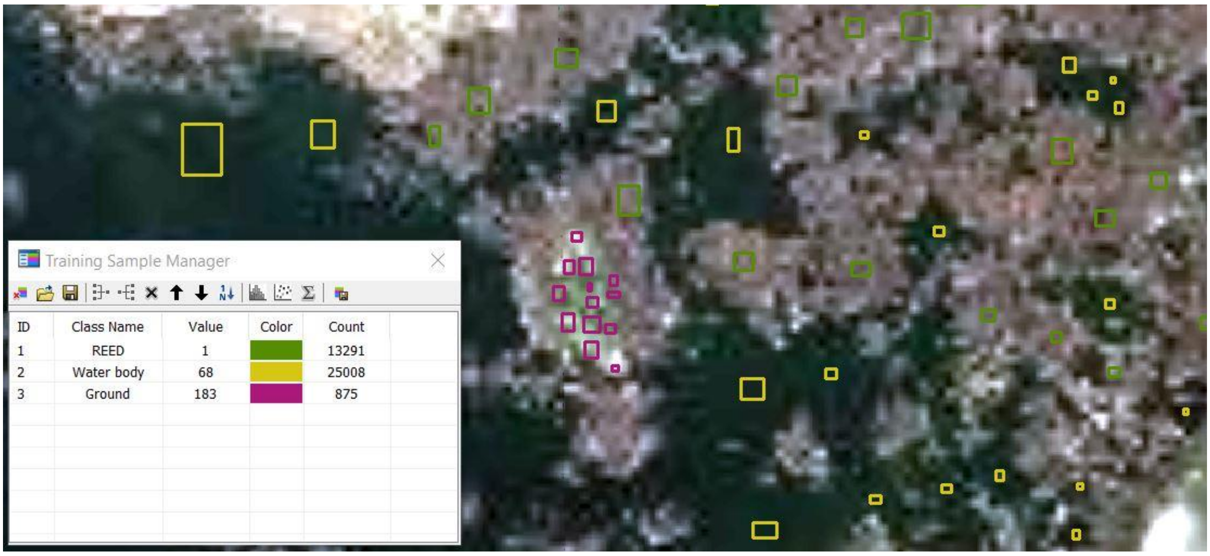

Fig. 4. Image classification: preparing the training sample - Lake-Ludas

The result of the GIS analysis is a file with the SHP extension that represents the water-covered and reed areas as polygons. Importing this file into HEC-RAS allows us to set the Manning roughness factor for different polygons.

After setting the bed geometry and the Manning roughness factors, a two-dimensional hydrodynamic modeling of the lake requires the construction of a computational grid. The size of the grid was determined at 10x10 meters, and a resolution of 2.5x2.5 meters was used at the connection points serving as the boundary condition.

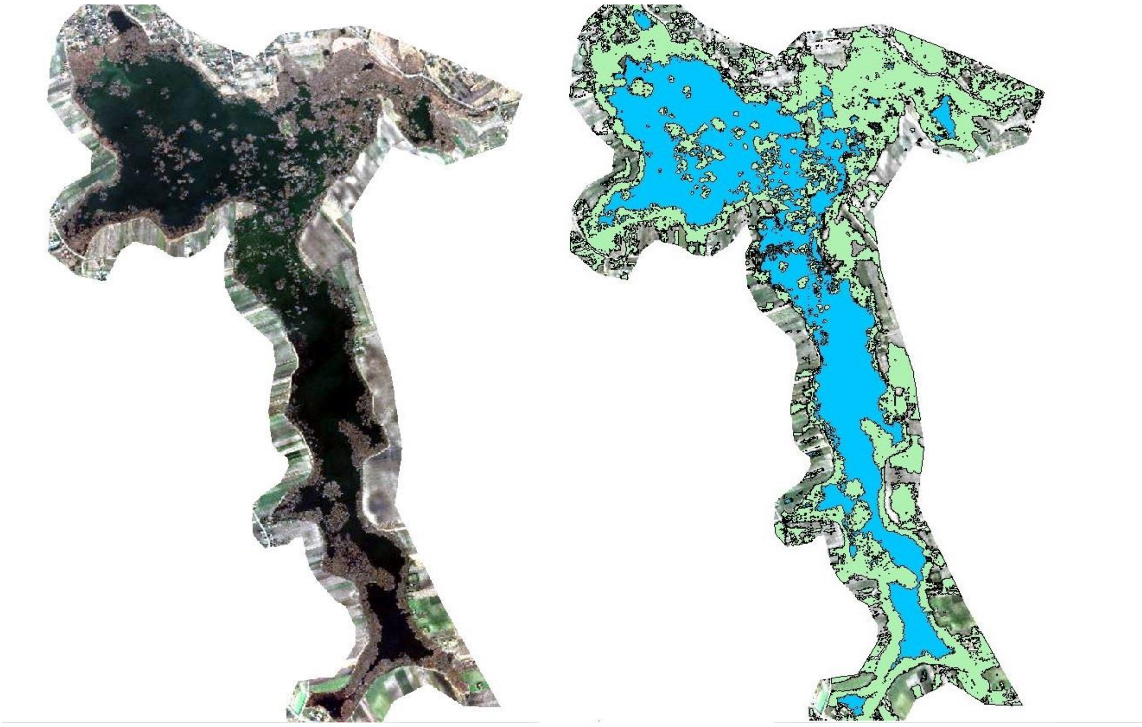

Fig. 5. Maximum-likelihood classification: Open water surface: blue; Reed coverage: green

First stage - modeling of initial state - investigation of flow conditions

For the analysis of the original conditions we used the measured water discharge of the Palić connecting channel and the 1.1 m^3/s maximum discharge observed in the Körös-ér. The velocity distribution in the two-dimensional flow area evolve according to experience (Fig. 6).

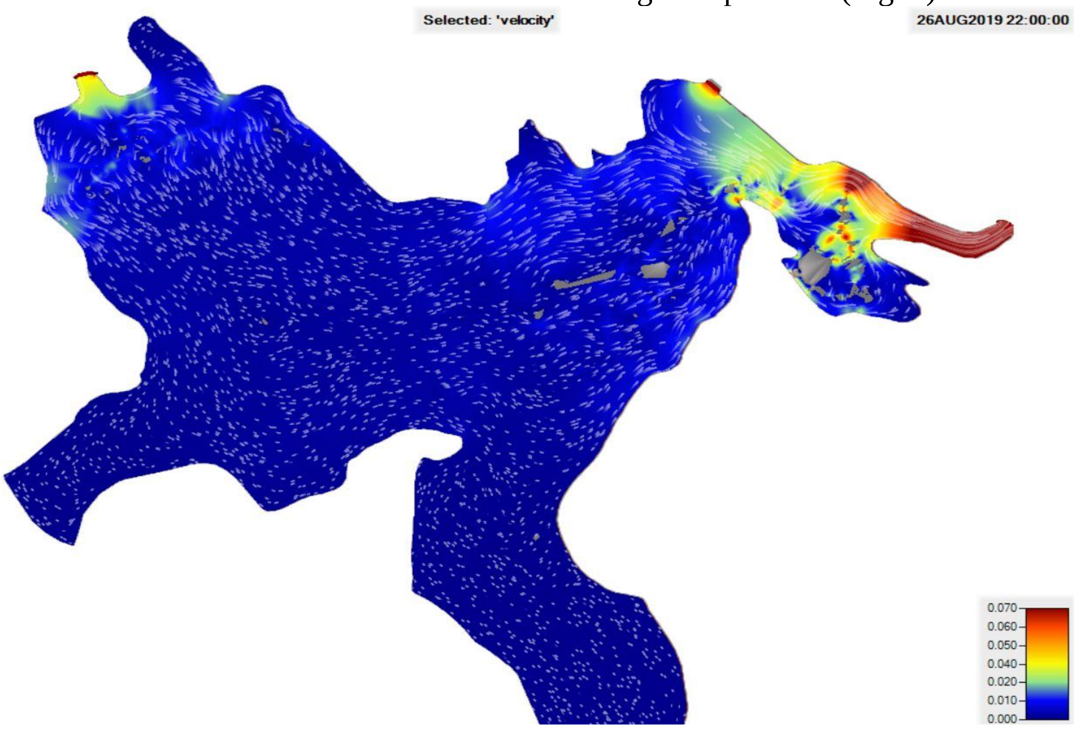

Fig. 6. Velocity-distribution and flow directions - Lake-Ludas

Flow rates are low and the volume of fluid that is heavily moved is small compared to the lake's extent. The maximum water velocity at the connection and discharge points is 0.11 m/s.

Second Stage – modeling of changes in upper boundary conditions

Using original bed geometry, the upper boundary conditions of the hydrodynamic model were modified by increasing the discharge from the Palić-connection channel to 2.2 m^3/s. Provided 0 discharge to the connecting Körös-ér. The aim of the analysis was to improve the flow conditions of Lake Ludas. The increased drainage of the interconnecting channel causes a rearrangement of the flow directions (Fig. 7).

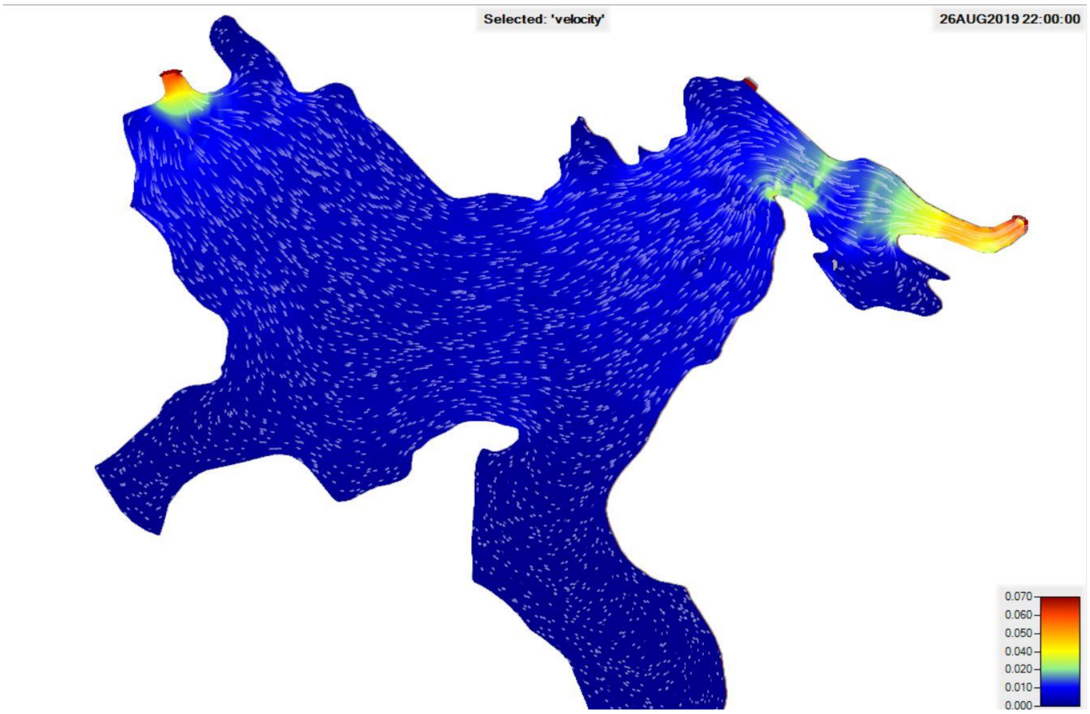

Fig. 7. Velocity-distribution and flow directions in second stage - Lake-Ludas

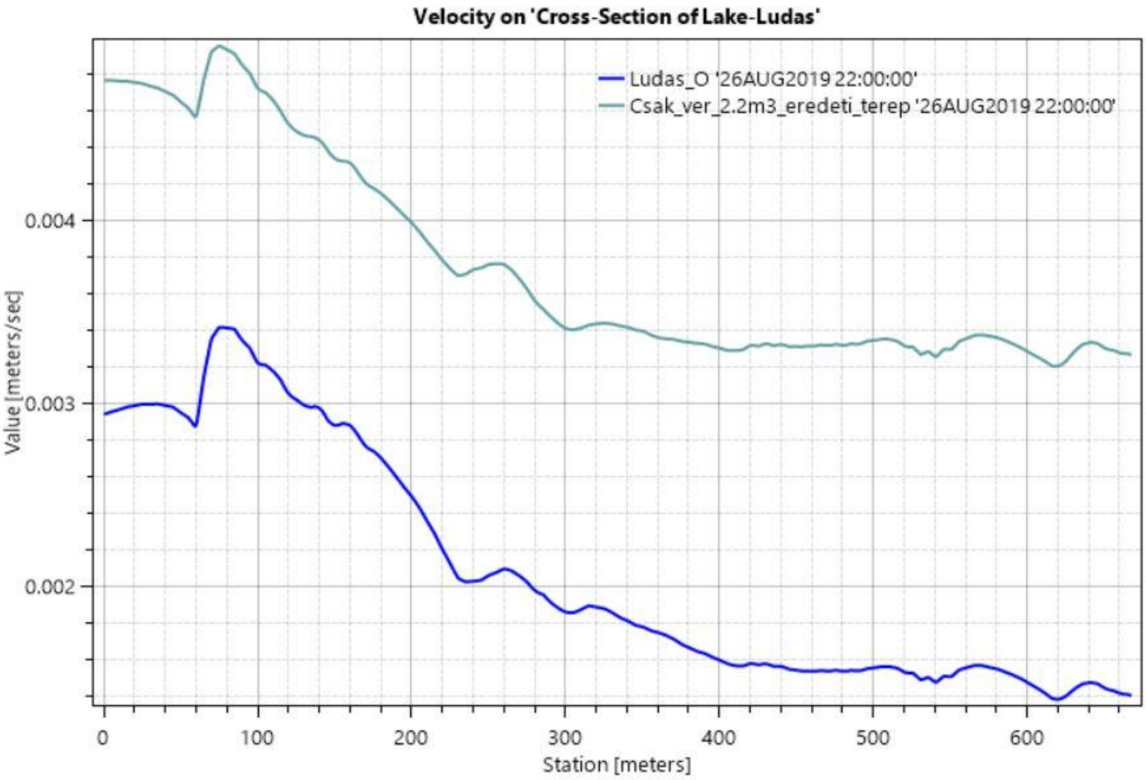

Fig. 8. Velocity: Cross-Section of Lake-Ludas

The results show that the lake is flushed over a larger area. Speed conditions in the middle section of the lake increase by an average of 5 m/h.

Third stage - modeling of modified geometry of lake bed

In the third phase, the aim was to improve the flow conditions of Lake Ludas through artificial interventions. The intervention is the dredging of the lakebed, which connects the Palić connecting channel to the outlet of Lake Ludas. In order to prevent the amount of water delivered by the Körös-ér to the Ludas Lake from flowing directly into the outflow section, an additional connecting dredging was planned, which will be connected to the Palić ditch in the middle of the lake (Fig. 9).

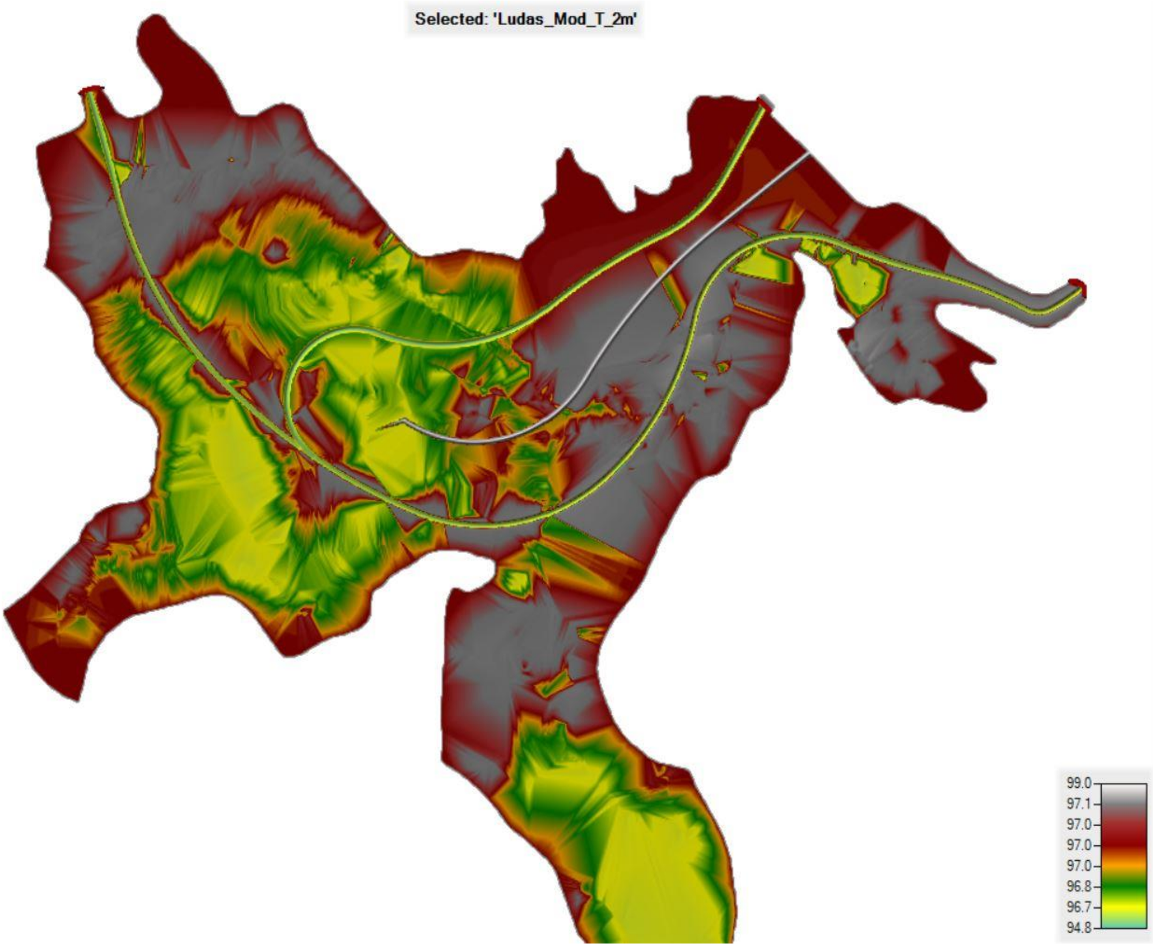

Fig. 9. Original and modified lakebed

The excavation section is 2 meters deep and has a slope of 1:2. In addition, a reed wall was added to change the direction of flow towards the center of the lake.

The purpose of the modified bed geometry was to increase the flow area of the lake, which is heavily moved. Changes in model geometry favorably affect the flow pattern. The intensively displaced water surface increases significantly (Fig. 10-11).

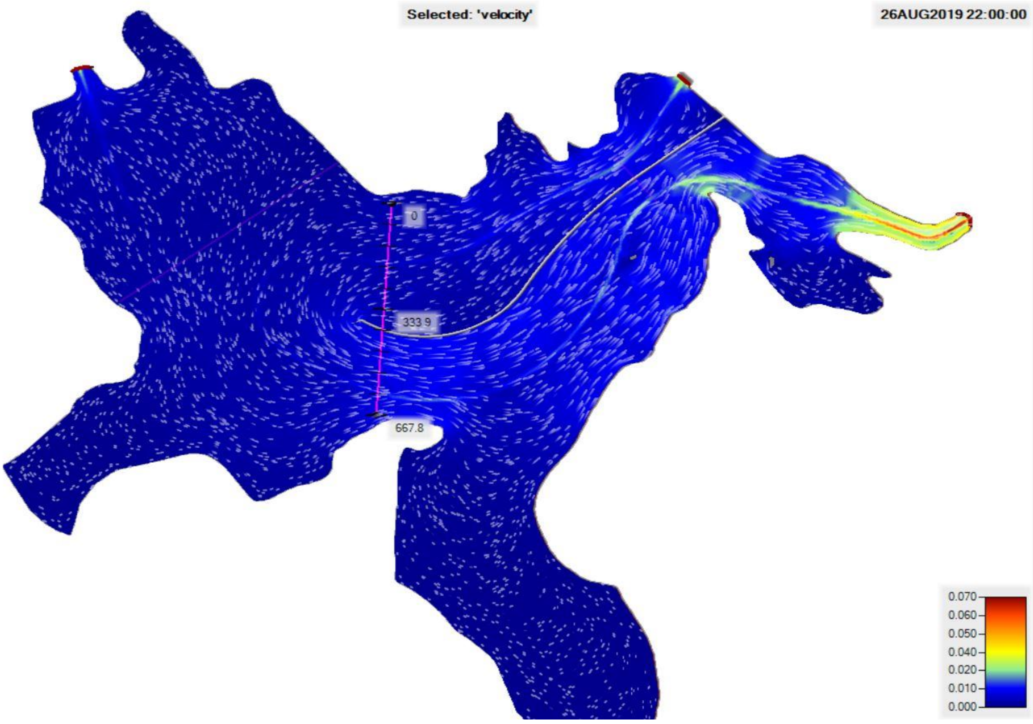

Fig. 10. Velocity-distribution and flow directions - modified geometry of Lake-Ludas

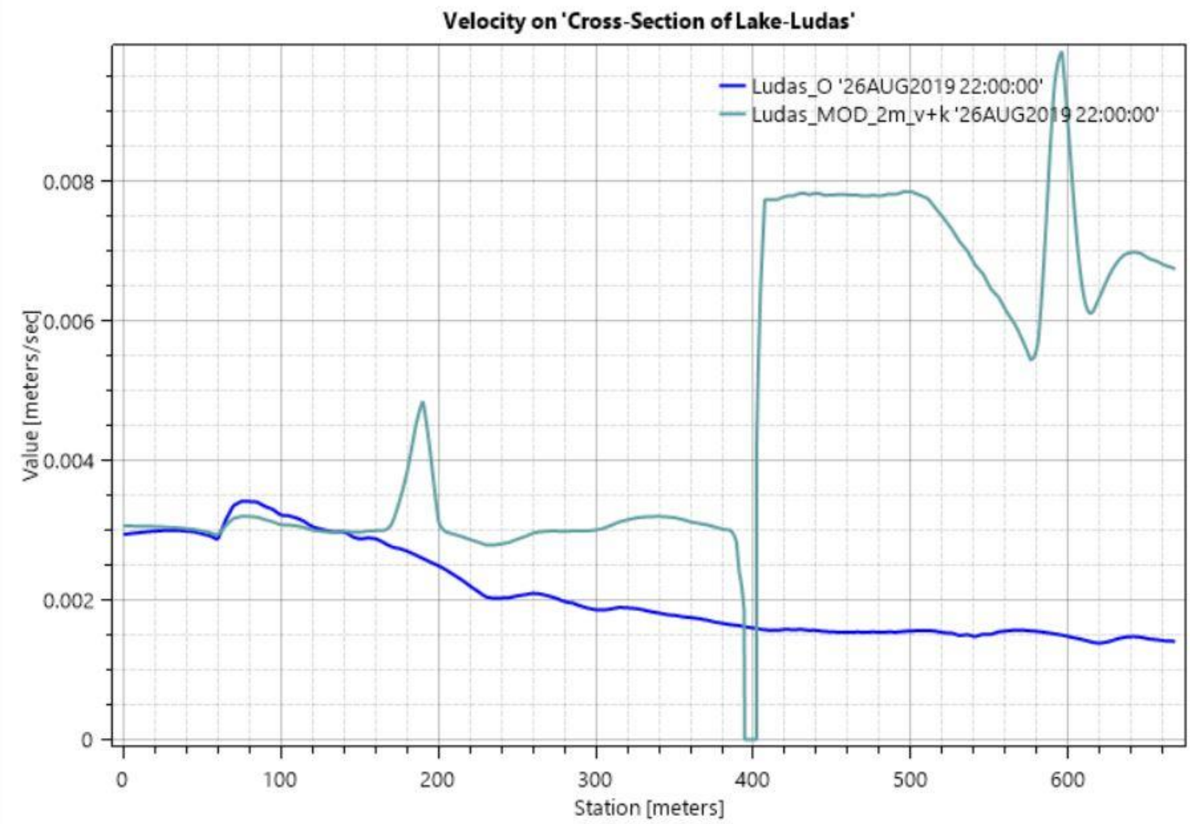

Fig. 11. Velocity-distribution and flow directions 2 - modified geometry of Lake-Ludas

Figure 11 shows an increase in water velocities. Blue for original condition, green for dredging. The figure shows 3 peaks from left to right: dredging - reed wall – dredging, the beneficial effect on velocity distribution.

CONCLUSIONS

With our work, we give an example for the support of the decision making processes by hydro-dynamic modeling.

In our case, a water system with a very complex system of problems can only be investigated and managed with international co-operation.

In the current practice, Hungarian water authority only manages the Hungarian part of the catchment and consequently has no maps, data, information or measurements from the Serbian part and vica versa. Without solving monitoring and data management issues on the transboundary level, a project was needed in order to collect all information, do measurements and try to find solutions for the different water related problems of the Palic and Ludas lakes.

In our conclusions, we can say that one of the biggest problems encountered is the extremely low, often zero flow rate of the Körös, which shall supply the Ludas lake with freshwater. Unfortunately, the phenomenon is clearly connected to the decreasing of the surface and groundwater levels in the central Hungarian plain, which has now been observed for more than 20 years. Solution to the water supply problem can only be elaborated in harmony with other Hungarian regional projects.

However, with our theoretical suggestions for dredging, a considerable improvement could be achieved locally in Serbian territory by removing a part of the sedimented nutrient-rich silt layer from the lake bed and at the same time, improving water circulation. These interventions, together with the already planned improvements in wastewater collection network and treatment in Palic, would help the unique biodiversity of Ludas Lake and the tourist attractions of Palic lake to remain.

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WATER RESOURCES OF THE LOWER DANUBE RIVER AND THEIR USE WITHIN THE TERRITORY OF UKRAINE

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ABSTRACT

The main hydrological characteristic of the Lower Danube River namely its water runoff and sediment yield are presented. Based on SRTM data the area of the river basin within the territory of Ukraine was determined. It is equal to 6454 km^2.

The basin areas of the largest rivers, flowing into the lakes of the Lower Danube River, were determined too. The features of their hydrochemical regime were studied as well.

Based on the remote sensing data it was specified the water area of four largest lakes in this territory namely Kahul, Yalpuh-Kuhurluy, Katlabukh and Kytai. This area at normal water level is as follows: Kahul – 90.6, Yalpuh-Kugurluy – 235, Katlabukh – 60.7, Kytai – 52.9 km^2.

Using the regular monitoring and remote sensing data, it was studied the water temperature and the ecological state of the lakes. It was evaluated the spatial and temporal features of algal bloom as well. The highest algal bloom is usually observed in August in sunny and warm weather.

It was presented the data about the water management and water use on the researched territory. The largest water intake is from the Danube River, much less water intake is from the local lakes. The most of water is used for irrigation needs.

Keywords: water resources, Lower Danube River, ecological state, remote sensing

INTRODUCTION

The Danube River is the largest river of Central Europe. The Ukrainian part of the river basin consists of two parts. One of them covers the southern part of the Ukrainian Carpathian Mountains and adjacent territory, the second one covers the territory on the left bank of the river near the river mouth. In the latter case this territory is located within Odeska oblast.

In the past the researched territory on the left bank of the river was a large flood plain, which was periodically flooded during high floods. That time there were some large and small lakes there, named as Danube Lakes. In 1960s this territory was protected against flooding by a very long dam, constructed on the left bank of the Danube River. The hydraulic connection between the river and lakes was performed by means of canals with regulative facilities on them.

The largest lakes, which nowadays can be considered as reservoirs, are as follows: Kahul, Yalpuh-Kugurluy, Katlabukh and Kytai. Sometimes lake Yalpuh-Kugurluy, which is the largest one in this region, is considered as two separated lakes Yalpuh and Kugurluy. The simple name Yalpuh for whole lake is also used. Much less are the lakes Kartal and Safyany. The first one locates to the west from lake Kugurluy, the second one to the south-west from lake Kartal. Actually, there is one more large water body, named lake Sasyk, which locates some apart. In the early 1980s it was transformed into the reservoir from the sea lagoon by means of a dam constructed on the sea shore (Fig. 1).

There are quite a lot of scientific works devoted to the water bodies in this territory. One of the most popular issue is the water runoff of the Danube River and its distribution along the river branches in the delta. The corresponding data are presented in the fundamental scientific paper [4] and in some articles [10].

Fig. 1. The Lower Danube River and the lakes on its left bank:
1 – Kahul, 2 – Kartal, 3 – Yalpuh-Kugurluy, 4 – Safyany 5 – Katlabukh, 6 – Kytai, 7 – Sasyk

Another important point of scientific researches is the water quality both the Lower Danube River and adjacent lakes. This issue is really rather important as water quality in these water bodies is quite poor. First of all, it concerns the water quality in the lakes. As a result of their artificial separation from the Danube River the water exchange in the lakes essentially decreased. The research works [1, 2, 9] showed that the water mineralization in the lakes can reach 3–4 mg/dm^3 and even more. The water mineralization in small rivers, flowing into these lakes, can exceed 5–7 mg/dm^3. As the result of that, water mineralization in the northern part of the lakes is larger than in the southern parts. This is the essential obstacle for the water use.

The results of study, as to the size of lake Yalpuh-Kugurluy, were presented in scientific article [3]. It was determined that the water area of this lake decreased compared to the design data – it is 226 km^2 at water level 2.43 m. The largest measured depth of this lake is 5.3 m. The results of similar study as to lake Kartal were presented in [11].

The water balance of lake Yalpuh-Kugurluy was specified in the scientific paper [5]. It was determined that the largest water amount to this lake comes from the Danube River. The main part of this amount is lost due to evaporation and *evapotransporation*.

Some results of the study on the bakterioplankton abundance in water are presented in the paper [7]. It was determined that this abundance compared to the conditions in 1949 increased greatly. The largest bakterioplankton abundance is observed in lake Kartal, some less it is in lake Kytai, the smallest one is in lake Kahul.

In spite of rather large number of studies, devoted to the water bodies of this region, there are some issues, which have not been sufficiently investigated yet. Among these issues there are as follows: modern water area of the lakes, river basin area of the Lower Danube River etc.

METHODOLOGY AND DATA

The study of water bodies in the observed region was based on the data of regular monitoring and remote sensing data. As to the regular monitoring of water runoff and sediment yield it was the observation data obtained from the Hydrometeorological Servise network. The hydrochemical data of the Hydrometeorological Service and relevant data from the State Agency of Water Resources of Ukraine ware used for the research of water quality.

The main source of remote sensing data was the results of land and water survey, obtained by Landsat 8 and Sentinell-2 satellites. The data of Shuttle Radar Topography Mission (SRTM) were used as well.

On the base of satellite data, it was determined the water area of the largest lakes located on the left bank of the Danube River near its mouth. These data were used for the study of water temperature and water quality as well. The processing of satellite data was carried out using ArcMAP 10 program.

The SRTM data was used for determining of river basin area of the Danube River within the territory of Ukraine and small local rivers. It was used the data with the highest resolution of 1 arc-second or about 30 m. The determination of the researched areas consisted of some stages. At first the water basins were contoured with an excess of area using SAS.Planet program. The obtained kmz-files were transformed by using Global Mapper program into shape-files, processed after that by ArcMAP 10 program. After the comparison of obtained images with high resolution images it was calculated the actual areas of the water basins. The methods of relevant researches are described in more details in [12].

RESULTS AND DISCUSSION

<u>The water runoff</u>. The Danube River is considered as the largest river of Europe after the Volga River. The hydrological observation on the Lower Danube River is being carried out at two main hydrological stations: Reni (163 km away from river mouth) and Izmail (94 km). The average water discharge at Reni station during 1981–2017 was 6530 m^3/sec or 206 km^3, at Izmail station (the period of 1959–2017) – 3810 m^3/sec or 120 km^3. During the last years (2001–2017) the part of water runoff, which *related to* Kyliyske river branch, where Izmail station is located, is 50 %. At the beginning of observation this share reached 60 %.

The sediment yield during 1978–2017 at Reni station was 32 mln t, at Izmail – 17 mln t. The average turbidity of water on both gauging stations is equal to 150 g/m^3.

<u>The water management</u>. About a half of water amount in this region is withdrawn from the Danube River by the canals connecting the river and the lakes. When a water level in the river is high, the gates are open and water goes to the lakes. When a water level in the river is lower than in the lakes, the gates are usually closed. In some cases the water exchange is performed by means of opening the gates on the hydro-technical facilities.

During the last years the water amount flowed annually into Danube lakes, is 300–400 mln m^3. Thus, in 2016 the total water volume, taken from the Danube River for Danube Lakes, was 301.1 mln m^3. The volume of water, returned to the river, was 128.9 mln m^3. That year 49.3 mln m^3 was taken for lake Kahul and 43.8 mln m^3 was returned to the river. The correspondent values for other lakes were as follows: Kartal – 12.4 and 13.6 mln m^3, Yalpuh-Kugurluy – 182.7 and 62.9 mln m^3, Safyany – 3.0 and 3.8 mln m^3, Katlabukh – 33.0 and 4.2 mln m^3, Kytai – 20.7 and 4.4 mln m^3.

As can be seen, the largest water exchange is observed in lakes Kahul, Kartal and Yalpuh-Kugurluy. The smallest water exchange is observed in lakes Katlabukh and Kytai.

The water inflow into Sasyk lake is significant as well. In 2016 it was 197.7 mln m^3.

The similar situation was in 2017. During this year the water intake for the lakes was as follows: Kahul – 20.4 mln m^3, Kartal – 30.4, Yalpuh-Kugurluy – 73.2, Katlabukh – 10.9, Kytai – 15.8. The water discharge was observed only from lake Kahul – 9.5 mln m^3. The water inflow into lake Sasyk was 146.4 mln m^3.

Besides the points of gravity water intake for the lakes, there are some other ones which take water from the Danube River by pump stations. Among the water consumers the largest ones are those, which take the water for irrigation, first of all for rice growing. One of the largest water consumers is located 3 km away to the east from Kylia town. There are also some facilities built for drinking water supply to local towns: Reni, Izmail, Kiliya and Vylkove. The first two towns use the underground water. The water intake systems of these towns are located on the flood plain of the

Danube River near its left bank. Two points of water intake for drinking water supply are located in Kiliya town, from which one is used for drinking water supply of this town, another one (Kiliya Group Water Supply System) – for Tatarbunary town and some adjacent villages. The last water intake point for drinking water supply on the Danube River is located in Vylkove town.

The total water intake from the Danube River during the last years was as follows: 2016 – 764, 2017 – 452, 2018 – 571 mln m^3.

Compared to the total withdrawn water amount, the amount actually used for human needs is greatly less. In 2016 this water amount was 96.4 mln m^3. From this amount 85.4 mln m^3 was used for irrigation (including 75.1 mln m^3 for rice growing) and 5.8 mln m^3 for drinking water supply.

In 2017 the total water use was 105.6 mln m^3, while the amount for irrigation was 93.7 mln m^3 (including 82.0 mln m^3 for rice growing). In 2018 the total water use was 136.1, including for irrigation needs – 117.3 mln m^3.

The water intake from Danube Lakes is relatively small – less than 10 mln m^3. The largest volume is taken from lake Katlabukh for irrigation needs. Among the water consumers there is Bolgrad town, which intakes water from lake Yalpuh.

During the last years the water amount used for the irrigation, tends to increase. For example, in 2010 this amount was 62.3 mln m^3. This increase was observed after essential decrease in the 1990s. Thus, one of the largest the Danube-Dniester Irrigation System, which was operated using the water from lake Sasyk, stopped its operation in the late 1990s. The main reason of that was the inadequate water quality. Chervonoyarska Irrigation System, which used water from the northern part of lake Kytai, also ceased the operation for the same reason.

The hydrochemical characteristics.

The regular monitoring of water quality on water bodies, located in the region, is carried out by Hydrometeorological Service and State Agency of Water Recourses of Ukraine.

The data show that water quality in different water bodies differs greatly. The smallest mineralization is observed in the Danube River where it is 330–350 mg/dm^3. Among the lakes the smallest values are recorded in lake Kahul, the largest ones – in lake Kytai (Table 1).

Table 1. Hydrochemical characteristics of the Lower Danube River and adjacent lakes during last years (mg/dm^3)

Station	Disol-ved oxygen	Minera-lization	mgN/dm^3			Total phos-phorus	BOD	COD
			NH_4	NO_2	NO_3			
Danube–Izmail	9.36	339	0.07	0.018	1.14	0.11	1.80	18.8
Kahul–Nahirne	9.33	568	0.08	0.009	0.32	0.10	4.12	53.6
Yalpuh–Bolgrad	10.5	1234	0.11	0.008	0.17	0.08	4.07	50.8
Yalpuh–Kosa	9.33	957	0.07	0.006	0.16	0.09	2.90	45.8
Kugurluy–Nova Nekrasivka	10.2	708	0.10	0.006	0.15	0.09	3.41	43.2
Katlabukh–Kyslitsa	9.40	1992	0.13	0.018	0.45	0.14	5.33	71.1
Kytai–Chervonyi Yar	8.46	4705	0.12	0.018	0.27	0.14	7.99	146

There is essential difference between water mineralization in different places of lake Yalpuh-Kugurluy. The largest mineralization is observed in the northern part of lake Yalpuh, the smallest one – in its southern part (lake Kugurluy), where the water exchange with the Danube River is the largest. In lakes Katlabukh and Kytai, where the amount of the Danube water is rather small, the water mineralization is the largest. In lake Kytai it can reach 5.5–6.0 g/dm^3, sulfate concentration – 2.0–2.3 g/dm^3.

As with water mineralization there is a great difference in biochemical *oxygen demand* (BOD) and *chemical oxygen demand* (COD) between researched water bodies. The highest values of these parameters are observed in lake Kytai, more precisely – in its northern part.

During two last decades the water quality in the lakes has been reduced as a result of the decrease in water exchange with the Danube River. The essential growth of water mineralization, biochemical oxygen demand, chemical oxygen demand, concentration of total phosphorus is observed in lakes Katlabukh and Kytai (Fig. 2).

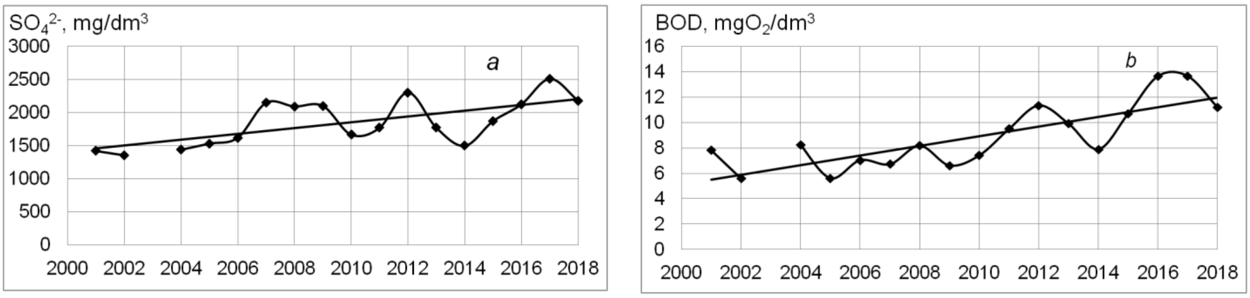


Fig. 2. The long-term changes in water quality in lake Kytai – near Chervonyi Yar village: a – sulfate concentration, biochemical ***oxygen demand***

The comparison these data with the data of the previous study proves the decline in water quality [1]. In fact, the worst water quality is observed in the small rivers, which flow into the lakes. For example, the water mineralization in the Aliyaga River, which flows into the northern part of lake Kytai, can exceed 8.0 g/dm^3. A little less water mineralization (6.0–7.0 g/dm^3) is observed in the Malyi Katlabukh River, which flows into the northern part of lake Katlabukh. The smallest mineralization (about 3.5 g/dm^3) is observed in the Yalpuh River, which is the largest tributary of the Danube River in the researched region.

The water inflow from the tributaries and the rise of salt concentration as a result of evaporation from the water area are main reasons of decline in water quality in the lakes.

<u>The hydrography of rivers and lakes</u>. Till today the data about the Danube River basin within the territory of Odeska oblast are not clarified enough. Using the method, described above, it was found out that this area is 6454 km^2. This result practically coincides with the data from the State Agency of Water Resources of Ukraine – 6416 km^2. It is about 20 % of the oblast territory or some less than 1% of the whole river basin area, which is which is considered some larger than 800,000 km^2 (Fig. 3).

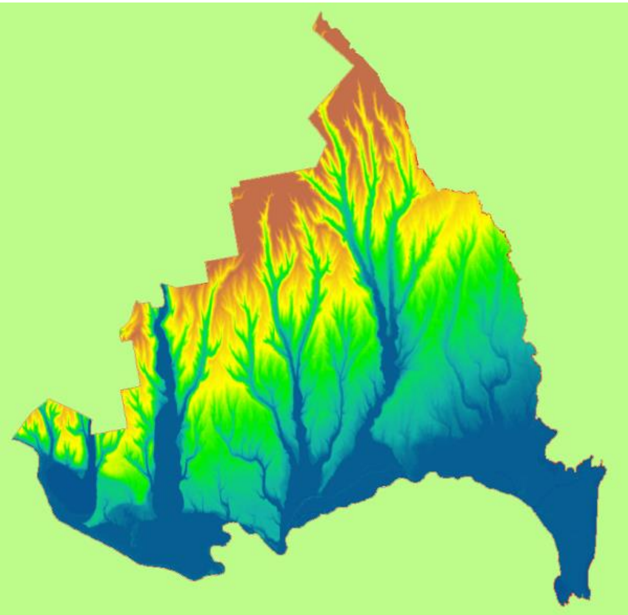
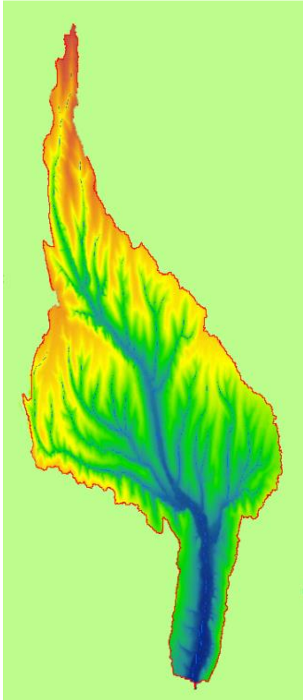


Fig. 3. The Lower Danube River basin within the boundaries of Ukraine

As to the largest tributaries of the Danube River within Odeska oblast the Kahul and Yalpuh Rivers, the area of their river basins is 613 and 3289 km^2, respectively (Fig. 4).



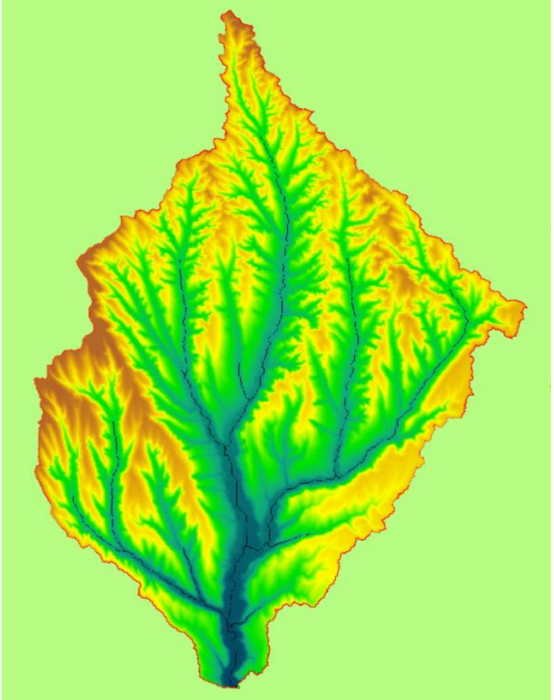


Fig. 4. The Kahul (on the left) and Yalpuh (on the right) River basins

The correspondent data on the area of river basins in the reference book [8] are as follows: the Kahul River – 605 km^2, the Yalpuh River – 3280 km^2. As it can be seen there is coincide of old and modern results.

Some larger differences were determined as to the length of the rivers. The length of the Yalpuh River, clarified using the satellite images, is 115.4 km. The length of the same river presented in the reference book [8], is much longer – 142 km. This fact can be explained by the significant hydraulic works along the river channel performed in recent decades. Nowadays the river channel in many sections is almost straight.

Another important point of the research is a water area of the lakes. As with the area of river basins it has not been studied enough. According to the design data, established 50 years ago, the areas of the lakes are as follows (Table 2).

Table 2. The design data of the lakes (reservoirs) of the Lower Danube River

Name	Usual water level, m	Minimum storage level, m	Volume, mln m^3		Area, km^2
			total	useful	
Kahul	3.5	2.0	240	142	99.2
Kartal	3.0	1.6	35.6	27.0	23.3
Yalpuh-Kugurluy	2.4	1.3	670	250	268
Safiany	1.7	0.7	6.85	4.05	4.19
Katlabukh	1.7	0.7	131.0	68.5	68.5
Kytai	1.5	0.6	125	52.5	60.0

These data shows that the depths of the lakes are rather small. The mean depths of the lakes are as follows: Kahul – 2.42 m, Kartal – 1.53, Yalpuh-Kugurluy – 2.50, Safiany – 1.63, Katlabukh – 1.91, Kytai – 2.08 m.

Most of the lakes, except Kytai one, is hydraulically connected with the neighboring ones. As a result of that the water level in the lakes is quite similar. It is somewhat larger in the lakes, located upstream, and it is a bit lower in the lakes, located downstream of the Danube River. The main data about water level in the four largest lakes according to the monitoring of the Hydrometeorological Service are presented in Table 3.

Table 3. Typical water level of the lakes (reservoirs) of the Lower Danube River during a long period of observation up to 2017, above sea level, m

Name of the lake and hydrological station	Level				
	Mean	Maxi-mum	Date	Mini-mum	Date
Kahul – Nahirne	3,04	4.04	28–31.05.1977	1.51	08–15.10.1991
Yalpuh-Kugurluy – Kosa	2,25	3.28	16–21.07.2010	0.79	17.11.1990
Katlabukh – Kyslytsa	1.38	2.60	22–23.06.1965	0.52	27.10.2012
Kytai – Chervony Yar	1.14	1.93	03.04.1969	–0.24	24, 31.10.1950

To determine water areas of the lakes, located on the left bank of the Lower Danube River, high-quality satellite images were used, obtained in the cold period of the year, when the vegetation on the banks and on shallow water was the smallest. The most suitable were the images obtained on 04.12.2016, 11.04.2017, 21.11.2017 and on 01.04.2019.

Using the method described above, the water areas of the researched lakes were determined. As of 04.12.2016 the water areas of the lakes were as follows: Kahul – 90.29, Yalpuh-Kugurluy, Katlabukh – 59.69, Kytai – 50.34 km^2. The water areas are shown in blue in Fig. 5.

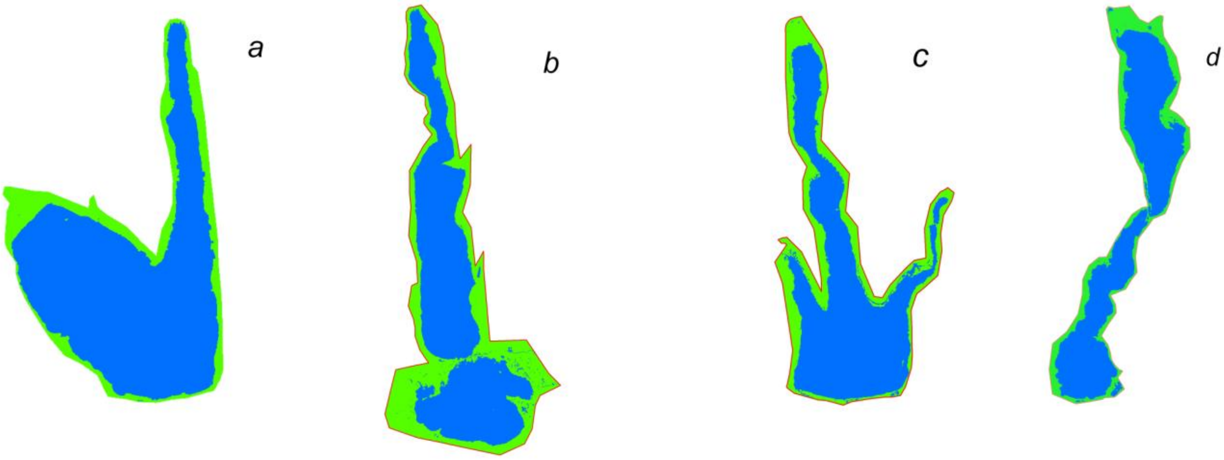


Fig. 5. Water areas (in blue) of the investigated lakes:
***a* – Kahul, *b* –** Yalpuh-Kugurluy, *c* – Katlabukh, *d* – Kytai

The water level in these lakes as of the above mentioned date (04.12.2016) was as follows: Kahul – 3.10 m, Yalpuh-Kugurluy – 2.12, Katlabukh –1.24, Kytai – 0.78 m. Similar calculations were performed based on other satellite images (Table 4).

Table 4.Water area of the largest lakes on the left bank of the Lower Danube River

Lake	04.12.2016		11.04.2017		21.11.2017	
	Area, km^2	Level, m	Area, km^2	Level, m	Area, km^2	Level, m
Kahul	90.29	3.10	90.50	3.35	90,09	2.85
Yalpuh-Kugurluy	227.2	2,12	228,8	2,24	226.3	1,83
Katlabukh	59.69	1.24	59.89	1.37	58.79	0.85
Kytai	50.34	0.78	50.65	0.97	48.81	0.47

These data show that at normal water level the water areas of the lakes are as follows: Kahul – 90.6, Yalpuh-Kugurluy – 235, Katlabukh – 60.7, Kytai – 52.9 km^2.

As it can be seen, the water areas of the lakes are now smaller than design data presented in the reference books. The difference is about 10 %. At the same time the water area of lake Yalpuh-Kugurluy is some larger than in the paper, devoted to the research of lake water area [3]. In the latter case the difference can be explained by the existence of small water areas isolated from the main water body. In our view this area should be considered as a lake area as at high water level this territory is actually covered by water.

The main reason of decreasing water area is the accumulation of sediments coming along with the water from the Danube River. There are three more factors of the water area decrease: growth of vegetation on shallow water, sediments coming along with the water of the tributaries and bank erosion.

Water temperature. There are some hydrological stations where the water temperature is measured. Some of them are located on the Danube River and its main river branches, some – on the lakes. All measurements are performed near the banks at rather small depths.

The result of the measurements shows that water temperature in lakes is almost the same. At the same time this temperature differs from the temperature in the Danube River and its main river branches. For example, the water temperature in July of 2017 was as follows: in the Danube River at Reni station – 26.8 °C, in the Danube River at Izmail station – 26.9 °C, in lake Kahul at Nahirne station – 25.7 °C, in Yalpuh at Kosa station – 25.8 °C, in Katlabukh – at Kyslitsa station – 25.4 °C.

The limited number of monitoring sites does not enable to determine the water temperature of the river and lakes in full. Under these circumstances it is desirable to use remote sensing data. Based on these data it can be stated that water temperature depends not only on the location of lakes but also on water depth, water turbidity and algal bloom rate. Moreover, it also depends on the wind intensity (Fig. 6).

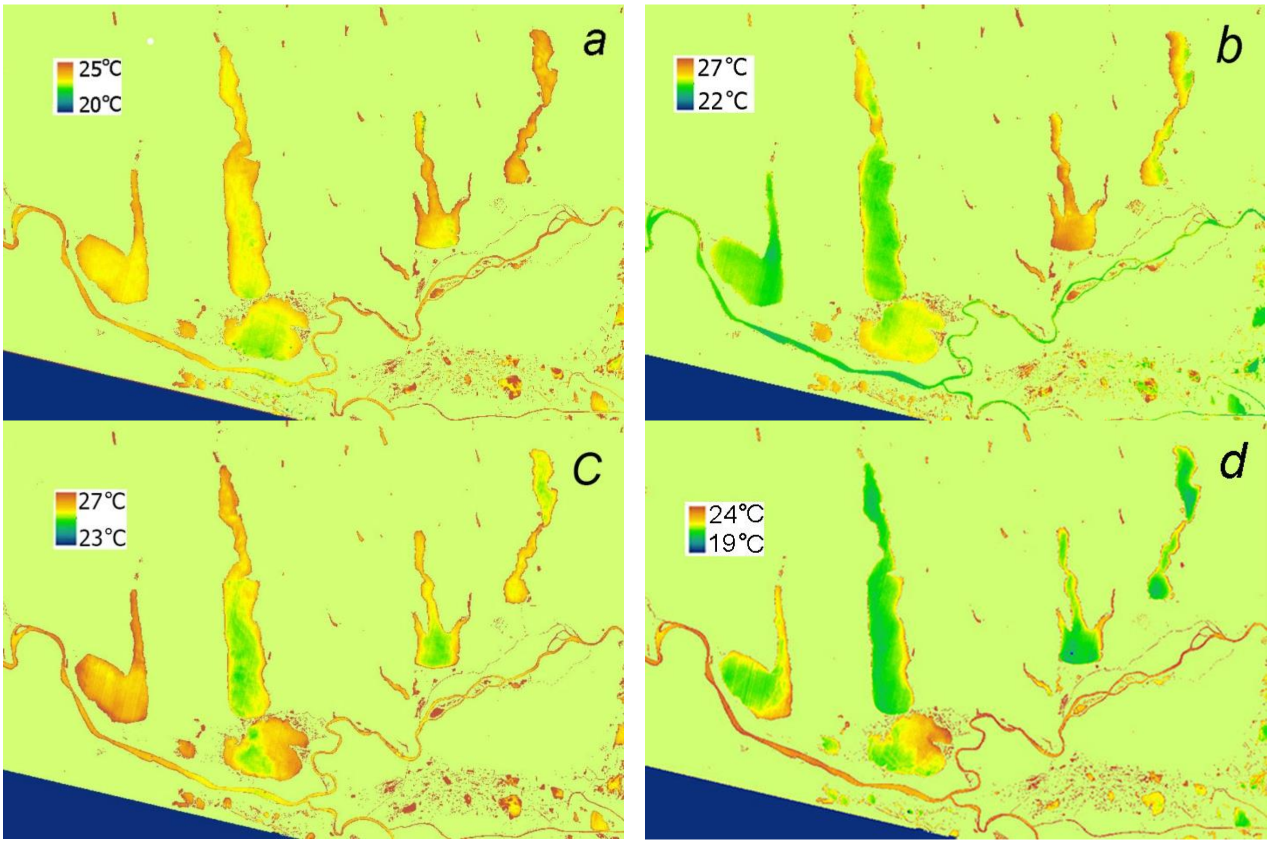


Fig. 6. Temperature of water surface in the lakes located on the Lower Danube River as of: *a* – 13.07.2016, *b* – **29.07.2016,** ***c*** **– 30.06.2017,** ***d*** **– 07.08.2019**

As it can be seen in the fig. 6, the researched lakes differ from each other by water temperature. As of 13.07.2016 the highest temperature was observed in lake Kytai, as of 29.07.2016 it was in lake Katlabukh, as of 30.06.2017 it was in lake Kahul, as of 07.08.2019 it was in lake Kugurluy.

It should be mentioned that the highest mean air temperature in these four cases was observed before satellite imagery as of 29.07.2016, when during 5 days it exceeded 25 °C. The lowest air temperature was observed before satellite imagery as of 07.08.2019, when during 5 days it was about 22 °C.

Algal bloom. The study of algal bloom was based on the satellite images obtained in the summer time of last years. We used the combination the images of visible part of spectrum B2, B3 and B4 of Landsat 8 satellite. The highest algal bloom in the lakes is usually observed in August in sunny and warm weather (Fig. 7).

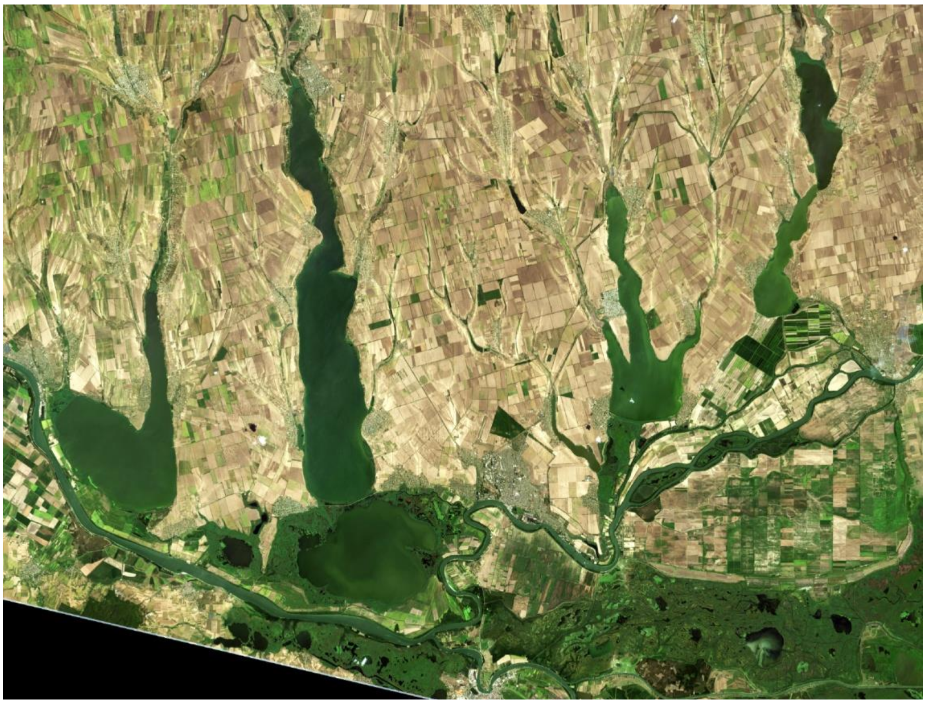


Fig. 7. Images of the lakes located near the Lower Danube River, made in the colors similar to the natural ones as of 07.08.2019

The obtained images show that algae bloom varies in space and time. The lowest algal bloom is observed usually in the northern part of lake Kytai. This water body is characterized by not only high water mineralization, but also a rather small pH value and the concentration of dissolved oxygen. In fact, there is another important reason of that – the large spread of red clay on the banks of the lake. It is not a coincidence that the village located on the bank of the lake is named as Chervony Yar.

CONCLUSIONS

The basin of the Lower Danube River within the territory of Ukraine is a unique region. This region is rich in heat and large water reservoirs at the same time. Besides the Danube River, there are some large lakes, partly transformed into reservoirs. They are Kahul, Yalpuh-Kugurluy, Katlabukh, Kytai and Sasyk. Based on the remote sensing data it was clarified the water areas of Danube Lakes. The determined areas are about 10 % less than design data.

The water quality in these lakes is not high – much worse than in the Danube River. There are two main reasons of that: small water exchange with the river and poor water quality of local rivers, which flow into the lakes. As a result, the water mineralization in the lakes usually exceeds 2 g/dm^3 and can even reach 4.5–5.0 g/dm^3 as in case of lake Kytai.

Using the data of regular monitoring and the remote sensing data, it was studied the water temperature and ecological state of the lakes. The water temperature depends on not only the location of the lakes but also on water depth, water turbidity and algal bloom. Moreover, it depends on the wind intensity.

The highest algal bloom in the lakes is usually observed in August in sunny and warm weather.

The water amount annually taken from the Danube River is 500–700 mln m^3. About half of this amount goes for feeding the lakes. The water amount, actually used for human needs, is comparably small. The largest water amount water is used for irrigation needs, first of all for rice growing.

The inadequate water quality in the lakes, mainly distant from the Danube River, is the important factor, which restricts the water use in the region. It leads to the concentration of main water consumers near the Danube River.

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MODERN HYDROGRAPHIC AND WATER MANAGEMENT ZONING OF UKRAINE'S TERRITORY – IMPLEMENTATION OF THE WFD-2000/60/EC

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ABSTRACT

In contrast to the hydrological and hydrochemical zoning, hydrographic and water management zoning of Ukraine (2016) was created on a basin basis, taking into account the boundaries of river basins, and not physiographic zoning. The main function of hydrographic and water management zoning is water management. Primary is hydrographic zoning, and water management - based on it. The description of modern hydrographic zoning of the territory of Ukraine, approved in 2016 by the Verkhovna Rada of Ukraine and included in the Water Code of Ukraine is given. Hydrographic zoning is carried out for the development and implementation of river basin management plans. On the territory of Ukraine nine areas of river basins are allocated: Dnipro; Dnister; Danube; Southern Bug; Don; Vistula; rivers of the Crimea; rivers of the Black Sea coast; rivers of the Azov Sea coast 13 sub-basins are allocated in four river basins district. The water management zoning is described - the division of hydrographic units into water management areas, which is carried out for the development of water management balances. In the regions of the river basins in the territory of Ukraine allocated 132 water management areas, 59 of which are located in the Dnipro basin. About 9,000 bodies of surface water allocated for monitoring in Ukraine. Approved zoning is the implementation of the provisions of the EU Water Framework Directive 2000/60 / EC in the management of water resources in Ukraine. Modern hydrographic and water management zoning of the territory of Ukraine approximates the management of water resources of the state to European requirements.

Keywords: hydrographic zoning, water management zoning, river basin district, sub-basin, water management area.

INTRODUCTION

The signing of the Association Agreement between Ukraine and the European Union (EU), which took place in 2014, opens up new opportunities and creates new standards in various spheres of public life, including the sphere of environmental protection. For Ukraine in the field of environmental protection, implementation of EU legislation takes place within the eight sectors regulated by 29 EU sources (EU directives and regulations) in this area. The directives and regulations establish common rules and standards that must be transposed (transposed) to domestic law. These rules and standards are not subject to discussion and should be fully achieved. EU law sources determine quantitative and qualitative indicators to be achieved by each country over a specified period of time.

In the Annex XXX of the Association Agreement between Ukraine and the EU, the following sectors related to environmental protection have been identified: 1) environmental management and integration of environmental policy into other sector policies; 2) the quality of atmospheric air; 3) management of waste and resources; 4) water quality and water management, including the marine environment; 5) nature protection; 6) industrial pollution and man-made threats; 7) climate change and protection of the ozone layer; 8) genetically modified organisms.

The European Union supports the implementation of the tasks facing each of the above sectors, funding from 2012 in Ukraine a technical assistance project called "Supplementing the Ministry of Environment and Natural Resources of Ukraine with the implementation of sectoral budget support".

Questions related to the Water Quality and Water Management sector in the European Union are regulated by six major water directives: 1) Water Framework Directive, full name – Directive 2000/60 / EC of the European Parliament and of the Council of 23 October 2000 on the establishment of the framework for Community action in the field of water policy (Directive 2000/60/EC); 2) Flood Directive – Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of risks of flooding; 3) Marine Strategy Framework Directive – Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 on establishing a framework for Community action in the field of environmental policy relating to the marine environment; 4) Urban Wastewater Treatment Directive – Council Directive 91/271/EEC of 21 May 1991 on urban waste water treatment; 5) Directive on drinking water– Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption; 6) Directive on nitrates – Council Directive 91/676 / EEC of 12 December 1991 on the protection of waters against pollution caused by nitrates from agricultural sources.

In Ukraine, water relations are regulated by the Water Code of Ukraine, adopted in 1995 (Water Code, 1995) and other acts.

PROBLEM STATEMENT AND SOURCE MATERIALS

Planned activities on implementation of EU Water Directives are being implemented in Ukraine. The schedule of achievement of goals for each of the directives, which specifies the terms of realization of certain tasks, has been developed. The most ambitious task is the implementation of the Water Framework Directive 2000/60/ EC, which are divided into stages in Ukraine.

The first stage (2014–2017) is the adoption of national legislation and determination of the authorized body; fixing at the legislative level the notion of unit of hydrographic zoning of the territory of the country; to develop a position on the basin management with the assignment of appropriate functions on it.

The second stage (2014–2020) is definition of areas of river basins and creation of mechanisms for management of international rivers, lakes and coastal waters; analysis of the characteristics of river basin districts; introduction of water quality monitoring programs.

The third stage (2014–2024) is preparation of river basin management plans, public consultation and publication of these plans.

The main task of this publication was to establish the dynamics of implementation of the WFD 2000/60/EC implementation plan in Ukraine, the characteristics of hydrographic zoning, approved by the Verkhovna Rada of Ukraine in 2016, as well as the specifics of water management zoning.

For solving the problem, the open materials of the state bodies of Ukraine were used, as well as the author's own work, which took part in the development of the scheme of hydrographical zoning of the territory of Ukraine.

RESULTS OF RESERCH

From the three above-mentioned stages of the implementation of the WFD 2000/60/EU in Ukraine, the period of implementation of the first phase (2014-2017) – the legislative-organizational. Briefly describe its results.

On October 4, 2016, the Verkhovna Rada of Ukraine adopted the Law of Ukraine "On Amendments to Certain Legislative Acts of Ukraine on Implementation of Integrated Approaches in the Management of Water Resources Based on Basin Principle" (№ 1641-VIII), which introduced a number of changes to the Water Code of Ukraine in 1995, aimed at introducing the provisions of the Water Framework Directive of the European Union into the practice of water resources management of the state. This law supplemented the Water Code of Ukraine with a number of new terms and concepts implemented with WFD 2000/60/EC, officially approved the hydrographical zoning of the territory of the state, recognizing that the river basin district is the main unit of management in the field of water use and protection.

New terms included in the Water Code of Ukraine. Article 1 of the Water Code of Ukraine, entitled "Definition of the main terms", after the adoption of the Law of Ukraine № 1641-VIII of October 4, 2016, was supplemented by a number of new normative terms that are characteristic of the EU WFD. Here is a list of new terms: basin management principle, water sector, water management zoning, water management systems, hydrographic zoning, eutrophication, ecological cost, ecological state of a surface of an array of surface waters, substantially changed massif of surface waters, quantitative status of an array of groundwater, limestone, an array of surface waters, array of groundwater, redistribution of water resources, transitional water, river basin management plan, flood risk management plan, coastal waters, river basin district, river the basin (catchment), the sub-basin, the chemical status of the surface water body, the chemical status of the groundwater body (Khilchevskyi, Grebin, 2017).

The basic concept of "basin management principle" is integrated (integrated) water resources management within the area of the river basin, which is the main unit of management in the field of water use and protection and water reproduction. The area of the river basin consists of a river basin (adjacent river basins) and associated coastal and groundwater. The area of the river basin can be divided into smaller units – sub-basins. Sub-basin is part of a river basin, the flow of water from which due to the connected reservoirs and watercourses is carried out to the main river basin or water-field downstream. The water management areas part of the river basin, for which water balance is being developed, limits are set for the collection of water from the water object and other parameters of the use of the water object (water use).

It is envisaged to develop a river basin management plan – a document containing an analysis of the state and a set of measures for achieving the goals set for each river basin district within the established time frame. The river basin management plans and the procedure for their development are approved by the Cabinet of Ministers of Ukraine every six years.

It should be noted that the executive authorities in Ukraine in the field of water use and protection and reproduction of water resources have the following departments: the central executive body, which ensures the formation of state policy in the field of environmental protection – the Ministry of Environment and Natural Resources of Ukraine, the central executive authority, which implements state policy in the field of water sector development (surface water) - the State Agency of Water Resources of Ukraine; central executive authority, which implements state policy in the field of geological study and rational use of subsoil (groundwater) – State Service of Geology and Subsoil of Ukraine; other bodies - in accordance with the law (Water Code, 1995).

Hydrological aspects of zoning of Ukrainian territory. For the territory of Ukraine (area 603,628 km^2) four basic types of zoning are used: hydrological, hydrochemical, hydrographic and water management.

Hydrological zoning was developed in 1968 on the basis of information on the regime of small and medium rivers, is a classic type of zoning on a physic-geographic basis. It also entered the modern "National atlas of Ukraine" (Budkina, Kozintseva, 2007). This zoning reflects the spatial patterns of the hydrological regime of the rivers, the conditions for the formation of water balance, is closely related to the physical and geographical zoning (relief, climate, soil and vegetation cover). According to these indicators, the three highest taxa (hydrological countries) are allocated on the territory of Ukraine – the plains of Ukraine, the Ukrainian Carpathians and the Crimean Mountains. Further, the division takes place in hydrological regions and subregions.

In the flat part of Ukraine, three hydrological zones are distinguished: excessive water content – covers the physical and geographical zone of mixed forests (the density of the river network is 0.25-0.5 km/km^2, surface runoff is 3.0-4.5 L/s from 1 km^2); sufficient water – corresponds to the forest-steppe physical and geographical zone (density of the river network is 0.4-0.8 km/km^2, surface runoff - 1.74 L/s from 1 km^2); lack of water – corresponds to the steppe zone (density of the river network in the south – 0.1-0.2 km/km^2, surface runoff – 0.2-0.5 L/s from 1 km^2, in the summer some rivers dry out).

In the Ukrainian Carpathians, the density of the river network is 1.0 km/km^2 or more. The rivers are mountainous, with significant slopes and speeds. The water content of the rivers is highest in the upper reaches of the Tysa River and reaches 35 L/s from 1 km^2, and in Transcarpathia – 15-25 L/s from 1 km^2.

In the Crimean Mountains, the density of the river network reaches 0.6-0.7 km/km^2, and surface runoff varies from 26 to 0.37 L/s from 1 km^2. Hydrological regime is unstable, some rivers dry up.

Hydrochemical zoning reflects the spatial physic-geographical, climatic and geological conditions of the formation of the chemical composition of the water of small and medium rivers (Almazov, Konenko, Kuzmenko, 1978). But the connection with the physical and geographical zoning is not as clearly defined as in hydrological zoning, as the influence of local geological and soil conditions is given. In the hydrochemical zonation, the distribution areas of a particular hydrochemical type of water are allocated and the value of their total mineralization is indicated. The main hydrochemical types of water (according to predominant ions) are as follows: 1) hydrocarbonate-calcium; 2) hydrocarbonate-calcium-magnesium-sodium; 3) sulfate-hydrocarbonate-calcium-sodium; 4) sulfate-chloride-sodium-calcium; 5) chloride-sulfate-sodium.

In general, the total mineralization of water of small and medium rivers in Ukraine is increasing (from 200-300 mg/L to 1,500-3,000 mg/L or more) from northwest to southeast – from the Ukrainian Polesie to the Azov Sea coast. In the same direction there is a change of the above-mentioned hydrochemical types of river waters (Khilchevskyi, Kurylo, Sherstyuk, 2018).

Hydrographic and water-management zoning of Ukraine are created on a basin basis, taking into account the boundaries of river basins, and not physical geographic zonation. For example, the largest area of the river basin of the Dnipro includes three physical-geographical zones: mixed forests, forest-steppe and steppe. In hydrographic zoning, the main taxonomic unit is the area of the river basin, which can be divided into sub-basins. The main function of hydrographic and water management zoning is water management, which can only be effective within the river basin. Primary is hydrographic zoning, and water management – based on it.

Hydrographic zoning of Ukrainian territory. Hydrographic zoning is the division of territory into a hydrographic unit, which is carried out to develop and implement river basin management plans. In 2013, a group of authors developed "Methods of hydrographic and water management zoning of the territory of Ukraine in accordance with the requirements of the Water Framework Directive of the European Union" (Methods, 2013). The work proposed the allocation of 9 river basin districts in Ukraine. In fact, this scheme of hydrographical zoning was approved by the Law of Ukraine No. 1641-VIII of October 4, 2016 In Ukraine, 9 river basin districts are legally approved: Dnipro river basin district; Dnister river basin district; Danube river basin district; Southern Bug river basin district; Don river basin district; Vistula river basin district; river basin district of the Crimea; river basin district of the Black Sea coast; river basin district of the Azov Sea coast (Fig. 1).

The law provides that within the established areas of river basins, the central executive body, which ensures the formation of state policy in the field of environmental protection, may allocate sub-basins. The Ministry of Ecology and Natural Resources of Ukraine in 2017 allocated 13 sub-basins within the four river basin districts: the Dnipro – 5 sub-basins, the Danube – 4 sub-basins, the Don – 2 sub-basins, the Vistula – 2 sub-basins (Names, 2017).

In the area of the Dnipro River basin, the following sub-basins are identified: the Upper Dnipro; the Middle Dnipro; the Lower Dnipro; the Prypyat River; the Desna River. In the area of the Danube River basin, the following sub-basins are identified: the Tysa River; the Prut River; the Siret River; Lower Danube. In the area of the Don River basin, the following sub-basins are singled out: the Siverskyi Donets River; Lower Don. In the area of the basin of the Vistula River, the following sub-basins are identified: the Western Bug River; the San River (Table 1). The Ministry of Environment and Natural Resources of Ukraine approves the boundaries of areas of river basins and sub-basins.

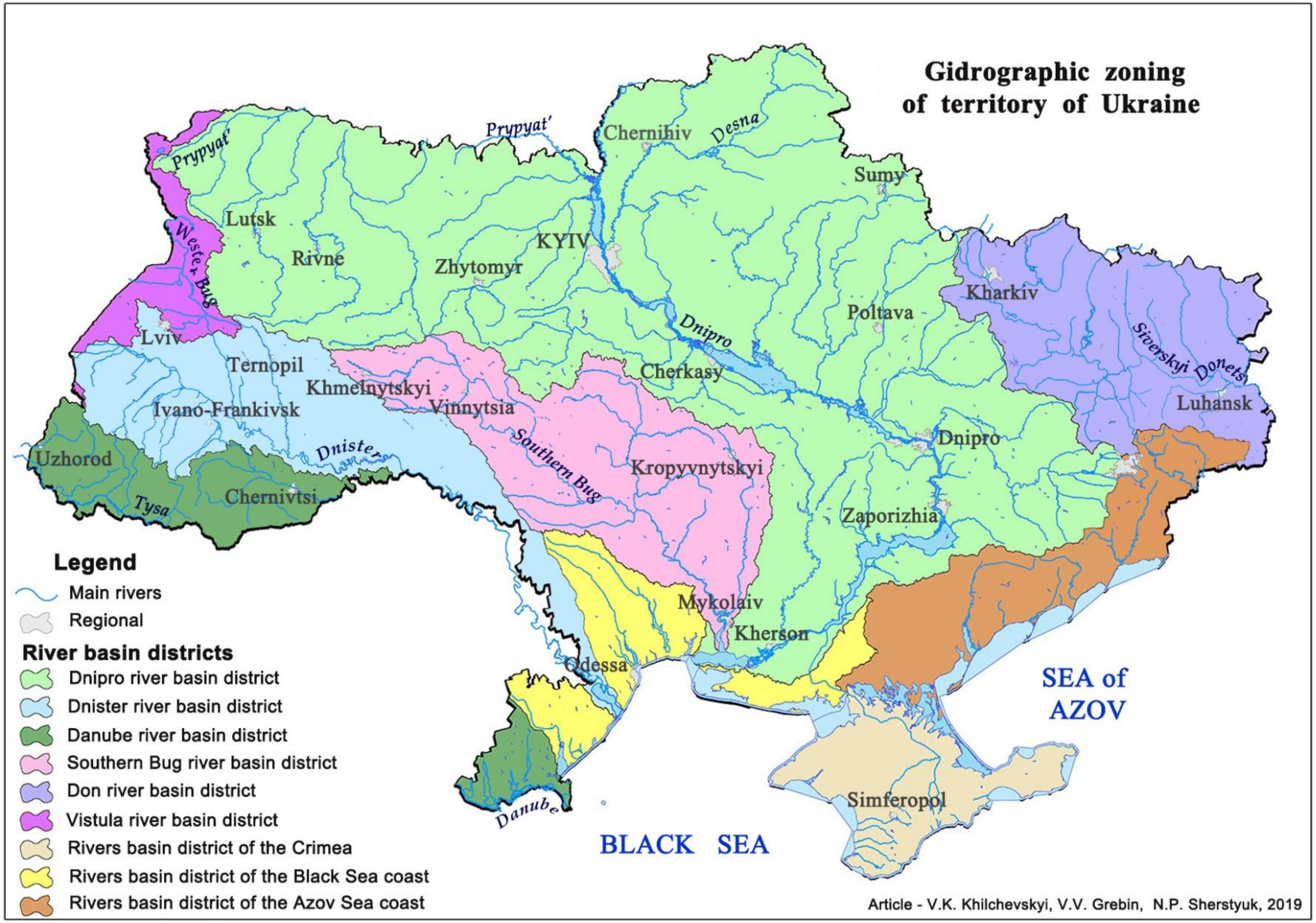

Fig. 1. Map diagram of the hydrographical zoning of the territory of Ukraine in 2016 by the river basin district

For detailing the hydrographic zoning of the territory of Ukraine, the development of a state water monitoring program, and the implementation of river basin management plans are allocated bodies water (for surface and groundwater). Bodies of surface water, are surface water bodies or their parts, for which environmental objectives are established and which are used to assess the achievement of these environmental objectives. In 9 districts of river basins on the territory of Ukraine, about 9,015 bodies of surface water have been allocated. In areas of river basins: Dnipro – 3,813 bodies of surface water (42 %); Dnister – 1,154 (13 %); Danube – 871 (10 %); Southern Bug – 1,089 (12 %); Don – 699 (8 %); Vistula – 249 (3 %); river basin district of the Crimea – 352 (4 %); river basin district of the Black Sea coast – 231 (2 %); river basin district of the Azov Sea coast – 557 (6 %).

Table 1. List of areas of river basins and sub-basins and the number of water management areas according to the hydrographical zoning of the territory of Ukraine in 2016

№ by order	The name of the river basin district	Catch-ment area, км^2	№ by ord-er	Sub-basin name	Catch-ment area, км^2	Number of water manage-ment areas
1	Dnipro river basin district	296,315	1	Upper Dnipro	2,315	1
			2	Middle Dnipro	109,527	23
			3	Lower Dnipro	82,625	15
			4	Prypyat River	68,366	13
			5	Desna River	33,482	7
2	Dnister river basin district	53,961	-	-	-	12
3	Danube river basin district	30,625	1	Tysa River	12,810	3
			2	Prut River	9,327	1
			3	Siret River	2,070	1
			4	Lower Danube	6,418	3
4	Southern Bug river basin district	63,700	-	-	-	11
5	Don river basin district	55,273	1	Siverskyi Donets River	54,901	19
			2	Lower Don River	372	1
6	Vistula river basin district	12,892	1	Western Bug River	10,410	2
			2	San River	2482	1
7	River basin districts of the Crimea	27,218	-	-	-	8
8	River basin district of the Black Sea coast	27,179	-	-	-	4
9	River basin district of the Azov Sea coast	36,866	-	-	-	7
Total	9	604,742*	Total	13		132

Note: 604,742* км^2 - total area of 9 river basin district (including coastal waters);
603,628 км^2 - the territory of Ukraine .

It should be noted that when optimizing the hydrographic zoning of the territory of Ukraine, the boundaries of ecoregions were specified, taking into account the passage of watershed lines and the elevation of water bodies above sea level as indirect factors, which have a preferential value in the absence of data on the composition of the hydrobiota (Grebin' et al. 2016).

The conducted hydrographic zoning facilitates the study of hydrography and hydrochemistry of transboundary river basins located on the territory of Ukraine and other states (Khilchevskyi, Zabokrytska, Sherstyuk, 2018; Khilchevskiy, Grebin, Zabokrytska, 2019).

Water-management zoning of the territory of Ukraine. Water management zoning – the division of hydrographic units into water management areas, which is carried out for the development of water management balances. The number and boundaries of water areas are approved by the Ministry of Ecology and Natural Resources of Ukraine. The water management areas are distributed by river basin areas, taking into account the basin principle of management. In 2017, 132 water management areas were allocated (Names, 2017) – Table 2.

Table 2. List of water management areaswithin the rivers basins districts and sub-basins according to the hydrographical zoning of the territory of Ukraine 2016 (Names, 2017)

Code	Names of the rivers basins districts, sub-basins and water management areas	Catchment area, км^2
1	2	3
M5.1	**1. DNIPRO RIVER BASIN DISTRICT**	**296,315**
M5.1.1	**Sub-basin Upper Dnipro – water management areas:**	**2,315**
M5.1.1.01	The Dnipro River from the state border to the beginning of the Kyiv reservoir (including the Sozh River within Ukraine)	2,315
M5.1.2	**Sub-basin Middle Dnipro – water management areas:**	**109,527**
M5.1.2.02	The Kyiv reservoir (including the Braginka River within Ukraine, excluding the Pripyat, Teteriv, Irpin rivers)	2,324
M5.1.2.03	The Dnipro River from the dam of the Kyiv reservoir to the dam of the Kaniv reservoir (excluding the Desna, Trubizh rivers)	5,391
M5.1.2.04	The Dnipro River from the dam of the Kaniv reservoir to the dam of the Kremenchug reservoir (excluding the Ros, Supiy, Sula, Tiasmyn rivers)	8,751
M5.1.2.05	The Teteriv River from the source to the gauging station Zhytomyr	5,244
M5.1.2.06	The Teteriv River from the gauging station Zhytomyr to the mouth of the Irsha River (including the Irsha River)	6,230
M5.1.2.07	The Teterev River from the mouth of the Irsha River to the mouth	3,371
M5.1.2.08	The Irpin River	3,252
M5.1.2.09	The Trubizh River	3,636
M5.1.2.10	The Ros River from the source to the boundary of the Kyiv and the Cherkasy regions	9,412
M5.1.2.11	The Ros River from the boundary of the Kyiv and the Cherkasy regions to the mouth	3,263
M5.1.2.12	The Supiy River	2,065
M5.1.2.13	The Sula River from the source to the border of the Sumy and Poltava regions	4,544
M5.1.2.14	The Sula River from the border of the Sumy and Poltava regions to the gauging station Lubny (excluding the Uday River)	2,268
M5.1.2.15	The Sula River from the gauging station Lubny to the mouth	4,129
M5.1.2.16	The Uday River	6,835
M5.1.2.17	The Tiasmyn River	4,312
M5.1.2.18	The Psel River from the state border to the border of the Sumy and Poltava regions	3,899
M5.1.2.19	The Psel River from the border of the Sumy and Poltava regions to the mouth of the Khorol River	5,484
M5.1.2.20	The Psel River from the mouth of the Khorol River to the mouth (excluding the Khorol River)	3,929
M5.1.2.21	The Khorol River	3,952
M5.1.2.22	The Vorskla River from the state border to the border of the Sumy and Poltava regions	3,687

Continuation of Table 2

1	2	3
M5.1.2.23	The Vorskla River from the border of the Sumy and Poltava regions to the mouth	8,355
M5.1.2.24	The Dnipro River from the dam of the Kremenchug reservoir to the dam of the Kamianske reservoir	5,184
M5.1.3	**Sub-basin Lower Dnipro – water management areas:**	**82,625**
M5.1.3.25	The Dnipro River from the dam of the Kamianske reservoir to the dam of the Dniprovsky reservoir (excluding the Oril, Samara rivers)	5,859
M5.1.3.26	The Dnipro River from the dam of the Dniprovsky reservoir to the dam of the Kakhovka reservoir	19,197
M5.1.3.34	The Gaychur River	2,295
M5.1.3.35	The Inhulets River from the source to the border of the Kirovograd and Dnipropetrovsk regions	4,680
M5.1.3.36	The Inhulets River from the border of the Kirovograd and Dnipropetrovsk regions to the border of the Dnipropetrovsk and Kherson regions (excluding the Saksahan River)	2,680
M5.1.3.37	The Inhulets River from the border of the Dnipropetrovsk and Kherson regions to the mouth	5,522
M5.1.3.38	The Saksahan River	2,074
M5.1.3.39	The Dnipro Liman	1,906
M5.1.4	**Sub-basin the Prypyat River – water management areas:**	**68,366**
M5.1.4.40	The Prypyat River from the source to the state border	11,425
M5.1.4.41	The Prypyat River from the gauging station of Mozyr to the mouth (within Ukraine)	2,244
M5.1.4.42	The Styr River from the source to the border of the Rivne and Volyn regions	6,317
M5.1.4.43	The Styr River within the Volyn region	4,003
M5.1.4.44	The Styr River from the border of the Volyn and Rivne regions to the state border	2,457
M5.1.4.45	The Horyn River from the source to the boundary of the Khmelnitskyi and Rivne regions	4,243
M5.1.4.46	The Horyn River from the border of the Khmelnytskyi and Rivne regions to the state border (excluding the Sluch River)	8,776
M5.1.4.47	The Sluch River from the source to the mouth of the Khomora River (including the Khomora River)	4,835
M5.1.4.48	The Sluch River from the mouth of the Khomora River to the mouth of the Korchyk River (including the Korchyk River)	5,428
M5.1.4.49	The Sluch River from the mouth of the Korchyk River to the mouth	3,893
M5.1.4.50	The Stvyha River	2,966
M5.1.4.51	The Ubort River from the source to the state border	4,028
M5.1.4.52	The Uzh River	7,744
M5.1.5	**Sub-basin the Desna River – water management areas:**	**33,482**
M5.1.5.53	The Desna River from the state border to the mouth of the Seym River	7,091
M5.1.5.54	The Desna River from the mouth of the Seym River to the stream gauge of Chernihiv (excluding the Seym, Snov rivers)	6,433
M5.1.5.55	The Desna River from the gauging stationof Chernihiv to the mouth (excluding the Oster River)	4,176
M5.1.5.56	The Seym River from the state border to the gauging station Mutyn	4,856
M5.1.5.57	The Seym River from the gauging station of Mutyn to the mouth	2,479
M5.1.5.58	The Snov River	4,983
M5.1.5.59	The Oster River	3,450

Continuation of Table 2

1	2	3
M5.2	**2. DNISTER RIVER BASIN DISTRICT – water management areas:**	**53,961**
M5.2.0.01	The Dnister River from the source to the mouth of the Stryi River	5,680
M5.2.0.02	The Stryi River	2,899
M5.2.0.03	The Dnister River from the mouth of the Stryi River to the mouth of the Hnyla Lypa River	5,842
M5.2.0.06	The Seret River	3,994
M5.2.0.07	The Dnister River from the mouth of the River Seret to the stream gauge Mohyliv-Podilskyi (excluding the Zbruch River)	9,613
M5.2.0.08	The Zbruch River	3,406
M5.2.0.09	The Dnister River from the stream gauge Mohyliv-Podilskyi to the state border	3,667
M5.2.0.10	The Dnister River from the state border to the mouth of the River Reut (within Ukraine)	6,456
M5.2.0.11	The Dnister River from the mouth of the Byk River to the mouth (within Ukraine)	6,456
M5.2.0.12	The Dnister Liman	831
M5.3	**3. DANUBE RIVER BASIN DISTRICT**	**30,625**
M5.3.1	**Sub-basin the Tysa River – water management areas:**	**12, 810**
M5.3.1.01	The Tysa River from the source to the state border	8,848
M5.3.1.02	The Latorycia River from the source to the state border	2,332
M5.3.1.03	The Uzh River from the source to the state border	1,629
M5.3.2	**Sub-basin the Prut River – water management area:**	**9,327**
M5.3.2.04	The Prut River from the source to the state border	9,327
M5.3.3	**Sub-basin the Siret River – water management area:**	**2,070**
M5.3.3.05	The Siret River from the source to the state border	2,070
M5.3.4	**Sub-basin Lower Danube - water management areas:**	**6,418**
M5.3.4.06	The Danube River from the state border to the mouth (excluding the Kahul, Yalpuh rivers)	4,981
M5.3.4.07	The Kahul River (including the Kahul Lake)	350
M5.3.4.08	The Yalpuh River (including the Yalpuh, Kuhurluy lakes)	1,085
M5.4	**4. SOUTHER BUG RIVER BASIN DISTRICT – water management areas:**	**63,700**
M5.4.0.01	The Southern Bug River from the source to the mouth of the Ikva River (including the Ikva River)	3,605
M5.4.0.02	The Southern Bug River from the mouth of the Ikva River to the gauging station Selyshche	5,505
M5.4.0.03	The Southern Bug River from gauging station Selyshche to the mouth of the Silnytsia River (including the Silnytsia River)	4,921
M5.4.0.04	The Southern Bug River from the mouth of the Silnytsia River to the mouth of the Synyukha River	13,249
M5.4.0.05	The Tikych River (including the Hnyly Tikych, Hirsky Tikych rivers)	6,723
M5.4.0.06	The Synyukha River (including the Velyka Vys River)	9,978
M5.4.0.07	The Southern Bug River from the mouth of the Synyukha River to the gauging station Oleksandrivka	2,163
M5.4.0.08	The Southern Bug River from stream gauge Oleksandrivka to the mouth (excluding the Inhul River)	7,821
M5.4.0.09	The Inhul River from the source to the mouth of the Berezivka River (including the Berezivka River)	5,751
M5.4.0.10	The Inhul River from the mouth of the Berezivka River to the mouth	4,086
M5.4.0.11	The Bug Liman	603
M6.5	**5. DON RIVER BASIN DISTRICT**	**55,273**
M6.5.1	**Sub-basin the Siverskyi Donets River – water management areas:**	**54,901**

Continuation of Table 2

1	2	3
M6.5.1.01	The Siverskyi Donets River from the state border to the dam of the Pechenízke reservoir	2,424
M6.5.1.02	The Siverskyi Donets River from the dam of the Pechenízke reservoir to gauging station of the Zmiiv (excluding the Udy River)	4,379
M6.5.1.03	The Udy River	3,212
M6.5.1.04	The Siverskyi Donets River from the gauging station Zmiiv to the mouth of the Bereka River	3,246
M6.5.1.05	The Bereka River	2,668
M6.5.1.06	The Siverskyi Donets River from the mouth of the Bereka River to the boundary of the Kharkiv and Donetsk regions (excluding the Oskil River)	1,044
M6.5.1.07	The Oskil River from the state border to the gauging station of Kupiansk	1,923
M6.5.1.08	The Oskil River from the gauging station Kupiansk to the mouth	2,006
M6.5.1.09	The Siverskyi Donets River from the border of Kharkiv and Donetsk regions to the border of the Donetsk and Luhansk regions (excluding the Kazennyi Torets, Bakhmutka rivers)	1.895
M6.5.1.10	The Kazennyi Torets River	5,204
M6.5.1.11	The Bakhmutka River	1,932
M6.5.1.12	The Siverskyi Donets River from the border of the Donetsk and Luhansk regions to the gauging station Lysychansk (excluding the Krasna, Borova)	840
M6.5.1.13	The Krasna River	3,332
M6.5.1.14	The Borova River	1,914
M6.5.1.15	The Siverskyi Donets River from the gauging station Lysychansk to the state border (excluding the Aidar, Luhan, Derkul rivers)	4,577
M6.5.1.16	The Aidar River	5,085
M6.5.1.17	The Luhan River	3,726
M6.5.1.18	The Derkul River	3,795
M6.5.1.19	The Velyka Kamianka River (within Ukraine)	1,619
M6.5.2	**Sub-basin Lower Don River – water management areas:**	**372**
M6.5.2.20	Tributaries of the Don River (within Ukraine)	372
A6.6	**6. VISTULA RIVER BASIN DISTRICT**	**12,892**
A6.6.1	**Sub-basin Western Bug River – water management areas:**	**10,410**
A6.6.1.01	The Western Bug River from the source to the state border	6,241
A6.6.1.02	The Western Bug River from the state border with the Republic of Poland to the state border with the Republic of Belarus	4,168
A6.6.2	Sub-basin San River – water management area:	2,482
A6.6.2.03	The San River and its tributaries (within Ukraine)	2,361
M5.7	7. RIVER BASIN DISTRICT OF THE CRIMEA – water management areas:	27,218
M5.7.0.01	The western coast of the Crimean peninsula (excluding the Kacha, Alma, Chorna, Belbek rivers)	8,327
M5.7.0.02	The Kacha River	669
M5.7.0.03	The Alma River	685
M5.7.0.04	The Chorna River	628
M5.7.0.05	The Belbek River	499
M5.7.0.06	The Southern coast of the Crimean peninsula	3,410
M6.7.0.07	The coast of the Azov Sea within the Crimean peninsula (excluding the Salhyr River)	8,502
M5.8	8. RIVER BASIN DISTRICT OF THE BLACK SEA COAST – water management areas:	27,179
M5.8.0.01	The Black Sea coast between the mouth of the Danube River and the Dnister Liman	6,211

Continuation of Table 2

1	2	3
M6.7.0.08	The Salhyr River	4,280
M5.8.0.02	The Black Sea coast between the Dnister Liman and the Dnipro Lyman (excluding the Tylihul River with estuary)	9,425
M5.8.0.03	The Tylihul River with estuary	5,506
M5.8.0.04	The Black Sea coast between the Dnipro Lyman and the Crimean peninsula	4,424
M.6.9	**9. RIVER BASIN DISTRICT OF THE AZOV SEA COAST– water management areas:**	**36,866**
M6.9.0.01	The coast of the Azov Sea from the Crimean peninsula to the state border (excluding the Molochna, Berda, Kalmius, Mius rivers)	8,502
M6.9.0.02	The Molochna River (including the Molochnyi Lyman)	5,493
M6.9.0.03	The Berda River	1,904
M6.9.0.04	The Kalmius River (excluding the Kalchik River)	3,782
M6.9.0.05	The Kalchik River	1,302
M6.9.0.06	The Mius River from the source to the state border (excluding the Krynka River)	2,365
M6.9.0.07	The Krynka River from the source to the state border	2,572

According to the river basin districts, the distribution 132 of water management areas is as follows: Dnipro – 59 (45 %); Dnister – 12 (9 %); Danube – 8 (6 %); Southern Bug – 11 (8 %); Don – 20 (16 %); Vistula – 3 (2 %); rivers of the Crimea – 8 (6 %); rivers of the Black Sea coast – 4 (3 %); rivers of the Azov Sea coast – 7 (5 %) - Fig. 2.

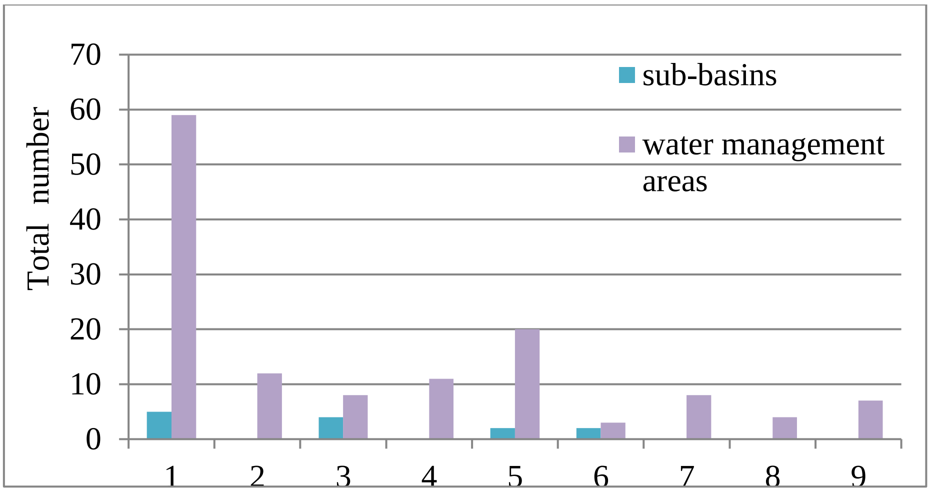

Fig. 2. Presence of sub-basins and water management areas within the rivers basins districts according to the hydrographical zoning of the territory of Ukraine in 2016: 1 – Dnipro; 2 – Dnister; 3 – Danube; 4 – Southern Bug; 5 – Don; 6 –Vistula; 7 – rivers of the Crimea; 8 – rivers of the Black Sea coast; 9 –rivers of the Azov Sea coast

In order to ensure the compilation of the state water cadastre in the section "Water Utilization", the coding of areas of river basins, sub basins and water areas is carried out (see Table 2). The code of the area of the river basin is formed from three characters: the first two characters are the code of the sea: A6 – the Baltic Sea, M5 – the Black Sea, M6 – the Azov Sea; the third sign is the serial number of the river basin district. The code for the sub-basin is formed from four characters: the first three characters are the code of the river basin district, the fourth sign is the serial number of the sub-basin within the corresponding of the river basin district. The code of the water management areas formed from six characters: the first three characters are the code of the river basin district, the fourth sign is the serial number of the sub-basin within the corresponding of the river basin district (in the absence of sub basins, the fourth sign is 0), the fifth and sixth signs are the serial number of the water management area within the respective of the river basin district.

As noted, water management areas are allocated for the development of water management balance for certain areas. The water management balances the ratio between available for use of water resources in a certain area and the needs of them within a certain region for a certain period of time. On the basis of water management balances, water intake limits from the water body and other parameters of the use of the water object (water use) are set by different water users representing industry, housing and communal services and agriculture. Water management balances an important mechanism for regulating access to water resources in Ukraine and its individual regions.

The flow of rivers of Ukraine without the Danube averages 87.1 km^3 per year, of which 52.4 km^3 (60%) is formed on the territory of the country. A further 123 km^3/year passes along the Kiliya branch of the Danube (the border between Ukraine and Romania). Thus, the total flow of all rivers in Ukraine is 210.1 km^3/year. With the population in Ukraine in 2013, 45.5 million people water availability indicators for 1 person is: 1.15 thousand m^3/year - local flow rivers; 1.91 thousand m^3/year - the total river flow of Ukraine without the Danube; 4.62 thousand m^3/year - the total flow of Ukrainian rivers along with the Danube. And if we take into account the downward trend in the population in Ukraine, in particular, in 2019 - 42.153 million people (Population, 2019), then we will get the following water availability indicators for 1 person: 1.24 thousand m^3/year - local flow rivers; 2.07 thousand m^3/year - the total river flow of Ukraine without the Danube; 4.98 thousand m^3/year - the total flow of Ukrainian rivers along with the Danube.

It should be noted that during 1991-2000, Ukraine experienced a sharp economic decline (2.5 times), after which a certain rise began. Analysis of water use statistics also shows that water withdrawal from natural reservoirs in Ukraine has been declining since 1990 (Table 3, Fig. 3.).

Table 3. Water abstraction from water bodies, its use and water disposal in Ukraine in 1990-2018 (including fresh and sea water), km^3 (Main indicators, 2019)

Indicator / years	1990	1995	2000	2005	2010	2013	2014*	2015	2016	2017	2018
Water abstraction from water bodies	35.6	25.9	18.3	15.1	14.8	13.6	11.5	9.7	9.9	9.2	11.3
Total water disposal	20.3	15.0	11.0	8.9	8.1	7.7	6.6	5.6	5.6	4.9	5.4

Note. * - starting from 2014, information was submitted without including data on the temporarily occupied territory of the Autonomous Republic of Crimea and part of the anti-terrorist operation zone in the Donbass.

The maximum water intake was reached in 1990, when 35.6 km^3 of water abstraction from natural water bodies. In 2000, water abstraction decreased by 1.9 times (18.3 km^3) compared to 1990. In 2010, water abstraction decreased by 2.4 times (14.9 km^3), and in 2013 - by 2.6 times (13.6 km^3). In 2014-2018 this figure was 9.2-11.5 km^3. In the same proportions, total water disposal also decreased.

The structure of water use in Ukraine by major sectors of the economy varies by year (Table 4). In some years, it is very close to European proportions. The largest water in Ukraine is used by industry - 45-63%; agriculture - 16-34%; housing and communal services - 17-28% (during 1995-2015). In Europe, the water use structure is as follows: 54% - industry; 25% - agriculture; 21% - housing and communal services (Water uses FAO's, 2016).

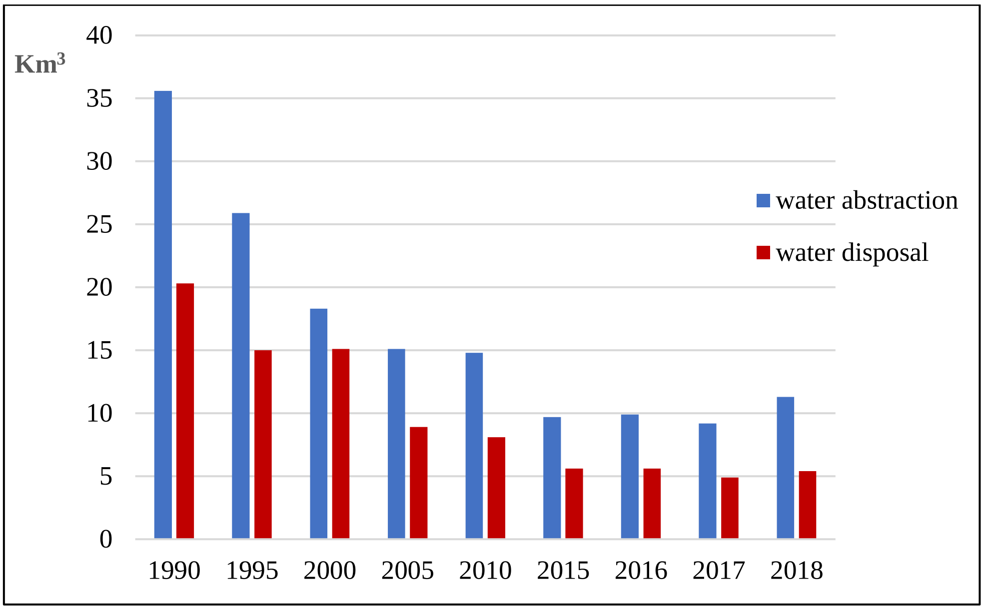

Fig. 3. Water abstraction from water bodies and total water disposal in Ukraine in 1990-2018, km^3

Table 4. Structure of water use in Ukraine in various sectors of the economy 1995-2015, % (National report, 2000, 2010, 2015)

Activity/years	1995	2000	2005	2010	2015
Industry	45	49	56	61	63
Agriculture	34	24	16	19	20
Housing and communal services	21	27	28	21	17

In order to further implement the plan of implementation of the provisions of the WFD 2000/60/EC, the Cabinet of Ministers of Ukraine approved the "Procedure for the development of a river basin management plan" (2017); «The procedure for conducting state water monitoring» (2018).The Ministry of Environment and Natural Resources of Ukraine approved the following documents: "The Procedure for the Development of Water Balances" (2017); "Typical position for the basin councils" (2017); "List of pollutants for the determination of the chemical status of surface and groundwater arrays and the ecological potential of an artificial or substantially modified surface water body" (2017); «Methodology for the determination of surface and ground water bodies» (2019).

CONCLUSIOS

1. The first stage of the implementation of the Water Framework Directive 2000/60 / EC in Ukraine was completed successfully.

2. Approved in 2016 at the legislative level, the hydrographic zoning of the territory of Ukraine meets the requirements of the Water Framework Directive of the European Union.

3. The main unit of hydrographical zoning is the area of the river basin, which in Ukraine is allocated nine (Dnipro, Dnister, Danube, Southern Bug, Don, Vistula, rivers of the Crimea; rivers of the Black Sea coast; rivers of the Azov Sea coast).

4. Within the four of the nine river basin districts, 13 sub-basins are allocated on the territory of Ukraine: a) Dnipro river basin district– the sub-basins of the Upper Dnipro, the Middle Dnipro, the Lower Dnipro, the Prypyat River, the Desna River; b) Danube river basin district- sub-basins the

Tysa River, the Prut River, the Siret River, Lower Danube; c) Don river basin district – sub-basins the Siverskyi Donets River, Lower Don; d) Vistula river basin district– the sub-basins of the Western Bug River, the San River.

5. Bodys of surface water, are surface water bodies or their parts, for which environmental objectives are established and which are used to assess the achievement of these environmental objectives. About 9000 bodies of surface water were allocated in the areas of river basins in Ukraine.

6. The main division of water zoning is water management area. In river basins of Ukraine, 132 water management area were allocated, of which 59 are located in the Dnieper basin. They are allocated for the calculation of water availability indicators for individual regions.

7. Water use in Ukraine today (about 10 km^3) has significantly decreased compared to the 1990 high (35.6 km^3).

8. Modern hydrographic and water management zoningof the territory of Ukraine approximates the management of water resources of the state to European requirements.

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