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Miriam Fendeková and Lotta Blaškovičová (Eds.)

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FOREWORD

The present work is a follow-up to the monograph ***Hydrologické sucho na Slovensku a prognóza jeho vývoja*** (Hydrological drought in Slovakia and the prognosis of its development), published in 2017. This work by a large team of authors, edited by M. Fendeková, J. Poórová and V. Slivová was the result of project APVV-0089-12 Prognosis of Hydrological Drought in Slovakia. Staff from the Faculty of Natural Sciences of Comenius University in Bratislava, the Faculty of Mathematics, Physics and Informatics of Comenius University in Bratislava and the Slovak Hydrometeorological Institute participated in the project from October 2013 to September 2017. The University of Natural Resources and Life Sciences (BOKU), Vienna and the Institute of Hydrology of the Slovak Academy of Sciences in Bratislava were research partners.

The aim of the monograph was to use detailed knowledge of climatic and hydrological conditions in Slovakia assisted by modelling tools to develop scenarios for the forecast development of elements of water balance to 2100.

Since the monograph was positively received by specialist and lay audiences in Slovakia, Czechia and Poland, we have decided to make the most important results of this research project available in a more concise and updated form for the broader foreign scientific community. The present monograph, ***Prognosis of hydrological drought development in Slovakia***, is also the Slovak scientific community's contribution to the international programme UNESCO-IHP VIII FRIEND-Water programme in the group EUROFRIEND - Low Flow and Droughts group.

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INTRODUCTION

Hydrological drought in surface and ground water resulting from meteorological drought is becoming increasingly common even in mild climate zones. The scientific study of hydrological drought includes several aspects of this phenomenon, particularly its causal factors, methods for its quantification and its temporal and spatial patterns of propagation.

The problem of drought has received major attention in the scientific community. The Scopus scientific database (https://www.scopus.com/results) returns more than 90,000 titles in various scientific disciplines for the keyword "drought", more than 80,000 having been published in the period 2000 to 2017. The first works on drought date from 1866 and there are nearly 70 for the 19th century. The scientific disciplines with the largest numbers of publications are hydrology, water management and water resources, landscape ecology, atmospheric, soil, agricultural and forestry sciences, and geochemistry. Publications can also be found in fields such as ecotoxicology, plant and animal physiology, molecular genetics and anthropology. Less attention has so far been given to the economic consequences of drought and the need for the involvement of the scientific community in the active preparation of measures to avoid or mitigate the adverse effects of drought in various areas of society. It is an area of growing concern, however, as can be seen by the numerous projects and events organised as part of strategic planning to mitigate or prevent the consequences of drought on the European level, and recent articles in scientific journals such as van Lanen et al. (2016), Blauhut et al. (2016), Schmitt et al. (2016), Freire-González et al. (2017, 2018), Rodrigues et al. (2018) or Hund et al. (2018).

Jumps in interest in drought occur especially in the wake of extreme events that affect large areas, often whole continents. The longest periods of drought are associated with arid and semi-arid areas, where they are a long-term or permanent feature of the climate. This publication considers drought as an extreme hydrological phenomenon associated mainly with areas in the temperate band. One of the longest-lasting droughts of the last century was the drought that affected more than 70% of the territory of the USA between 1933 and 1940, known as the Dust Bowl (Andreadis et al., 2005; Ganguli and Ganguly, 2016). The West Coast of the USA experienced a continuous drought from 2012 to 2015 centred on California. Australia experienced a drought from 2001 to 2009 that became known as the Millennium Drought (van Dijk et al., 2013). Europe has also been affected by significant long-lasting droughts. Drought is more frequent in the Mediterranean region and often affects Spain, Italy or Greece. Droughts on a pan-European scale have been occurring more frequently, for example in 2003 and in 2015. Slovakia experienced several major periods of drought in the last century, notably the years 1947, 1982–1983 and 1992–1994. There have also been several periods of drought in the 21st century that have affected various large parts of the territory of the Slovak Republic with varying intensity, such as 2003, 2008, 2011–2012 and 2015.

Drought research in Slovakia can be dated to the second half of the 1980s, when the researchers began to build a comprehensive picture of drought, its propagation as a result of the water cycle and its effects on several aspects of the environment and its potential impact on society. Most data was collected as part of the National Climate Programme of the Slovak Republic. Drought has previously been studied in many research projects under various grant schemes including both international programmes (COST, the 5th, 6th and 7th EU Framework Programmes) and Slovak bodies (VEGA, APVV). In Slovakia, drought research developed both in the academic sector – in the Faculty of Natural Sciences of Comenius University in Bratislava, the Faculty of Civil Engineering of the Slovak Technical University in Bratislava and the Faculty of Civil Engineering of the Technical University in Košice – in the Institute of Hydrology of the Slovak Academy of Sciences and in bodies under the Ministry of Environment of the Slovak Republic – the Slovak Hydrometeorological Institute and the Water Research Institute. One of the most recent projects was project APVV-0089-12 Prognosis of Hydrological Drought in Slovakia, the lead institution for which was the Department of Hydrogeology of the Faculty of Natural Sciences of Comenius University in Bratislava.

Despite the collection of a large amount of information, the phenomenon of drought has not yet been adequately explored, especially the prognosis for its future occurrence. Therefore, we are currently forced to rely on measures for the prevention and mitigation of its effects, which in many countries have been incorporated into action plans to combat the effects of drought.

The need to deal with the effects of drought and water scarcity motivated the drafting of the action plan *H2ODNOTA JE VODA* (Water is a Value), approved by the government of the Slovak Republic in March 2018 (https://www.minzp.sk/files/sekcia-vod/hodnota-je-voda/) The aim of the action plan is to implement preventive measures against drought and to eliminate the adverse effects of climate change. In accordance with the methodology and institutional framework of public policymaking, the action plan is a separate document linked to Act No. 364/2004 on and amending Act No 372/1990 on infractions, as amended (the Water Act), which creates conditions for mitigating the adverse effects of drought and water shortages. Drought and water shortages have been incorporated into the updated Slovak Water Plan, even though drought is not yet considered one of the major factors affecting the condition of surface and ground water bodies. There is a separate chapter on drought in the strategy for the environmental policy of the Slovak Republic to 2030 (https://www.minzp.sk/files/sekcia-vod/hodnota-je-voda/). It is, however, impossible to adopt preventative measures without knowing the local and regional characteristics of the climatic and hydrological regime in Slovakia.

The Authors of the present work would like to thank the whole team of authors who participated in tasks within the project and in writing the extended Slovak monograph ***Hydrologické sucho na Slovensku*** a ***prognóza jeho vývoja*** (Hydrological drought in Slovakia and the prognosis of its development), published in 2017, for their excellent cooperation. Without them this work could not have been produced. These include in particular Dr. Tobias Gauster from BOKU Wien (Austria), Ing. Zuzana Danáčová, PhD., Ing. Jana Poórová, PhD., RNDr. Ján Gavurník, Ing. Eugen Kullman, PhD., Mgr. Katarína Mikulová, PhD. and Ing. Viliam Šimor, PhD. from the Slovak Hydrometeorological Institute in Bratislava, and Prof. RNDr. Milan Lapin, PhD., Assoc. Prof. RNDr. Martin Gera, RNDr. Marián Melo, PhD., and Assoc. Prof. RNDr. Ján Pekár, CSc. from the Faculty of Mathematics, Physics and Computer Science of Comenius University in Bratislava.

1. DROUGHT – AN EXTREME METEOROLOGICAL AND HYDROLOGICAL PHENOMENON

One of the expected effects of climate change is that extreme meteorological and hydrological phenomena will occur more frequently. Meteorological and hydrological droughts undoubtedly rank amongst such phenomena. The effects of drought are a risk not just for nature and the landscape but also human society. The primary effect of a lack of precipitation is reduced water runoff, which leads to secondary effects. The major consequences include problems with supplies of drinking water and electricity, lower agricultural and industrial production but there are also problems such as the drying up of small watercourses and springs, worse quality of natural waters, the occurrence and spreading of forest fires and dust storms etc.

Drought differs from other natural catastrophes (floods, landslides, etc.) in that it develops slowly and may go unnoticed for a long time. Drought is a characteristic and permanent phenomenon in arid and semi-arid areas because of their specific climatic conditions. In the last decade, however, droughts have become more frequent in temperate climates and their adverse effects have been stronger and more intense.

Drought is a relative term and it can be defined from different angles. This is why there is still no single, unified definition of the phenomenon. In general, the term drought covers a complex of natural phenomena manifested in several parts of the Earth's climate system at various places and times. They occur mainly as a result of a negative precipitation anomaly and are characterised by a below average quantity of water and its poor availability in different parts of the water cycle (Ogallo and Gbeckor-Kove, 1989). It should be emphasised that drought is a natural part of the water cycle.

As stated earlier, there are many definitions of drought, which are mainly based on the identification of the start, severity and end of the phenomenon. As early as 1980, research by Wilhite and Glanz documented more than 150 published definitions of drought. Wilhite and Glanz (1985) divided this set of definitions into four basic categories: meteorological, hydrological, agricultural and socio-economic drought. The first three categories concern the definition of drought as a physical phenomenon caused by climate variability. Drought represents a natural shortage of water, although meteorologists, farmers and hydrologists would all look at it differently and give different definitions. The last category considers drought from the perspective of demand for water and its satisfaction, with reference to the cascade of effects of a deficit on socio-economic systems (Brown and Magary, 1998). According to Gibbs (1975), drought is a state in which the available quantity of water is insufficient to cover demand for use. Socio-economic drought expresses a water deficit in economic terms related to increased turnover and demand, which result from every type of drought (Stahl, 2001). The category of socio-economic drought thus clearly defines a deficiency of water in relation to need, which can be referred to as *water scarcity*.

A new aggregate definition of each category of drought based on research into definitions in world literature was published by Mishra and Singh (2010). An article by a broad team of authors under the leadership of van Loon (2016) addressed the issue of drought in a human-modified world with an emphasis on reframing drought definitions, understanding, and analysis approaches.

1.1. METEOROLOGICAL DROUGHT

Mishra and Singh (2010) characterise meteorological drought as a deficit of precipitation in a defined time period. In our view, the fact that climate change is bringing an increase in average air temperatures in many places leading to increased demand for water due to evaporation, it is not enough to monitor precipitation totals and attention must also be paid to potential evapotranspiration, albeit in simplified form. We therefore consider meteorological drought to be a lack of water caused by a lack of precipitation and increased evapotranspiration. The significant publications on methods for quantifying meteorological drought include the work of McKee et al. (1993) on the calculation of the Standardised Precipitation Index (SPI) and the work of Vincente-Serrano et al. (2010) on the calculation of the Standardised Precipitation and Evapotranspiration Index (SPEI). Examples of the application of these indices on the pan-European level can be found in Ionita et al. (2017), Marcos-Garcia et al. (2017), Bachmair et al. (2018), Richardson et al. (2018) and many other publications in the European and global research areas.

Studies focussing on the issue of meteorological drought have also been produced in Slovakia (Labudová in Fendeková, Poórová and Slivová Eds., 2017). Šamaj and Valovič (1972) made an early study of dry periods in Slovakia using a method of their own devising based on a minimum number of consecutive days with cumulative total precipitation below a threshold value. More recent works on meteorological drought include the findings of Tomlain (1980, 1991) and Patassiová et al. (2002). These authors worked not only with the value of the aridity index K, i.e. the relationship of total precipitation (P) and potential evapotranspiration (Eo), but also the Palmer Drought Severity Index (PDSI). Tomlain used this method to process data from 54 weather stations in Slovakia for the period 1931–1960 (Tomlain, 1980), and 1951–1980 (Tomlain, 1991). The PDSI has also been used to identify droughts in the period 1971–2003 at 18 selected stations in Slovakia (Litschmann and Klementová, 2004). The last year of the studied period was an extremely dry year, especially in the south-eastern part of Slovakia. This motivated a follow-up paper by Klementová and Litchmann (2004), evaluating the agro-climatic drought in Slovakia in 2003.

Agricultural drought is closely related to meteorological drought based on a deficiency of soil moisture. Skalský et al. (2012) modelled the complex relationships in the soil – plant – atmosphere system using the WOFOST model. The authors used the model to evaluate the effect of drought on spring barley in the period 1997–2007. A potential threat to spring barley was identified in the Záhorie Lowland, the upper part of Žitný ostrov, around Hurbanovo and in the southern part of the Eastern Slovak Lowland. One of the most recent studies of agricultural drought in Slovakia is Takáč (2015), which makes of the Standardised Precipitation Index (SPI), amongst other indicators. Labudová et al. (2017) identified a relationship between the incidence of meteorological drought and agricultural crop yields in the Danube and Eastern Slovak Lowlands.

In addition to theoretical studies that derive future forecasting models from records of droughts in a given historical period, drought research has participated in the development of effective drought monitoring and early warning systems. There are a number of such systems in other countries. One of the oldest is the US Drought Monitor (http://droughtmonitor.unl.edu/), a joint project of the National Drought Mitigation Center (University of Nebraska-Lincoln), the US Department of Agriculture and the National Oceanic and Atmospheric Administration (NOAA). Drought monitoring based on the SPI index and percentiles of aggregate precipitation is provided for south-eastern Europe by the Drought Management Centre for South-Eastern Europe.

Intersucho is a drought monitoring system that has operated in the Czech Republic since April 2014 (Labudová in Fendeková, Poórová and Slivová Eds., 2017). It focuses on monitoring soil saturation and the condition of vegetation. It began as a joint project of the Global Change Research Institute of the Academy of Sciences of the Czech Republic (CzechGlobe), Mendel University and Masaryk University in Brno. The current situation is updated once a week (on Mondays), together with a forecast of developments for the next seven days based on data from the GFS model. In 2015 the Slovak Hydrometeorological Institute (SHMÚ) joined the project and from autumn 2015 it has monitored drought not only in Czechia but also in Slovakia (www.intersucho.sk). SHMÚ has successfully developed its own drought monitoring system focussing on meteorological drought. Likewise, it makes weekly calculations of daily SPI and SPEI indices and a weekly CMI (Crop Moisture Index) index (http://www.shmu.sk/sk/?page=2162) and provides a forecast of the indices for the next seven days based on the output of the ECMWF(European Centre for Medium-Range Weather Forecasts) model.

The World Meteorological Organisation (WMO) recommends the use of the Standardised Precipitation Index (SPI) developed by McKee et al. (1993) to quantify meteorological drought. The calculation of the SPI uses a long-term series of monthly precipitation totals (a minimum of a thirty-year series is recommended) transformed using a theoretical probability distribution (most often a gamma distribution) to a time series with a normal frequency distribution. The gamma distribution function has the form:

$$f(x,\alpha) = \frac{\mathrm{x}^{\alpha-1} * \mathrm{e}^{-\mathrm{x}}}{\Gamma\alpha} \tag{1.1.1}$$

for $0 < x < \infty$, where α is the function shape parameter.

The formula for calculating the SPI is then as follows:

$$SPI = (P - P^\star)/(\sigma_p) \tag{1.1.2}$$

where:
P = total precipitation (mm)
$P^\star$ = the long-term mean precipitation (mm)
σ_p = the standard deviation of total precipitation.

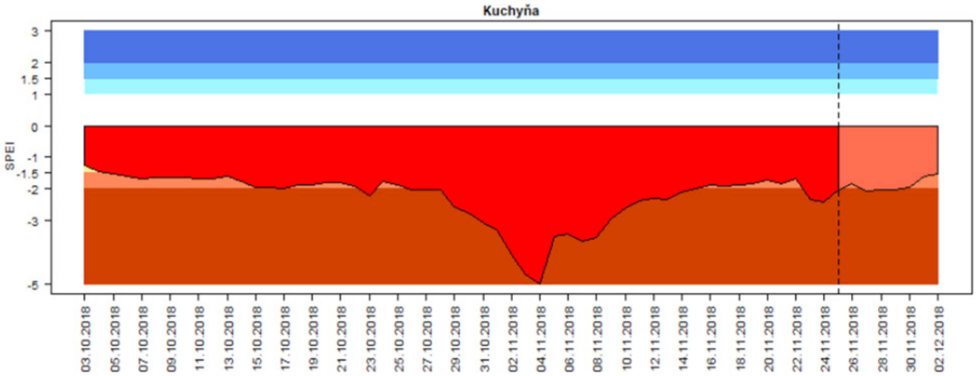
The average SPI value for a given location and time period is thus zero. A drought is defined as a long-term period in which the SPI is less than 1.0. The index limit values are shown in tab. 1.1.1. The effect of precipitation in surface and ground water can be measured using a three-monthly index SPI-3, a six-monthly index SPI-6 – which indicates the seasonal trend – and also a nine-monthly index SPI-9 and a twelve-monthly index SPI-12 – reflecting the long-term trend in precipitation (WMO, 2012). The advantage of this method of quantifying precipitation over a year is that it does not assess the year as a whole, which eliminates the possibility that the results will be affected by one or more periods of above-average or below-average precipitation, which would cause the year to be classified as having normal precipitation despite the fact that it included periods of extreme surplus or deficit in precipitation.

Besides the SPI, meteorological drought is often quantified using the standardised precipitation and evapotranspiration index (SPEI) which was developed by Vincente-Serrano et al. (2010). This index takes into consideration not only precipitation totals but also potential evapotranspiration so as to take account of the effect of air temperature on water consumption. The index is calculated using the same principle as the SPI but the SPEI does not use precipitation totals but the difference between precipitation and quantified potential evapotranspiration. The values obtained for SPEI are classified using the same scheme as for the SPI (tab. 1.1.1).

Tab. 1.1.1 Limit values of the standardized precipitation index SPI (according to McKee et al., 1993)

Standardized Precipitation Index (SPI)	
SPI value	**Classification**
2.00 and more	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Close to normal
-1.00 to -1.49	Moderately dry
-1.50 to -1.99	Very dry
-2.00 and less	Extremely dry

An example of the outputs of SHMÚ's drought monitoring, including the calculated and forecast values for SPI and SPEI for the meteorological station at Kuchyňa in Western Slovakia, is shown in fig. 1.1.1.



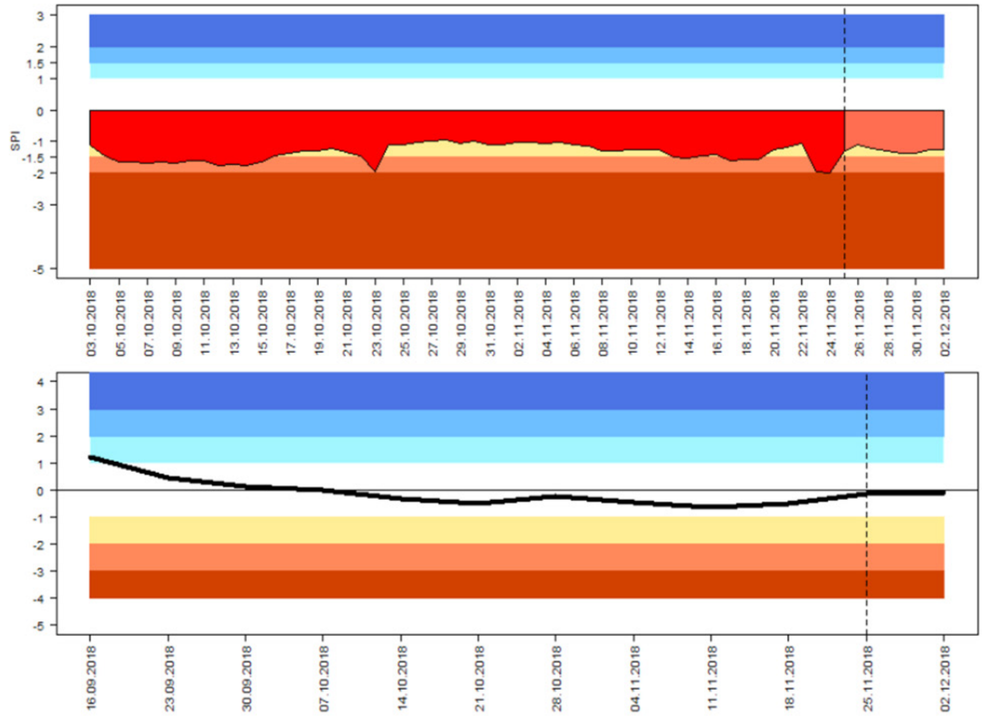


Fig. 1.1.1 SPI and SPEI at the Kuchyňa station from October 3 to November 25, 2018 (www.shmu.sk)

1.2. HYDROLOGICAL DROUGHT AND ITS MANIFESTATION IN SURFACE WATER FLOWS

Hydrological drought is a phase that follows meteorological drought. The effects of meteorological drought, above all the deficiency of precipitation, cause a fall in water levels and discharge in surface watercourses, lakes, reservoirs and groundwater. The time delay between the meteorological and hydrological phases of drought is different for surface and ground water and there is also significant variability in time delays within these subsystems. Groundwater is usually the last element of the water cycle to respond to a state of drought. In surface water the reaction to a precipitation deficit may be observed within a few days in the case of smaller basins with a fast runoff or within a few months if streamflow is fed by groundwater to a significant extent (Tallaksen and van Lanen Eds., 2004). Other factor that can influence the time of onset of hydrological drought include a river basin's size and other characteristics (physiographical, geological, morphological, soil types, land use), the feeding of surface water from groundwater, snow storage in the basin etc. Another major factor is human activity – water abstraction and discharges and manipulation via reservoirs, which can have a significant influence on streamflow in surface watercourses, especially in periods of low flow.

Another common use of the word drought is to refer to the lack of water when current water sources are insufficient to cover current demand for water. Water scarcity need not always be the result of drought or low flow but can also be caused by demand for water that is greater than the current availability of water.

One of the first works on drought was Yevjevich (1967), in which hydrological drought is formulated in mathematical terms as a stochastic process. Combined approaches to drought research were developed by Zelenhasić and Salvai (1987), Rossi et al. (1992) and Bonacci (1993). A review paper on drought research was presented by Smakhtin (2001). Regional aspects of drought were considered in Hisdal (2002). Hydrological drought was also defined and studied in Tallaksen and van Lanen Eds. (2004). Van Loon et al. (2010) presented a classification system for winter droughts. Van Loon and van Lanen (2012) considered the typology of droughts based on the processes that give rise to them. In 2015 van Loon and Laaha published a work on the influence of the physiographical parameters of a basin on the intensity of hydrological drought. The hydrological drought in 2015 was studied in van Lanen et al. (2016) and Laaha et al. (2017). The territory of Slovakia was featured in these two works.

Hydrological droughts or periods of low flow are a natural part of the hydrological regime of surface water. The surface runoff regime in Slovakia is typically characterised by increased spring runoff (see fig. 1.2.1) which occurs later in mountain areas with higher altitudes than in lowland watercourses because of the later melting of snow and reserves of snow that are also usually larger, which are significant factors affecting the spring runoff.

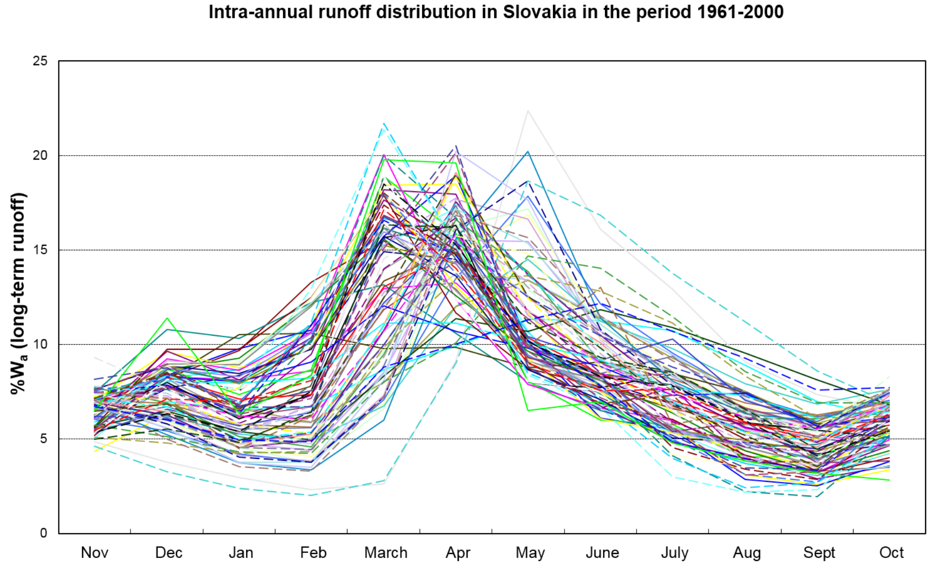


Fig. 1.2.1 Intra-annual runoff distribution in the Slovak territory (reference period 1961–2000)

Most Slovak watercourses have a period of low flow in the summer and autumn (usually from August to October) and in mountain areas there is a significant period of low flow in the winter (usually from December to February). The winter low-flow period is caused firstly by precipitation in the form of snow which does not contribute immediately to runoff in periods of low temperatures (below freezing), and also by the partial or complete freezing of watercourses. This fact has led to the use in drought studies of the concept of the hydrological year, which ensures that precipitation that falls as snow at the end of the calendar year but runs off mainly in spring is counted towards runoff in a closed time period / year. Different countries use a different definition of the hydrological year; the Slovak hydrological year runs from 01 November to 31 October of the following year.

The increased spring runoff is also an important factor for runoff conditions for the rest of the year. The analysis of drought has shown that dry periods in the summer and autumn are in many cases preceded by the absence of the usual periodic runoff, especially by a quantitative reduction in runoff in the usually high-flow spring months. Fig. 1.2.2 presents an example taken from the discharge history at the Štítnik gauging station on the River Štítnik in the river basin of the Slaná in the hydrological year 1993, showing the course of average daily and monthly discharges for the year against the coloured background of quantiles of long-term average monthly discharges for the reference period 1961–2000. The graph clearly shows the absence of the increased spring runoff in the usually high-flow months of March, April and May – the average monthly values for these months in 1993 are in the red-coloured quantile indicating less than 40% of the long-term average monthly discharge. In the summer months and in August and September there is a long period when the average daily discharge is less than 364-day discharge (Q_{364d} or $Q_{99,7\%}$), indicating a significantly dry period.

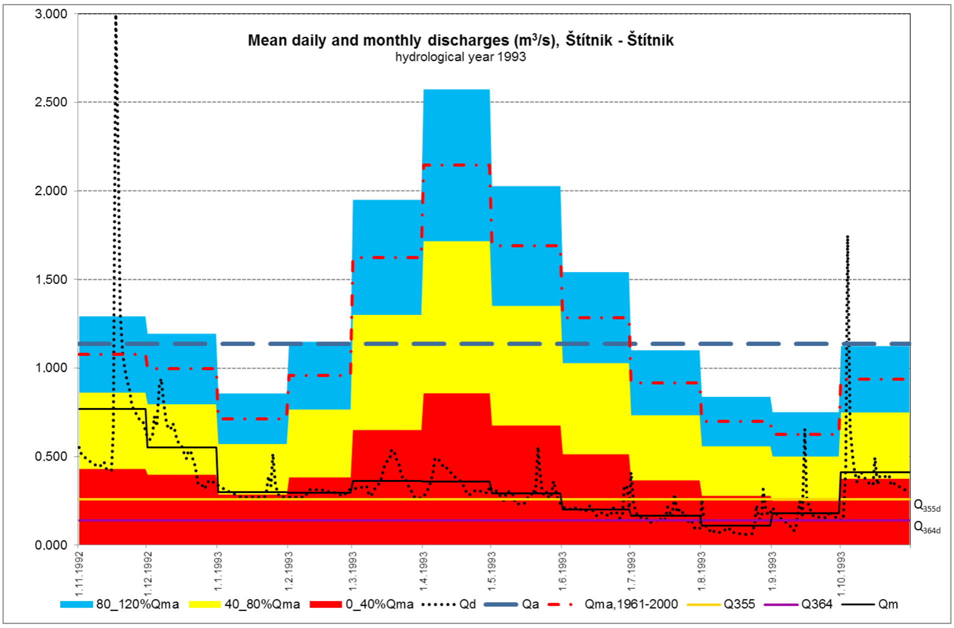


Fig. 1.2.2 Course of the average daily and monthly discharges in 1993 at the Štítnik - Štítnik gauging station

There is no standardised criterion for the quantitative definition of hydrological drought because of the diversity of meteorological, hydrological, agricultural aspects, amongst others, that must be considered while also having regard for the potential damage to several areas of the national economy (Meteorological vocabulary – explanatory terminological, 1993). The duration of low flow is defined as a continuous period during which discharge is below a selected threshold level (OTN 3113-1, 2005). The selection of the threshold discharge level is thus a key issue for defining periods of low flow and quantifying droughts in surface watercourses.

The assessment of low flow in surface watercourses considers multiple hydrological characteristics. The hydrological discharge regime related to drought is assessed using various time steps and for various periods. Indicators that can be calculated and statistically processed for a chosen study period include minimum average daily discharges (with monthly or annual time steps or for the whole period), M-day discharges (the flow duration curve of average daily discharges), minimum monthly and annual discharges (with occurrence date). Foreign literature tends to use percentiles more frequently than M-day discharges for flow duration curve. For comparison, the M-day discharge $\boldsymbol{Q_{300d}}$ roughly corresponds to the $\boldsymbol{Q_{80}}$ percentile, while the M-day discharge $\boldsymbol{Q_{330d}}$ roughly corresponds to the $\boldsymbol{Q_{90}}$ percentile.

Discharge characteristics are compared with long-term values for a reference period. Since 2006 the reference period for surface waters has been the period 1961–2000. The reference period that it replaced had been based on the years 1931–1980. Before that hydrological studies of quantity and water discharge regime had also used 1931–1940 and 1931–1960 as reference periods.

Non-discharge characteristics can also be used in the assessment of low flow. These include the temporal characteristics of drought (start date, number of days of low flow, the longest drought episode in the study period) and deficiency volumes (the volume of the water deficit for days of dry episodes below a given discharge threshold). Such analyses provide valuable information not only on the seasonal aspects of dry period occurrence and the duration of periods with sub-threshold discharge but also on the volume of the water deficit, which makes it possible to quantify the economic effects of the water deficiency for agriculture, industry, electricity generation and the like. It can also provide information on the potential negative effects of drought on nature and landscape.

The outputs of both methods are used, as a rule, when defining drought years or multi-year drought periods in a studied period based on an assessment of water levels and flows in each year for each studied discharge gauging station, the dating of the occurrence of minimal discharges, the duration of low-flow periods etc.

The next step is to evaluate discharge and non-discharge characteristics not only in time but also in space. The assessment of the current incidence of hydrological drought, its discharge and non-discharge characteristics in individual river basins, watercourses and profiles permits drought evaluation in the sub-basins of Slovakia and drought analyses on the regional level.

1.3. HYDROLOGICAL DROUGHT AND ITS MANIFESTATION IN SPRING YIELDS AND GROUNDWATER LEVELS

1.3.1. The current state of research into the effect of drought on groundwater

Evaluations of drought in groundwater based on the groundwater regime and spring yields is not very common in the literature. Eltahir and Yeh (1999) is a very important work on drought propagation in groundwater systems. The authors investigated the "propagation" of drought in groundwater systems using data observed in Illinois, USA. The authors observed a trend towards the increased persistence and severity of such droughts. Van Lanen and Peters (2000) present an overview of the definitions and effects of drought in groundwater. They define a groundwater drought as occurring when the groundwater heads in an aquifer fall below a threshold level over a certain period of time. This decrease below a threshold value has direct and secondary consequences. The direct consequences include a decrease in groundwater levels, reduced runoff to the surface element of the hydrosphere and reduced capillary rise. Secondary effects include the drying up of rivers, worse quality of surface and ground water, degradation of aquatic and terrestrial ecosystems, reduced crop yields etc. Later Peters and van Lanen (2001) defined this type of drought as a fall in the available groundwater with or without adverse effects which are the result of climate variability. Marani, Eltahir and Rinaldo (2001) demonstrated that a change in the persistence and severity of drought may be partially linked to non-linearity in the groundwater – discharge relationship (the groundwater rating curve) resulting from changes in the density of the stream network and changing groundwater levels. Other studies of the propagation of drought in groundwater systems include White, Falkland and Scott (1999) and Changnon, Huff and Hsu (1988), and the dissertation of Peters (2003) on the Pang (Great Britain) and Guadiana (Spain) river basins. Peters, Torfs, van Lanen and Bier (2003) include a discussion of the spatial distribution of drought in groundwater and the selection of indicators to represent it, which was followed up in Peters, Bier, van Lanen and Torfs (2006). The authors made a simulation of the spatial distribution of groundwater recharge, groundwater levels and groundwater discharge in the Pang River Basin. Groundwater levels were simulated using the MODFLOW model and groundwater recharge was simulated using the 1D SWAP model. Van Lanen (2006) addressed drought propagation through the hydrological cycle. Time series of simulated groundwater recharge, levels and runoff were obtained for humid and semi-arid climate regions. These parameters were simulated using the SIMGRO model and drought parameters were derived from the simulation with the assistance of the NIZOWKA software package. Tallaksen and van Lanen (2004) edited a monograph on issues related drought in surface and ground water. Multiscale evaluation of the Standardized Precipitation Index as a groundwater drought indicator was studied and applied by Kumar et al. (2016). Hund et al. (2018) is one of the most recent works on drought in groundwater.

Initially, drought research in Slovakia did not pay adequate attention to groundwater drought. It began to receive more attention from 1992, when Chalupka and Kullman (1992) published the first assessment of the groundwater regime in Slovakia from the perspective of natural decreases in the yields of selected springs. The first analytical studies of groundwater drought with mapping of the relationship between meteorological and hydrological drought were published even later, within the last 10 years. Burger (2005) discussed the concept and identification of hydrological drought as a groundwater deficit. Brušková (2007) evaluated meteorological drought and its influence on groundwater drought in the upper Torysa basin. Slivová (2007) analysed and modelled hydrological drought in her dissertation work. The main aim of the work was to select suitable parameters and methods for characterising hydrological drought in groundwater, to propose a methodological procedure for its evaluation and to study the relationship between meteorological drought and groundwater drought. The effect of hydrological drought on the quantitative and qualitative parameters of surface and groundwater was studied by Fendeková et al. (2009). Fendeková et al. (2010) developed an approach to the evaluation of drought in the groundwater component of the hydrosphere taking account of the hydrogeological properties of the rock environment and changes in water quality in droughts. Fendeková and Fendek (2012) presented research on the identification and classification of drought in surface and ground water in the upper Nitra River Basin. Stojkovová wrote her dissertation (2014) on methods for evaluating drought in groundwater level regimes. Kullman et al. (2015) published a study of the spatial distribution of drought effects in groundwater based on groundwater level regimes and spring yields in all parts of Slovakia in 2014 using numerical data from selected sampling sites in the Slovak hydrological monitoring network for groundwater. A study of groundwater in the hydrological year 2015 using the same methodology as for 2014 was published by Slivová a Kullman (2016). An evaluation of drought based on spring yields in the Nízke Tatry Mountains was published by Vrablíková and Fendeková (2016) while the seasonality of minimum spring yields was the topic of Vrablíková's dissertation (2017). Slivová et al. (2016) analysed the incidence of drought in groundwater in all parts of Slovakia over three hydrological years 2013, 2014 and 2015. Fendeková et al. (2017a, 2017b, 2017c, 2018) published studies of drought in selected river basins in Slovakia.

1.3.2. Factors affecting groundwater drought

The occurrence of drought depends primarily on the climatic factors that influence the water levels in a basin, the size of runoff and the hydrological flow regime. Such factors include precipitation, air temperature, ground evaporation, air humidity and wind conditions. Secondary factors include surface features such as the relief of the territory, vegetation, lakes, marshland, reservoirs and the stream network, which regulate surface runoff, and factors such as soil and the geological and hydrogeological characteristics of aquifers, which regulate base flow (Balco, 1990). Groundwater is not always evenly distributed within a river basin. The unevenness of its distribution in space and time depends on climatic, geological and hydrogeological factors. Other significant factors include the hydrophysical properties of rocks and the character of their open fracturing, which determines different conditions for infiltration, accumulation and discharge in the rock environment. Hydrological drought in groundwater is caused by an increasing soil moisture deficit during summer and a lack of precipitation during winter (or another wet season). In temperate climates, the deficit of soil moisture increases during the summer because evapotranspiration is greater than total precipitation.

Groundwater is the last element to be affected by drought in the time sequence of hydrological drought. The phenomenon occurs if the supply of surface water to groundwater ceases. In this case the drought in surface and ground water develops more or less concurrently. It is also possible for the delay between meteorological and hydrological drought to last several months. Groundwater reserves recover slowly, which means that the effects of drought in groundwater may be perceptible long after the end of meteorological drought (Peters and van Lanen, 2001).

In hydrology and hydrogeology, seasonality means regular cyclical change in a studied component in the course of one hydrological year. For the purposes of hydrogeology such elements may include groundwater levels or spring yield, while in hydrology they include the water stage or the discharge.

There has recently been an increase in attention to the problem of the seasonal occurrence of hydrological, hydrogeological and meteorological phenomena and their regional expression. The foreign literature on the evaluation of the seasonality of spring yields includes works such as Orehová (2002), Ledvinka and Lamačová (2014), and Moniewsky (2015). In hydrology the issue of the seasonality of discharges, both minimum and maximum, has been discussed by several Slovak and foreign scholars such as Čunderlík (1999), Kohnová and Szolgay (2000), Kohnová et al. (2008), Števková et al. (2012), Burn (1997), Laaha and Blöschl (2006), Parajka et al. (2009; 2010) and many others. In hydrogeological research the seasonal component of spring yields has been evaluated in the quantitative analysis of spring regimes of Slovakia (Fendeková et al., 1995; Fendeková, 1996; Fendeková and Fendek, 2005).

1.3.3. Initial data and evaluation methods of spring yields seasonality

The seasonality of minimum spring yields was analysed in a set of 75 springs from the database of the Slovak Hydrometeorological Institute (Fig. 1.3.3.1, Tab. 1.3.3.1), which provided the project with weekly data on spring yields for the hydrological years 1980–2012.

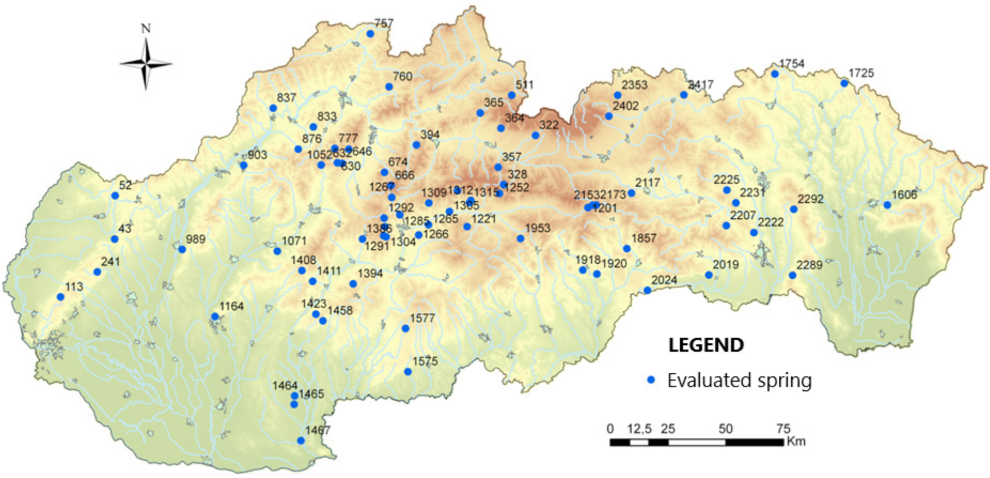


Fig. 1.3.3.1 Location of the evaluated springs

In addition to the data on weekly spring yields, the analysis incorporated meteorological data and the physiographical parameters of the environment around the outflow of the springs. Meteorological data on average total annual precipitation **(*P*)** and average annual air temperature **(*t*)** was provided by the Slovak Hydrometeorological Institute in the form of map layers from the climate atlas of Slovakia (Climatic atlas of Slovakia, 2015).

The physiographic characterisation of a territory in hydrological and hydrogeological practice is based on the characteristics used to define a hydrological basin, though defining a hydrogeological watershed divide is much more complicated and complex. Likewise, it can sometimes be extremely difficult to determine the infiltration-accumulation area for a specific spring. The physiographical data for evaluation was therefore based on the surroundings of the spring outlet and the seasonality of spring yields was analysed using the following factors that can be represented in numerical terms: altitude above sea level of the spring outflow **(*Alt*)**, the coefficient of transmissivity of the rock environment **(*T*)** (Malík et al., 2007; 2013) and the compass orientation of the spring area **(*CO*)**. A summary of data on the meteorological and physiographical characteristics of the evaluated springs is given in Table 1.3.3.2.

Tab. 1.3.3.1 Characteristic of evaluated springs

No. (SHMI)	Location	Name of the spring	Type of the spring	Geological environment	Mountains name (Mazúr and Lukniš, 1986)
43	Jablonica	Stužková	karstic[1]	limestone	Malé Karpaty
52	Sobotište	Janíkov mlyn	fissure-bariére[2]	claystone and sandstone	Biele Karpaty
113	Pernek	Štôla	outflow from the adit[3]	biotic mica schists and para-gneisses	Malé Karpaty
241	Horné Orešany	Husí stok	bedded [1]	cherty and marly limestone	Malé Karpaty
322	Pribylina	Pleso	erosional [4]	glacifluvial sediments	Podtatranská kotlina basin
328	Vyšná Boca	Bocianka	fissure-bariére[5]	dolomite, schists, sandstone	Nízke Tatry
357	Liptovský Ján	Nad škopovou 2	fissure-karstic[6]	dolomite	Nízke Tatry
364	Žiar	Medzivŕšky	bariére[4]	Triassic carbonates	Podtatranská kotlina basin
365	Huty	Kvačianska dolina 1	fissure[7]	limestone and dolomite	Chočské vrchy
394	Ľubochňa	Salatín č.3	karstic-fissure[8]	limestone and dolomite	Veľká Fatra
511	Vitanová/ Oravice	Mihulčie	fissure-bariére[7]	siltstone, limestone, breccia	Tatry
630	Vrícko	Vrícko 2	fissure [9]	dolomite and limestone	Malá Fatra
632	Kláštor pod Znievom	Studenec	fissure-karstic[10]	dolomite	Žiar
646	Valča	Valčianska dolina 2	fissure[3]	limestone and dolomite	Malá Fatra
666	Blatnica	Dolné Veterné	fissure[11]	marly limestone	Veľká Fatra
674	Blatnica	Pod Dedošovou skalou	fissure[11]	limestone	Veľká Fatra
757	Čadca	U Šimčiska	conus[3]	sandstone-claystone (flysch)	Kysucké Beskydy
760	Belá/Kubíková	Veľhora	not estimated	conglomerate and sandstone	Kysucká vrchovina
777	Rajecká Lesná	Brčné	bedded[3]	dolomite	Malá Fatra
833	Bodiná	Biela voda	erosional[12]	conglomerate and limestone	Súľovské vrchy
837	Ihrište	Káčerovská	conus-fissure[12]	sandstone and marl	Javorníky
876	Pružina	Bobot	bariére[3]	limestone (contact with conglomerate and sandstone)	Žilinská kotlina basin
903	Kolačín	Ľahké zeme	fissure[12]	dolomite	Strážovské vrchy
989	Banka	Vápnište	fissure[1]	dolomite	Považský Inovec
1052	Kľačno	Kamenná dolina	fissure[1]	limestone	Malá Fatra
1071	Kolačno	Valachov	not estimated	dolomite	Tríbeč
1164	Drážovce	Šindoľka	fissure[13]	limestone	Tríbeč

1201	Telgárt	Hron	karstic[14]	limestone	Horehronské podolie depression
1221	Osrblie	Teplica	fissure[15]	dolomite	Veporské vrchy
1252	Jarabá	Žliabok	conus-fissure[15]	ortho-gneisses	Nízke Tatry
1265	Slovenská Ľupča	Driekyňa	conus-fissure[16]	dolomite	Zvolenská kotlina basin
1266	Môlča	Teplica	karstic-fissure[16]	dolomite	Zvolenská kotlina basin
1267	Horný Harmanec	V rigole	fissure[8]	clayey shale (probably limestone as bedrock)	Veľká Fatra
1285	Úľanka	Medzi vodami	fissure[17]	dolomite	Starohorské vrchy
1287	Králiky	Pod kameňolomom	fissure[16]	dolomite	Starohorské vrchy
1291	Kordíky	Pod širokou	fissure[16]	andesite agglomerate	Kremnické vrchy
1292	Kordíky	Na Table	fissure [16]	andesite agglomerate	Kremnické vrchy
1304	Badín	Pod kordíckou chatou	fissure[16]	andesite agglomerate	Kremnické vrchy
1305	Nemecká	Pod motorestom	krastic[15]	limestone	Horehronské podolie depression
1307	Jasenie	Zo štôly	outfow from the adit[15]	ortho-gneiss	Nízke Tatry
1309	Moštenica	Kyslá 1,2	bedded[17]	dolomite	Starohorské vrchy
1312	Dolná Lehota	Vrabec	fissure[15]	limestone	Horehronské podolie depression
1315	Dolná Lehota	Dolný	fissure[15]	carbonatic conglomerate	Horehronské podolie depression
1386	Horná Ves	U Hrantu	fissure[18]	andesite	Kremnické vrchy
1394	Podhorie	Handrlová	fissure, bariére[19]	limestone and andesite porphyry	Štiavnické vrchy
1408	Veľké Pole	Studňa	not estimated	sandstone, quartzite, dolomite	Tribeč
1411	Horné Hámre	Kajlovka	outfow from the adit[20]	andesite	Vtáčnik
1423	Brehy	Liešna dolina	outfow from the adit [3]	andesite	Štiavnické vrchy
1458	Pukanec	Ergi štôlňa	outfow from the adit[21]	andesite	Štiavnické vrchy
1464	Veľký Dvor	Bažantnica	bedded[21]	fluvial sediments of river terraces	Podunajská pahorkatina
1465	Nýrovce	Pri JRD	bedded[21]	fluvial sediments of river terraces	Podunajská pahorkatina
1467	Kamenín	Studená studňa	bedded [21]	fluvial sediments of river terraces	Podunajská pahorkatina
1575	Čebovce	Malá studňa	bedded [22]	sands, sandstone, conglomerate	Juhoslovenská kotlina basin
1577	Senohrad	Dolný mlyn	not estimated	epiclastic volcanic breccia of andesites	Krupinská planina

1606	Kamenica n. Cirochou	Pod Drieňovou	not estimated	carbonate breccia, conglomerates	Beskydské predhorie
1725	Vyšný Komárnik	Pod dolhoncom	fissure-conus[23]	sandstone and claystone	Laborecká vrchovina
1754	Chmeľová	Podstavy 4	bedded-conus[3]	claystone flysch	Busov
1857	Gemerská Poloma	Hámor	bedded[24]	gravels (Neogene)	Revúcka vrchovina
1918	Nandraž	Pri kasni	karstic-fissure[25]	dolomite	Slovenský kras
1920	Gemerské Teplice	Hlavište 1+2	bedded[26]	dolomite	Slovenský kras
1953	Tisovec	Pod dielom	karstic-fissure [27]	dolomite	Veporské vrchy
2019	Drienovec	Jaskyňa	karstic-fissure[26]	limestone	Slovenský kras
2024	Silická Jablonica	Mlynský	bedded [26]	limestone	Slovenský kras
2117	Smižany	V lesnici	bedded [26]	carbonate	Spišsko-gemerský kras
2153	Dobšinská ľadová jaskyňa	V spišskom potoku 2	bedded [26]	limestone, quartzite	Spišsko-gemerský kras
2173	Dobšinská ľadová jaskyňa	Pod traťou	bedded [26]	limestone and dolomite	Spišsko-gemerský kras
2207	Veľký Folkmar	V orlašskom potoku	bariére [24]	limestone and dolomite	Volovské vrchy
2222	Družstevná pri Hornáde	Irenka	bedded [28]	dolomite, shale	Čierna Hora
2225	Hrabkov	Teplica	fissure[28]	carbonate conglomerates and sandstone	Šarišská vrchovina
2231	Miklušovce	Pod Obišankou	fissure[28]	dolomite	Čierna Hora
2289	Rákoš	Rákošské lúky	conus[29]	delluvial sediments with andesite boulders	Slanské vrchy
2292	Lúčina	V suchej doline	not estimated	epiclastic volcanic breccia of andesites	Slanské vrchy
2353	Jezersko	Pod svahom	bedded[30]	sandstone, claystone	Spišská Magura
2402	Tatranská Kotlina	Malý šumivý	bariére[4]	limestone	Tatry
2417	Matysová	V obci	fissure[31]	sandstone, fine-grained conglomerate	Ľubovnianska vrchovina

Remark: description of springs was taken from the original manuscripts kept in the Geological Survey of Slovakia. The full reference of respective manuscripts can be found in Fendeková, Poórová and Slivová Eds. (2017). 1 - Malík et al., 2012, 2 - Tupý et al., 2004, 3 - Fendeková et al., 1995, 4 - Hanzel et al., 1990, 5 - Rapant, 1994, 6 - Dovina et al., 1984, 7 -Dovina et al., 1990, 8 - Malík and Kordík, 1999, 9 - Ftorková and Galisová, 1990, 10 - Černák et al., 2014, 11 - Malík et al., 2014, 12 - Remšík et al., 2004, 13 - Bačová et al., 1984, 17 - Malík and Kováčová, 2007, 15 - Zakovič et al., 2012, 16 - Malík et al., 2000a, 17 - Zakovič et al., 1999, 18 - Auxt et al., 1989, 19 - Páleník and Tischliar, 1999, 20 - Bučeková et al., 2001, 21 - Malík et al., 1999, 22 - Scherer et al., 2014, 23 - Zakovič et al., 1988, 24 - Grecula at al., 2011, 25 - Malík at al., 2000b, 26 - Hanzel et al., 2012a, 27- Švasta et al., 2004, 28- Malík et al., 1997, 29 - Tometz, 2004, 30 - Jetel at al., 1993, 31 - Pramuka et al., 2010.

Tab. 1.3.3.2 Meteorological and physical-geographical characteristics of the discharge areas of evaluated springs

No.	Altitude (m a.s.l.)	t (°C)	P (mm)	Compass orient.	Transmissivity ($m^2 \cdot s^{-1}$)	No.	Altitude (m a.s.l.)	t (°C)	P (mm)	Compass orient.	Transmissivity ($m^2 \cdot s^{-1}$)
43	250	8.8	751.3	W	7.58 E-04	1305	420	7.5	804.8	SE	6.19 E-04
52	300	8.3	730.9	SW	1.76 E-04	1307	885	4.8	1,140.4	NW	1.08 E-05
113	375	7.8	823.9	E	3.46 E-05	1309	570	5.9	991.5	E	1.04 E-03
241	302	8.7	802.8	S	2.01 E-04	1312	550	6.5	882.2	W	6.19 E-04
322	883	5.2	911.4	S	9.20 E-04	1315	520	6.8	877.5	NW	8.15 E-04
328	1178	1.9	1,405.4	SE	6.19 E-04	1386	460	7.2	793.0	E	2.86 E-04
357	764	4.6	1,071.8	NE	3.55 E-03	1394	525	7.1	763.2	NW	4.07 E-04
364	870	5.0	928.8	SW	9.20 E-04	1408	465	7.6	836.9	NE	3.43 E-04
365	764	5.3	989.4	S-SE	1.04 E-03	1411	300	8.4	777.3	NW	2.89 E-04
394	733	4.7	1,290.3	SW	1.04 E-03	1423	525	7.9	864.7	E	2.89 E-04
511	950	4.4	1,312.2	N	3.58 E-04	1458	390	8.5	723.9	SW	1.16 E-03
630	590	6.1	1,039.9	NE	1.04 E-03	1464	145	10.2	574.1	N	1.71 E-03
632	594	5.8	1,063.2	SW	1.04 E-03	1465	136	10.3	577.6	NE	1.08 E-03
646	575	5.8	1,096.9	NE	1.71 E-03	1467	114	10.1	554.7	SE	1.71 E-03
666	900	3.3	1,407.1	NE	3.58 E-04	1575	205	9.4	612.1	E	3.35 E-04
674	689	5.4	1,082.5	NW	6.25 E-04	1577	550	7.3	696.7	W	4.07 E-04
757	630	5.8	1,075.3	SW	6.04 E-05	1606	215	8.5	769.5	N	3.58 E-04
760	700	5.7	1,121.6	SW	6.03 E-05	1725	395	6.7	946.7	W	6.03 E-05
777	641	4.7	1,260.9	SE	1.04 E-03	1754	450	6.7	897.6	S	1.01E-04
833	361	6.8	859.9	N-NE	3.58 E-04	1857	330	8.0	726.9	N	3.10 E-04
837	390	7.3	814.6	NW-N	4.77 E-05	1918	293	8.1	705.2	S	1.04 E-03
876	420	7.3	880.0	W	6.19 E-04	1920	245	8.5	667.4	SW	1.04 E-03
903	310	8.0	811.2	W	1.04 E-03	1953	750	5.3	890.9	S	5.53 E-04
989	200	9.1	642.6	NE	1.04 E-03	2019	250	8.7	646.3	SW	1.71 E-03
1052	603	5.2	1,125.1	SW	6.19 E-04	2024	263	8.8	672.2	N	3.21 E-04
1071	270	8.9	673.5	S	1.04 E-03	2117	550	6.1	750.9	SE	3.10 E-04
1164	160	9.6	679.4	S	6.19 E-04	2153	925	4.6	1,013.3	SE	1.04 E-03
1201	935	4.4	1,030.7	NW	6.19 E-04	2173	850	4.6	997.7	N	7.11 E-04
1221	630	5.9	1,054.3	SE	1.02 E-03	2207	500	6.7	760.7	SW	6.25 E-04
1252	845	4.2	1,184.5	SE	1.08 E-05	2222	375	7.5	728.3	N	6.65 E-04
1265	450	7.5	769.2	NE	1.04 E-03	2225	445	6.9	686.8	W	3.58E-04
1266	460	7.2	762,7	SW	1.04 E-03	2231	465	6.9	704.4	NE	1.04 E-03
1267	725	4.9	1,157.8	SW	4.31 E-04	2289	430	7.7	849.6	SW	3.21 E-04
1285	400	7.3	933.9	W	1.04 E-03	2292	500	6.9	923.5	SW	4.07 E-04
1287	670	5.8	1,048.9	NE	1.04 E-03	2353	715	5.4	896.1	NW	1.76 E-04
1291	900	4.5	1,128.1	SE	2.89 E-04	2402	865	4.8	958.2	S	3.43 E-04
1292	830	4.9	1,105.2	NE	2.89 E-04	2417	600	5.8	835.6	NE	6.04 E-05
1304	775	5.1	1,065.6	SW	2.89 E-04						

1.3.3.1. Evaluation of seasonality

A basic statistical analysis of the data was carried out before the evaluation of seasonality of spring yields. Average month spring yields were calculated for the hydrological years 1980–2012. The statistical parameters analysed were average values (mean $\bar{x}$ and median x_{med}), extreme values (minimum x_{min} and maximum x_{max}) and coefficients of variation (C_v), asymmetry (C_s) and slope (E). After the statistical evaluation of average monthly spring yields, the parameters of their minimum yields were determined.

The **minimum yield** was defined as:

- Threshold value – minimum yield equal to or lower than $\mathbf{Q_{90d}}$, obtained from the long-term flow duration curve for weekly spring yields
- Absolute minimum annual yield $\mathbf{Q_{Amin}}$.

The minimum yield $\mathbf{Q_{90}}$ was determined for the long-term period (1980–2012) and annual, summer - $\mathbf{Q_{90S}}$ (months 4–10) and winter - $\mathbf{Q_{90W}}$ (months 11–3) periods. Individual decades were also evaluated as follows: $\mathbf{Q_{90\,1}}$ (1980–1989); $\mathbf{Q_{90\,2}}$ (1990–1999); $\mathbf{Q_{90\,3}}$ (2000–2009) and $\mathbf{Q_{90\,4}}$ (2000–2012). The absolute annual minimum yield $\mathbf{Q_{Amin}}$ was determined for the whole studied period 1980–2012 and also for the summer $\mathbf{Q_{AminS}}$ (months 4–10) and winter $\mathbf{Q_{AminW}}$ (months 11–3) seasons. An example of the statistical and graphical evaluation of spring yields for spring no. 52 Sobotište - Janíkov mlyn is shown in Figure 1.3.3.1.1.

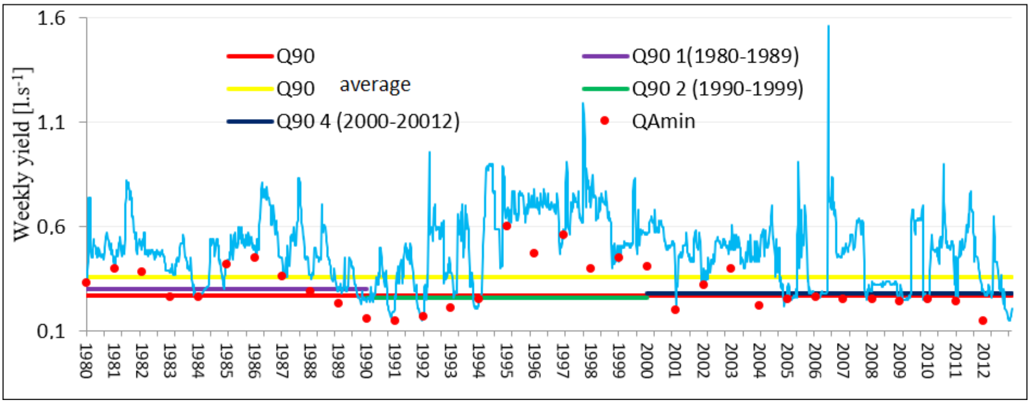


Fig. 1.3.3.1.1 Evaluated parameters of the minimum yield drawn together with the weekly time series plot - Sobotište spring No. 52 example

Seasonality is one of the components of time series analysis. In hydrogeology the evaluation of the seasonality component is based on a **seasonality graph** that evaluates average and minimum monthly spring yields. Another approach to the evaluation of seasonality is provided by the use of directional statistics, in the form of **Burn's vector** (Burn, 1997) and probability analysis – **relative frequency histogram**. The analysis was based on the dates of the absolute minimum annual yield Q_{Amin} and minimum yields below Q_{90} in each time interval.

The Burn's vector method is based on the date of an extreme phenomenon in the *i*-th year. The occurrence date is converted to a Julian date (J_i), which represents the number of days in the i-th year from 01 January to the occurrence date, inclusive (Burn, 1997). To take account of leap years, the month of February is assumed to have 28.25 days and an average year has 365.25 days. The values J_i range from 1 (01 January) to 365.25 (31 December). Next, the Julian date (J_i) of the occurrence of the i-th phenomenon is converted to an angle θ_i in radians or degrees based on the formula (Burn, 1997):

$$\theta_i = (JulianDate)_i \frac{2\pi}{365}, \qquad (1.3.3.1.1)$$

or:

$$\theta_i = J_i \frac{360°}{365{,}25}, \qquad (1.3.3.1.2)$$

or:

$$\theta_i \in \{0{,}98; 360°\} \qquad (1.3.3.1.3)$$

The transformation of the Julian date into an angle allows the occurrence date of the annual minimum of the hydrological phenomenon to be expressed as a vector with a unit length and an orientation θ_i on a unit circle representing the calendar year. The oriented angles θ_i calculated in this way are applied to the circle in an anti-clockwise direction. The average angle is then calculated as:

$$\theta_i = arctg\left(\frac{\bar{y}}{\bar{x}}\right), \bar{\theta} \in \langle 0°; 360° \rangle \qquad (1.3.3.1.4)$$

where: $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} cos\,\theta_i$, and $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} sin\,\theta_i$,

which determines the x and y coordinates of the angles $\theta_{i.}$ where n is the number of years analysed.

The average angle can be converted to the average day (date) of occurrence of the annual minimum of the hydrological phenomenon using the following formulas:

$$MD = \bar{\theta}\frac{365}{2\pi}, \qquad (1.3.3.1.5)$$

and:

$$\bar{J} = \bar{\theta}\frac{365{,}25}{360°}, \bar{J} \in \langle 0; 365{,}25 \rangle \qquad (1.3.3.1.6)$$

Besides the average occurrence date of the annual minimum phenomenon, the average values of the $\boldsymbol{x}$ and $\boldsymbol{y}$ coordinates can be used to define an index of seasonal concentration of minimum values of the hydrological phenomenon based on the following formula:

$$\bar{r} = \sqrt{\bar{x}^2 + \bar{y}^2}, \bar{r} \in \langle 0; 1 \rangle \qquad (1.3.3.1.7)$$

where represents the level of dispersion of data (occurrence dates) in terms of a value between 0 and 1. In the extreme case that = 0, the annual minimum yields are distributed evenly through the year; the other extreme represents a situation where all the annual minimum yields are observed on the same day of the year. The higher the value of , the more regular the occurrence of annual minimum yields.

After calculating the Burn vector, which represents the average occurrence date of minimum yields with a certain probability of occurrence, a histogram was made of the relative frequency of the occurrence dates of minimum yields.

A **frequency histogram** or seasonality histogram (Laaha, 2002) permits a more detailed characterisation of the seasonal distribution of minimal yields in the year. As in the case of Burn's vector, the evaluation is based on the Julian date of occurrence of yields below $\boldsymbol{Q_{90}}$ and $\boldsymbol{Q_{Amin}}$. The histogram visualises the occurrence of minimum yields in each month of the hydrological year.

1.3.3.2. Regionalisation methods

The computed seasonality indexes and selected physiographical parameters (precipitation, air temperature, altitude of outflow, coefficient of transmissivity and compass orientation) were used to regionalise the minimum spring yields. The basic method for regionalisation was cluster analysis. A correlation analysis was conducted prior to the cluster analysis. Its aim was to detect linear dependencies between variables. If there was a strong, statistically significant correlation between the variables – a multicollinearity effect, it would be necessary to eliminate it before the clustering process. Factor analysis and principal component analysis methods were used for this purpose. The clustering process was then carried out. Regionalisation was carried out using Ward's hierarchical clustering method with squared Euclidean distance.

1.3.4. Methods for evaluating groundwater drought in groundwater levels

The parameters used to evaluate groundwater drought include not only groundwater inflows and outflows but also spring yields and groundwater levels, because these provide a characterisation of groundwater reserves that is directly measurable with reasonable accuracy and frequency. These parameters are influenced by multiple factors but the main ones include climatic, hydrological and geomorphological factors, and not least also geological and hydrogeological factors.

The quantitative parameters for evaluating drought in groundwater are essentially the same as for droughts in surface water. They include a percentage of the flow duration curve, the mean annual minimum *M-day values – MAM (M-days)* and baseline runoff, which can be calculated from a time series of groundwater inflow, groundwater levels or groundwater runoff. The flow duration curve is used in the same way as for surface streamflow and provides similar information. When setting *MAM (M-days)*, the time series is divided into annual periods using either the calendar or hydrological year, and the smallest value is identified for each annual period. These values are compiled into the annual minimum series (*AMS*) The relative minimum level is compared with the minima for other years to determine the severity of the drought. The time series may have high inter-year variability and the minimum for one year may be higher than another year's maximum. There can also be droughts that last more than one year (multi-year droughts). The MAM method identifies this as two separate droughts however.

Another possibility for measuring droughts is the threshold method. The threshold value can also be applied to groundwater inflows, groundwater levels and groundwater runoff. Various methods can be used to determine the threshold level, a common one being a flow duration curve. The key step in this method is defining the limit φ_0, or Q_0, at which drought will begin to manifest if the groundwater level (or spring yield) falls below it. The end of the period is defined as the time when the groundwater characteristics again rise above the set threshold. This can be a definition of the start and end of a drought (Tallaksen, 2000). The threshold value can be fixed (constant) or variable. A constant value is used for the evaluated time series whereas a variable threshold fluctuates during the evaluated period. Variable threshold values include monthly or daily values or a moving average from a number of time steps (Stahl, 2001). Usual threshold values fall between the *50th* and *95th percentiles*. The deficiency characteristics of droughts can be used as the main parameter of drought severity in groundwater.

A set of values below the threshold value create a partial duration series (*PDS*). The severity of a drought is usually defined by the deficit *D*. This method can also use parameters such as drought length *L* or drought intensity *I*.

The use of time series acquired using different methods (a partial data series *PDS* and an annual minimum series *AMS*) gives different results for the evaluation of droughts. *PDS* gives much less frequent incidence of droughts and much higher variability in drought severity. The advantage of *PDS* over *AMS* is the possibility to detect multi-year droughts.

Groundwater drought can also be identified by calculating the cumulative deviation of the groundwater level (φ_t) from the threshold value (φ_D). The calculation of cumulative deviation (*CD(t))* over time is equivalent to the Sequent Peak Algorithm (SPA) method.

Mean annual groundwater levels or spring yields allow each hydrological year to be classified in terms of wetness. Above or below average wetness in a hydrological year compared to the relative number of mean annual groundwater levels or spring yields can be expressed using a five-point scale as shown in table 1.3.4.1 (Kříž, 1983).

Tab. 1.3.4.1 Scale of classification of average annual groundwater stages and spring yields (according to Kříž, 1983)

Overstepping (%)	Labelling of the year	Symbol
Below 11	Extremally wet	EW
11–40	Wet	W
41–60	Normal	N
61–90	Dry	D
over 90	Extremally dry	ED

The SANDRE method is currently used to analyse the occurrence of drought in groundwater in Slovakia. This method is used to evaluate the hydrologic situation (occurrence of drought) in groundwater in France by the SANDRE organisation (Service d' administration nationale des données et référentiels sur l' eau). The method is based on the statistical comparison of values for individual months in the studied period (e.g. hydrological year, calendar year etc.) with the long-term monthly average for a selected reference period represented by a coherent, uninterrupted series of measurements. The length of the reference period depends on data availability but the general principle is the longer the time series, the more accurate the results. A 30-year time series is recommended as a minimum. Five separate categories are created for each month in the study period based on statistical processing of the average monthly values for the identical month in the reference period (tab. 1.3.4.2) (http://www.sandre.eaufrance.fr/). The limit values for the categories are φ_{10}, φ_{40}, φ_{60}, φ_{90} in the case of groundwater levels and Q_{10}, Q_{40}, Q_{60}, Q_{90} in the case of spring yields. Not the least important point to note for the evaluation of drought is that it must reflect the natural regime of groundwater and spring yields.

Tab. 1.3.4.2 Groundwater drought evaluation categories according to SANDRE method (http://www.sandre.eaufrance.fr/)

Groundwater table and spring yield	Significantly lower than the long-term average (1981–2010) $< \varphi_{10\%}, < Q_{10\%}$	Lower than the long-term average (1981–2010) $\varphi_{10\%} - \varphi_{40\%}$, $Q_{10\%} - Q_{40\%}$	Equal to the long-term average (1981–2010) $\varphi_{40\%} - \varphi_{60\%}$, $Q_{40\%} - Q_{60\%}$	Above the long-term average (1981–2010) $\varphi_{60\%} - \varphi_{90\%}$ $Q_{60\%} - Q_{90\%}$	Significantly higher than the long-term average (1981–2010) $> \varphi_{90\%} > Q_{90\%}$
Value	1	2	3	4	5

Notes: 1 – the groundwater level (a quantile value less than or equal to $\varphi_{10\%}$) and spring yield (a quantile value less than or equal to $Q_{10\%}$) is significantly below the long-term average for the reference period (drought); 2 - the groundwater level (a quantile value less than or equal to $\varphi_{40\%}$) and spring yield (a quantile value less than or equal to $Q_{40\%}$) is lower than the long-term average for the reference period; 3 - the groundwater level (a quantile value less than or equal to $\varphi_{60\%}$) and spring yield (a quantile value less than or equal to $Q_{60\%}$) is equal to the long-term average for the reference period; 4 – the groundwater level (a quantile value less than or equal to $\varphi_{90\%}$) and spring yield (a quantile value less than or equal to $Q_{90\%}$) is above the long-term average for the reference period; 5 - the groundwater level (a quantile value greater than $\varphi_{90\%}$) and spring yield (a quantile value greater than $Q_{90\%}$) is significantly higher than the long-term average for the reference period (wet).

2. BRIEF DESCRIPTION OF THE STUDIED RIVER BASINS

The selection of river basins chosen for study was designed to provide representation of various parts of Slovakia with different hydrological regimes and also to ensure that the basins would be large enough for appropriate calibration of the hydrological balance in analyses using hydrological models. The larger basin areas also provided better coverage of the territory of Slovakia in maps forecasting the occurrence of drought based on climate scenarios for developments in coming years.

A disadvantage of selecting larger basins is that discharge in a much of the basin is significantly affected by human activity, particularly by manipulation in reservoirs in the basin and water use (water abstraction and discharging). On the other hand, the input data that is used for average daily, monthly and annual flows characterises the real situation in the watercourses. A list of the studied catchments with their basic characteristics is given in table 2.1 and their locations are shown in fig. 2.1.

Tab. 2.1 Basic characteristics of evaluated basins

No of the station	Station name	Stream	Hydrological number	River kilometre	Basin size (km^2)	Altitude of the "0" of the water-gauge (m a.s.l.)
5030	Šaštín-Stráže	Myjava	4-13-03-073	15.18	644,89	164.25
5550	Liptovský Mikuláš	Váh	4-21-02-027	346.60	1,107.21	567.73
6200	Kysucké Nové Mesto	Kysuca	4-21-06-105	8.00	955.09	346.14
6730	Nitrianska Streda	Nitra	4-21-12-017	91.10	2,093.71	158.27
7290	Brehy	Hron	4-23-04-110	93.90	3,821.38	194.27
7330	Holiša	Ipeľ	4-24-01-058	157.20	685.67	172.40
7900	Vlkyňa	Rimava	4-31-03-146	1.60	1,377.41	150.77
8870	Košické Oľšany	Torysa	4-32-04-151	13.00	1,298.30	185.70
9500	Hanušovce nad Topľou	Topľa	4-30-09-132	47.50	1,050.05	160.40
8320	Chmeľnica	Poprad	3-01-03-088	60.10	1,262.41	507.41

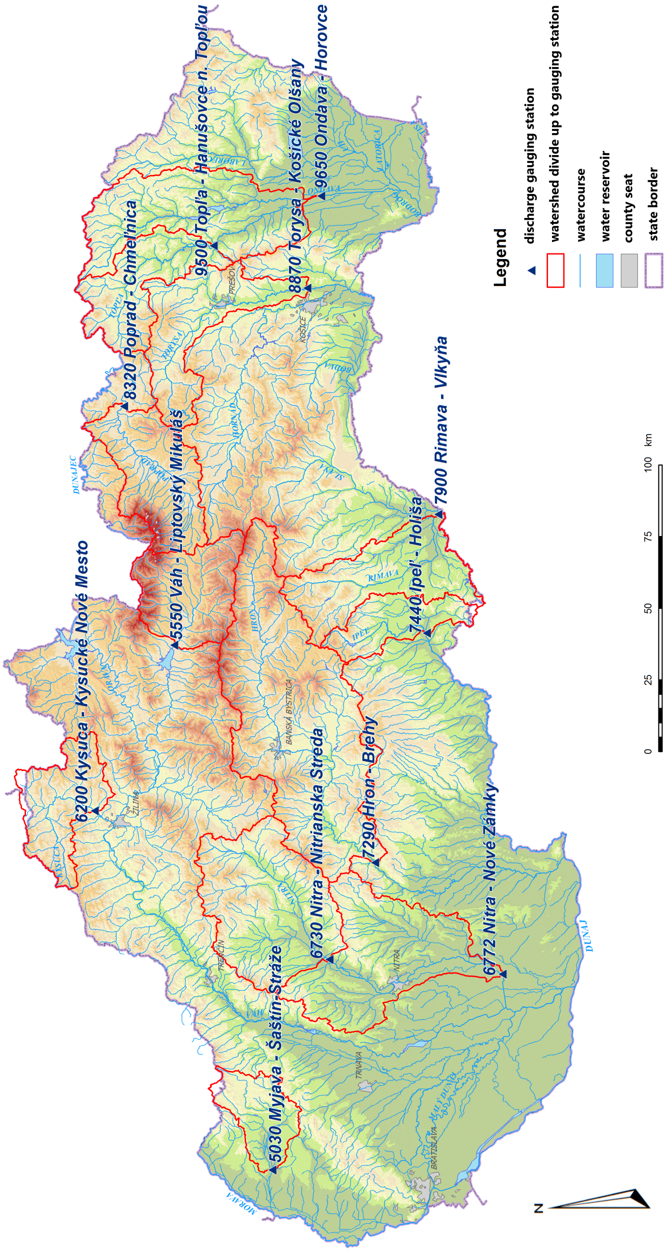
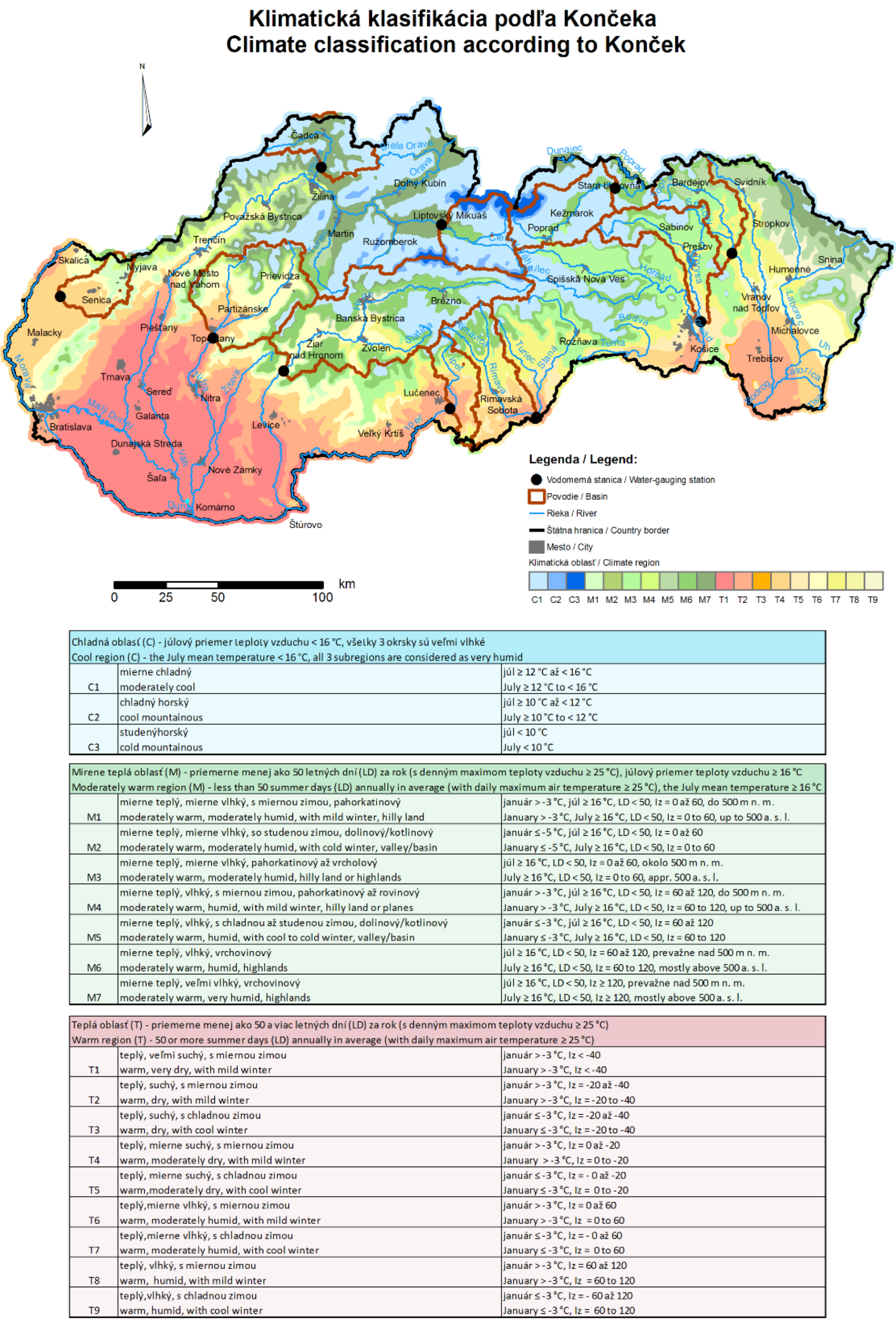


Fig. 2.1 Locations of the evaluated river basins

Some of the catchments were enlarged to their final gauging station, e.g. to Nové Zámky on the Nitra, and Kamenín on the Hron, when modelling hydrological balance elements using the FRIER model and compiling prognoses for the development of their parts to 2100.

Figure 2.2 is a map of the climate classification of the Slovak territory according to Konček marked with the studied catchments.



Chladná oblasť (C) - júlový priemer teploty vzduchu < 16 °C, všetky 3 okrsky sú veľmi vlhké Cool region (C) - the July mean temperature < 16 °C, all 3 subregions are considered as very humid		
C1	mierne chladný moderately cool	júl ≥ 12 °C až < 16 °C July ≥ 12 °C to < 16 °C
C2	chladný horský cool mountainous	júl ≥ 10 °C až < 12 °C July ≥ 10 °C to < 12 °C
C3	studenýhorský cold mountainous	júl < 10 °C July < 10 °C

Mirene teplá oblasť (M) - priemerne menej ako 50 letných dní (LD) za rok (s denným maximom teploty vzduchu ≥ 25 °C), júlový priemer teploty vzduchu ≥ 16 °C Moderately warm region (M) - less than 50 summer days (LD) annually in average (with daily maximum air temperature ≥ 25 °C), the July mean temperature ≥ 16 °C		
M1	mierne teplý, mierne vlhký, s miernou zimou, pahorkatinový moderately warm, moderately humid, with mild winter, hilly land	január > -3 °C, júl ≥ 16 °C, LD < 50, Iz = 0 až 60, do 500 m n. m. January > -3 °C, July ≥ 16 °C, LD < 50, Iz = 0 to 60, up to 500 a. s. l.
M2	mierne teplý, mierne vlhký, so studenou zimou, dolinový/kotlinový moderately warm, moderately humid, with cold winter, valley/basin	január ≤ -5 °C, júl ≥ 16 °C, LD < 50, Iz = 0 až 60 January ≤ -5 °C, July ≥ 16 °C, LD < 50, Iz = 0 to 60
M3	mierne teplý, mierne vlhký, pahorkatinový až vrcholový moderately warm, moderately humid, hilly land or highlands	júl ≥ 16 °C, LD < 50, Iz = 0 až 60, okolo 500 m n. m. July ≥ 16 °C, LD < 50, Iz = 0 to 60, appr. 500 a. s. l.
M4	mierne teplý, vlhký, s miernou zimou, pahorkatinový až rovinový moderately warm, humid, with mild winter, hilly land or planes	január > -3 °C, júl ≥ 16 °C, LD < 50, Iz = 60 až 120, do 500 m n. m. January > -3 °C, July ≥ 16 °C, LD < 50, Iz = 60 to 120, up to 500 a. s. l.
M5	mierne teplý, vlhký, s chladnou až studenou zimou, dolinový/kotlinový moderately warm, humid, with cool to cold winter, valley/basin	január ≤ -3 °C, júl ≥ 16 °C, LD < 50, Iz = 60 až 120 January ≤ -3 °C, July ≥ 16 °C, LD < 50, Iz = 60 to 120
M6	mierne teplý, vlhký, vrchovinový moderately warm, humid, highlands	júl ≥ 16 °C, LD < 50, Iz = 60 až 120, prevažne nad 500 m n. m. July ≥ 16 °C, LD < 50, Iz = 60 to 120, mostly above 500 a. s. l.
M7	mierne teplý, veľmi vlhký, vrchovinový moderately warm, very humid, highlands	júl ≥ 16 °C, LD < 50, Iz ≥ 120, prevažne nad 500 m n. m. July ≥ 16 °C, LD < 50, Iz ≥ 120, mostly above 500 a. s. l.

Teplá oblasť (T) - priemerne menej ako 50 a viac letných dní (LD) za rok (s denným maximom teploty vzduchu ≥ 25 °C) Warm region (T) - 50 or more summer days (LD) annually in average (with daily maximum air temperature ≥ 25 °C)		
T1	teplý, veľmi suchý, s miernou zimou warm, very dry, with mild winter	január > -3 °C, Iz < -40 January > -3 °C, Iz < -40
T2	teplý, suchý, s miernou zimou warm, dry, with mild winter	január > -3 °C, Iz = -20 až -40 January > -3 °C, Iz = -20 to -40
T3	teplý, suchý, s chladnou zimou warm, dry, with cool winter	január ≤ -3 °C, Iz = -20 až -40 January ≤ -3 °C, Iz = -20 to -40
T4	teplý, mierne suchý, s miernou zimou warm, moderately dry, with mild winter	január > -3 °C, Iz = 0 až -20 January > -3 °C, Iz = 0 to -20
T5	teplý, mierne suchý, s chladnou zimou warm,moderately dry, with cool winter	január ≤ -3 °C, Iz = - 0 až -20 January ≤ -3 °C, Iz = 0 to -20
T6	teplý,mierne vlhký, s miernou zimou warm, moderately humid, with mild winter	január > -3 °C, Iz = 0 až 60 January > -3 °C, Iz = 0 to 60
T7	teplý,mierne vlhký, s chladnou zimou warm, moderately humid, with cool winter	január ≤ -3 °C, Iz = - 0 až 60 January ≤ -3 °C, Iz = 0 to 60
T8	teplý, vlhký, s miernou zimou warm, humid, with mild winter	január > -3 °C, Iz = 60 až 120 January > -3 °C, Iz = 60 to 120
T9	teplý,vlhký, s chladnou zimou warm, humid, with cool winter	január ≤ -3 °C, Iz = - 60 až 120 January ≤ -3 °C, Iz = 60 to 120

Fig. 2.2 Position of river basins within the regional scheme of the climatic classification of the Slovak territory according to Konček (Konček and Petrovič, 1957)

The River Myjava to the discharge gauging station Šaštín-Stráže

The Myjava River Basin belongs to the Slovak part of the sub-basin of the Lower Morava and is located on the east side of its upper section (fig. 2.1).

Climate conditions

The Myjava River Basin can be divided into two parts under Konček's climate classification scheme. The first part is that which in geographical terms is situated in the Borská Lowland, which is a moderately dry sub-region with a mild winter in a warm region (fig. 2.2). The average annual air temperature here in the period 1981–2010 was around 9.5°C. The large part of the catchment in the Biele Karpaty Mountains and the Myjava Upland is a moderately warm, moderately humid hilly region with a mild winter, with an annual average air temperature around 9°C, which gradually decreases with increasing altitude. The highest parts of the catchment are a humid, highland sub-region of a moderately warm region (fig. 2.2). Average annual precipitation in the basin is around 700 mm.

Hydrological conditions

The River Myjava is one of the three most important tributaries of the River Morava in the territory of Slovakia, the other two being the Malina and the Rudava, and the Myjava is the largest of them. The source is in the Biele Karpaty Mountains below the summit of Šibeničný Vrch. Its length is 80.1 km to the confluence with the Morava and the total area of the catchment is 745.34 km^2. The sub-basin of the Morava, including the Myjava, is characterised by a runoff regime with the highest average monthly runoff in the spring, in March and April, which is usually directly related to the runoff from melting snow in the Czech, Austrian and Slovak parts of the catchment. The lowest mean monthly discharges are typically in the summer-autumn period, usually occurring in the months of August and September.

The shape of the Myjava Basin in the studied profile to the Šaštín-Stráže discharge gauging station (fig. 2.1) is elongated with an average slope of 6°. Its highest point is 809.1 m a.s.l. and its lowest is 167.4 m a.s.l. The stream network density is 1.22 km.km^{-2} and forest covers 34.9% of the basin. The main land cover type in the basin is arable land, which covers up to 44%.

Hydrogeological conditions

In geological-tectonic and hydrogeological terms, the Myjava Basin belongs mainly to the main Biele Karpaty unit of the outer flysch zone, which is dominated by pelitic rocks with characteristic intergranular and fisssure permeability. Springs typically have large variations in their yield and are insignificant for the purposes of water management. The other tectonic unit forming part of the basin is the Clippen Belt zone, which begins in the Myjava Valley near the village of Podbranč and extends to the east towards Myjava and Rudník. It is made up of various rock types including mainly crinoidal, nodular, radiolarian and marly limestones and marlstones but also sandstones, shales and conglomerates. South and southeast of the Clippen Belt zone (Bradlové pásmo) lies the Myjava Upland, whose western part is made up of Neogene rocks. Their lithological composition is very varied with the best water permeation being in conglomerates, sandstones, coral limestone and organogenic limestones with fissure or fissure-intergranular permeability.

Factors influencing natural discharge

- The influence of the Kunov Reservoir on the Teplica
- No significant abstraction of surface water

- Significant discharging: waste water treatment plants at Senica (0.066 $m^3.s^{-1}$), Myjava – Turá Lúka (0.047 $m^3.s^{-1}$) and Brezová pod Bradlom (0.024 $m^3.s^{-1}$)
- Summary groundwater abstraction: 0.047 $m^3.s^{-1}$.

The River Váh to the discharge gauging station at Liptovský Mikuláš

The River Váh, with a length of 367 km from its confluence with the Danube to the confluence of the Čierny Váh and the Biely Váh, is the longest river in Slovakia. Its basin covers 19,696 km^2, which is around 40% of the total area of Slovakia. The studied part of the Váh basin (fig. 2.1) to the discharge gauging station at Liptovský Mikuláš is situated in the upper section of the river in the north-eastern part of the Váh River Basin, which differs from the other parts of the basin in having a colder climate and a higher altitude.

Climate conditions

The studied basin is situated in a cool region (Landscape Atlas of Slovakia, 2002). Most of the area is a moderately cool and very humid sub-region within the cool region. At higher altitudes in the mountain ranges Malá Fatra, Veľká Fatra, Oravské Beskydy, Orava Highland, Choč, Tatry and Nízke Tatry, the sub-region classification is cool mountain and on the peaks of the Malá Fatra, Nízke Tatry and Západné Tatry Mountains to cold mountain (fig. 2.2). The average annual air temperature in the lowest-lying parts of this section of the Váh River Basin are up to 7°C and gradually decrease with increasing altitude. On the ridges of the Západné Tatry Mountains they can be as low as -3°C. Total annual precipitation in this region is around 1,100 mm ranging from 1,700 mm at the highest points in the Tatry and Nízke Tatry Mountains to just 700 mm in the lowest lying parts of the studied catchment.

Hydrological conditions

The catchment upstream from the Liptovský Mikuláš discharge gauging station (fig. 2.1) is drained mainly by the rivers Biely Váh and Čierny Váh and streams in the Západné Tatry Mountains. The basin of the Čierny Váh has its highest runoff in April and, less often, in May. The basin of the Biely Váh has a very balanced runoff regime all year round with a moderate peak in April and lower flow in January and February. The tributaries in the Západné Tatry Mountains have a large maximum runoff in May and a high share of runoff in June. The high flow of the mountain watercourses is due to the later melting of snow at high altitudes. The shape of the studied sub-basin is fan-shaped with an average slope of 17.3°. Its highest point is 2,406.2 m a.s.l. and its lowest is 566.0 m a.s.l. The stream network density is 1.52 $km.km^{-2}$ and forest covers 59.1 % of the basin. The main land cover type in the basin is coniferous forests, which cover up to 42.7%.

Hydrogeological conditions

The central part of the studied area is the hydrogeological complex of the Central Carpathian Palaeogene built by the layer sequence of the Sub-Tatra Group. They are made up of a group of sub-horizontally laid flysch strata tectonically differentiated into blocks. The rocks with the greatest hydrogeological significance in the Sub-Tatra Group are the basal layers of conglomerates, breccias, sandstones and limestones with good fracture permeability enhanced by transverse fault tectonics. Spring yields range from 2 to 15 $l.s^{-1}$ and in a few cases are even higher. At the edge of the territory is the crystalline basement of the Tatry and Nízke Tatry Mountains, overlaid by the Mesozoic sequences of Tatricum, Fatricum and Hronicum units. The Mesozoic Fatricum and Hronicum are especially likely to have carbonate structures with karst-fissure permeability. Karst springs with high yields occur very frequently on the northern slopes of the Nízke Tatry Mountains (around the Jánska and Demänovská Valleys). The covering units are made up of alluvial deposits, with additional glacigenic and slope sediments in mountain areas. The territory also has chemical sediments – travertine, especially in the vicinity of Bešeňová and Lúčky.

Factors influencing natural discharge

- The effect of reservoirs on the water balance has not been evaluated; the Čierny Váh hydroelectric pump storage plant is located in the upper part of the basin
- No significant abstraction of surface water
- Significant discharging: none
- Summary groundwater abstraction: 0.315 $m^3.s^{-1}$.

River Kysuca to the Kysucké Nové Mesto discharge gauging station

The Kysuca River Basin belongs to the sub-basin of the River Váh and is located on the north side of its upper section (fig. 2.1).

Climate conditions

The Kysuca River Basin includes two climatic sub-regions (Landscape Atlas of Slovakia, 2002). The lower valleys close to the river are a very humid highland sub-region of a moderately warm region, with an average annual air temperature of around 7.5°C (for the period 1981–2010). The upper parts of the basin at altitudes higher than around 600 m a.s.l. form a moderately cool, very humid sub-region of a cool region with an average annual temperature of up to 5°C (Fig. 2.2). The basin receives around 1,060 mm of atmospheric precipitation per year on average.

Hydrological conditions

The River Kysuca has its source on the north slope of Hričovec Mountain (1,062 m a.s.l.) and its length to its confluence with the Váh is 65.60 km. The area of the basin is 1,037.67 km^2. It has a significant runoff peak in April, with an autumn minimum in September and/or a winter minimum in January. The shape of the studied sub-basin is fan-shaped with an average slope of 13.8°. Its highest point is 1,234.5 m a.s.l. and its lowest is 347.2 m a.s.l. The stream network density is 1.94 $km.km^{-2}$ and forest covers 65.3 % of the basin. The main land cover type in the basin is coniferous forests, which cover up to 36.0 %.

Hydrogeological conditions

Most of the studied basin is situated in the Flysch Belt of the Outer Western Carpathians which dates from the Palaeogene Age. This belt is characterised by the rhythmic alternation of pelitic (claystone) and psammitic (sandstone) sediments. The rock can be characterised as weakly water-bearing and poorly permeable with the properties of an aquitard, which means that there is limited groundwater circulation that is restricted mainly to the recharge zone, with limited possibilities for accumulation. Springs in the flysch complex have an average yield of 0.5 $l.s^{-1}$.

Factors influencing natural discharge:

- The reservoir at Nová Bystrica influences the River Bystrica (a left-hand tributary of the Kysuca)
- Significant abstractions of surface water: SeVS Water Company Žilina (0.228 $m^3.s^{-1}$) from the Nová Bystrica reservoir

- Significant discharging: the Čadca wastewater treatment plant (0.100 $m^3.s^{-1}$)
- Summary groundwater abstraction: 0.009 $m^3.s^{-1}$.

The River Nitra to the Nitrianska Streda discharge gauging station

The Nitra River Basin belongs to the sub-basin of the River Váh and is located in its central section (fig. 2.1). For the purposes of the FRIER model and drought prognoses, the territory was extended to the final gauging station on the Nitra at Nové Zámky (fig. 2.1).

Climate conditions
The studied basin covers several climate areas (Landscape Atlas of Slovakia, 2002) from a dry sub-region of a warm climate region through humid to very humid hilly land or highlands in a warm climate region to a moderately cool very humid sub-region of the cool region (fig. 2.2). The average annual air temperature in the hilly part of the basin ranges from 9 to 10°C, while at higher altitudes in the Strážovské Vrchy and Považský Inovec Mountains it is around 5°C. The average annual total atmospheric precipitation is about 800 mm in the studied area.

Hydrological conditions
The River Nitra has its source on a south-facing slope just below the Fačkovské Sedlo Pass, which is on the border between the Strážovské Vrchy and Malá Fatra Mountains. The length of the river to its confluence with the Váh is 165.86 km and the basin covers an area of 4,501.15 km^2. Runoff peaks in the months of March and April and has its autumn minimum in August and September. The shape of the studied sub-basin is elongated to fan-shaped with an average slope of 10.1°. Its highest point is 1,341.9 m a.s.l. and its lowest is 159.3 m a.s.l. The stream network density is 1.29 $km.km^{-2}$ and forest covers 54.1 % of the basin. The main land cover type in the basin is broad-leaf forests, which cover up to 41.2 %.

Hydrogeological conditions
The central part of the area is made up of Neogene sediments that are impermeable from a hydrogeological perspective covered by alluvial deposits of the Nitra River and its tributaries. The right edge of the territory is formed by the Strážovské Vrchy Mountains, whose geological composition is a crystalline basement overlaid with a sequence of Mesozoic covering layers that emerge at the surface mainly in the vicinity of Bojnice. Springs in crystalline basement have low, unstable yields whereas higher yields are typical for the Mesozoic complexes (e.g. the Kamenná Dolina Spring). The territory also has partial borders with the Malá Fatra a Kremnické Vrchy Mountains. The left side is bordered by the Žiar Mountains, which have a strongly developed crystalline basement at their core. To the south are the neovolcanic Vtáčnik Mountains. The basin of the Žitava, the most significant of the Nitra's left-hand tributaries is bordered on the right by the core mountain range Považský Inovec, with pronounced Mesozoic covering and on the left by the volcanic mountain range Pohronský Inovec. In areas built on neovolcanic rocks, groundwater sources are genetically linked to a zone of increased fracturing of the rock structure, volcanic sediments with intergranular permeability and significant tectonic zones. Important factors for aquifer development are intensely fractured tectonic fault lines with a drainage effect on broader rock areas and well-fractured andesite and related volcaniclastic rocks. Some spring yields are in the range of a few decilitres but there are also springs with yields of 2 to 5 $l.s^{-1}$, occasionally 5 to 10 $l.s^{-1}$ and above 10 $l.s^{-1}$ in rare cases. They typically have an unstable regime with changes in water temperature and yields.

Factors influencing natural discharge:

- The Nitrianske Rudno Reservoir influences flows in the Nitrica River
- Significant surface water abstractions: from the Nitrianske Rudno Reservoir to the SE Nitrianske Rudno Reservoir (0.221 $m^3.s^{-1}$) and the chemical works in Nováky (0.062 $m^3.s^{-1}$)
- Significant discharging: the wastewater treatment plant in Prievidza (0.173 $m^3.s^{-1}$), Handlová Mine (0.134 $m^3.s^{-1}$), Partizánske (0.130 $m^3.s^{-1}$), and Cigeľ Mine (0.113 $m^3.s^{-1}$)
- Summary groundwater abstraction: 0.594 $m^3.s^{-1}$.

The River Hron to the discharge gauging station at Brehy

The sub-basin of the Hron has a total surface area of 5,464.56 km^2 (fig. 2.1). For the purposes of the FRIER model and drought prognoses, the territory was extended to the final gauging station on the Hron at Kamenín (fig. 2.1).

Climate conditions

Temperatures in the sub-basin of the River Hron depend mainly on altitude, the exposure of slopes and the configuration of the relief. It includes (Landscape Atlas of Slovakia, 2002) moderately humid sub-regions of a warm region with a mild winter in the Zvolen Basin and cold mountain sub-regions of the cool climate region at the highest altitudes in the Nízke Tatry Mountains (fig. 2.2). The average annual air temperature reaches 9°C in the lowest and southernmost part of the sub-basin and decreases going from south to north reaching 8°C in the Zvolen Basin area and 6 to 7°C in the lower parts of the upper reaches. The air temperature changes with altitude; in the Slovenské Rudohorie Mountains the average annual air temperature is 3 to 4°C and at the highest points in the Nízke Tatry Mountains -1°C. There are typically major difference in the spatial distribution of precipitation. Moderately humid and very humid sub-regions alternate over relatively short distances. Average total annual precipitation in the period 1981–2010 was 890 mm. In the highest parts of the Nízke Tatry and Veľká Fatra Mountains average total annual precipitation is over 1,500 mm while on the ridges of the other mountain ranges it is over 900 mm. In the lowest areas of the sub-basin of the Hron, average total annual precipitation is between 600 and 700 mm.

Hydrological conditions

The River Hron has its source in the upper Hron Valley around 3 km east of the village of Telgárt below the Besník Pass. The whole sub-basin is located in the territory of Slovakia and forms a natural hydrological unit because all the water that rises in it comes from our territory. The river's length from its source to its confluence with the Danube is 278.5 km. The runoff regime in the sub-basin of the Hron has its maximum monthly runoff in April and the lowest average monthly runoff in September. As with the flow pattern through the year, the maximum flows during floods are concentrated in the spring period, usually in April. Other frequent periods for flooding are the summer months, especially between June and August. The shape of the studied sub-basin is elongated with an average slope of 14.3°. Its highest point is 2,036.9 m a.s.l. and its lowest is 189.9 m a.s.l. The stream network density is 1.49 $km.km^{-2}$ and forest covers 63.3 % of the basin. The main land cover type in the basin is broad-leaf forests, which cover up to 30.6 %.

Hydrogeological conditions

The sub-basin of the Hron is characterised by a varied and complex geological-tectonic structure. Veporidic basement rocks form the crystalline core of the Nízke Tatry, Starohorské and Veporské Vrchy Mountains together with Mesozoic Fatricum and Hronicum in the southern slopes of the Nízke Tatry and Veľká Fatra Mountains. Neogene volcanic rocks make up the system of volcanic mountains in the Central Slovak province (Kremnické Vrchy, Štiavnické Vrchy, Javorie, Poľana). The southern part of the basin is made of Neogene sedimentary rocks. The groundwater in the Nízke Tatry, Starohorské and Veporské Vrchy Mountains can be characterised in general as water of a fissure or fissure-karst character. Granitic rocks have more fissures than schist. As in the crystalline basement, the younger Palaeozoic rocks have numerous springs with low or unstable yields that rarely exceed 0.3 $l.s^{-1}$ and depend almost exclusively on atmospheric precipitation. There are significant aquifers in the Mesozoic carbonates which are dominated by a karst-fissure environment that supports major sources of groundwater, especially in the Veľká Fatra and the Harmanec syncline (Tunel, Matanová, Čierno 1 and 2, Veľké and Malé Cenovo, Zalámaná 1, 2 and 3 springs), but also the springs Jergaly, Pod starým mlynom and others. These have a yield of several tens, locally even hundreds, of litres per second. The fissure springs fed by the recharge zone in extrusive neo-volcanic rocks usually have low yields up to 1.5 $l.s^{-1}$. Higher yields were obtained from hydrogeological boreholes in the tectonic zone running through the valley of the Neresnica River (a left-hand tributary of the Hron near Zvolen) including the water sources Podzámčok (current yield around 70 $l.s^{-1}$) and Dobrá Niva (15 $l.s^{-1}$). Tertiary sediments form the top layer of the geological structure of the Hron sub-basin mainly in its central and lower parts. Older Palaeogene rocks are found in the upper Hron Valley, especially in the Brezno Basin. The main types are Eocene limestone-sandstone complexes that are generally poorly permeable or impermeable.

Factors influencing natural discharge:

- Transfer of water from the River Turiec (Váh) to the Hron via the Turčekovský Aqueduct
- The Hriňová and Môťová Reservoirs influence flows in the Slatina
- Significant abstractions of surface water: The mining company Kremnická banská spoločnosť Kremnica (0.237 $m^3.s^{-1}$ from the Dedičná Štôlňa and 0.210 $m^3.s^{-1}$ from Kremnický Potok), StVS Water Company Hriňová (0.132 $m^3.s^{-1}$)
- Significant discharging: the wastewater treatment plants of Kremnická banská spoločnosť Kremnica (0.544 $m^3.s^{-1}$) and Banská Bystrica City (0.457 $m^3.s^{-1}$)
- Summary groundwater abstraction: 0.650 $m^3.s^{-1}$.

The River Ipeľ to the discharge gauging station at Holiša

The studied sub-basin belongs to the basin of the River Ipeľ and is located in its northern section (fig. 2.1).

Climate conditions

The overall south-facing orientation of the sub-basin of the Ipeľ influences its climate conditions. The Lučenec Basin is a dry sub-region of the warm region with a mild winter (fig. 2.2). The average annual air temperature is around 9.5°C. The highest points in the Veporské Vrchy Mountains belong to moderately cool, very humid sub-region in a cool region (Landscape Atlas of Slovakia, 2002). Average annual air temperatures are in the range 5–6°C. Average total annual precipitation in the sub-basin is only around 650 mm while in the lowest parts of the Lučenec Basin it is on average 100 mm less.

Hydrological conditions
The River Ipeľ has its source in the Veporské Vrchy Mountains around 2 km south of the village of Lom nad Rimavicou. Its total length is 199 km and the area of the sub-basin is 5,151.04 km^2. The runoff regime in the sub-basin of the Ipeľ has its maximum monthly runoff in March and the lowest average monthly runoff in the summer-autumn period, in August and September. As with the runoff regime of the Ipeľ through the year, which is dominated by spring runoff, flooding occurs mainly in spring, between February and April, with maximum flows usually occurring in March. The spring discharge waves are mainly of a mixed type combining rain and melting snow. There are two main periods of low flow in the sub-basin of the Ipeľ – the summer-autumn depression in flow, whose lowest point is in September and a secondary winter depression, whose lowest point is usually in January. The shape of the studied sub-basin to the discharge gauging station (fig. 2.1) is fan-shaped with an average slope of 8.8°. Its highest point is 1,111.1 m a.s.l. and its lowest is 375.46 m a.s.l. The stream network density is 1.3 km.km^{-2} and forest covers 46.9 % of the basin. The main land cover type in the basin is broad-leaf forests, which cover up to 40.0 %.

Hydrogeological conditions
The studied sub-basin is located in a region of Tertiary rocks which make up by far the largest part of the sub-basin of the Ipeľ River. They are very varied both in lithofacial composition and stratigraphic range resulting from volcanic and sedimentary activity: sandstones, siltstones, conglomerates and rhyodacite tuffs, grey sands with coal seams and lake claystones. These rocks are not significant from a hydrogeological point of view because Neogene sediments act as aquitards. The peaks of the Cerova Highland are made up of intrusion bodies of andesite, basalt, agglomerates and tuffs. In the highest part of the sub-basin there are the Veporidic basement rocks of the Veporské Vrchy Mountains, which have fissure permeability leading to the occurrence of relatively insignificant springs with yields of up to 1 l.s^{-1}.

Factors influencing natural discharge:

- The effect of the Málinec Water Reservoir
- Significant abstraction of surface water: StVS Water company Málinec (0.093 m^3.s^{-1})
- Significant discharging: the Fiľakovo wastewater treatment plant (0.022 m^3.s^{-1})
- Summary groundwater abstraction: 0.057 m^3.s^{-1}.
-

The River Rimava to the discharge gauging station at Vlkyňa

The Rimava River Basin belongs to the sub-basin of the River Slaná and is located in its western section (fig. 2.1).

Climate conditions
The climate conditions of this basin are very similar to the climate conditions in the sub-basin of the River Ipeľ. The southern part of the Rimava Basin is a dry sub-region of a warm region with a mild winter while the higher parts in the Veporské Vrchy Mountains and the Muránska Planina are classified as moderately cool, very humid sub-regions of a cool region (Landscape Atlas of Slovakia, 2002). The average annual temperature in the basin ranges from 5°C in the mountainous northern part of the territory to 9.5°C in the southern part of the Rimava Basin. Average total annual precipitation ranges from 550 mm to 1,000 mm depending on altitude.

Hydrological conditions

The River Rimava has its source in the Slovenské Rudohorie Mountains at an altitude of around 1,130 m a.s.l. on the south-eastern slope of Fabova Hoľa (1,439 m a.s.l.). Its total length to the confluence with the Slaná is 83.12 km and the area of the sub-basin is 1,378.43 km^2. The runoff regime in the basin of the Rimava, like that of the River Slaná, has its maximum monthly runoff in the spring, in March and April, and the lowest average monthly runoff in the summer-autumn period, especially in September. The highest runoff is in the spring and maximum flows are also concentrated in the spring period. More than half of annual maximum discharges were recorded in these months. The spring discharge waves in the sub-basin of the Slaná are mainly of a mixed type produced both by rain and runoff from melting snow. These flood waves usually have a larger volume and longer duration than flood waves produced only by rainfall. The summer is another frequent period for floods in the sub-basin of the Slaná; the floods usually occur between June and August as a result of torrential rain and are characterised by maximum surges of relatively high significance but a lesser volume of water in the flood wave. The shape of the studied sub-basin to the discharge gauging station (fig. 2.1) is elongated with an average slope of 10.5°. Its highest point is 1,395.8 m a.s.l. and its lowest 150.8 m a.s.l. The stream network density is 1.4 km.km^{-2} and forest covers 48.7 % of the basin. The main land cover type in the basin is broad-leaf forests, which cover up to 36.9 %.

Hydrogeological conditions

The geological structure of the Rimava River Basin within the sub-basin of the River Slaná is very diverse in both its stratigraphy and lithology. This fact in combination with the complicated tectonic structure leads to significant hydrogeological differences. The main influences on the formation of stream valleys in the Slaná's catchment were the geological and tectonic conditions. The valleys cut across several different geological formations. The upper and middle parts of the watercourses pass through schist and granitic rocks of the Veporské Vrchy Mountains and the Mesozoic rocks of the western part of the Slovak Karst (Tisovec Karst, Licince Upland), while the lower parts are modelled in Neogene Tertiary sediments that are mainly claystone covered with Quaternary alluvial deposits. The thickness of deposits in the fluvial plain of the Rimava ranges mainly from 4.2 to 5.5 m, reaching 6.8 m in places. The thickness of water-bearing gravels ranges from 1.6 to 4.7 m. The yield of individual boreholes ranges mainly from 1 to 4 l.s^{-1}, but can be 9 l.s^{-1} in some places. The valley of the Rimava is bordered with terraces of highly variable thickness and inhomogeneous lithological composition.

Factors influencing natural discharge:

- Discharges are influenced by the Klenovec Reservoir on the Klenovecká Rimava and the Teplý Vrch Reservoir on the Blh
- Significant abstractions of surface water: StVS Rimavská Sobota (0.082 m^3.s^{-1})
- Significant discharging: the Rimavská Sobota wastewater treatment plant (0.082 m^3.s^{-1})
- Summary groundwater abstraction: 0.034 m^3.s^{-1}.

The River Torysa to the discharge gauging station at Košické Olšany

The Torysa River Basin belongs to the sub-basin of the River Hornád and is located in its eastern section (fig. 2.1).

Climate conditions

Due to its complex, rugged orography, the sub-basin of the River Hornád includes several climate regions (Landscape Atlas of Slovakia, 2002). These proceed gradually from a moderately cool sub-region of a cool region in the north (the Levočské Vrchy and Čergov Mountains) to a warm, moderately dry sub-region with a cool winter in the southern part of the basin (fig. 2.2). The average annual air temperature ranges from 3 to 4°C in the Levočské Vrchy Mountains to 9°C in the Košice Basin. Average total annual rainfall in the period 1981 to 2010 was 730 mm but in the Čergov and Levočské Vrchy Mountains it can be as high as 1,100 mm.

Hydrological conditions

The River Torysa has its source in the Levočské Vrchy Mountains to the northwest of the village of Torysky below the ridge between the peaks Javorina (1,225 m a.s.l.) and Javor (1,206 m a.s.l.) at an altitude of around 1,040 m a.s.l. Its total length to its confluence with the Hornád is 129.0 km and the surface area is 1,348.98 km^2. The typical runoff regime in the Hornád River Basin has its maximum monthly runoff in the spring, in March, April and May, and the lowest average monthly runoff in the autumn, usually in September. There are two concentrated periods of low flow in the sub-basin of the Hornád – the summer-autumn depression in flow, whose lowest point is between August and October and a secondary winter depression, whose lowest point is usually in January. The shape of the studied basin to the discharge gauging station Košické Olšany (fig. 2.1) is elongated, with an average slope of 9.8°. Its highest point is 1,263.9 m a.s.l. and its lowest 186.5 m a.s.l. The stream network density is 1.49 km.km^{-2} and forest covers 42.7 % of the basin. The main land cover types in the basin are broad leaf forests covering 32.1% and arable land covering 29.4 %.

Hydrogeological conditions

The sub-basin of the Hornád River includes all geological formations from the Palaeozoic to the Quaternary and it is a region with a high prevalence of impermeable or poorly permeable rocks with moderate to low permeability. Typical feature of the studied basin include the Palaeozoic crystalline rocks of the Slovenské Rudohorie and Branisko Mountains (granitoids, highly and moderately metamorphosed schist) which are weakly permeable and therefore fissure permeability is the dominant form of permeability. In such an environment the main source of groundwater is atmospheric precipitation. Spring yields range from 0.1 to 1.0 l.s^{-1} and in a few cases are even higher. The basin is filled with flysch rocks laid down in the Inner Carpathian Palaeogene covered with Quaternary alluvial deposits. These Quaternary deposits from the Torysa and its tributaries include significant water sources (Brezovička, Brezovica and others). Another hydrogeologically significant formation is groundwater in the limestone-dolomitic strata complex in Branisko (e.g. Hlavný prameň, Vyšný Slavkov).

Factors influencing natural discharge:

- There is no effect from reservoirs and water transfers
- Significant surface water abstraction: Prešov waterworks (0.047 m^3.s^{-1})
- Significant discharging: the wastewater treatment plants of Prešov - Kendice (0.205 m^3.s^{-1}) and Sabinov (0.029 m^3.s^{-1})
- Summary groundwater abstraction: 0.177 m^3.s^{-1}.

The River Topľa to the discharge gauging station at Hanušovce nad Topľou

The Topľa River Basin belongs to the sub-basin of the River Bodrog and is located in its western section (fig. 2.1).

Climate conditions
The sub-basin of the Bodrog has various climate conditions because it covers a territory from areas 200 m a.s.l. to the mountain ridges of the Nízke Beskydy Mountains, which are above 1,000 m a.s.l. The studied sub-basin to the discharge gauging station at Hanušovce nad Topľou includes several climate regions and sub-regions (Landscape Atlas of Slovakia, 2002) – from a moderately humid sub-region of a warm region with a cool winter in the lowest-lying areas to a humid highland sub-region of a moderately warm region (fig. 2.2). At the highest altitudes, above 600 m a.s.l., the climate is a moderately cool and very humid sub-region of a cool region. The average total annual precipitation in the catchment is 750 mm and the highest annual total precipitation levels, up to 1,000 mm, occur at the ridges of the mountains on the northern border of the catchment. The average annual air temperature in the sub-basin of the Bodrog River is 7.5 to 8.5°C in the lowest-lying areas, 6 to 7°C at higher altitudes and 4 to 6°C on the mountain ridges.

Hydrological conditions
The River Topľa has its source in the Čergov Mountains. Its total length to the confluence with the Ondava is 131.37 km and the area of its basin is 1,544.00 km^2. The runoff regime in the basin of the Bodrog River has its maximum monthly runoff in the spring, in March and April, and the lowest average monthly runoff in the summer-autumn period, in August and September. The largest runoff is usually in spring and peak discharges are also occurring in the spring, mainly in March. Spring floods typically have larger volumes because they are usually the result of melting snow or, in some cases, a mixture of melting snow and rain. There are two concentrated periods of low flow in the year – the summer-autumn depression in flow, whose lowest point is between August and October and a secondary winter depression, whose lowest point is usually in January. The shape of the studied basin to the discharge gauging station Hanušovce nad Topľou (fig. 2.1) is elongated to fan-shaped, with an average slope of 10.7°. Its highest point is 1,129.5 m a.s.l. and its lowest 154.2 m a.s.l. The stream network density is 1.84 km.km^{-2} and forest covers 55.4 % of the basin. The main land cover type in the basin is broad-leaf forests, which cover up to 42.8 %.

Hydrogeological conditions
The catchment of the Topľa and Ondava is mainly built on the flysch rocks of the Magura unit of the Outer Flysch Belt. The rocks are made up of claystone and sandstone and have both intergranular and fissure permeability. This unit has a low water-bearing capacity and spring yields are in the range 0.1 – 1.0 l.s^{-1}. Precipitation is the main factor affecting spring yields.

Factors influencing natural discharge:
- There is no effect from reservoirs and water transfers
- No significant abstraction of surface water
- Significant discharging: Bardejov wastewater treatment plant (0.069 m^3.s^{-1})
- Summary groundwater abstraction: 0.060 m^3.s^{-1}.
-

The River Poprad to the discharge gauging station at Chmeľnica

The Poprad River Basin is part of the sub-basin of the Dunajec and the Poprad and the catchment area is 1,889.21 km^2 (fig. 2.1).

Climate conditions
The majority of the basin, apart from the eastern part of the Poprad and Ľubovňa Basins are situated in a cool and very humid region according to Končekʼs climate classification scheme (Landscape Atlas of Slovakia, 2002). All three sub-regions are represented at different altitudes, from moderately cool in the Poprad Basin to cold mountainous at high mountain locations in the Tatry Mountains (fig. 2.2). The average annual air temperature at altitudes around 1,000 m a.s.l. is 5°C and on the ridges of the Tatry Mountains -3.5°C. The territory in the eastern parts of the Poprad and Ľubovňa Basins is situated in a moderately warm region with the southern part of the basin being a moderately warm, very humid, highland sub-region and the northern part being a moderately warm, moderately humid hilly-to-highland sub-region. The average annual air temperature here is around 6.5°C. Average annual total atmospheric precipitation in the basin is around 880 mm but it is unevenly distributed. The highest levels of precipitation, around 1,700 mm, fall in the highest parts of the Tatry Mountains while lower-lying areas of the Poprad Basin receive much less annual total atmospheric precipitation, only around 600 mm.

Hydrological conditions
Water from this sub-basin flows to the main basin of the Vistula and from there to the Baltic Sea. The official source of the River Poprad is the tarn Popradské Pleso in the Mengus Valley in the Tatry Mountains. The total length of the river to the border between Slovakia and Poland is 104.3 km. The Dunajec and Poprad sub-basin is characterised by a runoff regime with maximum mean monthly discharges in the spring-summer period, in May and June, and with lowest mean monthly discharges in the winter, in January and February, which is a typical regime for mountain rivers. The sub-basin has its largest runoff in late spring and summer and the highest discharges are also concentrated in the spring and summer. Flood waves typically have larger volumes in this period because they are caused by melting snow or simultaneous rain and melting snow. The season for low flow in the sub-basin of the Dunajec and Poprad is during the winter runoff depression, whose lowest point is in January or February. The shape of the studied sub-basin to the discharge gauging station (fig. 2.1) is elongated with an average slope of 10.7°. Its highest point is 2,597.3 m a.s.l. and its lowest 507.99 m a.s.l. The stream network density is 1.68 km.km^{-2} and forest covers 43.6 % of the basin. The main land cover types in the basin are arable land (22.9%), meadows and pasture (21.7%) and coniferous forests (20.6%).

Hydrogeological conditions
The oldest hydrogeological complex in the sub-basin of the Dunajec and the Poprad is the crystalline basement of the south and central part of the Tatry Mountains, which supports the younger formations, which are mainly from the Mesozoic Era. The basins are filled with Inner Carpathian Palaeogene rocks that act as aquitards and form a barrier on which springs emerge. Quaternary sediments provide an important environment for groundwater accumulation in the Poprad Basin. They are made up in part of fluvial sediments deposited in the floodplains of the Poprad River, the Dunajec River and their larger tributaries but mainly by glacial and glacio-fluvial sediments in the Poprad Basin and the Vysoké Tatry Mountains. In the Vysoké Tatry and Belianske Tatry Mountains, glacigenic sediments are the most significant groundwater aquifers. Spring types include barrier, erosion and line springs with yields mainly in the range 5.0 to 15.0 l.s^{-1}, though in places even over 20.0 l.s^{-1}.

Factors influencing natural discharge:

- There is no effect from reservoirs and water transfers
- Surface water abstractions: Stará Ľubovňa (0.030 m^3.s^{-1}), Biela Voda (0.017 m^3.s^{-1})

- Significant discharging: waste water treatment plants at Poprad (0.471 $m^3.s^{-1}$), Stará Ľubovňa (0.073 $m^3.s^{-1}$) and Kežmarok (0.067 $m^3.s^{-1}$)
- Summary groundwater abstraction: 0.164 $m^3.s^{-1}$.

Figure 2.3 shows a map of Slovakia marked with runoff conditions (average annual runoff depth) and the borders of the studied basins.

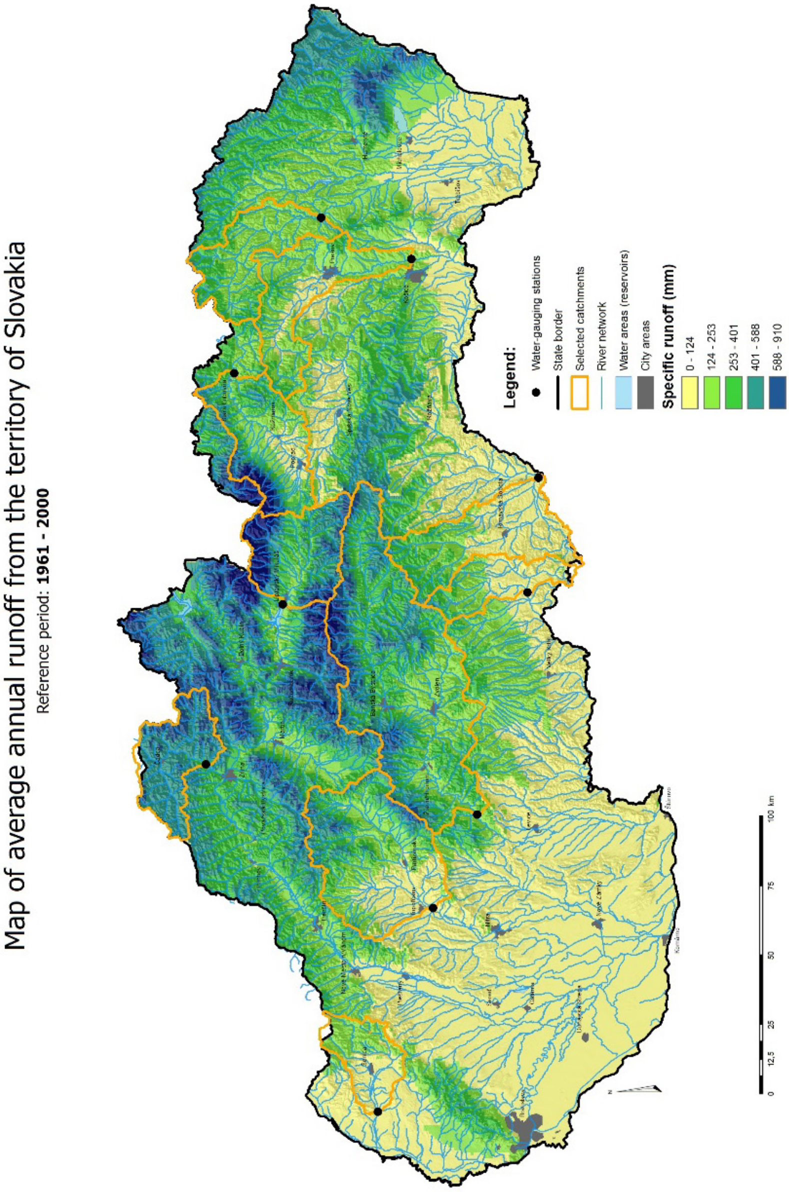


Fig. 2.3 Runoff conditions of Slovakia – average annual runoff depth (mm)

3. DEVELOPMENT AND PROGNOSIS OF METEOROLOGICAL DROUGHT IN SLOVAKIA

3.1. CHARACTERISTICS OF THE METEOROLOGICAL SITUATION IN SLOVAKIA IN THE YEARS 1981 TO 2015

The processing of air temperature was based the Methodological Regulation for the Computation of Climate Normals. The Methodological Regulation defines the basic concepts and the methods for computing and using climate normals. This material is fully in accordance with the recommendations of the World Meteorological Organisation (WMO) published in 1983 (WMO, 1983) and the previously applicable methodology (Nosek, 1972), which the current document clarifies and extends.

3.1.1. Definitions and terms

The term climate normal means a statistical characterisation of the climate calculated from a sufficiently long time series of meteorological measurements and observations in a climatically stable period to represent the climate of a given location. The term characterisation of the climate means a characterisation that is suitable for a given purpose. The WMO defines a normal as a statistical characterisation computed uniformly from data covering at least three consecutive decades. The standard normals are 1931–1960 and 1961–1990. Other periods, even if they are 30 years long, were previously referred to as long-term averages. At present, partly in response to climate change, the WMO is considering defining the period 1981–2010 as a normal and we have used this period for reference in view of the recency of the measurements used in the present work.

Comparisons of current weather (or a defined period with a certain type of weather defined by a meteorological feature or characteristics) with a normal or long-term average must abide by the following rules:

- The term **deviation from the normal or long-term average** is used for characteristics that can have positive or negative values (e.g. air temperature)
- The term **percentage of the normal or long-term average** is used for characteristics that can only have non-negative values (total atmospheric precipitation, sunshine etc.)
- The term **qualitative assessment** and the degrees: normal, above normal, much above normal and extremely above normal phenomenon or below normal, much below normal and extremely below normal phenomena are used for percentage ranges in the incidence of a meteorological element or its parameter, as shown in tab. 3.1.1.1
- When computing the probability of repetition (once in 10; 30; 100 years etc.), the interval boundaries for the evaluation of monthly (seasonal) average air temperatures and monthly (seasonal) totals of atmospheric precipitation were based on quantiles of monthly (seasonal) average air temperatures for the period 1951–1980 and determined

occurrence of monthly (seasonal) total precipitation in the period 1901–1970 based on Petrovič and Šoltýs (1984), and Šamaj and Valovič (1978) respectively

- Quantitative assessment of precipitation uses Dub's system (Dub, 1957) – tab. 3.1.1.2
- The homogeneity (inhomogeneity) of the 1981–2010 (and other values in the series 1981–2015) was verified using software implementing MASH (Multiple Analysis of Series for Homogenization), a method approved and recommended in the project ACTION COST-ES0601 and its working groups as one of the possible methods for detecting inhomogeneity in a time series, complemented by MISH (Meteorological Interpolation Software for Homogenization).

Tab. 3.1.1.1 Qualitative evaluation of meteorological elements or parameter occurrence

Labelling	Safety in percent
EaN-extremely above-normal	<2%
SaN-strongly above-normal	2–9.9%
aN-above-normal	10–24.9%
N-normal	25–75%
bN-below normal	75.1–90%
SbN-strongly below-normal	90.1–98%
EbN-extremely below-normal	>98%

Tab. 3.1.1.2 Qualitative evaluation of precipitation according to Dub (1957)

Labelling	Range in percent
EW-extremely wet	above 140%
VW-very wet	121 to 140%
W-wet	111 to 120%
N-normal	90 to 110%
D-dry	80 to 89%
VD-very dry	60 to 79%
ED-extremely dry	below 60%

3.1.2. Air temperature

The evaluation of air temperature used a complete or completed (homogenised) series of monthly values compared with the 1981–2010 normal (or long-term average). Evaluation is based on data from around 70 climatological stations that recorded observations in the period 1981–2015 and have a complete or completed series of observations and an available value of the normal (or long-term average) for the 1981–2010 period.

Years with normal temperatures (average annual air temperature was assessed as normal at more than 50% of climatological stations) include 1981–1983, 1988–1990, 1992–1993, 1998–1999, 2001, 2003 – 2006 and 2010.

Years with below-normal temperatures (average annual air temperature was assessed as below normal at more than 50% of climatological stations) include 1984–1987, 1991 and 1996.

Years with above-normal temperatures (average annual air temperature was assessed as above normal at more than 50% of climatological stations) include 1994, 2000, 2002, 2007–2009 and 2011–2015.

One of the years in which a particularly significant percentage of below-normal values were identified was **1985**. In 1985, 100% of the climatological stations had an average annual temperature below the 1981–2010 normal, with 3.4% of stations have below-normal values, 44.1% of stations having much below-normal values and 52.5% having extremely below-normal values. Months that contributed strongly to the below-normal character of the weather included January, with the temperature much below normal at 92.9% of climatological stations and extremely below normal at 2.9%, February, which was much below normal at 85.9% of stations and extremely below normal at 14.1% of stations, and June, when the monthly average temperature was extremely below normal at 88.4% of measuring sites. Below-normal monthly air temperatures were recorded also at a large percentage of climatological stations in July (38.8%), in August (22.1%), September (36.2%), October (40%) and even more significantly in November, when, on a more detailed scale, 19.4% of stations recorded a below-normal monthly air temperature and 67.6% recorded much below-normal values. Air temperature in the warm half of the year was recorded as below normal at 45% of climatological stations and much below normal at 50%. In the winter of 1984/1985, the temperature was recorded as below normal at 96.6% of climatological stations and extremely below normal at 3.1%. The much below-normal and extremely below-normal values were evenly distributed across the whole territory of Slovakia and there were no regional differences.

The year **2007** is an example of a year with above normal temperatures. The average annual air temperature was significantly above normal, with the full 100% of climatological stations recording temperatures in the above-normal range. An above-normal annual value compared to the average annual air temperature for the 1981–2010 normal was recorded at 6.8% of the climatological stations, much above-normal at 81.4% and extremely above-normal at 11.9% There were only two months with below-normal temperatures in 2007 – September and November. Above-normal months included January (above-normal at 5.7% of climatological stations, much above-normal at 41.4% and extremely above-normal at 51.4%), March (above-normal at 56.7% of stations and much above-normal at 43.3% of stations), April (significantly above-normal values at 71% of stations and much above-normal at 6% of stations). The trend continued in May, with above-normal temperatures at 57.4% of stations and much-above-normal values at 2.9%, in June, with 39.1% above normal and 60.9% much above normal and in July with 43.3% above normal and 37.3% much above normal values. August ended this significantly warm period with above-normal temperatures at 47.1% of climatological stations and much-above-normal average monthly air temperatures at 16.2% of stations. Temperatures for the warm half-year as a whole were above normal at 43.3% of climatological stations and much above normal at 50% of climatological stations. The winter of 2006/2007 had much above-normal temperatures at 7.8% of climatological stations and extremely above-normal temperatures at 92.2% of stations. Examination of the territorial distribution of temperatures found that much above-normal temperatures occurred regularly throughout Slovakia with the extremely above-normal temperatures occurring in Eastern Slovakia, in the Spiš region, in and around Košice (Abov) and in Lower Zemplín.

3.1.3. Atmospheric precipitation

The evaluation of precipitation in the period 1981–2015 was based on data from 500 rain gauge stations in the territory of Slovakia. The evaluation of the precipitation character of a year was based on relative total atmospheric precipitation, expressed in terms of the total precipitation as a percentage of the normal. Qualitative assessment was based on Dub's method, in which the annual total is expressed as a percentage of the long-term average (in this case the 1981–2010 normal). Categorisation based on relative total precipitation is very clear and permits the assessment of precipitation variability if a long-term average is available for the studied location.

One of the years with the lowest total precipitation, and therefore also with the lowest percentage of the 1981–2010 normal) is **2003**. This year was dry at 19.8% of stations, very dry at 74.4% of stations and extremely dry at 3% of stations. The year in which the 500 rain gauge stations were most frequently recorded as having total annual precipitation within the normal range was **1998**. The year **2010** was evaluated as a wet year for 96.6% of stations. To go into more detail: 1.6% of stations were categorised as wet, 19.6% as very wet and as many as 78.4% of stations were extremely wet.

Looking at the annual precipitation totals for Slovakia in the 1981–2015 period as a whole, prior to 1993 years are more frequently classified as dry under Dub's system (sometimes consecutive years), while extremely dry years occur after 2002 but with several years between them (2003, 2011). If 50% of the total number of rain gauge stations is taken as the threshold for identifying a period of normal total precipitation, the most normal (homogeneous) period of annual total precipitation in Slovakia is the period 1991–2001. The highest number of annual precipitation totals classified as normal from the total 500 rain gauge stations was, however, in 1988. After 1993 the number of years classified as wet years began to increase, reaching its maximum in 2010, which was classified as wet based on total annual precipitation at all rain gauge stations.

3.2. METHOD FOR THE PREPARATION OF CLIMATE CHANGE SCENARIOS

Mean global and regional air temperatures have increased in the last several decades more than any time during the history of instrumental measurement. Significant achievements have been reached recently in the field of climatic modeling – the World modeling centers included into the models nearly complete global climatic system (i.e. also the cryosphere, lithosphere and biosphere). The General Atmospheric Circulation Models (GCMs) outputs can be obtained also in the format of daily data time series (means and extremes) with the grids resolution of about 300x300 km. This resolution can be improved by the method of the nested Regional Circulation models (RCMs) with final grids resolution about up to 10x10 km.

Two Regional Circulation models (Dutch KNMI and German MPI) have been used for design of climate change scenarios for Slovakia region (van Meijgaard et al., 2008 (KNMI); Jacob, 2001; Jacob et al., 2001 (MPI)). The selected RCMs manifested as the best ones at description of real climate in the Central Europe in 1961–1990 from the point of view of annual course and occurrence of characteristic values (variability, number of specific days and extremes).

The RCMs offer outputs of several variables with daily frequency for the period 1950/51 to 2100. These models represent a more detail integration of the atmospheric and oceanic dynamic equations with the grid point resolution about 25x25 km. These models have 19x10 grid points in the Slovakia region and its neighborhood with a detailed topography and appropriate expression of all topographic elements larger than 25 km. All models applied the SRES IPCC GHGs emission scenarios (IPCC, 2007; 2014). The RCMs use the medium pessimistic scenario SRES A1B with global warming by 2.9°C until 2100 compared to 1961–1990.

Based on the models outputs and the measured meteorological data, daily scenarios for a number of climatic and precipitation stations all over Slovakia have been designed. These climate change scenarios to be successful for utilizing in the impact studies featured in several socio-economic analyses.

The chapter on climate change scenarios was created with the support of the projects APVV-0303-11 and APVV-0089-12. The authors also thank the Slovak Hydrometeorological Institute for data. This task was partly supported also by the Grant Agency of the Slovak Republic under the project VEGA No. 1/0940/17.

3.2.1. Data and methods

The scenarios of climate change and changes in the water balance elements were prepared up to the time horizon of the year 2100. The modified RCMs model outputs and the measured data at about 30 meteorological stations in 1951–2016 were used for this purpose. These scenarios have been prepared for the following variables: the daily means of maxima and minima of air temperature, relative air humidity, daily total of precipitation, potential and actual evapotranspiration.

Daily data from the Slovak Hydrometeorological Institute (SHMI) as air temperature (T), relative air humidity (H) and precipitation (P), have been analyzed for selected meteorological stations in Slovakia from year 1951–2016. Additional elements such as a soil moisture (W) and a potential evapotranspiration (E_o) were calculated by analytical methods.

The process of climatic data and characteristics elaboration as time series for 1951–2100 can be divided into several steps (Damborská et al., 2016; Lapin et al., 2016). To prepare scenarios the RCMs outputs must be regionally modified at use of observed climate from the stations network. Statistical modification of the distribution curves takes place in the first case. The reason is to improve statistical characteristics of modeled time series during the control period compared to the observed ones within the same period considered here as reference. Comparison is done for means and variance. The final goal at the downscaling is to obtain the modified model output in the same format as the measured data. However some climatic elements are not available among the GCMs and RCMs outputs so they must be calculated by some analytic physical or semi-experimental methods based on the other measured climatic data (evapotranspiration etc.). For the calculations of downscaling coefficients the period 1961-1990 was considered as the reference and the period 1951–2016 as the control one for the evaluation of downscaling reliability.

Using obtained statistics, we are ready to adjust the modeled data in the future in such a way as to best capture the predicted climatic characteristics of the region. It results in minimization of deviations caused by inaccuracies from the inputs or the model structure of the simplified equations. Depending on the type of concrete variable, the statistical parameters in the reference period are determined.

3.2.2. Air temperature scenarios

Daily mean temperature is generally used as a universal measurement for climate change study. The air temperature is measured at a height of around two meters above the surface by a classic mercury thermometer at 7, 14 and 21 h MLT (mean local time). Three stations: Hurbanovo (115 m a.s.l., SW Slovakia), the Košice airport (230 m a.s.l., SE Slovakia) and Liptovský Hrádok (640 m a.s.l., N Slovakia) were selected to calculate the areal deviations of the monthly and seasonal means from the long-term averages in the period 1901–2000. Only insignificant changes showed between the mean deviations calculated from more stations for the period 1981–2010 and those calculated by the three stations mentioned.

The deviations of the mean temperatures and trends in Slovakia for a cold half-year (CHY, Oct.–March) and a warm half-year (WHY, Apr.–Sept.) are illustrated in Fig. 3.2.2.1. It is clear that the mean temperature in Slovakia has increased by about 2°C since 1881 as a linear trend. Nearly the same increase has also occurred since 1881 both in the CHY and WHY.

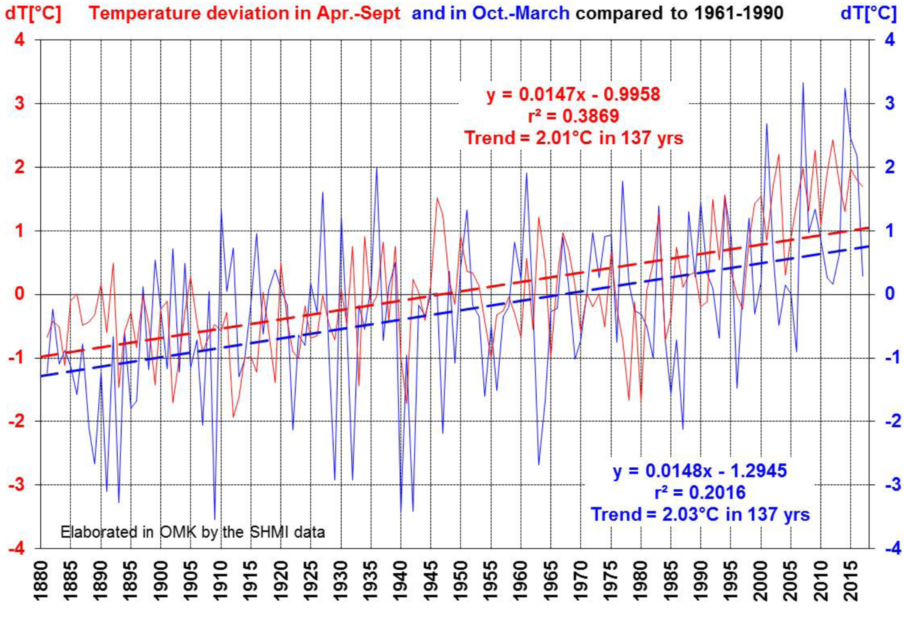


Fig. 3.2.2.1 Deviations of mean temperatures (***dT***) and trends in Slovakia for a cold half-year (CHY, Oct.–March) and a warm half-year (WHY, Apr.–Sept.) in 1881–2017

A higher increase in the mean temperature can be observed in the months from January to August (Fig. 3.2.2.2 for Hurbanovo).

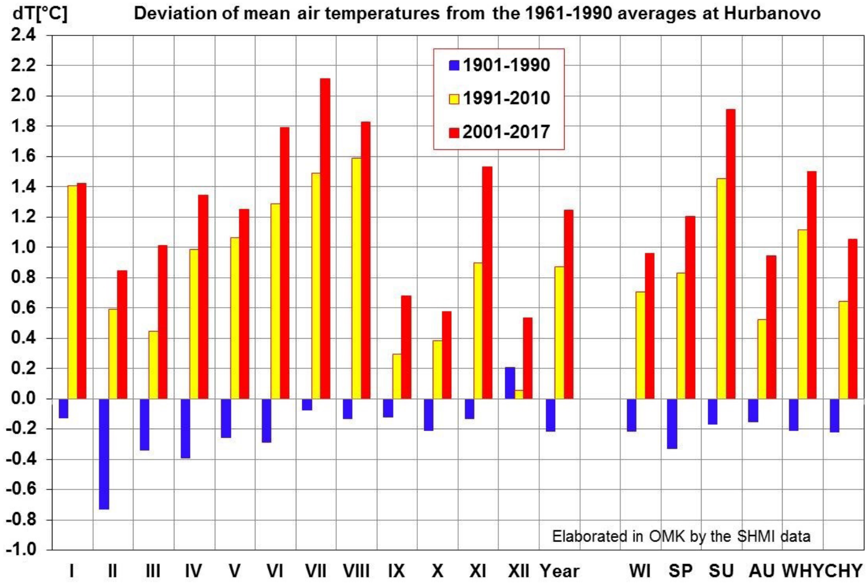


Fig. 3.2.2.2 Deviation of mean monthly and seasonal temperatures (***dT***) at Hurbanovo from the 1961–1990 averages in 1901-2016 (preliminary 2017)

In Fig. 3.2.2.3, the mean warm half-year air temperature (*T*) measured at Hurbanovo in 1951–2016 and modified model outputs by MPI and KNMI from year 1951–2100 are shown. In spite of the fact that the measured values fit very well with the modelled ones, it is evident that modelled values are right different in individual years. The differences among the models are increasing by the end of the 21st century.

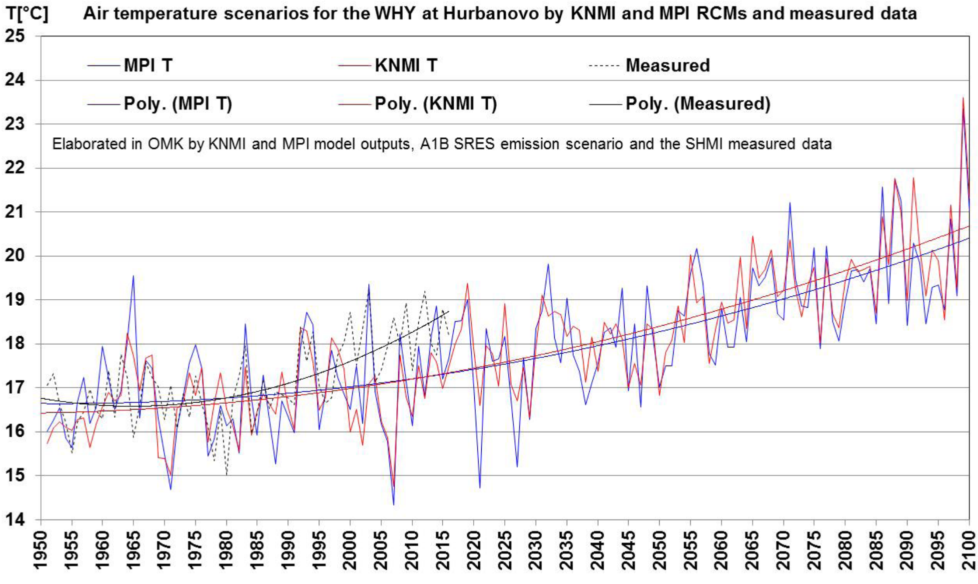


Fig. 3.2.2.3 Scenarios of mean warm half-year air temperature (T) at Hurbanovo for 1951–2100 and measured values in 1951–2016

3.2.3 Precipitation totals scenarios

Precipitation totals and precipitation events occurrence are the most problematic variables in the process of climate change scenarios design. Generally, precipitation totals increase with rising air temperature because of increasing water vapour concentration in the atmosphere by about 6% per 1°C. On the other hand, precipitation regime is significantly influenced by upwind and lee effects due to the topography, what means that precipitation regime depends predominantly on the direction of atmospheric circulation. Another important factor is cyclonicity, mainly suitable conditions for the vertical motions in the atmosphere. It seems that the regional models RCMs can express all the factors mentioned above as physically interpreted processes more precisely.

Daily precipitation totals are measured in Slovakia with the Metra 886 national gauge (1 m above ground and with a 500 cm^2 orifice). Fig. 3.2.3.1 illustrates annual and seasonal precipitation totals from year 1881–2016/17.

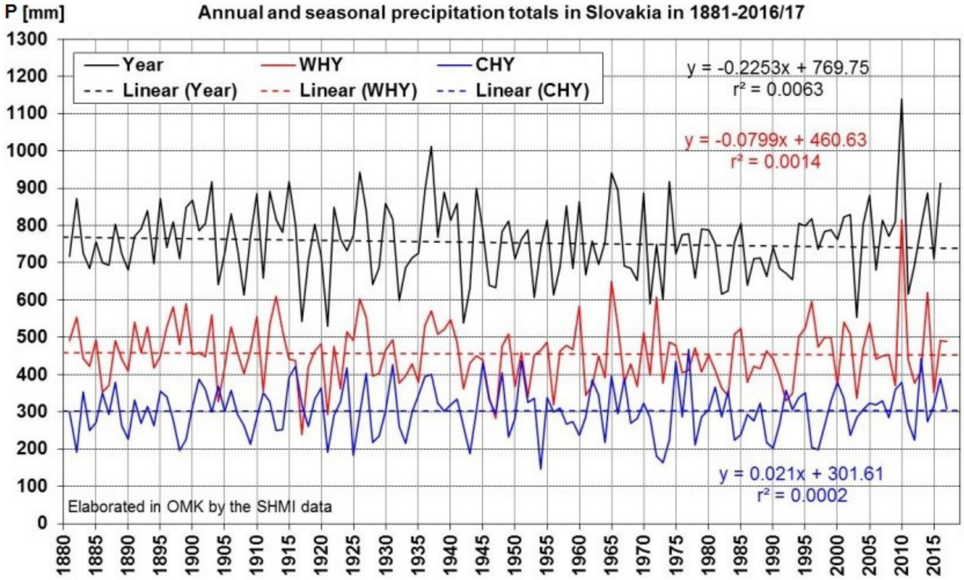


Fig. 3.2.3.1 Annual and seasonal (CHY (Oct.–March) and WHY (Apr.–Sept.)) precipitation totals in Slovakia from year 1881–2016/17 (based on 203 stations)

Since 1881, any significant trends have not been exhibited. In the CHY a decreasing trend can be identified in southern Slovakia and an increasing trend in northern Slovakia (Fig. 3.2.3.2). Since 1995, the annual and seasonal totals have a greater variability. Also an increasing share of the convective precipitation has been registered.

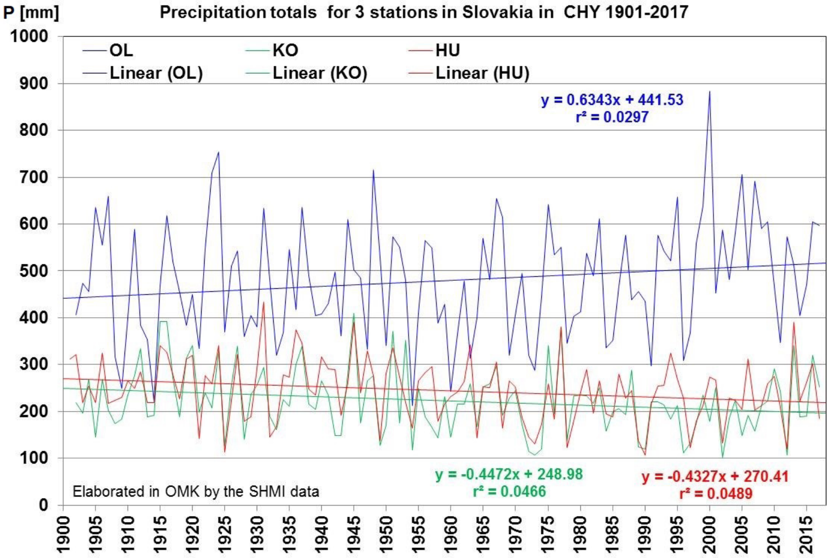


Fig. 3.2.3.2 Cold half-year (CHY, Oct.–March) precipitation totals for 3 stations in Slovakia from year 1881/82–2016/17 (Hurbanovo (HU), 115 m a.s.l., SW Slovakia, Košice (KO), 230 m a.s.l., SE Slovakia, Oravská Lesná (OL), 780 m a.s.l., NW Slovakia)

The total annual precipitation (*R*) has increasing trend by about 10% (more in northern Slovakia, less in southern Slovakia) up to 2100. Fig. 3.2.3.3 shows the precipitation scenarios for warm half-year at Hurbanovo by KNMI and MPI models from year 1951–2100 and measured values in 1951–2016. It can be seen that the summer precipitation totals demonstrate mostly decreasing trend, especially in southern Slovakia.

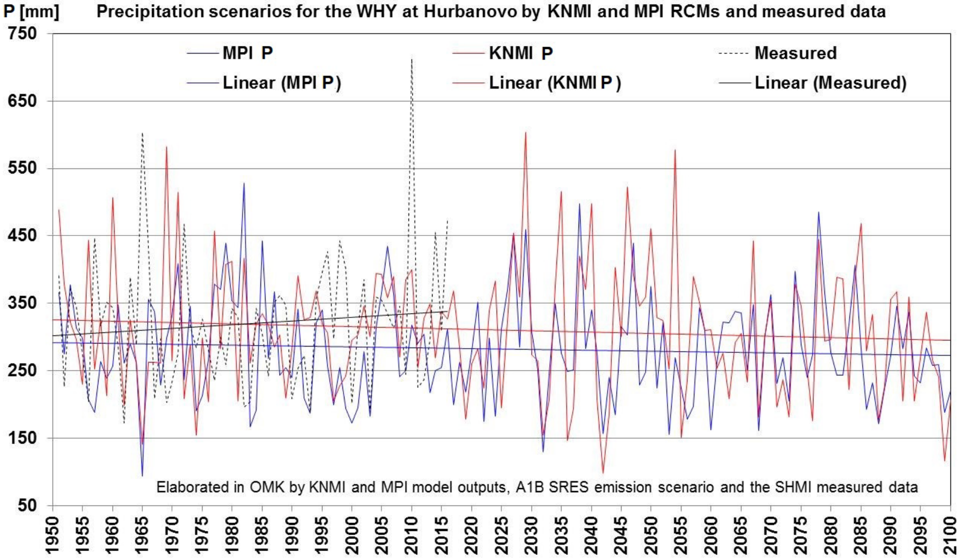


Fig. 3.2.3.3 Scenarios of warm half-year precipitation totals (R) at Hurbanovo in 1951–2100 and measured values in 1951–2016

3.2.4. Air humidity scenarios

The air humidity (*RH*) is not considered as a frequently applied climatic element in climate change scenarios. However, the air humidity characteristics play a very important role in all impact models. The air humidity can be expressed in several variables (the water vapor pressure, the absolute humidity, the specific humidity, the relative humidity and the saturation deficit). We decided to apply only *RH* outputs as primary source for all other air humidity variables calculation. The air humidity is measured by dry and wet mercury thermometers (the psychrometric method) under the same conditions as the air temperature in Slovakia.

The KNMI model outputs are very close to the measured data and have a slightly higher variability (Fig. 3.2.4.1). This comparison proofs that the regional RCMs outputs as much more reliable than the global GCMs ones.

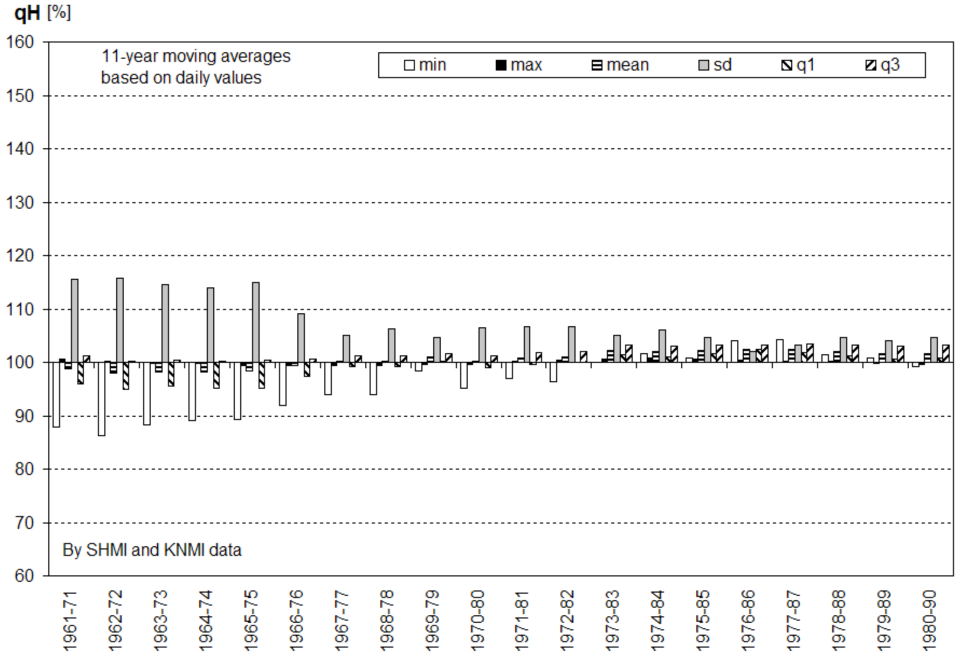


Fig. 3.2.4.1 Quotients of model KNMI outputs and measured annual relative humidity characteristics (in %) at Hurbanovo; *min* and *max* – the annual minimum in daily means, mean – the annual mean, *sd* – annual standard deviation from daily means, *q1* and *q3* – the lower and upper quartile from daily means

Fig. 3.2.4.2 illustrates the mean relative air humidity and trends for a cold half-year (Oct.–March) and a warm half-year (Apr.–Sept.) at Hurbanovo station from year 1901–2016. The trends in relative humidity at Hurbanovo are comparable to other lowland stations (a decrease in WHY means by about 5% since 1901). A slightly decreasing trend is observed in the mountains and in the northern half of Slovakia. Deviation of monthly and seasonal relative air humidity means (*dRH*) from the 1961–1990 averages in 1901–2016 at Hurbanovo are illustrated in Fig. 3.2.4.3. It can be seen that the mean relative humidity demonstrates the most significant decrease in the months from March to August.

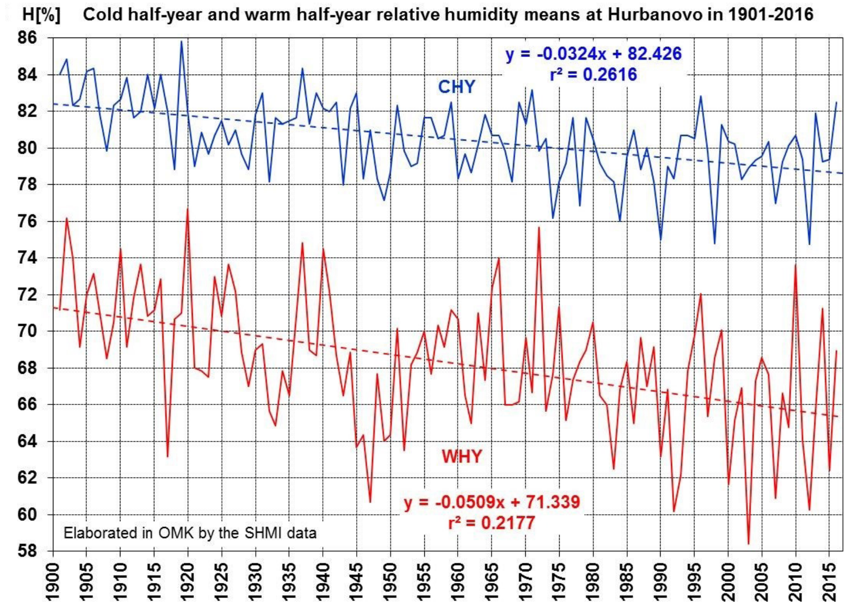


Fig. 3.2.4.2 Mean relative air humidity and trends for a cold half-year (CHY, Oct.–March) and a warm half-year (WHY, Apr.–Sept.) at Hurbanovo in 1901–2016

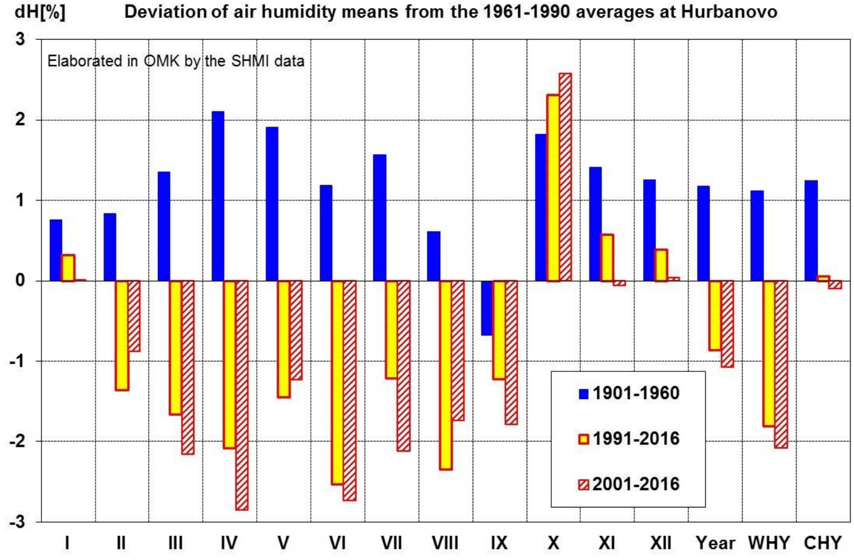


Fig. 3.2.4.3 Deviation of monthly and seasonal relative air humidity means at Hurbanovo from the 1961–1990 averages in 1901–2016

The annual and warm half-year scenarios of the mean relative air humidity show only an insignificant decreasing trend or no trend up to 2100. On the other hand, the saturation deficit (Δ) has probably positive trend for the whole country. As demonstrated in Fig. 3.2.4.4, a greater increase in Δ is expected in the WHY for the southern lowlands of Slovakia.

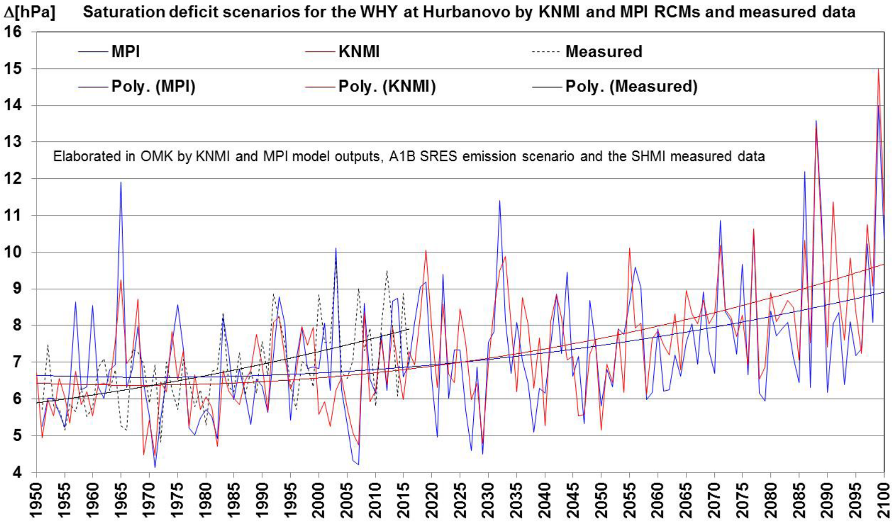


Fig. 3.2.4.4 Scenarios of the mean warm half-year saturation deficit at Hurbanovo from year 1951–2100 and measured values in 1951–2016

3.2.5. Potential and actual evapotranspiration scenarios

The potential evapotranspiration is a complex hydrologic, meteorological and climatic variable depending on temperature (radiation balance), wind speed (turbulence conditions), saturation deficit and active Earth surface properties (including vegetation type) at well saturated upper soil layer and unchanged meteorological conditions. So the process of scenario design is more problematic. To calculate the monthly and seasonal totals of evapotranspiration, we decided to apply quite simple Zubenok (Zubenok, 1976) and complex Budyko methods (Budyko, 1974) modified by Tomlain (Tomlain, 1980) for Slovakia.

The Zubenok method is based on saturation deficits only. The semi-empiric Zubenok formula was calculated for each month during the year and for some specific geobotanic areas (like desert, semidesert, steppe, forest-steppe, deciduous forest, conifer forest and tundra). The daily values of saturation deficits were calculated from the modified RCMs outputs for the daily averages of air temperature and relative humidity. The calculated monthly averages of the saturation deficits from the daily values are very reliable. So this method is comfortable for calculating of the monthly potential evapotranspiration totals up to the year 2100.

Evapotranspiration totals have been calculated in Slovakia as monthly values for 32 stations since 1951. Fig. 3.2.5.1 and 3.2.5.2 demonstrate the mean potential and actual evapotranspiration for selected stations in Slovakia during the periods 1951–1990 and 1991–2016. It is obvious that an increase of potential evapotranspiration follows the rising of air temperature and saturation deficit. Changes in actual evapotranspiration are due to changes of potential evapotranspiration, precipitation and the soil moisture availability.

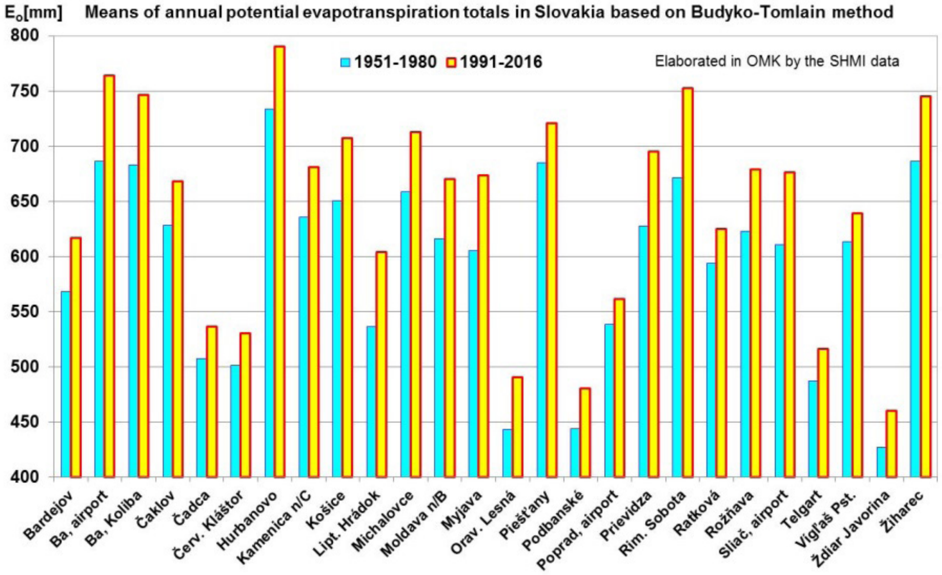


Fig. 3.2.5.1 Mean potential evapotranspiration totals at 26 stations in Slovakia for the periods 1951–1990 and 1991–2016 by the Budyko-Tomlain method (Michalovce, 112 m a.s.l., Ždiar Javorina, 1020 m a.s.l.)

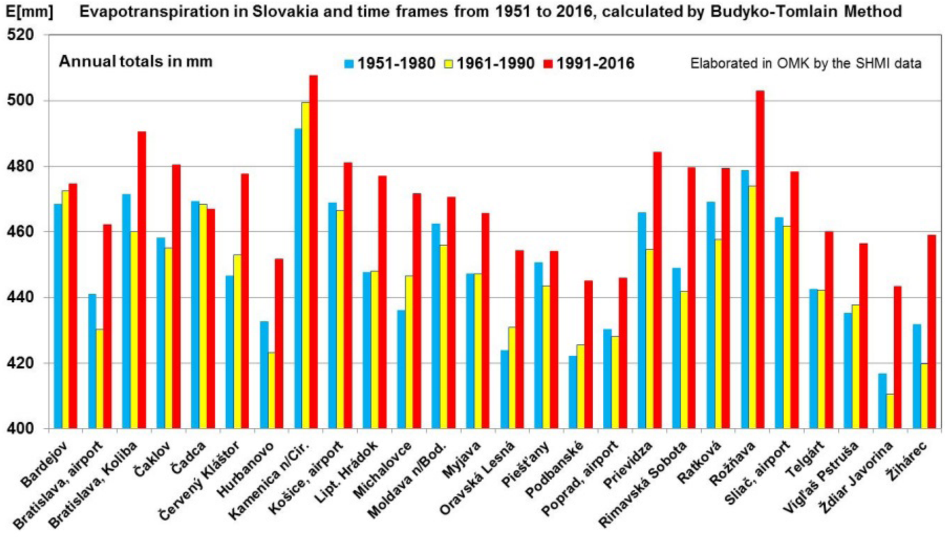


Fig. 3.2.5.2 Mean actual evapotranspiration totals at 26 stations in Slovakia from years 1951–1990 and 1991–2016 by the Budyko-Tomlain method

Fig. 3.2.5.3 illustrates possible changes in the warm half-year and cold half-year potential evapotranspiration totals at Hurbanovo from the period 1951 to 2100. It can be seen a significantly increasing trend in season April–September by KNMI and MPI saturation deficit scenarios. On the other hand, the interannual variability shows a rise. A similar development can be expected for the other lowland sites and the lower localities in northern Slovakia.

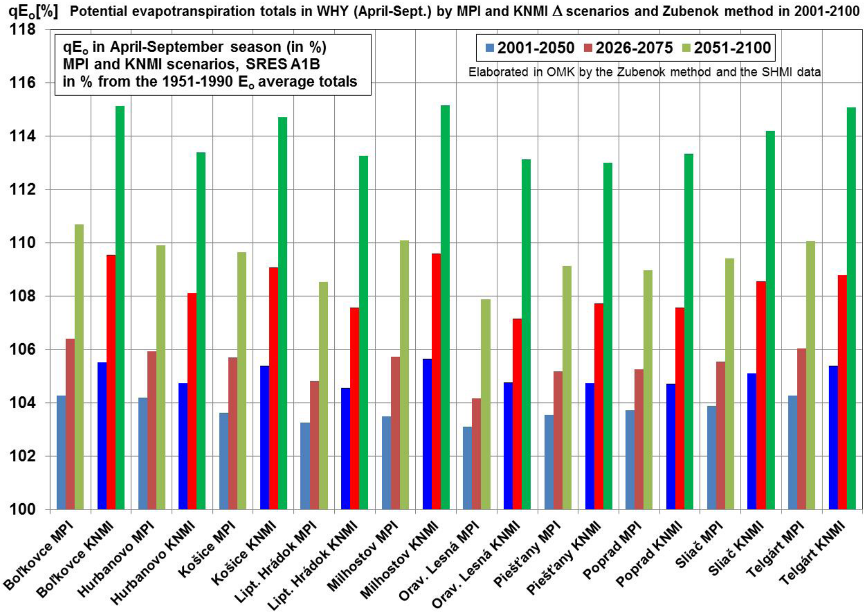


Fig. 3.2.5.3 Scenarios of potential evapotranspiration totals at 10 stations in Slovakia by the KNMI and MPI saturation deficit scenarios and the Zubenok method from years 2001–2100 (Milhostov, 105 m a.s.l., Telgárt, 901 m a.s.l.)

3.2.6. Conclusions on climate change scenarios results

Elaboration of regional models outputs by statistical downscaling brought huge amount of daily data as scenarios, convenient for the further processing and elaboration of the climatic characteristics, extreme events, etc. The scenarios of climate change and changes in the water balance elements were prepared up to the time horizon of the year 2100. For this purpose, the modified model outputs and the measured data at about 30 meteorological stations from years 1951–2016 were used.

The results showed that means of air temperature has increased in the 30-year averages by about 2°C to 4°C up to the end of the 21st century and precipitation totals about 10% in annual totals (more in the north and less in the south of Slovakia). Our analysis indicates that the precipitation and air humidity regime change will modify the air temperature daily range probably comparably as the increase in daily mean temperature.

The changes in regimes and the climatic elements variability on a shorter scale (daily and hourly data) effect also the hydrological cycle and processes. The presented study indicates significant increase in the variability of precipitation, including long periods with low precipitation totals and short periods with very high precipitation totals. It may lead to the great changes in the soil water, the intensity of precipitation, the totals of areal evapotranspiration and the runoff regime. It seems that the probability of occurrence of droughts, flash or regional floods will increase in Slovakia. The models elaboration has confirmed the serious risk of unusual hydrologic situations appearance in the near future.

4. DEVELOPMENT AND PROGNOSIS OF THE HYDROLOGICAL DROUGHT OCCURRENCE IN WATERCOURSES

4.1. CHARACTERISTICS OF THE HYDROLOGICAL SITUATION IN SLOVAKIA IN THE YEARS 1981 TO 2016

From a time perspective, the hydrological evaluation of discharge characteristics can be conducted using daily, monthly and annual intervals, or multi-year periods. Even smaller time steps (e.g. hours) are useful for the evaluation of fast-changing hydrological events such as flash floods. Hydrological drought is typically characterised by a slow onset and gradual decrease. The smallest interval in its evaluation is therefore usually the series of average daily discharges and related statistics.

Evaluation of the relationship between precipitation and runoff in Slovakia in the studied period shows a trend with a slight linear increase in runoff (fig. 4.1.1).

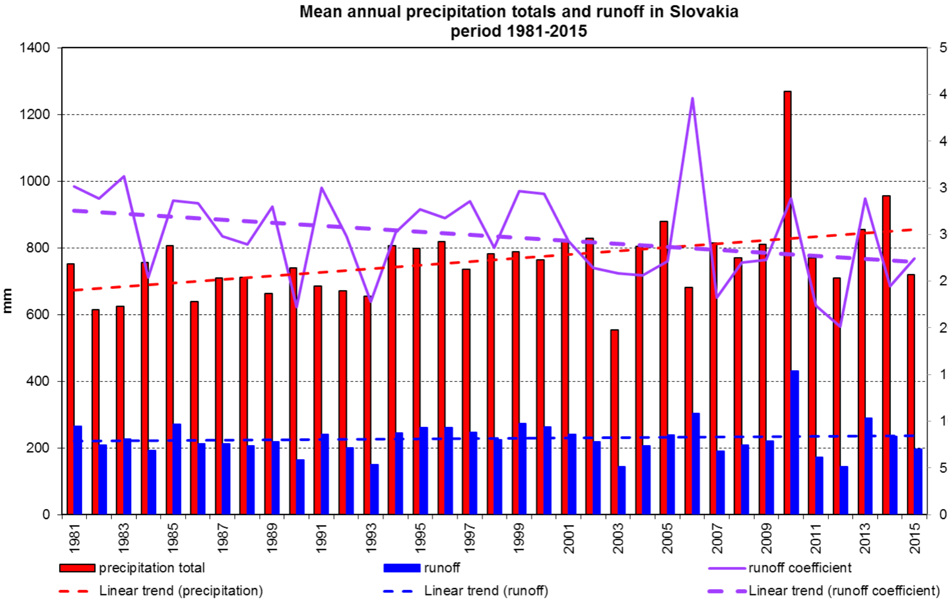


Fig. 4.1.1 Annual runoff, precipitation totals and runoff coefficient development for the Slovak territory in the relevant years within the 1981–2015 period

This trend is significantly influenced by the fact that the start of the period falls in a multi-year period of low flow and therefore the overall evaluation of precipitation, runoff and the runoff coefficient is presented for the longer period 1931–2016 (fig. 4.1.2, 4.1.3).

In the longer time period there is clearly a moderate increasing trend in annual precipitation totals in Slovakia and also a decreasing trend in annual surface water runoff from the territory of Slovakia. The runoff coefficient expresses runoff as a proportion of precipitation and therefore has a logical decreasing trend. In figure 4.1.3 showing the development of the runoff coefficient, the period 1978–1990 is highlighted because of the steeper decrease in values for the runoff coefficient, which is also documented by the 10-year moving average with annual time steps.

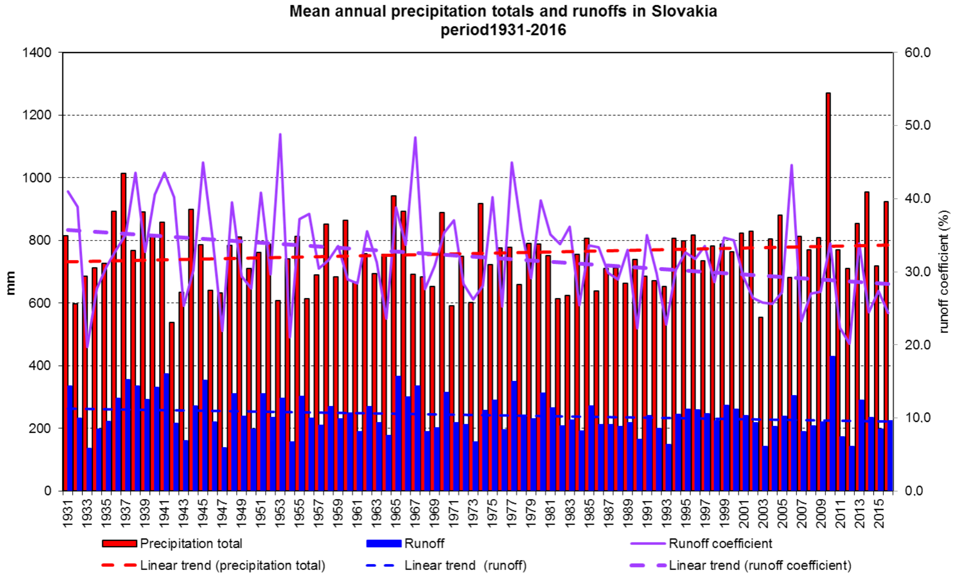


Fig. 4.1.2 Annual runoff, precipitation totals and runoff coefficient development for the Slovak territory in relevant years within the 1931–2016 period

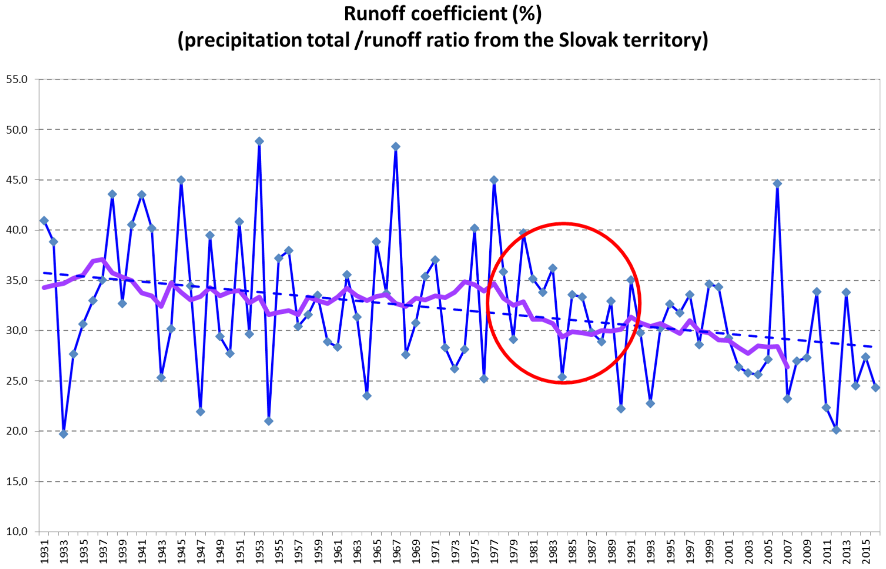


Fig. 4.1.3 Runoff coefficient from the Slovak territory (%) in the relevant years within the 1931–2016 period, 10-year moving average and linear trend

The long-term average of the runoff coefficient is nearly equal to the value for the reference period 1961–2000 (32.3%), while in the period 1981–2015 the average value decreased to 29.8% while for the 15 years from 2001 to 2015 it was lower still–27.9%. The decreasing trend in the runoff coefficient is clearly the result of increasing losses in the water balance equation. Most losses are in the form of water vapour as a result of increasing air temperature. The basic factors influencing runoff from our territory are thus the volume of precipitation and air temperature (Majerčáková et al., 2011).

4.1.1. Average annual discharges

In order to ensure comparability of discharge data between watercourses with different size characteristics, the computation of annual average discharges for the hydrological years in the 1981–2012 period uses relative values, i.e. the percentage ratio of average annual discharge ($\boldsymbol{Q}_r$) and the long-term average discharge for the reference period 1961–2000 ($\boldsymbol{Q}_a$) for individual discharge gauging stations. The relative runoff values in the evaluated profiles are compared in table 4.1.1.1, with the use of colour to distinguish dry, normal and wet years.

In 1982 there were significantly below-average values in nearly all the evaluated basins except the Myjava, with relative values being in the 60–85% range, except for the Nitra and the Kysuca, which had around 90% of average levels. In 1984 there was below-average flow in the range 60–90% of $\boldsymbol{Q}_a$ in basins other than the Hron and the Ipeľ.

There were longer periods of low flow in several of the studied profiles in the period 1986 to 1993, when below-average values occurred especially in the central part of Slovakia (Hron, Ipeľ, Rimava) in 1989–1993 and in the Myjava River Basin and in 1988–1993 in the Nitra River Basin. The Poprad had low flow in the years 1986–1988, 1990 and 1993 interrupted by periods of normal or above-average flow in 1989, 1991 and 1992. In this period, there was significant drought in all the studied profiles in 1990 and especially in 1993, when all the river basins were affected and the relative value $\boldsymbol{Q}_r/\boldsymbol{Q}_a$ fell to 25–28% in the Ipeľ and Rimava River Basins and other profiles had relative values in the range 42–76%.

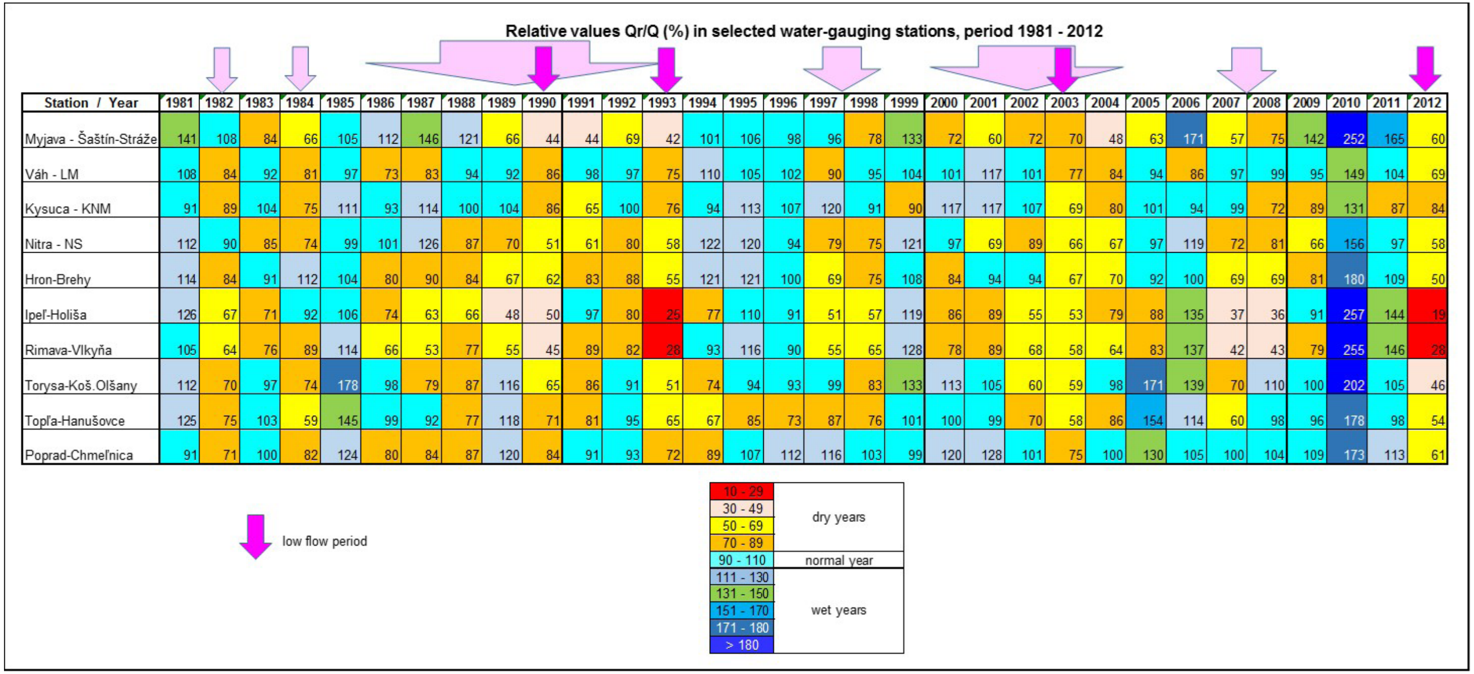
In the years 1997–1998, below-normal values for average annual discharges were once again recorded in the central part of Slovakia (Nitra, Hron, Ipeľ, Rimava) in the range 50–80%, and in the east (Topľa) in the range 76–87%.

Another period when average annual discharges fell below the long-term average was 2000–2004. The most significantly affected basins were the Myjava, Nitra, Ipeľ and Rimava, and in 2002–2003 also the Torysa and the Topľa. The driest year in this period was 2003, when there were again below-average levels in all the studied profiles ranging from 53% to 77%.

In 2007–2008 below average values of $\boldsymbol{Q}_r$ were recorded in the studied profiles of the Myjava, Nitra, Hron, Ipeľ and Rimava, with the Ipeľ and Rimava having only around 40% of their long-term values.

At the end of the studied period, there was the unusually wet year 2010, when the values of $\boldsymbol{Q}_r/\boldsymbol{Q}_a$ ranged from 150% to 255% except for the Kysuca with around 130%. Values decreased in 2011 and in 2012 all profiles were evaluated as significantly below average. The relative value for the Ipeľ was only 19%, for the Rimava 28%. The other profiles ranged from 46% to 60% except for the Váh with 69% and the Kysuca with 84% of the long-term average.

Tab. 4.1.1.1 Occurrence of dry periods in evaluated profiles – average annual discharges (relative values Q_r/Q_a (%))



Relative values Qr/Q (%) in selected water-gauging stations, period 1981 - 2012

Station / Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Myjava - Šaštín-Stráže	141	108	84	66	105	112	146	121	66	44	44	69	42	101	106	98	96	78	133	72	60	72	70	48	63	171	57	75	142	252	165	60
Váh - LM	108	84	92	81	97	73	83	94	92	86	98	97	75	110	105	102	90	95	104	101	117	101	77	84	94	86	97	99	95	149	104	69
Kysuca - KNM	91	89	104	75	111	93	114	100	104	86	65	100	76	94	113	107	120	91	90	117	117	107	69	80	101	94	99	72	89	131	87	84
Nitra - NS	112	90	85	74	99	101	126	87	70	51	61	80	58	122	120	94	79	75	121	97	69	89	66	67	97	119	72	81	66	156	97	58
Hron-Brehy	114	84	91	112	104	80	90	84	67	62	83	88	55	121	121	100	69	75	108	84	94	94	67	70	92	100	69	69	81	180	109	50
Ipeľ-Holiša	126	67	71	92	106	74	63	66	48	50	97	80	25	77	110	91	51	57	119	86	89	55	53	79	88	135	37	36	91	257	144	19
Rimava-Vlkyňa	105	64	76	89	114	66	53	77	55	45	89	82	28	93	116	90	55	65	128	78	89	68	58	64	83	137	42	43	79	255	146	28
Torysa-Koš.Olšany	112	70	97	74	178	98	79	87	116	65	86	91	51	74	94	93	99	83	133	113	105	60	59	98	171	139	70	110	100	202	105	46
Topľa-Hanušovce	125	75	103	59	145	99	92	77	118	71	81	95	65	67	85	73	87	76	101	100	99	70	58	86	154	114	60	98	96	178	98	54
Poprad-Chmeľnica	91	71	100	82	124	80	84	87	120	84	91	93	72	89	107	112	116	103	99	120	128	101	75	100	130	105	100	104	109	173	113	61

10 - 29	dry years
30 - 49	
50 - 69	
70 - 89	
90 - 110	normal year
111 - 130	wet years
131 - 150	
151 - 170	
171 - 180	
> 180	

Based on the classified values, 2012 was the driest year in the profiles of the Váh, Hron, Ipeľ, Topľa, Torysa and Poprad. The Myjava and the Hron had their driest year in 1993, the Kysuca in 1991 and the Nitra in 1990. Taking the set of the three driest years for each profile, the years that occur most frequently are 2012 and 1993 followed by somewhat fewer occurrences for 2003 and 1990. Taking the set of the five driest years for each profile, the year 1993 occurs most frequently followed by 2012, 2003, 1990 and 2007.

4.1.2. Average monthly discharges

When evaluating the minimum values for mean monthly discharges, it is necessary to take account of the natural seasonality of discharges in each watercourse and profile. The distribution of discharges in the year can be represented by the long-term average discharges for individual months in the year $\boldsymbol{Q_{ma}}$ over the reference period (currently 1961–2000). The studied profiles have different periods of minimum values for average monthly discharges in the reference period – in the southern areas they are mainly in the summer or autumn months (e.g. Myjava – September, October, August; Nitra – September, August, October) whereas further north they tend to be in the winter and autumn months (e.g. Váh – February, January, December; Poprad – January, February, December).

This same distribution is found in the lowest mean monthly discharge values in the reference period 1981–2012 in the selected profiles. Table 4.1.2.1 shows the lowest values of $\boldsymbol{Q_m}$ recorded in the studied profiles during the studied period with the month and year of their occurrence.

Tab. 4.1.2.1 Occurrence of average monthly absolute minimum discharges in evaluated profiles in the period 1981–2012

Gauging station	Stream	Month and year of minimum monthly discharge Q_m (min) occurrence	Q_m (min) value ($m^3.s^{-1}$)	% Q_{ma}
Šaštín-Stráže	Myjava	08.1990	0.407	25
Liptovský Mikuláš	Váh	01.1985	4.976	50
Kysucké Nové Mesto	Kysuca	08.1992	1.523	13
Nitrianska Streda	Nitra	09.2003	2.940	40
Brehy	Hron	09.2003	9.967	41
Holiša	Ipeľ	08.1993	0.049	4
Vlkyňa	Rimava	08.1993	0.492	17
Košické Olšany	Torysa	01.2004	1.316	30
Hanušovce nad Topľou	Topľa	12.1986	1.330	22
Chmeľnica	Poprad	12.1986	2.819	34

Taking the 10 lowest mean monthly discharges for each year of the chosen period and each profile, the months that occur most frequently are the same as or close to the months in which the lowest long-term mean monthly discharges for the reference period occur in the relevant profile.

In the profile Myjava - Šaštín-Stráže, the lowest discharges are most often in August, September or October, i.e. the summer-autumn period (lowest long-term mean monthly discharges for the reference period: September, October, August). **In the profile Váh - Liptovský Mikuláš**, the lowest mean monthly discharges in the studied period occurred most often January, February and March, i.e. the winter period (long-term: February, January, December). The lowest mean monthly discharges **in the profile Kysuca - Kysucké Nové Mesto** occurred mainly in August, September, November and October (long-term: November, January).

In the profile Nitra - Nitrianska Streda, the lowest mean monthly discharges were recorded in the summer-autumn period, mainly in September, August and October (long-term: September, August, October, July). **In the profile Hron - Brehy**, the lowest mean monthly discharges occurred mainly in September, August and November, i.e. in the summer-autumn period (long-term: September, August, January, July). **In the profile Ipeľ - Holiša**, the most frequent months for the lowest mean monthly discharges were August, July and September, i.e. the summer-autumn months (long-term: September, August, July and October). **In the profile Rimava - Vlkyňa**, the lowest mean monthly discharges were most often recorded in the summer-autumn period – September, August and July, which is the same as the long-term minimum monthly discharges.

In the profile Torysa - Košické Olšany, the lowest mean monthly discharges occurred mainly in the winter months January, December and September (long-term: September, January, November, December). **In the profile Topľa - Hanušovce nad Topľou**, the lowest values were recorded in January, December, October and September (long-term: September, January, October). **In the profile Poprad - Chmeľnica**, the lowest mean monthly discharges in the studied period occurred in the winter months February, December and January, which were also the months with the lowest long-term average.

The course of mean monthly discharges in selected studied profiles in the period 1981–2012 compared to the long-term mean monthly discharges (in terms of quantiles to 40%, 80% and 120% of Q_{ma}) is shown in fig. 4.1.2.1 to 4.1.2.4 with the coloured background representing the quantiles of Q_{ma} as follows.

🟦	1. quantile (80 to 120% of $\boldsymbol{Q}_{ma\ 1961-2000}$ – normal discharge)
🟨	2. quantile (40 to 80% of $\boldsymbol{Q}_{ma\ 1961-2000}$ – below-normal discharge)
🟥	3. quantile (less than 40% of $\boldsymbol{Q}_{ma\ 1961-2000}$ – critical value of the below-normal discharge)

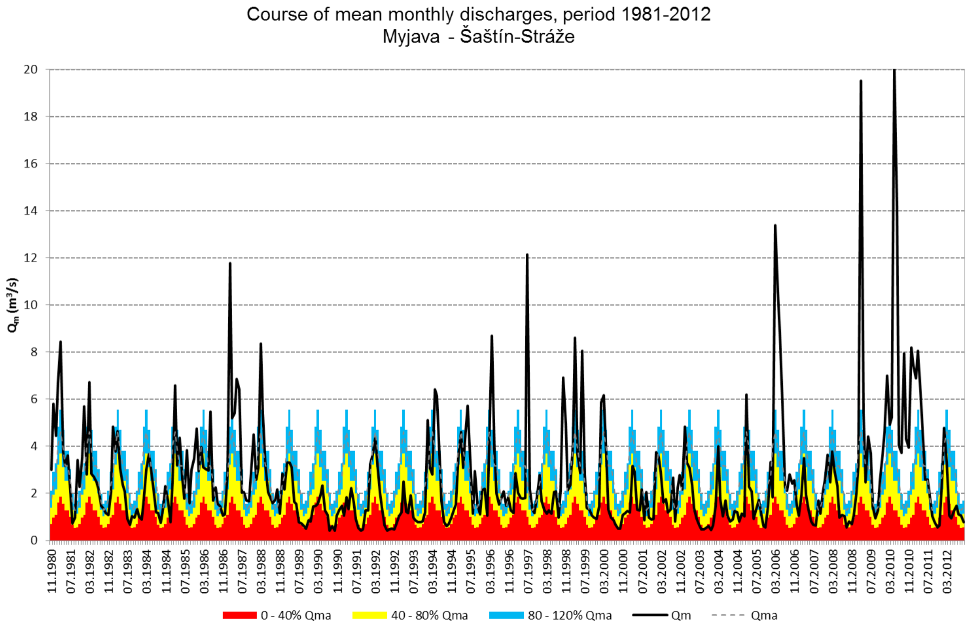


Fig. 4.1.2.1 Course of average monthly discharges for the period 1981–2012, profile Myjava - Šaštín - Stráže

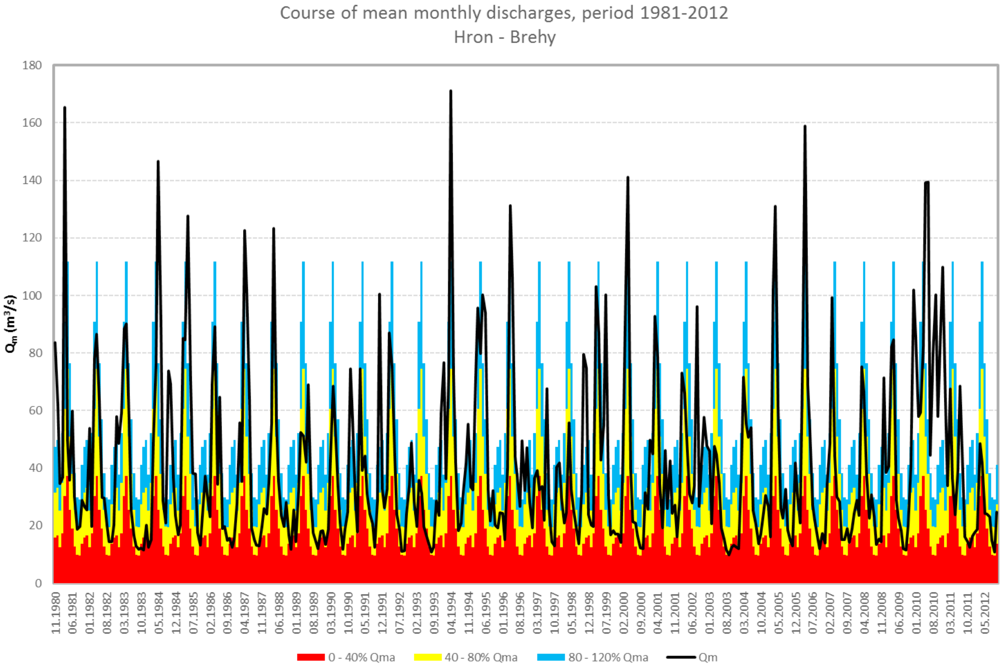


Fig. 4.1.2.2 Course of average monthly discharges for the period 1981–2012, profile Hron - Brehy

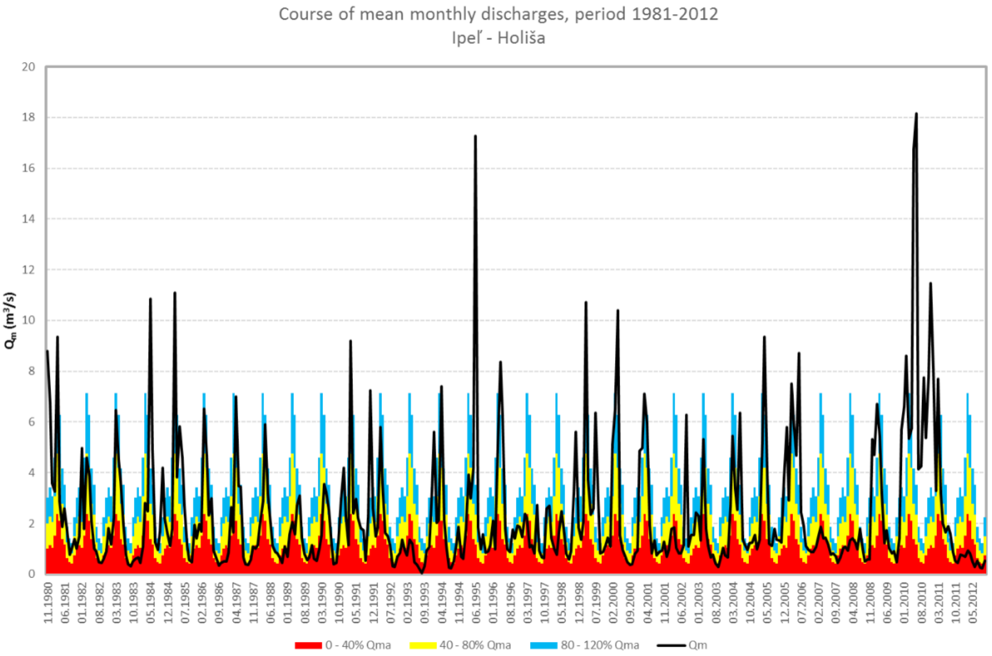


Fig. 4.1.2.3 Course of average monthly discharges for the period 1981–2012, profile Ipeľ - Holiša

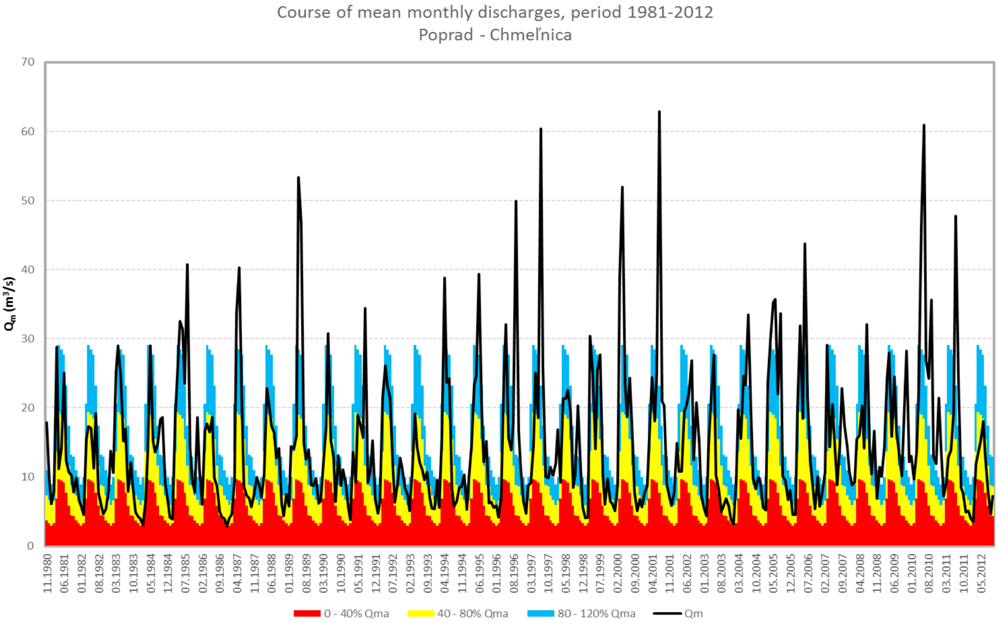


Fig. 4.1.2.4 Course of average monthly discharges for the period 1981–2012, profile Poprad - Chmeľnica

Mean monthly discharges can also be evaluated using relative values, the percentage of the long-term values for mean monthly discharges for the corresponding months of the year (Q_m/Q_{ma} (%)). In this case, the months with minimum relative values for monthly discharges do not usually correspond to the months with the absolute lowest discharges. While the lowest discharges typically occur in the summer-autumn period or winter (water bound up in snow and ice), minimum relative values for monthly discharges occur also in the spring months, when there is usually increased runoff due to melting snow. Certain years' lower discharge values in these months compared to the long-term averages can be caused by various factors (decreased snow storage, earlier/later spring runoff, air temperature, the volume and distribution of precipitation etc.). Although the values for such periods are not usually the absolute minimum for the year, the relative value can be significantly lower and the runoff deficit compared to the normal may comprise relatively large volumes, which can carry over to the next period.

Table 4.1.2.2 shows the relative values of average monthly discharges in each of the studied profiles in the period 1981–2012 with colour highlights based on the quantiles of % Q_{ma} as defined above. From the grouping of colours representing significant below-average monthly discharge values (yellow – less than 80% of the long-term average for the corresponding month and red – less than 40% of the long-term average discharge value for the corresponding month), it is clear when dry periods occurred in consecutive months and influenced several of the studied profiles at once. The main such dry periods are as follows:

1983/1984: Relative monthly discharge values less than 80% Q_{ma} occurred in all the studied profiles from month 6/1983 and continued in most cases until 3/1984 or 4/1984. Discharge values below 40% Q_{ma} were recorded on the Myjava in 7/1983, on the Kysuca in 7/1983–9/1983, from 8/1983 on the Ipeľ and in the period 10/1983-2/1984 on the Hron, Ipeľ and Rimava. In the eastern parts of the territory (Torysa, Topľa, Poprad) relative values below 40% occurred in 2/1984 and 3/1984.

1986/1987: In most of the studied profiles, relative month discharges Q_m/Q_{ma} (%) below 80% occurred between 7/1986 and 12/1986 but continued on the Ipeľ, Rimava, Torysa, Topľa and Poprad until 3/1987. Within that group, values below 40% Q_{ma} occurred in central and eastern Slovakia from 10/1986 to 1/1987.

1992/1993: The start of this dry period that affected all of Slovakia was recorded in most of the studied profiles from 5/1992 (except on the Váh and in eastern Slovakia) and affected all areas from 7/1992. The dry period continued until 11/1993 and in the east until 12/1993. The Myjava was strongly affected, with relative monthly discharge values below 40% Q_{ma} almost continuously from 7/1992 to 7/1993, with the exception of 3/1993 (54%) and 6/1993 (60%). In other areas values < 40% Q_{ma} were recorded nearly everywhere in 5/1993–6/1993, on the Torysa also in 7/1993–8/1993, and on the Ipeľ and Rimava from 7/1993 to 9/1993. In August 1993 the Ipeľ at Holiša had a discharge of just 4% $Q_{ma4/1961-2000}$.

1995/1996: Discharges with a relative value below 80% Q_{ma} occurred in nearly all the studied profiles from 10/1995 to 3/1996 and values below 40 % Q_{ma} were recorded mainly in 2/1996, on the Kysuca in 2/1996 and 3/1996 and on the Váh in 3/1996.

1997: Average monthly discharges below 80% of long-term averages occurred in most profiles from 12/1996 to 6/1997 and discharges below 40% Q_{ma} occurred on the Kysuca from 12/1996 to 1/1997, in the central part of Slovakia (Hron, Ipeľ, Rimava) in 4/1997, continuing on the Ipeľ and Rimava until 6/1997.

1998: Monthly discharges below 80% Q_{ma} occurred on the Myjava, Nitra, Ipeľ and Rimava in 1/1998 and in the other profiles from 2/1998 to 3/1998 (in 3/1998 most profiles had relative values below 40%). Values below 80% Q_{ma} continued in most profiles until 8/1998.

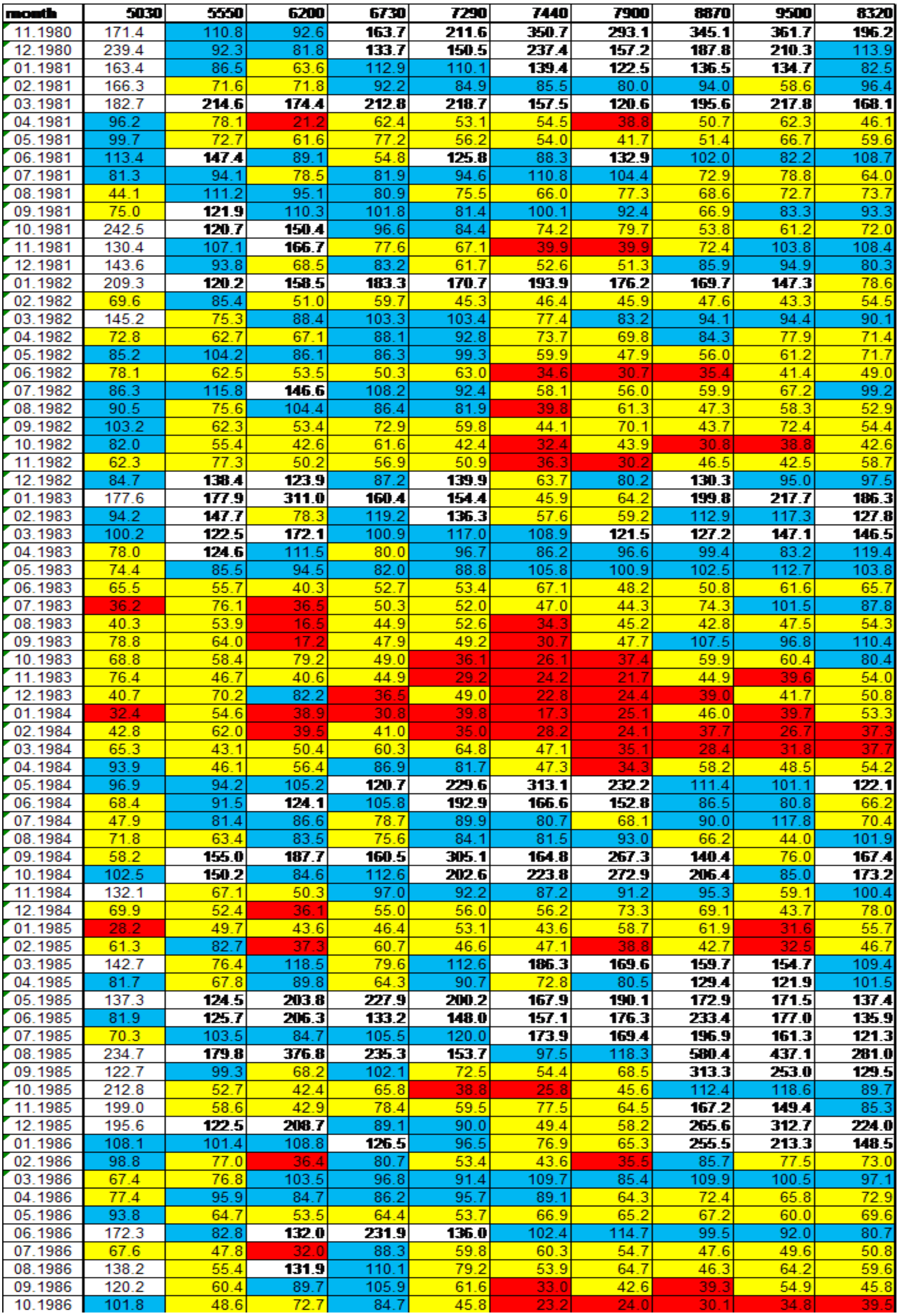
2000/2001: In most of the studied profiles relative values for monthly discharges below 80 % Q_{ma} occurred from 5/2000 to 12/2000, on the Myjava until 6/2001, with relative values below 40% in 6/2000–7/2000, 9/2000–10/2000 and 2/2001. Values below 40% were recorded on the Hron, Rimava and Torysa in 10/2000 and on the Ipeľ in from 9/2000 to 12/2000.

2003/2004: The start of the dry period was recorded in most of the territory from 2/2003 (in the east, in 12/2002 – 1/2003). The profiles on the Kysuca, Ipeľ, Torysa and Topľa had values below 40% Q_{ma} right from the start of the dry period in 2/2003. The period with significantly below-average relative monthly discharge values continued until 1/2004 except for the Ipeľ and Topľa, where it continued to 2/2004 and the Rimava and Torysa, where it continued to 4/2004. In 4/2004 relative monthly discharge values were again below 80% in all the studied profiles. Periods with relative values < 40% Q_{ma} were recorded for 9 consecutive months on the Myjava from 6/2003–2/2004, on the Kysuca from 6/2003 – 9/2003, in central and eastern parts of Slovakia mainly in 10/2003, 12/2003 and 1/2004, and in a smaller number of profiles in the period from 4/2003 to 2/2004.

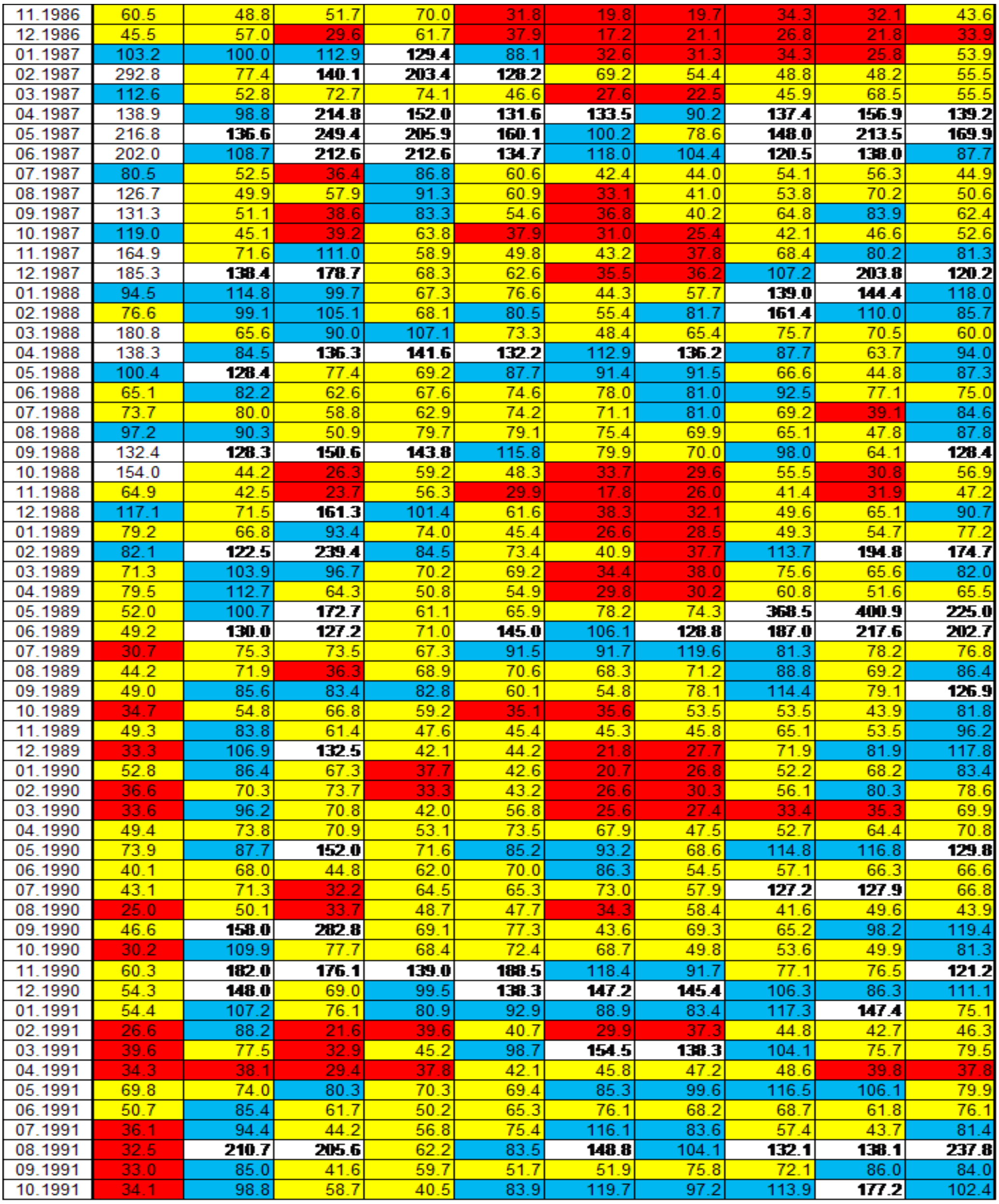
2007/2008: In most of the studied profiles dry months began in autumn 2006, in the months 10/2006 – 12/2006 and many profiles had relative monthly discharge values below 40% (Kysuca, Hron, Ipeľ, Rimava, Topľa). On the Myjava, the dry period lasted from 12/2006 to 8/2007 and it had relative values below 40% Q_{ma} in the period 6/2007–8/2007. Most profiles had monthly discharges with relative values below 80% Q_{ma} from 4/2007 to 8/2007 (in 6–7/2007 in all the studied profiles). The Rimava, Torysa and Topľa had relative monthly discharge values below 40% in the period 4/2007–7/2007. The profiles on the Ipeľ, Rimava and partially on the Hron continued to have discharges below 80% Q_{ma} continuously until the next dry period in 2008, which affected most of the territory particularly in the months 4/2008–6/2008. The profiles Ipeľ – Holiša and Rimava – Vlkyňa the dry period (< 80% Q_{ma}) was continuous from 10/2006 to 6/2008, i.e. for 21 consecutive months, within which period discharges were below 40% Q_{ma} in 14 months on the Ipeľ and in 12 months on the Rimava.

2011/2012: The hydrological drought in 2012 that began with a precipitation deficit in 2011 began to manifest in hydrological conditions in the spring of 2011 in the months 3/2011–6/2011 and then again from 9/2011 until the end of the study period 10/2012. It was particularly intense on the Myjava and in central and eastern parts of the territory, which experienced relative values below 40% especially in the months 11–12/2011 and 8–9/2012. The Ipeľ had a dry period with relative mean monthly discharges below 40% from 10/2011 to 10/2012.

Tab. 4.1.2.2 Average monthly discharges in evaluated profiles – relative values of Q_m/Q_{ma} (%)

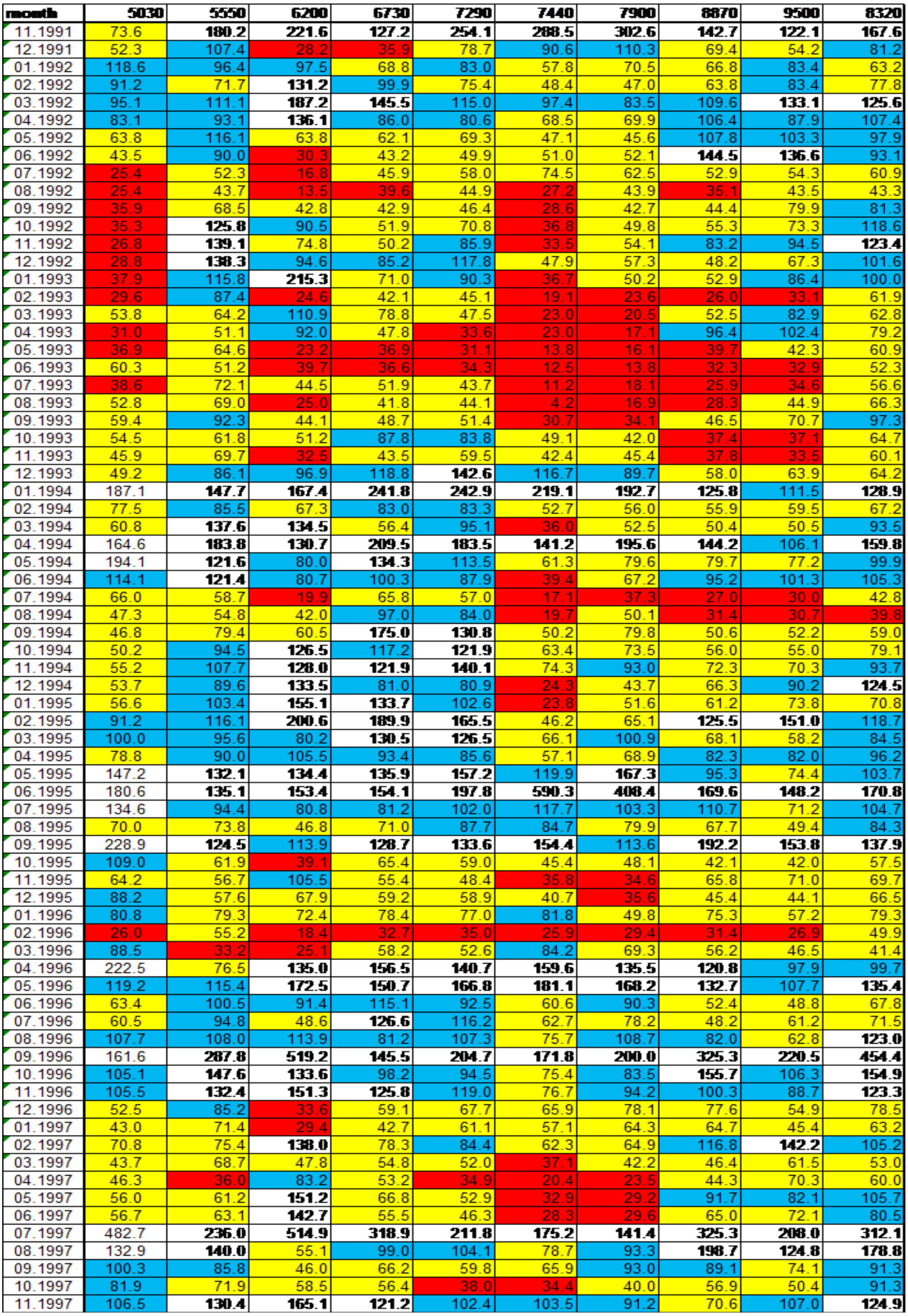


month	5030	5550	6200	6730	7290	7440	7900	8870	9500	8320
11.1980	171.4	110.8	92.6	163.7	211.6	350.7	293.1	345.1	361.7	196.2
12.1980	239.4	92.3	81.8	133.7	150.5	237.4	157.2	187.8	210.3	113.9
01.1981	163.4	86.5	63.6	112.9	110.1	139.4	122.5	136.5	134.7	82.5
02.1981	166.3	71.6	71.8	92.2	84.9	85.5	80.0	94.0	58.6	96.4
03.1981	182.7	214.6	174.4	212.8	218.7	157.5	120.6	195.6	217.8	168.1
04.1981	96.2	78.1	21.2	62.4	53.1	54.5	38.8	50.7	62.3	46.1
05.1981	99.7	72.7	61.6	77.2	56.2	54.0	41.7	51.4	66.7	59.6
06.1981	113.4	147.4	89.1	54.8	125.8	88.3	132.9	102.0	82.2	108.7
07.1981	81.3	94.1	78.5	81.9	94.6	110.8	104.4	72.9	78.8	64.0
08.1981	44.1	111.2	95.1	80.9	75.5	66.0	77.3	68.6	72.7	73.7
09.1981	75.0	121.9	110.3	101.8	81.4	100.1	92.4	66.9	83.3	93.3
10.1981	242.5	120.7	150.4	96.6	84.4	74.2	79.7	53.8	61.2	72.0
11.1981	130.4	107.1	166.7	77.6	67.1	39.9	39.9	72.4	103.8	108.4
12.1981	143.6	93.8	68.5	83.2	61.7	52.6	51.3	85.9	94.9	80.3
01.1982	209.3	120.2	158.5	183.3	170.7	193.9	176.2	169.7	147.3	78.6
02.1982	69.6	85.4	51.0	59.7	45.3	46.4	45.9	47.6	43.3	54.5
03.1982	145.2	75.3	88.4	103.3	103.4	77.4	83.2	94.1	94.4	90.1
04.1982	72.8	62.7	67.1	88.1	92.8	73.7	69.8	84.3	77.9	71.4
05.1982	85.2	104.2	86.1	86.3	99.3	59.9	47.9	56.0	61.2	71.7
06.1982	78.1	62.5	53.5	50.3	63.0	34.6	30.7	35.4	41.4	49.0
07.1982	86.3	115.8	146.6	108.2	92.4	58.1	56.0	59.9	67.2	99.2
08.1982	90.5	75.6	104.4	86.4	81.9	39.8	61.3	47.3	58.3	52.9
09.1982	103.2	62.3	53.4	72.9	59.8	44.1	70.1	43.7	72.4	54.4
10.1982	82.0	55.4	42.6	61.6	42.4	32.4	43.9	30.8	38.8	42.6
11.1982	62.3	77.3	50.2	56.9	50.9	36.3	30.2	46.5	42.5	58.7
12.1982	84.7	138.4	123.9	87.2	139.9	63.7	80.2	130.3	95.0	97.5
01.1983	177.6	177.9	311.0	160.4	154.4	45.9	64.2	199.8	217.7	186.3
02.1983	94.2	147.7	78.3	119.2	136.3	57.6	59.2	112.9	117.3	127.8
03.1983	100.2	122.5	172.1	100.9	117.0	108.9	121.5	127.2	147.1	146.5
04.1983	78.0	124.6	111.5	80.0	96.7	86.2	96.6	99.4	83.2	119.4
05.1983	74.4	85.5	94.5	82.0	88.8	105.8	100.9	102.5	112.7	103.8
06.1983	65.5	55.7	40.3	52.7	53.4	67.1	48.2	50.8	61.6	65.7
07.1983	36.2	76.1	36.5	50.3	52.0	47.0	44.3	74.3	101.5	87.8
08.1983	40.3	53.9	16.5	44.9	52.6	34.3	45.2	42.8	47.5	54.3
09.1983	78.8	64.0	17.2	47.9	49.2	30.7	47.7	107.5	96.8	110.4
10.1983	68.8	58.4	79.2	49.0	36.1	26.1	37.4	59.9	60.4	80.4
11.1983	76.4	46.7	40.6	44.9	29.2	24.2	21.7	44.9	39.6	54.0
12.1983	40.7	70.2	82.2	36.5	49.0	22.8	24.4	39.0	41.7	50.8
01.1984	32.4	54.6	38.9	30.8	39.8	17.3	25.1	46.0	39.7	53.3
02.1984	42.8	62.0	39.5	41.0	35.0	28.2	24.1	37.7	26.7	37.3
03.1984	65.3	43.1	50.4	60.3	64.8	47.1	35.1	28.4	31.8	37.7
04.1984	93.9	46.1	56.4	86.9	81.7	47.3	34.3	58.2	48.5	54.2
05.1984	96.9	94.2	105.2	120.7	229.6	313.1	232.2	111.4	101.1	122.1
06.1984	68.4	91.5	124.1	105.8	192.9	166.6	152.8	86.5	80.8	66.2
07.1984	47.9	81.4	86.6	78.7	89.9	80.7	68.1	90.0	117.8	70.4
08.1984	71.8	63.4	83.5	75.6	84.1	81.5	93.0	66.2	44.0	101.9
09.1984	58.2	155.0	187.7	160.5	305.1	164.8	267.3	140.4	76.0	167.4
10.1984	102.5	150.2	84.6	112.6	202.6	223.8	272.9	206.4	85.0	173.2
11.1984	132.1	67.1	50.3	97.0	92.2	87.2	91.2	95.3	59.1	100.4
12.1984	69.9	52.4	36.1	55.0	56.0	56.2	73.3	69.1	43.7	78.0
01.1985	28.2	49.7	43.6	46.4	53.1	43.6	58.7	61.9	31.6	55.7
02.1985	61.3	82.7	37.3	60.7	46.6	47.1	38.8	42.7	32.5	46.7
03.1985	142.7	76.4	118.5	79.6	112.6	186.3	169.6	159.7	154.7	109.4
04.1985	81.7	67.8	89.8	64.3	90.7	72.8	80.5	129.4	121.9	101.5
05.1985	137.3	124.5	203.8	227.9	200.2	167.9	190.1	172.9	171.5	137.4
06.1985	81.9	125.7	206.3	133.2	148.0	157.1	176.3	233.4	177.0	135.9
07.1985	70.3	103.5	84.7	105.5	120.0	173.9	169.4	196.9	161.3	121.3
08.1985	234.7	179.8	376.8	235.3	153.7	97.5	118.3	580.4	437.1	281.0
09.1985	122.7	99.3	68.2	102.1	72.5	54.4	68.5	313.3	253.0	129.5
10.1985	212.8	52.7	42.4	65.8	38.8	25.8	45.6	112.4	118.6	89.7
11.1985	199.0	58.6	42.9	78.4	59.5	77.5	64.5	167.2	149.4	85.3
12.1985	195.6	122.5	208.7	89.1	90.0	49.4	58.2	265.6	312.7	224.0
01.1986	108.1	101.4	108.8	126.5	96.5	76.9	65.3	255.5	213.3	148.5
02.1986	98.8	77.0	36.4	80.7	53.4	43.6	35.5	85.7	77.5	73.0
03.1986	67.4	76.8	103.5	96.8	91.4	109.7	85.4	109.9	100.5	97.1
04.1986	77.4	95.9	84.7	86.2	95.7	89.1	64.3	72.4	65.8	72.9
05.1986	93.8	64.7	53.5	64.4	53.7	66.9	65.2	67.2	60.0	69.6
06.1986	172.3	82.8	132.0	231.9	136.0	102.4	114.7	99.5	92.0	80.7
07.1986	67.6	47.8	32.0	88.3	59.8	60.3	54.7	47.6	49.6	50.8
08.1986	138.2	55.4	131.9	110.1	79.2	53.9	64.7	46.3	64.2	59.6
09.1986	120.2	60.4	89.7	105.9	61.6	33.0	42.6	39.3	54.9	45.8
10.1986	101.8	48.6	72.7	84.7	45.8	23.2	24.0	30.1	34.8	39.5

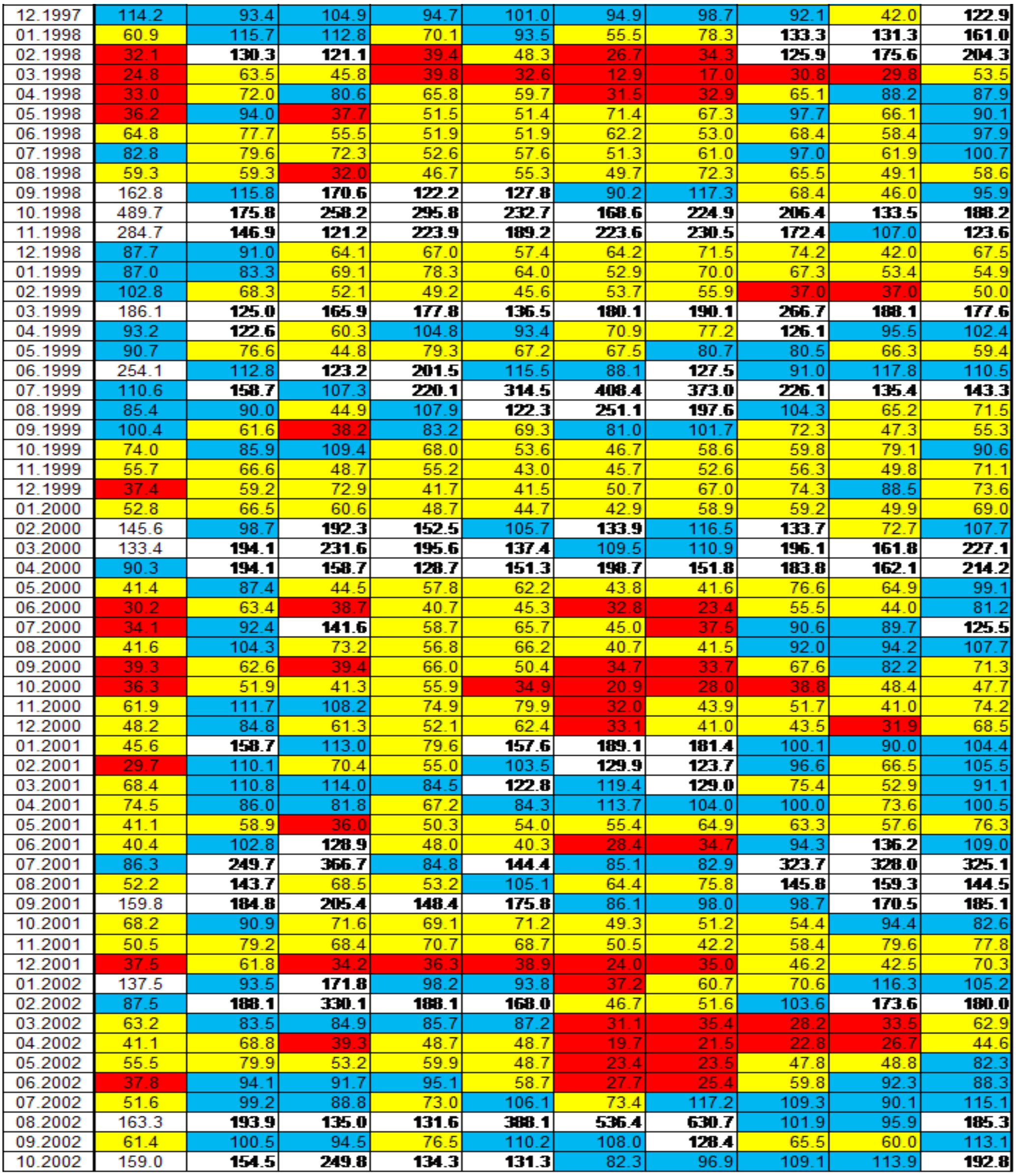


11.1986	60.5	48.8	51.7	70.0	31.8	19.8	19.7	34.3	32.1	43.6
12.1986	45.5	57.0	29.6	61.7	37.9	17.2	21.1	26.8	21.8	33.9
01.1987	103.2	100.0	112.9	**129.4**	88.1	32.6	31.3	34.3	25.8	53.9
02.1987	292.8	77.4	**140.1**	**203.4**	**128.2**	69.2	54.4	48.8	48.2	55.5
03.1987	112.6	52.8	72.7	74.1	46.6	27.6	22.5	45.9	68.5	55.5
04.1987	138.9	98.8	**214.8**	**152.0**	**131.6**	**133.5**	90.2	**137.4**	**156.9**	**139.2**
05.1987	216.8	**136.6**	**249.4**	**205.9**	**160.1**	100.2	78.6	**148.0**	**213.5**	**169.9**
06.1987	202.0	108.7	**212.6**	**212.6**	**134.7**	118.0	104.4	**120.5**	**138.0**	87.7
07.1987	80.5	52.5	36.4	86.8	60.6	42.4	44.0	54.1	56.3	44.9
08.1987	126.7	49.9	57.9	91.3	60.9	33.1	41.0	53.8	70.2	50.6
09.1987	131.3	51.1	38.6	83.3	54.6	36.8	40.2	64.8	83.9	62.4
10.1987	119.0	45.1	39.2	63.8	37.9	31.0	25.4	42.1	46.6	52.6
11.1987	164.9	71.6	111.0	58.9	49.8	43.2	37.8	68.4	80.2	81.3
12.1987	185.3	**138.4**	**178.7**	68.3	62.6	35.5	36.2	107.2	**203.8**	**120.2**
01.1988	94.5	114.8	99.7	67.3	76.6	44.3	57.7	**139.0**	**144.4**	118.0
02.1988	76.6	99.1	105.1	68.1	80.5	55.4	81.7	**161.4**	110.0	85.7
03.1988	180.8	65.6	90.0	107.1	73.3	48.4	65.4	75.7	70.5	60.0
04.1988	138.3	84.5	**136.3**	**141.6**	**132.2**	112.9	**136.2**	87.7	63.7	94.0
05.1988	100.4	**128.4**	77.4	69.2	87.7	91.4	91.5	66.6	44.8	87.3
06.1988	65.1	82.2	62.6	67.6	74.6	78.0	81.0	92.5	77.1	75.0
07.1988	73.7	80.0	58.8	62.9	74.2	71.1	81.0	69.2	39.1	84.6
08.1988	97.2	90.3	50.9	79.7	79.1	75.4	69.9	65.1	47.8	87.8
09.1988	132.4	**128.3**	**150.6**	**143.8**	115.8	79.9	70.0	98.0	64.1	**128.4**
10.1988	154.0	44.2	26.3	59.2	48.3	33.7	29.6	55.5	30.8	56.9
11.1988	64.9	42.5	23.7	56.3	29.9	17.8	26.0	41.4	31.9	47.2
12.1988	117.1	71.5	**161.3**	101.4	61.6	38.3	32.1	49.6	65.1	90.7
01.1989	79.2	66.8	93.4	74.0	45.4	26.6	28.5	49.3	54.7	77.2
02.1989	82.1	**122.5**	**239.4**	84.5	73.4	40.9	37.7	113.7	**194.8**	**174.7**
03.1989	71.3	103.9	96.7	70.2	69.2	34.4	38.0	75.6	65.6	82.0
04.1989	79.5	112.7	64.3	50.8	54.9	29.8	30.2	60.8	51.6	65.5
05.1989	52.0	100.7	**172.7**	61.1	65.9	78.2	74.3	**368.5**	**400.9**	**225.0**
06.1989	49.2	**130.0**	**127.2**	71.0	**145.0**	106.1	**128.8**	**187.0**	**217.6**	**202.7**
07.1989	30.7	75.3	73.5	67.3	91.5	91.7	119.6	81.3	78.2	76.8
08.1989	44.2	71.9	36.3	68.9	70.6	68.3	71.2	88.8	69.2	86.4
09.1989	49.0	85.6	83.4	82.8	60.1	54.8	78.1	114.4	79.1	**126.9**
10.1989	34.7	54.8	66.8	59.2	35.1	35.6	53.5	53.5	43.9	81.8
11.1989	49.3	83.8	61.4	47.6	45.4	45.3	45.8	65.1	53.5	96.2
12.1989	33.3	106.9	**132.5**	42.1	44.2	21.8	27.7	71.9	81.9	117.8
01.1990	52.8	86.4	67.3	37.7	42.6	20.7	26.8	52.2	68.2	83.4
02.1990	36.6	70.3	73.7	33.3	43.2	26.6	30.3	56.1	80.3	78.6
03.1990	33.6	96.2	70.8	42.0	56.8	25.6	27.4	33.4	35.3	69.9
04.1990	49.4	73.8	70.9	53.1	73.5	67.9	47.5	52.7	64.4	70.8
05.1990	73.9	87.7	**152.0**	71.6	85.2	93.2	68.6	114.8	116.8	**129.8**
06.1990	40.1	68.0	44.8	62.0	70.0	86.3	54.5	57.1	66.3	66.6
07.1990	43.1	71.3	32.2	64.5	65.3	73.0	57.9	**127.2**	**127.9**	66.8
08.1990	25.0	50.1	33.7	48.7	47.7	34.3	58.4	41.6	49.6	43.9
09.1990	46.6	**158.0**	**282.8**	69.1	77.3	43.6	69.3	65.2	98.2	119.4
10.1990	30.2	109.9	77.7	68.4	72.4	68.7	49.8	53.6	49.9	81.3
11.1990	60.3	**182.0**	**176.1**	**139.0**	**188.5**	118.4	91.7	77.1	76.5	**121.2**
12.1990	54.3	**148.0**	69.0	99.5	**138.3**	**147.2**	**145.4**	106.3	86.3	111.1
01.1991	54.4	107.2	76.1	80.9	92.9	88.9	83.4	117.3	**147.4**	75.1
02.1991	26.6	88.2	21.6	39.6	40.7	29.9	37.3	44.8	42.7	46.3
03.1991	39.6	77.5	32.9	45.2	98.7	**154.5**	**138.3**	104.1	75.7	79.5
04.1991	34.3	38.1	29.4	37.8	42.1	45.8	47.2	48.6	39.8	37.8
05.1991	69.8	74.0	80.3	70.3	69.4	85.3	99.6	116.5	106.1	79.9
06.1991	50.7	85.4	61.7	50.2	65.3	76.1	68.2	68.7	61.8	76.1
07.1991	36.1	94.4	44.2	56.8	75.4	116.1	83.6	57.4	43.7	81.4
08.1991	32.5	**210.7**	**205.6**	62.2	83.5	**148.8**	104.1	**132.1**	**138.1**	**237.8**
09.1991	33.0	85.0	41.6	59.7	51.7	51.9	75.8	72.1	86.0	84.0
10.1991	34.1	98.8	58.7	40.5	83.9	119.7	97.2	113.9	**177.2**	102.4

Tab. 4.1.2.2 Average monthly discharges in evaluated profiles – relative values of Q_m/Q_{ma} (%) - continuation

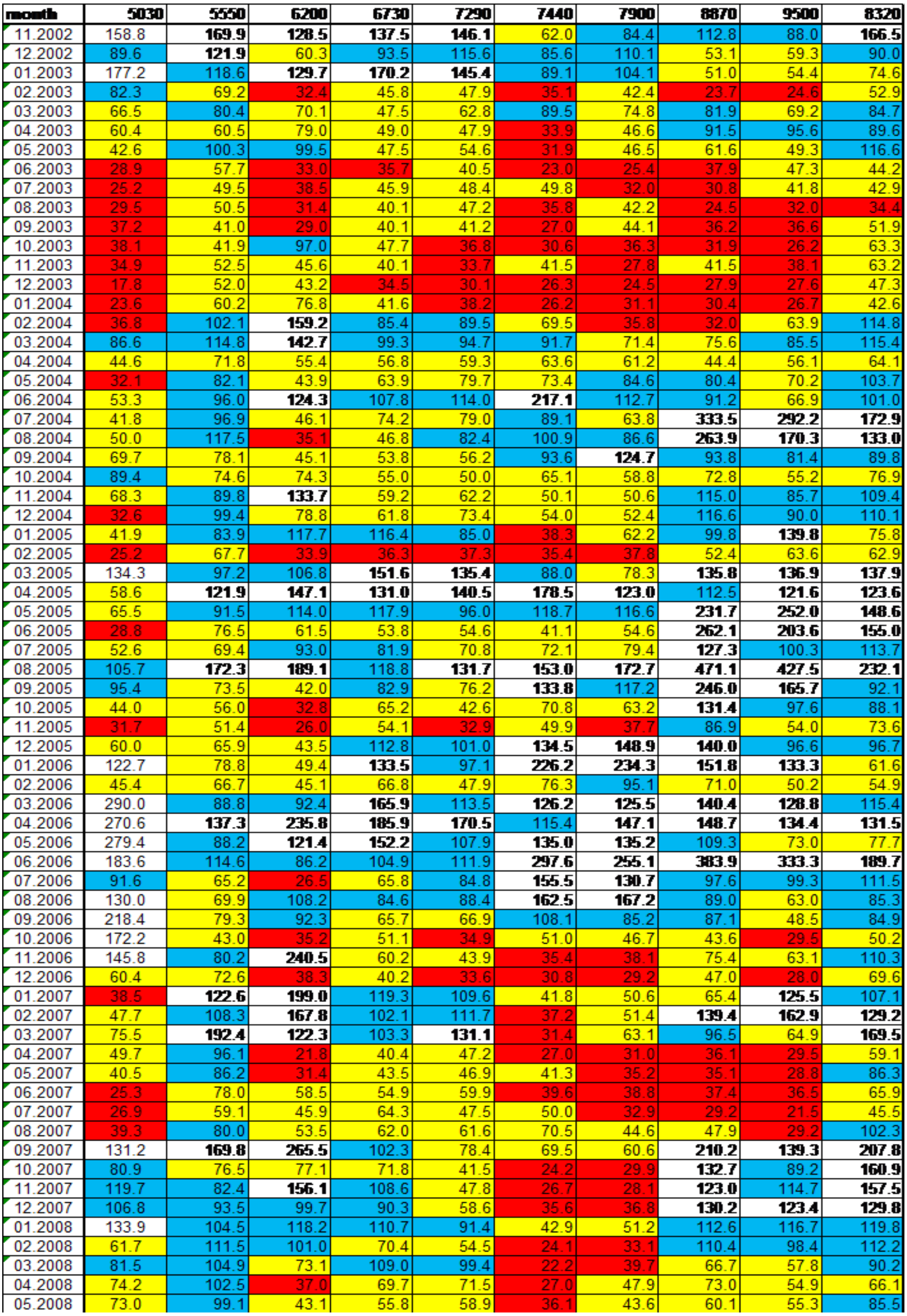


month	5030	5550	6200	6730	7290	7440	7900	8870	9500	8320
11.1991	73.6	180.2	221.6	127.2	254.1	288.5	302.6	142.7	122.1	167.6
12.1991	52.3	107.4	28.2	35.9	78.7	90.6	110.3	69.4	54.2	81.2
01.1992	118.6	96.4	97.5	68.8	83.0	57.8	70.5	66.8	83.4	63.2
02.1992	91.2	71.7	131.2	99.9	75.4	48.4	47.0	63.8	83.4	77.8
03.1992	95.1	111.1	187.2	145.5	115.0	97.4	83.5	109.6	133.1	125.6
04.1992	83.1	93.1	136.1	86.0	80.6	68.5	69.9	106.4	87.9	107.4
05.1992	63.8	116.1	63.8	62.1	69.3	47.1	45.6	107.8	103.3	97.9
06.1992	43.5	90.0	30.3	43.2	49.9	51.0	52.1	144.5	136.6	93.1
07.1992	25.4	52.3	16.8	45.9	58.0	74.5	62.5	52.9	54.3	60.9
08.1992	25.4	43.7	13.5	39.6	44.9	27.2	43.9	35.1	43.5	43.3
09.1992	35.9	68.5	42.8	42.9	46.4	28.6	42.7	44.4	79.9	81.3
10.1992	35.3	125.8	90.5	51.9	70.8	36.8	49.8	55.3	73.3	118.6
11.1992	26.8	139.1	74.8	50.2	85.9	33.5	54.1	83.2	94.5	123.4
12.1992	28.8	138.3	94.6	85.2	117.8	47.9	57.3	48.2	67.3	101.6
01.1993	37.9	115.8	215.3	71.0	90.3	36.7	50.2	52.9	86.4	100.0
02.1993	29.6	87.4	24.6	42.1	45.1	19.1	23.6	26.0	33.1	61.9
03.1993	53.8	64.2	110.9	78.8	47.5	23.0	20.5	52.5	82.9	62.8
04.1993	31.0	51.1	92.0	47.8	33.6	23.0	17.1	96.4	102.4	79.2
05.1993	36.9	64.6	23.2	36.9	31.1	13.8	16.1	39.7	42.3	60.9
06.1993	60.3	51.2	39.7	36.6	34.3	12.5	13.8	32.3	32.9	52.3
07.1993	38.6	72.1	44.5	51.9	43.7	11.2	18.1	25.9	34.6	56.6
08.1993	52.8	69.0	25.0	41.8	44.1	4.2	16.9	28.3	44.9	66.3
09.1993	59.4	92.3	44.1	48.7	51.4	30.7	34.1	46.5	70.7	97.3
10.1993	54.5	61.8	51.2	87.8	83.8	49.1	42.0	37.4	37.1	64.7
11.1993	45.9	69.7	32.5	43.5	59.5	42.4	45.4	37.8	33.5	60.1
12.1993	49.2	86.1	96.9	118.8	142.6	116.7	89.7	58.0	63.9	64.2
01.1994	187.1	147.7	167.4	241.8	242.9	219.1	192.7	125.8	111.5	128.9
02.1994	77.5	85.5	67.3	83.0	83.3	52.7	56.0	55.9	59.5	67.2
03.1994	60.8	137.6	134.5	56.4	95.1	36.0	52.5	50.4	50.5	93.5
04.1994	164.6	183.8	130.7	209.5	183.5	141.2	195.6	144.2	106.1	159.8
05.1994	194.1	121.6	80.0	134.3	113.5	61.3	79.6	79.7	77.2	99.9
06.1994	114.1	121.4	80.7	100.3	87.9	39.4	67.2	95.2	101.3	105.3
07.1994	66.0	58.7	19.9	65.8	57.0	17.1	37.3	27.0	30.0	42.8
08.1994	47.3	54.8	42.0	97.0	84.0	19.7	50.1	31.4	30.7	39.8
09.1994	46.8	79.4	60.5	175.0	130.8	50.2	79.8	50.6	52.2	59.0
10.1994	50.2	94.5	126.5	117.2	121.9	63.4	73.5	56.0	55.0	79.1
11.1994	55.2	107.7	128.0	121.9	140.1	74.3	93.0	72.3	70.3	93.7
12.1994	53.7	89.6	133.5	81.0	80.9	24.3	43.7	66.3	90.2	124.5
01.1995	56.6	103.4	155.1	133.7	102.6	23.8	51.6	61.2	73.8	70.8
02.1995	91.2	116.1	200.6	189.9	165.5	46.2	65.1	125.5	151.0	118.7
03.1995	100.0	95.6	80.2	130.5	126.5	66.1	100.9	68.1	58.2	84.5
04.1995	78.8	90.0	105.5	93.4	85.6	57.1	68.9	82.3	82.0	96.2
05.1995	147.2	132.1	134.4	135.9	157.2	119.9	167.3	95.3	74.4	103.7
06.1995	180.6	135.1	153.4	154.1	197.8	590.3	408.4	169.6	148.2	170.8
07.1995	134.6	94.4	80.8	81.2	102.0	117.7	103.3	110.7	71.2	104.7
08.1995	70.0	73.8	46.8	71.0	87.7	84.7	79.9	67.7	49.4	84.3
09.1995	228.9	124.5	113.9	128.7	133.6	154.4	113.6	192.2	153.8	137.9
10.1995	109.0	61.9	39.1	65.4	59.0	45.4	48.1	42.1	42.0	57.5
11.1995	64.2	56.7	105.5	55.4	48.4	35.8	34.6	65.8	71.0	69.7
12.1995	88.2	57.6	67.9	59.2	58.9	40.7	35.6	45.4	44.1	66.5
01.1996	80.8	79.3	72.4	78.4	77.0	81.8	49.8	75.3	57.2	79.3
02.1996	26.0	55.2	18.4	32.7	35.0	25.9	29.4	31.4	26.9	49.9
03.1996	88.5	33.2	25.1	58.2	52.6	84.2	69.3	56.2	46.5	41.4
04.1996	222.5	76.5	135.0	156.5	140.7	159.6	135.5	120.8	97.9	99.7
05.1996	119.2	115.4	172.5	150.7	166.8	181.1	168.2	132.7	107.7	135.4
06.1996	63.4	100.5	91.4	115.1	92.5	60.6	90.3	52.4	48.8	67.8
07.1996	60.5	94.8	48.6	126.6	116.2	62.7	78.2	48.2	61.2	71.5
08.1996	107.7	108.0	113.9	81.2	107.3	75.7	108.7	82.0	62.8	123.0
09.1996	161.6	287.8	519.2	145.5	204.7	171.8	200.0	325.3	220.5	454.4
10.1996	105.1	147.6	133.6	98.2	94.5	75.4	83.5	155.7	106.3	154.9
11.1996	105.5	132.4	151.3	125.8	119.0	76.7	94.2	100.3	88.7	123.3
12.1996	52.5	85.2	33.6	59.1	67.7	65.9	78.1	77.6	54.9	78.5
01.1997	43.0	71.4	29.4	42.7	61.1	57.1	64.3	64.7	45.4	63.2
02.1997	70.8	75.4	138.0	78.3	84.4	62.3	64.9	116.8	142.2	105.2
03.1997	43.7	68.7	47.8	54.8	52.0	37.1	42.2	46.4	61.5	53.0
04.1997	46.3	36.0	83.2	53.2	34.9	20.4	23.5	44.3	70.3	60.0
05.1997	56.0	61.2	151.2	66.8	52.9	32.9	29.2	91.7	82.1	105.7
06.1997	56.7	63.1	142.7	55.5	46.3	28.3	29.6	65.0	72.1	80.5
07.1997	482.7	236.0	514.9	318.9	211.8	175.2	141.4	325.3	208.0	312.1
08.1997	132.9	140.0	55.1	99.0	104.1	78.7	93.3	198.7	124.8	178.8
09.1997	100.3	85.8	46.0	66.2	59.8	65.9	93.0	89.1	74.1	91.3
10.1997	81.9	71.9	58.5	56.4	38.0	34.4	40.0	56.9	50.4	91.3
11.1997	106.5	130.4	165.1	121.2	102.4	103.5	91.2	70.6	107.0	124.9

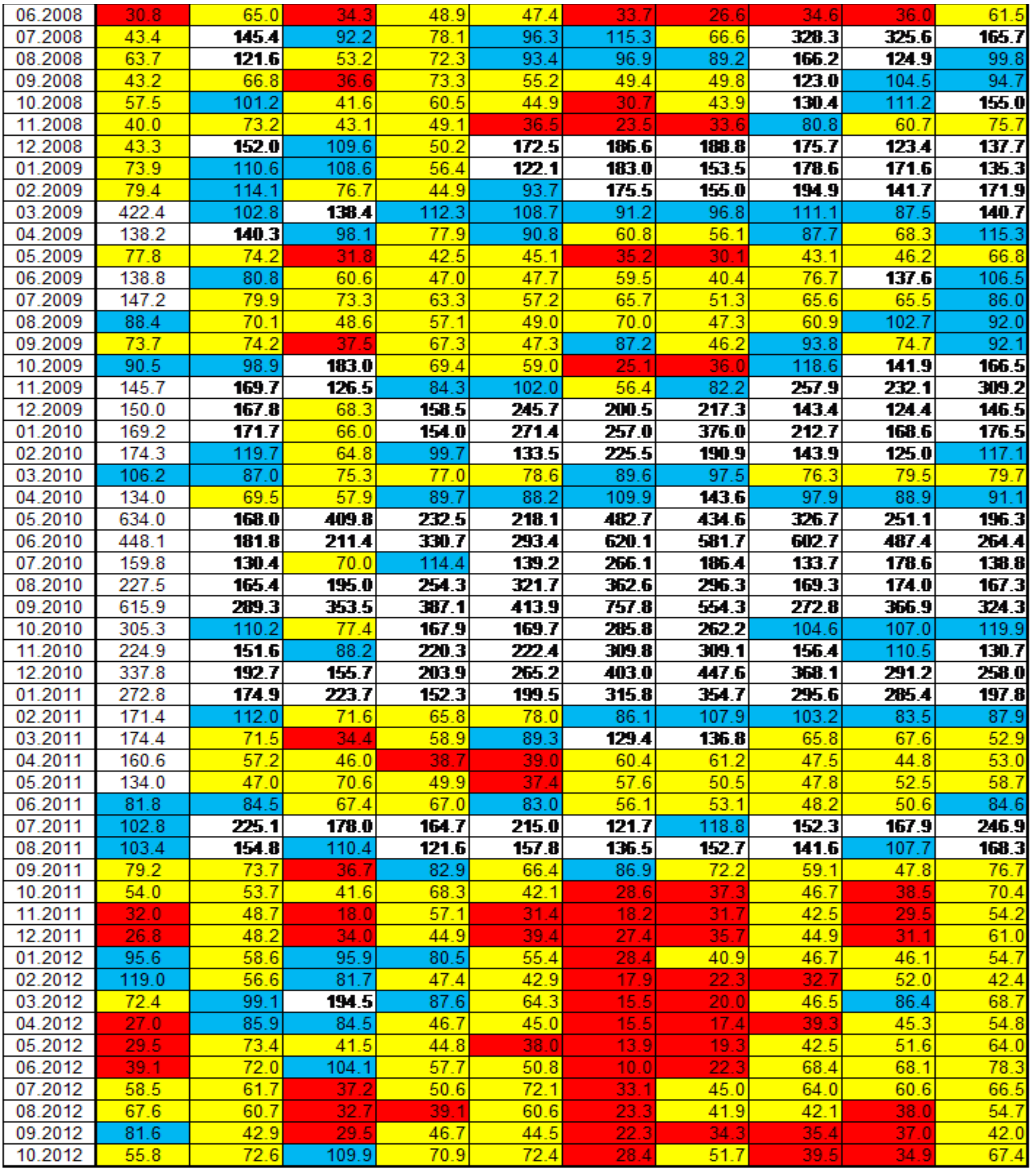


12.1997	114.2	93.4	104.9	94.7	101.0	94.9	98.7	92.1	42.0	**122.9**
01.1998	60.9	115.7	112.8	70.1	93.5	55.5	78.3	**133.3**	**131.3**	**161.0**
02.1998	32.1	**130.3**	**121.1**	39.4	48.3	26.7	34.3	**125.9**	**175.6**	**204.3**
03.1998	24.8	63.5	45.8	39.8	32.6	12.9	17.0	30.8	29.8	53.5
04.1998	33.0	72.0	80.6	65.8	59.7	31.5	32.9	65.1	88.2	87.9
05.1998	36.2	94.0	37.7	51.5	51.4	71.4	67.3	97.7	66.1	90.1
06.1998	64.8	77.7	55.5	51.9	51.9	62.2	53.0	68.4	58.4	97.9
07.1998	82.8	79.6	72.3	52.6	57.6	51.3	61.0	97.0	61.9	100.7
08.1998	59.3	59.3	32.0	46.7	55.3	49.7	72.3	65.5	49.1	58.6
09.1998	162.8	115.8	**170.6**	**122.2**	**127.8**	90.2	117.3	68.4	46.0	95.9
10.1998	489.7	**175.8**	**258.2**	**295.8**	**232.7**	**168.6**	**224.9**	**206.4**	**133.5**	**188.2**
11.1998	284.7	**146.9**	**121.2**	**223.9**	**189.2**	**223.6**	**230.5**	**172.4**	107.0	**123.6**
12.1998	87.7	91.0	64.1	67.0	57.4	64.2	71.5	74.2	42.0	67.5
01.1999	87.0	83.3	69.1	78.3	64.0	52.9	70.0	67.3	53.4	54.9
02.1999	102.8	68.3	52.1	49.2	45.6	53.7	55.9	37.0	37.0	50.0
03.1999	186.1	**125.0**	**165.9**	**177.8**	**136.5**	**180.1**	**190.1**	**266.7**	**188.1**	**177.6**
04.1999	93.2	**122.6**	60.3	104.8	93.4	70.9	77.2	**126.1**	95.5	102.4
05.1999	90.7	76.6	44.8	79.3	67.2	67.5	80.7	80.5	66.3	59.4
06.1999	254.1	112.8	**123.2**	**201.5**	115.5	88.1	**127.5**	91.0	117.8	110.5
07.1999	110.6	**158.7**	107.3	**220.1**	**314.5**	**408.4**	**373.0**	**226.1**	**135.4**	**143.3**
08.1999	85.4	90.0	44.9	107.9	**122.3**	**251.1**	**197.6**	104.3	65.2	71.5
09.1999	100.4	61.6	38.2	83.2	69.3	81.0	101.7	72.3	47.3	55.3
10.1999	74.0	85.9	109.4	68.0	53.6	46.7	58.6	59.8	79.1	90.6
11.1999	55.7	66.6	48.7	55.2	43.0	45.7	52.6	56.3	49.8	71.1
12.1999	37.4	59.2	72.9	41.7	41.5	50.7	67.0	74.3	88.5	73.6
01.2000	52.8	66.5	60.6	48.7	44.7	42.9	58.9	59.2	49.9	69.0
02.2000	145.6	98.7	**192.3**	**152.5**	105.7	**133.9**	116.5	**133.7**	72.7	107.7
03.2000	133.4	**194.1**	**231.6**	**195.6**	**137.4**	109.5	110.9	**196.1**	**161.8**	**227.1**
04.2000	90.3	**194.1**	**158.7**	**128.7**	**151.3**	**198.7**	**151.8**	**183.8**	**162.1**	**214.2**
05.2000	41.4	87.4	44.5	57.8	62.2	43.8	41.6	76.6	64.9	99.1
06.2000	30.2	63.4	38.7	40.7	45.3	32.8	23.4	55.5	44.0	81.2
07.2000	34.1	92.4	**141.6**	58.7	65.7	45.0	37.5	90.6	89.7	**125.5**
08.2000	41.6	104.3	73.2	56.8	66.2	40.7	41.5	92.0	94.2	107.7
09.2000	39.3	62.6	39.4	66.0	50.4	34.7	33.7	67.6	82.2	71.3
10.2000	36.3	51.9	41.3	55.9	34.9	20.9	28.0	38.8	48.4	47.7
11.2000	61.9	111.7	108.2	74.9	79.9	32.0	43.9	51.7	41.0	74.2
12.2000	48.2	84.8	61.3	52.1	62.4	33.1	41.0	43.5	31.9	68.5
01.2001	45.6	**158.7**	113.0	79.6	**157.6**	**189.1**	**181.4**	100.1	90.0	104.4
02.2001	29.7	110.1	70.4	55.0	103.5	**129.9**	**123.7**	96.6	66.5	105.5
03.2001	68.4	110.8	114.0	84.5	**122.8**	119.4	**129.0**	75.4	52.9	91.1
04.2001	74.5	86.0	81.8	67.2	84.3	113.7	104.0	100.0	73.6	100.5
05.2001	41.1	58.9	36.0	50.3	54.0	55.4	64.9	63.3	57.6	76.3
06.2001	40.4	102.8	**128.9**	48.0	40.3	28.4	34.7	94.3	**136.2**	109.0
07.2001	86.3	**249.7**	**366.7**	84.8	**144.4**	85.1	82.9	**323.7**	**328.0**	**325.1**
08.2001	52.2	**143.7**	68.5	53.2	105.1	64.4	75.8	**145.8**	**159.3**	**144.5**
09.2001	159.8	**184.8**	**205.4**	**148.4**	**175.8**	86.1	98.0	98.7	**170.5**	**185.1**
10.2001	68.2	90.9	71.6	69.1	71.2	49.3	51.2	54.4	94.4	82.6
11.2001	50.5	79.2	68.4	70.7	68.7	50.5	42.2	58.4	79.6	77.8
12.2001	37.5	61.8	34.2	36.3	38.9	24.0	35.0	46.2	42.5	70.3
01.2002	137.5	93.5	**171.8**	98.2	93.8	37.2	60.7	70.6	116.3	105.2
02.2002	87.5	**188.1**	**330.1**	**188.1**	**168.0**	46.7	51.6	103.6	**173.6**	**180.0**
03.2002	63.2	83.5	84.9	85.7	87.2	31.1	35.4	28.2	33.5	62.9
04.2002	41.1	68.8	39.3	48.7	48.7	19.7	21.5	22.8	26.7	44.6
05.2002	55.5	79.9	53.2	59.9	48.7	23.4	23.5	47.8	48.8	82.3
06.2002	37.8	94.1	91.7	95.1	58.7	27.7	25.4	59.8	92.3	88.3
07.2002	51.6	99.2	88.8	73.0	106.1	73.4	117.2	109.3	90.1	115.1
08.2002	163.3	**193.9**	**135.0**	**131.6**	**388.1**	**536.4**	**630.7**	101.9	95.9	**185.3**
09.2002	61.4	100.5	94.5	76.5	110.2	108.0	**128.4**	65.5	60.0	113.1
10.2002	159.0	**154.5**	**249.8**	**134.3**	**131.3**	82.3	96.9	109.1	113.9	**192.8**

Tab. 4.1.2.2 Average monthly discharges in evaluated profiles – relative values of Q_m/Q_{ma} (%) - continuation



month	5030	5550	6200	6730	7290	7440	7900	8870	9500	8320
11.2002	158.8	**169.9**	**128.5**	**137.5**	**146.1**	62.0	84.4	112.8	88.0	**166.5**
12.2002	89.6	**121.9**	60.3	93.5	115.6	85.6	110.1	53.1	59.3	90.0
01.2003	177.2	118.6	**129.7**	**170.2**	**145.4**	89.1	104.1	51.0	54.4	74.6
02.2003	82.3	69.2	32.4	45.8	47.9	35.1	42.4	23.7	24.6	52.9
03.2003	66.5	80.4	70.1	47.5	62.8	89.5	74.8	81.9	69.2	84.7
04.2003	60.4	60.5	79.0	49.0	47.9	33.9	46.6	91.5	95.6	89.6
05.2003	42.6	100.3	99.5	47.5	54.6	31.9	46.5	61.6	49.3	116.6
06.2003	28.9	57.7	33.0	35.7	40.5	23.0	25.4	37.9	47.3	44.2
07.2003	25.2	49.5	38.5	45.9	48.4	49.8	32.0	30.8	41.8	42.9
08.2003	29.5	50.5	31.4	40.1	47.2	35.8	42.2	24.5	32.0	34.4
09.2003	37.2	41.0	29.0	40.1	41.2	27.0	44.1	36.2	36.6	51.9
10.2003	38.1	41.9	97.0	47.7	36.8	30.6	36.3	31.9	26.2	63.3
11.2003	34.9	52.5	45.6	40.1	33.7	41.5	27.8	41.5	38.1	63.2
12.2003	17.8	52.0	43.2	34.5	30.1	26.3	24.5	27.9	27.6	47.3
01.2004	23.6	60.2	76.8	41.6	38.2	26.2	31.1	30.4	26.7	42.6
02.2004	36.8	102.1	**159.2**	85.4	89.5	69.5	35.8	32.0	63.9	114.8
03.2004	86.6	114.8	**142.7**	99.3	94.7	91.7	71.4	75.6	85.5	115.4
04.2004	44.6	71.8	55.4	56.8	59.3	63.6	61.2	44.4	56.1	64.1
05.2004	32.1	82.1	43.9	63.9	79.7	73.4	84.6	80.4	70.2	103.7
06.2004	53.3	96.0	**124.3**	107.8	114.0	**217.1**	112.7	91.2	66.9	101.0
07.2004	41.8	96.9	46.1	74.2	79.0	89.1	63.8	**333.5**	**292.2**	**172.9**
08.2004	50.0	117.5	35.1	46.8	82.4	100.9	86.6	**263.9**	**170.3**	**133.0**
09.2004	69.7	78.1	45.1	53.8	56.2	93.6	**124.7**	93.8	81.4	89.8
10.2004	89.4	74.6	74.3	55.0	50.0	65.1	58.8	72.8	55.2	76.9
11.2004	68.3	89.8	**133.7**	59.2	62.2	50.1	50.6	115.0	85.7	109.4
12.2004	32.6	99.4	78.8	61.8	73.4	54.0	52.4	116.6	90.0	110.1
01.2005	41.9	83.9	117.7	116.4	85.0	38.3	62.2	99.8	**139.8**	75.8
02.2005	25.2	67.7	33.9	36.3	37.3	35.4	37.8	52.4	63.6	62.9
03.2005	134.3	97.2	106.8	**151.6**	**135.4**	88.0	78.3	**135.8**	**136.9**	**137.9**
04.2005	58.6	**121.9**	**147.1**	**131.0**	**140.5**	**178.5**	**123.0**	112.5	**121.6**	**123.6**
05.2005	65.5	91.5	114.0	117.9	96.0	118.7	116.6	**231.7**	**252.0**	**148.6**
06.2005	28.8	76.5	61.5	53.8	54.6	41.1	54.6	**262.1**	**203.6**	**155.0**
07.2005	52.6	69.4	93.0	81.9	70.8	72.1	79.4	**127.3**	100.3	113.7
08.2005	105.7	**172.3**	**189.1**	118.8	**131.7**	**153.0**	**172.7**	**471.1**	**427.5**	**232.1**
09.2005	95.4	73.5	42.0	82.9	76.2	**133.8**	117.2	**246.0**	**165.7**	92.1
10.2005	44.0	56.0	32.8	65.2	42.6	70.8	63.2	**131.4**	97.6	88.1
11.2005	31.7	51.4	26.0	54.1	32.9	49.9	37.7	86.9	54.0	73.6
12.2005	60.0	65.9	43.5	112.8	101.0	**134.5**	**148.9**	**140.0**	96.6	96.7
01.2006	122.7	78.8	49.4	**133.5**	97.1	**226.2**	**234.3**	**151.8**	**133.3**	61.6
02.2006	45.4	66.7	45.1	66.8	47.9	76.3	95.1	71.0	50.2	54.9
03.2006	290.0	88.8	92.4	**165.9**	113.5	**126.2**	**125.5**	**140.4**	**128.8**	115.4
04.2006	270.6	**137.3**	**235.8**	**185.9**	**170.5**	115.4	**147.1**	**148.7**	**134.4**	**131.5**
05.2006	279.4	88.2	**121.4**	**152.2**	107.9	**135.0**	**135.2**	109.3	73.0	77.7
06.2006	183.6	114.6	86.2	104.9	111.9	**297.6**	**255.1**	**383.9**	**333.3**	**189.7**
07.2006	91.6	65.2	26.5	65.8	84.8	**155.5**	**130.7**	97.6	99.3	111.5
08.2006	130.0	69.9	108.2	84.6	88.4	**162.5**	**167.2**	89.0	63.0	85.3
09.2006	218.4	79.3	92.3	65.7	66.9	108.1	85.2	87.1	48.5	84.9
10.2006	172.2	43.0	35.2	51.1	34.9	51.0	46.7	43.6	29.5	50.2
11.2006	145.8	80.2	**240.5**	60.2	43.9	35.4	38.1	75.4	63.1	110.3
12.2006	60.4	72.6	38.3	40.2	33.6	30.8	29.2	47.0	28.0	69.6
01.2007	38.5	**122.6**	**199.0**	119.3	109.6	41.8	50.6	65.4	**125.5**	107.1
02.2007	47.7	108.3	**167.8**	102.1	111.7	37.2	51.4	**139.4**	**162.9**	**129.2**
03.2007	75.5	**192.4**	**122.3**	103.3	**131.1**	31.4	63.1	96.5	64.9	**169.5**
04.2007	49.7	96.1	21.8	40.4	47.2	27.0	31.0	36.1	29.5	59.1
05.2007	40.5	86.2	31.4	43.5	46.9	41.3	35.2	35.1	28.8	86.3
06.2007	25.3	78.0	58.5	54.9	59.9	39.6	38.8	37.4	36.5	65.9
07.2007	26.9	59.1	45.9	64.3	47.5	50.0	32.9	29.2	21.5	45.5
08.2007	39.3	80.0	53.5	62.0	61.6	70.5	44.6	47.9	29.2	102.3
09.2007	131.2	**169.8**	**265.5**	102.3	78.4	69.5	60.6	**210.2**	**139.3**	**207.8**
10.2007	80.9	76.5	77.1	71.8	41.5	24.2	29.9	**132.7**	89.2	**160.9**
11.2007	119.7	82.4	**156.1**	108.6	47.8	26.7	28.1	**123.0**	114.7	**157.5**
12.2007	106.8	93.5	99.7	90.3	58.6	35.6	36.8	**130.2**	**123.4**	**129.8**
01.2008	133.9	104.5	118.2	110.7	91.4	42.9	51.2	112.6	116.7	119.8
02.2008	61.7	111.5	101.0	70.4	54.5	24.1	33.1	110.4	98.4	112.2
03.2008	81.5	104.9	73.1	109.0	99.4	22.2	39.7	66.7	57.8	90.2
04.2008	74.2	102.5	37.0	69.7	71.5	27.0	47.9	73.0	54.9	66.1
05.2008	73.0	99.1	43.1	55.8	58.9	36.1	43.6	60.1	55.3	85.5



06.2008	30.8	65.0	34.3	48.9	47.4	33.7	26.6	34.6	36.0	61.5
07.2008	43.4	145.4	92.2	78.1	96.3	115.3	66.6	328.3	325.6	165.7
08.2008	63.7	121.6	53.2	72.3	93.4	96.9	89.2	166.2	124.9	99.8
09.2008	43.2	66.8	36.6	73.3	55.2	49.4	49.8	123.0	104.5	94.7
10.2008	57.5	101.2	41.6	60.5	44.9	30.7	43.9	130.4	111.2	155.0
11.2008	40.0	73.2	43.1	49.1	36.5	23.5	33.6	80.8	60.7	75.7
12.2008	43.3	152.0	109.6	50.2	172.5	186.6	188.8	175.7	123.4	137.7
01.2009	73.9	110.6	108.6	56.4	122.1	183.0	153.5	178.6	171.6	135.3
02.2009	79.4	114.1	76.7	44.9	93.7	175.5	155.0	194.9	141.7	171.9
03.2009	422.4	102.8	138.4	112.3	108.7	91.2	96.8	111.1	87.5	140.7
04.2009	138.2	140.3	98.1	77.9	90.8	60.8	56.1	87.7	68.3	115.3
05.2009	77.8	74.2	31.8	42.5	45.1	35.2	30.1	43.1	46.2	66.8
06.2009	138.8	80.8	60.6	47.0	47.7	59.5	40.4	76.7	137.6	106.5
07.2009	147.2	79.9	73.3	63.3	57.2	65.7	51.3	65.6	65.5	86.0
08.2009	88.4	70.1	48.6	57.1	49.0	70.0	47.3	60.9	102.7	92.0
09.2009	73.7	74.2	37.5	67.3	47.3	87.2	46.2	93.8	74.7	92.1
10.2009	90.5	98.9	183.0	69.4	59.0	25.1	36.0	118.6	141.9	166.5
11.2009	145.7	169.7	126.5	84.3	102.0	56.4	82.2	257.9	232.1	309.2
12.2009	150.0	167.8	68.3	158.5	245.7	200.5	217.3	143.4	124.4	146.5
01.2010	169.2	171.7	66.0	154.0	271.4	257.0	376.0	212.7	168.6	176.5
02.2010	174.3	119.7	64.8	99.7	133.5	225.5	190.9	143.9	125.0	117.1
03.2010	106.2	87.0	75.3	77.0	78.6	89.6	97.5	76.3	79.5	79.7
04.2010	134.0	69.5	57.9	89.7	88.2	109.9	143.6	97.9	88.9	91.1
05.2010	634.0	168.0	409.8	232.5	218.1	482.7	434.6	326.7	251.1	196.3
06.2010	448.1	181.8	211.4	330.7	293.4	620.1	581.7	602.7	487.4	264.4
07.2010	159.8	130.4	70.0	114.4	139.2	266.1	186.4	133.7	178.6	138.8
08.2010	227.5	165.4	195.0	254.3	321.7	362.6	296.3	169.3	174.0	167.3
09.2010	615.9	289.3	353.5	387.1	413.9	757.8	554.3	272.8	366.9	324.3
10.2010	305.3	110.2	77.4	167.9	169.7	285.8	262.2	104.6	107.0	119.9
11.2010	224.9	151.6	88.2	220.3	222.4	309.8	309.1	156.4	110.5	130.7
12.2010	337.8	192.7	155.7	203.9	265.2	403.0	447.6	368.1	291.2	258.0
01.2011	272.8	174.9	223.7	152.3	199.5	315.8	354.7	295.6	285.4	197.8
02.2011	171.4	112.0	71.6	65.8	78.0	86.1	107.9	103.2	83.5	87.9
03.2011	174.4	71.5	34.4	58.9	89.3	129.4	136.8	65.8	67.6	52.9
04.2011	160.6	57.2	46.0	38.7	39.0	60.4	61.2	47.5	44.8	53.0
05.2011	134.0	47.0	70.6	49.9	37.4	57.6	50.5	47.8	52.5	58.7
06.2011	81.8	84.5	67.4	67.0	83.0	56.1	53.1	48.2	50.6	84.6
07.2011	102.8	225.1	178.0	164.7	215.0	121.7	118.8	152.3	167.9	246.9
08.2011	103.4	154.8	110.4	121.6	157.8	136.5	152.7	141.6	107.7	168.3
09.2011	79.2	73.7	36.7	82.9	66.4	86.9	72.2	59.1	47.8	76.7
10.2011	54.0	53.7	41.6	68.3	42.1	28.6	37.3	46.7	38.5	70.4
11.2011	32.0	48.7	18.0	57.1	31.4	18.2	31.7	42.5	29.5	54.2
12.2011	26.8	48.2	34.0	44.9	39.4	27.4	35.7	44.9	31.1	61.0
01.2012	95.6	58.6	95.9	80.5	55.4	28.4	40.9	46.7	46.1	54.7
02.2012	119.0	56.6	81.7	47.4	42.9	17.9	22.3	32.7	52.0	42.4
03.2012	72.4	99.1	194.5	87.6	64.3	15.5	20.0	46.5	86.4	68.7
04.2012	27.0	85.9	84.5	46.7	45.0	15.5	17.4	39.3	45.3	54.8
05.2012	29.5	73.4	41.5	44.8	38.0	13.9	19.3	42.5	51.6	64.0
06.2012	39.1	72.0	104.1	57.7	50.8	10.0	22.3	68.4	68.1	78.3
07.2012	58.5	61.7	37.2	50.6	72.1	33.1	45.0	64.0	60.6	66.5
08.2012	67.6	60.7	32.7	39.1	60.6	23.3	41.9	42.1	38.0	54.7
09.2012	81.6	42.9	29.5	46.7	44.5	22.3	34.3	35.4	37.0	42.0
10.2012	55.8	72.6	109.9	70.9	72.4	28.4	51.7	39.5	34.9	67.4

4.1.3. Mean daily discharges

The mean daily discharges for each profile in the period 1981–2012 were analysed by comparing them with M-day discharge values for the reference period 1961–2000 indicative of low flow **Q_{330d} ($Q_{90\%}$)**, **Q_{355d} ($Q_{97\%}$)** and **Q_{364d} ($Q_{99.7\%}$).** Episodes were selected with discharges below **Q_{330d}** that lasted for at least 10 days without interruptions lasting more than 3 consecutive days.

Myjava - Šaštín-Stráže

During the studied period the discharge gauging station Myjava - Šaštín-Stráže had two significantly longer periods when the mean daily discharges were below Q_{330d} – from July 1992 to

December 1992 (a total of 149 days) and from July 2003 to January 2004 (a total of 190 days). A total of 26 low flow periods meeting the given criteria were identified including a total of 1,030 days with $Q_d < Q_{330d}$, 80 days with $Q_d < Q_{355d}$ and 1 day with $Q_d < Q_{364d}$ (fig. 4.1.3.1).

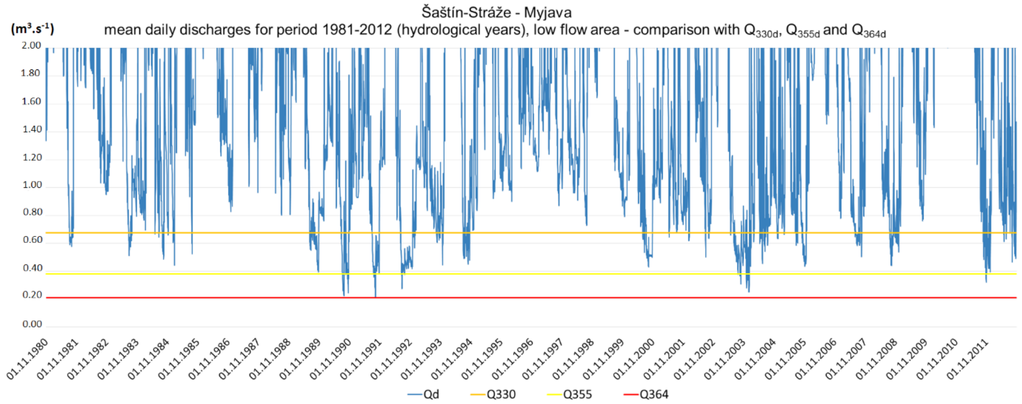


Fig. 4.1.3.1 Course of average daily discharges in the Myjava - Šaštín-Stráže profile

Váh - Liptovský Mikuláš

In the profile Váh - Liptovský Mikuláš the longest dry period with daily discharges below Q_{330d} was from November 2011 to February 2012 (a total of 111 days). Other significant periods included January to March 1996 (a total of 68 days) and December 1984 to February 1985 (a total of 67 days). A total of 35 low flow periods meeting the given criteria were identified including a total of 1,300 days with $Q_d < Q_{330d}$, 533 days with $Q_d < Q_{355d}$ and 50 days with $Q_d < Q_{364d}$.

Kysuca - Kysucké Nové Mesto

The most severe dry periods in the Kysuca River Basin with mean daily discharges below Q_{330d} were the periods July – October 1983 (a total of 74 days) and July – September 1992 (a total of 46 days). A total of 34 low flow periods meeting the given criteria were identified including a total of 789 days with $Q_d < Q_{330d}$, 206 days with $Q_d < Q_{355d}$ and 24 days with $Q_d < Q_{364d}$.

Nitra - Nitrianska Streda

The longest dry period recorded in the profile Nitra - Nitrianska Streda with mean daily discharges below Q_{330d} in the studied years was July – November 1983 (a total of 133 days). Another very significant dry period in terms of days with discharge below the 355-day and 364-day discharge levels was June to October 2012 (a total of 119 days). A total of 36 low flow periods meeting the given criteria were identified including a total of 1,327 days with $Q_d < Q_{330d}$, 420 days with $Q_d < Q_{355d}$ and 58 days with $Q_d < Q_{364d}$.

Hron - Brehy

The longest periods of drought recorded at the Hron - Brehy discharge gauging station with daily discharges below Q_{330d} were July – October 1983 (a total of 89 days), July – October 1992 (a total of 86 days) and July – October 2009 (a total of 79 days). A total of 51 low flow periods meeting the given criteria were identified including a total of 1,658 days with $Q_d < Q_{330d}$, 612 days with $Q_d < Q_{355d}$ and 93 day with $Q_d < Q_{364d}$ (fig. 4.1.3.2).

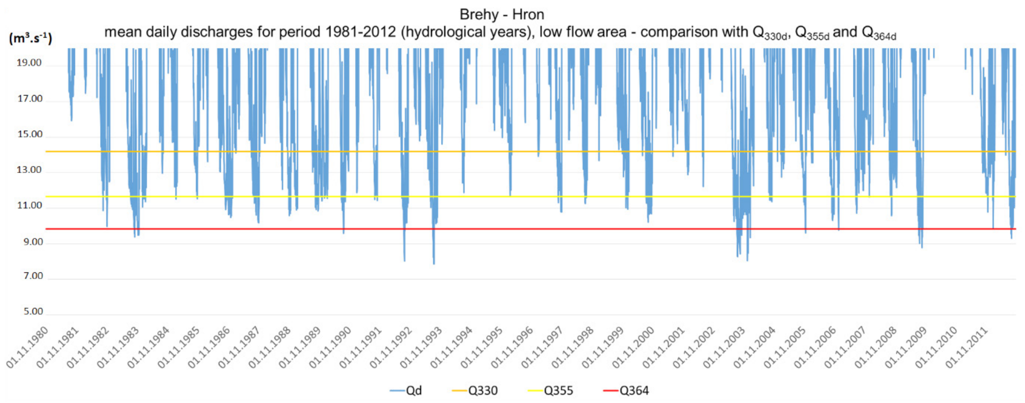


Fig. 4.1.3.2 Course of average daily discharges in the Hron - Brehy profile

Ipeľ - Holiša

By far the longest dry period recorded at the Ipeľ - Holiša discharge gauging station with mean daily discharges lower than $\mathbf{Q}_{330d}$ in the 1981 – 2012 period was the period from May to October 1993, which lasted a total of 146 days. A total of 39 low flow periods meeting the given criteria were identified including a total of 837 days with $\mathbf{Q}_d < \mathbf{Q}_{330d}$, 329 days with $\mathbf{Q}_d < \mathbf{Q}_{355d}$ and 52 days with $\mathbf{Q}_d < \mathbf{Q}_{364d}$.

Rimava - Vlkyňa

The discharge gauging station at Vlkyňa on the Rimava recorded 3 long periods when mean daily discharges were less than $\mathbf{Q}_{330d}$ for more than 100 days (including short interruptions): August – December 1986 (a total of 111 days), July – November 1987 (a total of 130 days) and May – October 1993 (a total of 146 days). A total of 43 low flow periods meeting the given criteria were identified including a total of 1,234 days with $\mathbf{Q}_d < \mathbf{Q}_{330d}$, 246 days with $\mathbf{Q}_d < \mathbf{Q}_{355d}$ and 45 days with $\mathbf{Q}_d < \mathbf{Q}_{364d}$.

Torysa - Košické Olšany

The longest dry period with mean daily discharges with a value less than $\mathbf{Q}_{330d}$ in the profile Torysa - Košické Olšany was the period September 1986 to February 1987 (a total of 159 days). A total of 22 low flow periods meeting the given criteria were identified including a total of 718 days with $\mathbf{Q}_d < \mathbf{Q}_{330d}$, 106 days with $\mathbf{Q}_d < \mathbf{Q}_{355d}$ and 0 days with $\mathbf{Q}_d < \mathbf{Q}_{364d}$.

Topľa – Hanušovce nad Topľou

The two longest periods of daily discharges below $Q_{330d,}$ at Hanušovce nad Topľou were from November 1986 to February 1987 (a total of 94 days) and August to October 2003 (a total of 83 days). A total of 40 low flow periods meeting the given criteria were identified including a total of 984 days with $\mathbf{Q}_d < \mathbf{Q}_{330d}$, 317 days with $\mathbf{Q}_d < \mathbf{Q}_{355d}$ and 47 days with $\mathbf{Q}_d < \mathbf{Q}_{364d}$.

Poprad - Chmeľnica

The longest dry period recorded at Chmeľnica on the Poprad was from January to March 1984 (a total of 80 days). The second longest dry period was from October to December 1986 (a total of 79 days). This period was followed in quick succession by two more dry periods of short duration but with discharge values < Q_{364d} for over 10 days in 09/01/1987–13/02/1987 (a total of 36 days) and 25/02/1987 to 25/03/1987 (a total of 29 days). A total of 29 low flow periods meeting the given criteria were identified including a total of 958 days with $Q_d < Q_{330d}$, 304 days with $Q_d < Q_{355d}$ and 49 days with $Q_d < Q_{364d}$ (fig. 4.1.3.3).

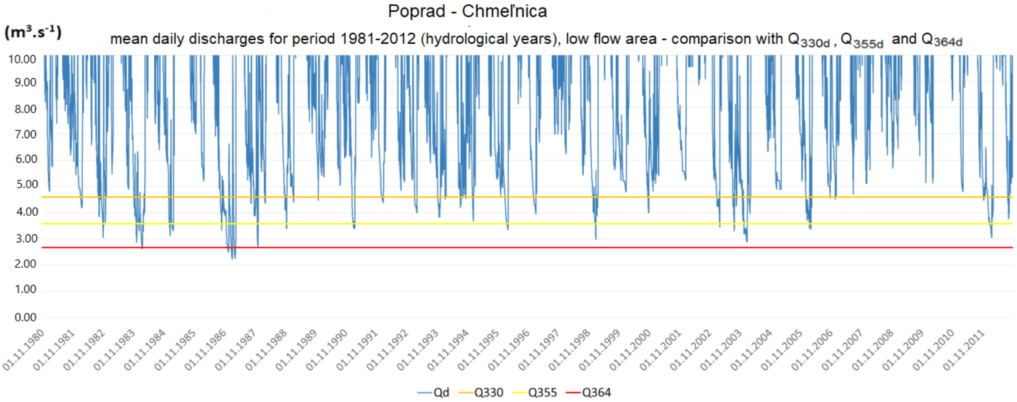


Fig. 4.1.3.3 Course of average daily discharges in the Poprad - Chmeľnica profile

Table 4.1.3.1 summarises the outputs for the individual studied discharge gauging stations. From the summary it is clear that the largest number of dry episodes meeting the chosen criteria were recorded at Brehy on the Hron (51 episodes), Vlkyňa on the Rimava (43 episodes) and Hanušovce on the Topľa (40 episodes). The most days with discharge below Q_{330d} meeting the set criteria were recorded at Brehy on the Hron, Nitrianska Streda on the Nitra and Liptovský Mikuláš on the Váh. The longest continuous periods (with short interruptions) were recorded at Šaštín-Stráže on the Myjava (190 days – Fig. 4.1.3.1), Košické Oľšany on the Torysa (159 days), Holiša on the Ipeľ and Vlkyňa on the Rimava (146 days). In terms of the months when the longest low flow episodes occurred, episodes were recorded during the summer-autumn period at the following stations: Kysucké Nové Mesto (Kysuca), Nitrianska Streda (Nitra), Brehy (Hron); the stations at Holiša (Ipeľ) and Vlkyňa (Rimava) had low flow seasons than ran through the spring and summer to the autumn; the stations at Liptovský Mikuláš (Váh), Hanušovce (Topľa) a Chmeľnica (Poprad) had low flow episodes in the winter; at Košické Oľšany (Torysa) the dry episode occurred in the autumn-winter period and at Šaštín-Stráže (Myjava) the longest low-flow period extended through the summer, autumn and winter months.

Tab. 4.1.3.1 Occurrence and duration (days) of low flow periods in evaluated discharge gauging profiles

Gauging profile	No. of periods	Duration (d) $Q < \mathbf{Q}_{330}$	Duration (d) $Q < \mathbf{Q}_{355}$	Duration (d) $Q < \mathbf{Q}_{364}$	Longest period duration (d)	Month of the year	Year
Šaštín-Stráže	26	1 030	80	1	190	7,8,9,10,11,12,1	2003/2004
Liptovský Mikuláš	35	1 300	533	50	111	11,12,1,2	2011/2012
Kysucké Nové Mesto	34	789	206	24	74	7,8,9,10	1983
Nitrianska Streda	36	1 327	420	58	133	7,8,9,10,11	1983
Brehy	51	1 658	612	93	89	7,8,9,10	1983
Holiša	39	837	329	52	146	5,6,7,8,9,10	1993
Vlkyňa	43	1 234	246	45	146	5,6,7,8,9,10	1993
Košické Oľšany	22	718	106	0	159	9,10,11,12,1,2	1986/1987
Hanušovce nad Topľou	40	984	317	47	94	11,12,1,2	1986/1987
Chmeľnica	29	958	304	49	80	1,2,3	1984

4.2. MODELLING OF RELATIONSHIPS BETWEEN PRECIPITATION AND RUNOFF

4.2.1. The Bilan water balance model

The Bilan model (T. G. Masaryk Water Research Institute, 2015) simulates elements of the water balance for basins. The structure of the model is based on equations that describe the basic principles of the water balance on the surface, in the soil zone (with the influence of covering vegetation) and in the groundwater zone. The calculation of the energy balance is based on air temperature. The model can operate with daily or monthly time series and the results of computations for the present research were given with daily steps.

The input data for computation of the water balance (when working with a daily time series) are the daily precipitation totals representing average total rainfall on the surface of the basin, air temperature and optionally also the relative air humidity. This parameter can be replaced by direct entry of the average value of potential evapotranspiration on the surface of the basin. The model parameters are calibrated (by an optimisation algorithm) using simulated and observed average daily runoff values at the basin's outlet expressed as runoff depth in millimetres.

The model simulates the time series of daily potential evapotranspiration, ground evaporation, infiltration to the soil and groundwater recharge from the soil. For each time step the model also simulates the quantity of water contained in snow cover, in soil and groundwater storage. These variables relate to the whole basin. For the model working with daily time steps, runoff is divided into direct runoff and baseflow.

The model uses six calibration parameters that are calibrated using an optimisation algorithm though the model offers some options for users to select from. The global algorithm incorporates the SCE-UA method (Shuffled Complex Evolution - The University of Arizona) described by Qingyun et al. (1994), with complex evolution based on the differential evolution (DE) method described by Stron and Priece (1997). The optimisation functions available are mean square error (MSE), mean absolute error (MQAE), mean absolute percentage error (MAPE), the Nash–Sutcliffe coefficient (NS) (Nash and Sutcliffe, 1970) and its logarithmic version (LNNS). The purpose of optimisation is to achieve the best possible match between the observed and simulated discharge series.

Air temperature and, if selected, relative air humidity are used to calculate potential evapotranspiration; air temperature is also used to distinguish between winter and summer conditions (regime type). Where snow cover occurs, algorithms are used to compute water accumulation in snow and snow melting. Water from melting snow infiltrates into the soil and this infiltrated water may be withdrawn by agricultural crops or other vegetation. Crops and other vegetation use soil moisture up to a certain potential extent (potential evapotranspiration) for as long as the water supply exists. If there is insufficient water in the soil, ground evaporation is reduced below its potential rate. In rainy periods, when precipitation exceeds potential evapotranspiration, the surplus is mainly fed into soil moisture. If the maximum storage capacity is exceeded, water percolates to the groundwater level. Direct surface runoff occurs in the event of high precipitation totals.

The input data is read into the model from a text file whose first row specifies the start date of the time series in the format YYYY MM DD, the year, month and day being separated by spaces. The input data are given in the order precipitation ***P*** (mm), observed runoff ***R*** (mm), air temperature ***T*** (°C) and relative air humidity ***H*** (%). The fifth column can be used for any variable (groundwater runoff, the level of groundwater…) which can be used in the visualisation of model outputs. The model can use the sixth column for potential evapotranspiration and the seventh for data on water use.

Potential evapotranspiration is estimated from the saturation deficit using functions (in the form of tables) derived for individual months of the year and various bioclimatic zones (Gidrometeoizdat, 1976). The saturation deficit (in mb) is calculated from air temperature and relative air humidity data. The daily values for potential evapotranspiration are calculated as monthly values divided by 30. An alternative method calculates potential evapotranspiration using a relationship derived by Oudin et al. (2010) based on the entered air temperatures and the catchment latitude in degrees. The value of extra-terrestrial solar radiation is then calculated for each time step and from this the value for potential evapotranspiration.

The following free calibration parameters are used:

- ***Spa*** – capacity of soil moisture storage (mm)
- ***Dgm*** – temperature/snow melting factor
- ***Alf*** – parameter controlling outflow from direct runoff storage
- ***Soc*** – parameter controlling distribution of percolation into direct runoff and groundwater recharge under summer conditions
- ***Mec*** – parameter controlling distribution of percolation into direct runoff and groundwater recharge under conditions of snow melting
- ***Grd*** – parameter controlling outflow from groundwater storage – base flow.

When optimisation is completed, the output panel displays the optimised output calibration parameters and the time series of hydrological parameters in the following structure:

- ***P*** (mm) – basin precipitation
- ***T*** (°C) – basin air temperature
- ***H*** (%) – basin relative air humidity
- ***R*** (mm) – observed runoff at outlet
- ***PET*** (mm) – potential evapotranspiration
- ***RT*** (mm) – ground evaporation
- ***INF*** (mm) infiltration into the soil
- ***PERC*** (mm) percolation through the soil to groundwater
- ***RC*** (mm) – recharge of groundwater storage
- ***DR*** (mm) – direct runoff
- ***BF*** (mm) – base flow (simulated)
- ***RM*** (mm) – total runoff (simulated)
- ***SS*** (mm) – snow water storage
- ***SW***(mm) – soil moisture
- ***GS*** (mm) – groundwater storage.

Results can be visualised for any combination of variables in daily, monthly or annual time series. The model can also display quantile plots of monthly data, Gumbel plots (focusing on extreme values of the monthly series) or a constant threshold can be entered to identify wet or dry periods.

4.2.2. The FRIER model

The FRIER Model was created in dissertation work (Horvát, 2007) and has since been undergone continuous improvement thanks to many projects such as the APVV project LPP-0254-07 (Hlavčová and Horvát, 2011), or the WATCH project in the 6th EU Framework Programme. The basic conception of the model is based on the structure of the physically-oriented WetSpa model (Wang et al., 1996) but it has been modified and reprogrammed to better model runoff from precipitation and melting snow in Slovak conditions. The model divides a basin into uniform spatial units on a grid scale, in which the water balance and the runoff simulation are calculated to the basin's outlet. The modelled elements of the water balance include liquid and solid precipitation, interception, soil moisture, infiltration, actual evapotranspiration, surface runoff, interflow in the root zone, percolation into the groundwater, groundwater runoff and groundwater storage in the saturated zone. Transformation of the surface runoff in a basin is simulated by approximating a diffusive wave model using the geometric and hydraulic characteristics of hill slopes and the stream network. Interflow is calculated using Darcy's law and a method of approximating the kinematic wave model. The model with spatially distributed parameters cooperates with the program ArcView GIS and the preparation of spatially distributed data is linked to the GIS environment. Some inputs to the model are prepared in the form of digital maps while hydrometeorological data and data on physiographical properties of the environment are entered in text form.

The model works with the following digital spatial data:

- A digital elevation model (DEM)

- A map of soil types
- A map of land use, watershed divides
- Stream network
- Geographical locations of precipitation, climatological and discharge gauges.

The digital elevation model and the maps of land use and soil types in raster format are the basis for derivation of most of the model's spatial parameters. The maps of watershed divides and the stream network are line vector files that are used for the sub-division of the basin and assessment of the accuracy of the stream network generated by the model.

The model uses four types of hydrometeorological data:

- Daily (hourly) total precipitation in the form of point measurements from stations ($mm.d^{-1}$, $mm.h^{-1}$)
- Daily (hourly) total potential evapotranspiration calculated at stations ($mm.d^{-1}$, $mm.h^{-1}$)
- Average daily (hourly) values air temperature in the form of point measurements from stations (°C)
- Average daily (hourly) discharges at the basin's outlet ($m^3.s^{-1}$).

Precipitation data for each time period is distributed to individual basin cells using the Thiessen polygons method. Potential evapotranspiration in each time period and cell is calculated using the Blaney-Criddle (Blaney and Criddle, 1950) equation based on air temperature and the solar radiation index or other methods for which input data is available. Measured discharge is compared with simulated discharges to evaluate the accuracy of the model but is not needed for discharge simulation itself.

The model includes several global parameters (GP) that apply to the whole basin:

- GP for precipitation:
  a) Coefficient for the effect of rain intensity on surface runoff ***K_run*** (-)
  b) Maximum rain intensity P_{max} ($mm.d^{-1}$, $mm.h^{-1}$), for which ***K_run***=1
- GP for the formation of solid precipitation or snow melting:
  a) Threshold temperature T0 for the formation of snow water storage, at which rain changes to snow (°C)
  b) "Degree-day" coefficient for melting snow ***K_snow*** ($mm.°C^{-1}.d^{-1}$)
  c) Coefficient for correction of the quantity of solid precipitation ***K_rain*** (-)
- GP for land use: coefficient of relative representation of impermeable surfaces on urban land K_imp (-)
- GP for soil moisture: relative initial soil moisture Kss (-), expressed as the relationship to field water capacity
- GP for evapotranspiration: coefficient Kep (-) for the correction of actual evapotranspiration
- GP for interflow: the scaling factor for interflow Ki (-) is the ratio of horizontal and vertical filtration coefficients reflecting the effect of organic material and root systems in the top layer of soil
- GP forgroundwater runoff: the coefficient of the groundwater depletion hydrograph Kg (-) expresses the regime of groundwater depletion for an average sub-basin; the total is divided into several sub-basins

- GP for groundwater storage: initial groundwater volume G0 and maximum groundwater volume Gmax (mm).

In the first phase of modelling the instantaneous unit hydrographs (IUH) are counted for each cell to the basin and sub-basin outlets and the IUH of the main streams. Next the runoff simulation determines the following output quantities:

- Average basin precipitation (mm)
- Surface runoff at the basin outlet ($m^3.s^{-1}$)
- Interflow at the basin outlet ($m^3.s^{-1}$)
- Groundwater runoff at the basin outlet ($m^3.s^{-1}$)
- Total runoff at the basin outlet ($m^3.s^{-1}$)
- Elements of the basin water balance (mm):
    a) Average basin precipitation
    b) Interception
    c) Average soil moisture
    d) Infiltration
    e) Evapotranspiration
    f) Percolation from the root zone
    g) Surface runoff
    h) Interflow
    i) Groundwater runoff
    j) Total runoff
    k) Change in groundwater storage.

The FRIER program includes an algorithm for computing the depth of soil freezing that allows a more precise specification of the currently active part of the soil layer. Precipitation-runoff models do not take account of it because of the difficulty of determining it. The possibility to calibrate groundwater runoff is of vital importance in drought modelling, helping to specify the computation of interflow and groundwater runoff. A method for separating BFI runoff from measured runoff developed by the British Institute of Hydrology (Institute of Hydrology, 1980) was tested as a means of obtaining more accurate computation of processes in the saturated zone. The Nash-Sutcliff coefficient (Nash and Sutcliffe, 1970) was used for comparison with simulated runoff. The accuracy of the groundwater runoff estimate was also enhanced by removal of its direct limiting by a parameter from above so that now it is indirectly limited by groundwater storage in the basin and its gravitational flow to the basin outlet. The number of days that water spends in the saturated zone is a significant data point for the estimate of groundwater runoff; in the model it is calibrated by the ***B_UH*** parameter.

4.3. CHARACTERISTICS OF PRECIPITATION-RUNOFF RELATIONSHIPS IN THE STUDIED BASINS

4.3.1. Results of modelling using the Bilan model

Data was calibrated and processed using the Bilan model for the following basins: the Myjava to Šaštín-Stráže, the Váh to Liptovský Mikuláš, the Kysuca to Kysucké Nové Mesto, the Nitra to Nitrianska Streda, the Hron to Brehy, the Ipeľ to Holiša, the Rimava to Vlkyňa, the Poprad to Chmeľnica, the Torya to Košické Olšany and the Topľa to Hanušovce nad Topľou.

The modelling was based on climate data calculated for the full area of the basin and hydrological data for the relevant discharge profile. The climatological variables were precipitation (mm), average air temperature (°C) and average relative air humidity (%) and the hydrological variable was the runoff depth in the basin at the final profile (mm). The processing of climatological data to cover the studied area of the basin was carried out for the project by the Slovak Hydrometeorological Institute (SHMÚ). Potential evapotranspiration was computed using the nomogram method (see Chapter 4.2.1). The model was calibrated with groundwater runoff calculated according to the Kille method and the BFI method using data on average daily discharges for the whole of the studied period 1981–2012. In most cases the optimisation criterion used was MAPE (see Chapter 4.2.1) with values ranging from 0.31 (Váh Basin) to 0.77 (Nitra Basin); the NS coefficient (see Chapter 4.2.1) was used for the Topľa Basin with a resulting value 0.66 while MSE (see Chapter 4.2.1) was used for the Kysuca with the resulting value 2.4.

The standard method used to determine groundwater runoff in Slovakia is the Kille method. Its disadvantage is that it requires a long time series of reference data – at least 10 years of average daily discharge values. The Kille method (Kille, 1970) uses graphical analysis and statistical methods to calculate the value of groundwater runoff from the minimum average daily discharge rate for each month in a sufficiently long time series (at least ten years). These rates are plotted graphically in order of size (Q against number of values) producing a graph similar to the cumulative frequency graph for the discharges. In the lower part of the set of ordered points of monthly minimum daily discharge rates for the whole measurement period, linear regression is used to identify a section (usually in the range $5 \leq n \leq 50$ values) with a linear course and the highest correlation coefficient. Next, an exponential regression equation based on the correlation coefficient is used to identify a section of the lower part of the set of points with the best approximation by exponential function. The obtained exponential equation is used to calculate the reduced value of the monthly minimum discharges in the upper part of the set of points. Next, the sum of the monthly minimum discharges in the lower part of the set of points and the reduced values of the monthly minimum discharges in the area of the exponential curve (the upper part of the set of points) is divided by the number of data points to give the value for groundwater runoff (baseflow) (Fendeková and Fendek, 1999).

From around 2005, Slovak researchers began to use the local minimum method to handle tasks involving the calculation of groundwater runoff. This is an automated separation method based on daily time steps. It uses average daily discharges and is based on the separation of the minimum discharge value from an N-day time period. This minimum value is multiplied by a correction factor (usually with a value of 0.9) and compared with the value obtained by the same method in the previous and following time steps. If the value obtained is less than or equal to both compared values, it is kept in the time series and becomes a “turning point” for deriving the separation line between direct runoff and groundwater runoff (baseflow). Otherwise it is discarded and analysis proceeds to the next N-day section. The turning points are joined to derive the separation line and the values between the turning points are obtained by linear interpolation. The resulting time series represents groundwater runoff (base flow) in daily steps.

The original program was developed in Great Britain (Institute of Hydrology, 1980) and was referred to as BFI (Base Flow Index) The original program worked with 5 days as the fixed value of the ***N-day*** time period. The correction factor was set to 0.9 based on calibration. Using the 5-day time period in Slovak river basins produced too high values for groundwater runoff that could not be compared with the previously used methods (Kille method, Foster separation scheme, Kliner-Kňežek method etc.). To tackle this problem, the BFI was revised by Gregor (2011) into BFI+2.0 and BFI+3.0 (Gregor 2013), which allows the length of the ***N-day*** time period to be set to any range and likewise it is also possible to select the value of the correction factor ***f***. The program is freely available from www.hydrooffice.org.

Previous studies have shown, using groundwater runoff values calculated using the Kille method as a comparison value, that the most suitable length of the time step is N = 15–30 depending on the studied basin. In their study of the River Nitra, Fendeková and Fendek (2012) used a time step ***N*** = 20 and this length of time step was also found to be optimal for basins in the Slovak part of the Tatry Mountains (Fendeková et al., 2014). In basins in Kysuce and Orava, on the other hand, the optimal length of the time step was ***N*** = 15. The reference values for groundwater runoff (base flow) calculated using the Kille and BFI methods and used in the calibration of the Bilan model for the studied basins are shown in Table 4.3.1.1.

Tab. 4.3.1.1 Values of the baseflow estimated by Kille´s and BFI methods

River basin	Basin size (km²)	Groundwater runoff (Kille) ($m^3.s^{-1}$)	Groundwater runoff (Kille) (mm)	Groundwater runoff (BFI) (mm)
Myjava	644.89	1.250	61	64*
Váh	1107.21	9.878	281	282**
Kysuca	995.09	4.219	134	144*
Nitra	2093.71	6.417	97	96**
Hron	3821.38	17.387	143	160*
Ipeľ	685.67	0.883	41	43*
Rimava	1377.41	2.090	48	56*
Poprad	1262.41	6.448	161	162***
Torysa	1298.30	3.109	76	78*
Topľa	1050.05	3.000	90	90*

Explanation: * ***N*** = 15, ** ***N*** = 20, *** ***N*** = 25

The outputs of the model solutions were used to calculate daily totals (mm) for the following elements of the water balance: potential evapotranspiration P_{ETP}, total evaporation from the basin ***ET***, infiltration of soil (unsaturated zone) ***INF***, percolation to the saturated zone ***PERC***, recharge of groundwater storage ***RC***, direct runoff of precipitation ***DR***, base flow (simulated) ***BF*** and total runoff (simulated) ***RM***. In the daily series, the Bilan program does not calculate a value for interflow.

Other elements of the water table that were output included water storage in snow ***SS***, water storage in the unsaturated zone (soil) ***SW***, groundwater storage ***GS*** and storage for direct runoff ***DS***.

The results of the modelling of the elements of the water balance by the Bilan model are shown in Table 4.3.1.2. The results were assessed based on the course of observed runoff (*R*), the modelled runoff (*RM*) and the baseflow (*BF*). An example of the results for the Myjava Basin (to the Šaštín-Stráže discharge gauging station) is shown in Fig. 4.3.1.1. From Fig. 4.3.1.1 it is clear that there is a very good fit between observed and modelled runoff. A comparison of the course of average monthly values find the best fit in the period of the accumulation and culmination of discharges (months XI–III) and slight undervaluing of the start of the discharge period (IV–VI). In other months the differences between the observed and modelled discharges is small and there is a good general match on seasonality. The values for groundwater runoff (baseflow) follow the course of the modelled runoff.

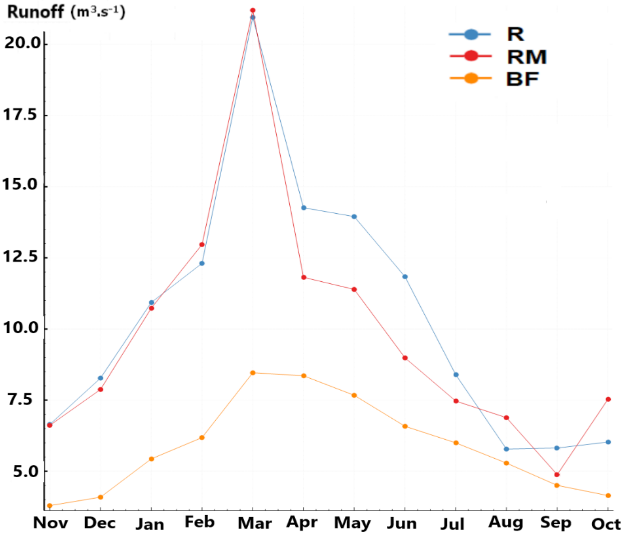


Fig. 4.3.1.1 Comparison of runoff compounds for the Myjava River basin

The evaluation of the size and relationship of the runoff components for each of the studied basins is set out in Table 4.3.1.3. Because the Bilan model does not compute the value of interflow in the daily time series, Table 4.3.1.3 shows only the values for direct, groundwater and total runoff.

Infiltration ***INF*** reflects precipitation conditions and represents entry to the root (unsaturated) layer of the Bilan model. The highest values were modelled (Tab. 4.3.1.2) for the basins of the Kysuca (792 mm), Hron (762 mm) and Poprad (760 mm).

The value for ground evaporation (***ET***, evapotranspiration) reflects the temperature conditions in the basin in combination with altitude. The highest values were modelled (Tab. 4.3.1.2) for the basins of the Myjava (536 mm), Ipeľ (510 mm) and Rimava (504 mm). The lowest value was calculated for the Váh Basin (275 mm). There was a similar situation in the values for potential evapotranspiration (***PET***) which were highest in the basins of the Nitra (768 mm), Ipeľ (749 mm), Myjava (733 mm) and Torysa (712 mm). The lowest potential evapotranspiration was computed for the basins of the Váh (364 mm) and Poprad (472 mm).

Tab. 4.3.1.2 Hydrological balance of evaluated basins for the period 1981–2012, inputs and outputs of the Bilan model

Parameter	**Myjava**	**Váh**	**Kysuca**	**Nitra**	**Hron**	**Ipeľ**	**Rimava**	**Poprad**	**Torysa**	**Topľa**
Input data										
Precipitation *P* (mm)	653	737	812	591	788	625	644	793	678	678
Air temperature *T* (°C)	9	2,5	8	9,7	7	9	8	4	9	8
Air humidity *H* (%)	76	81	79	75	77	75	76	77	77	78
Runoff (observed) *R* (mm)	125	542	334	205	336	108	126	373	182	225
Elements of the hydrological balance										
Potential evapotranspiratrion P_{ETP} (mm)	733	364	602	768	600	749	661	472	712	664
Areal evaporation *ET* (mm)	536	275	450	403	471	510	504	434	512	497
Infiltration *INF* (mm)	630	678	792	567	762	606	623	760	649	636
Percolation *PERC* (mm)	118	461	362	187	397	113	140	360	165	180
Groundwater storage recharge *RC* (mm)	70	293	153	99	183	48	56	179	92	139
Direct runoff *DR* (mm)	48	168	209	88	123	65	85	180	73	41
Baseflow *BF* (mm)	71	294	153	99	183	48	56	179	92	138
Total runoff (simulated) *RM* (mm)	118	462	362	187	307	114	141	359	166	180
Elements of the water storage										
Water storage in snow SS (mm)	3	33	6	3	9	2	5	8	4	11
Soil moisture (water storage in the unsaturated zone) *SW* (mm)	131	30	61	22	121	103	158	190	56	81
Water storage in the saturated zone *GS* (mm)	46	122	16	9	78	23	44	37	41	27
Water storage for direct runoff *DS* (mm)	1	3	2	2	2	1	2	2	1	0

The highest percentage levels of direct runoff (Tab. 4.3.1.3) were modelled in the basins of the Rimava (60%), Kysuca (58%), Ipeľ (57%) and Poprad (50%) while the lowest levels were in the basins of the Hron (4%), Topľa (23%), Váh (36%) and Torysa (44%).

The highest values for base flow (Tab. 4.3.1.2) were calculated for the basins of the Váh (294 mm), Hron (183 mm), Poprad (179 mm) and Kysuca (153 mm), and the lowest were for the Ipeľ (48 mm), Rimava (56 mm), Myjava (71 mm), Torysa (92 mm) and Nitra (99 mm). The percentage ratio of base flow to total runoff (Tab. 4.3.1.3) was highest in the basins of the Hron (96%), Topľa (77%) and Váh (64%). Overall, the highest runoff of water (Tab. 4.3.1.2) was in the basins of the Váh (462 mm), Kysuca (362 mm) and Poprad (359 mm), and the lowest was in the basins of the Ipeľ (114 mm), Myjava (118 mm) a Rimava (141 mm).

Tab. 4.3.1.3 Evaluation of runoff components in the modelled basins

Basin	Direct runoff *DR* (mm)	Baseflow *BF* (mm)	Total runoff *RM* (mm)	Runoff ratio *DR*:*BF* (%)
Myjava	48	70	118	41:59
Váh	168	294	462	36:64
Kysuca	209	153	362	58:42
Nitra	88	99	187	47:53
Hron po Brehy	123	121	307	04:96
Ipeľ	65	49	114	57:43
Rimava	85	56	141	60:40
Poprad	207	156	363	50:50
Torysa	73	92	166	44:56
Topľa	41	138	180	23:77

4.3.2. Results of modelling using the FRIER model

The project included calibration and processing of models for the following basins: the Myjava to Šaštín-Stráže, the Váh to Liptovský Mikuláš, the Kysuca to Kysucké Nové Mesto, the Nitra to Nové Zámky (the full basin), the Hron to Kamenín (the full basin), the Ipeľ to Holiša (the upper basin), the Poprad to Chmeľnica (all the basin in Slovakia), the Hornád to Žďaňa (all the basin in Slovakia), the Torysa to Košické Oľšany as a sub-basin of the Hornád (the full basin), the Slaná to Lenártovce (all the basin in Slovakia, to the confluence with the Rimava), the Rimava to Vlkyňa (the full basin), the Bodva to Hosťovce (the full basin), the Ondava to Horovce (the full basin), the Topľa to Hanušovce nad Topľou as a sub-basin of the Ondava (the full basin) and the Laborec to Humenné (before the Zemplínska Šírava Lake).

The aim was to include as large as possible a part of the territory of Slovakia in the analysis and prognosis of drought. Analysis was limited by the locations of discharge gauging stations, the location of the state border, tributaries from other countries and the existence of large reservoirs on streams, which influenced discharges in lower-lying profiles. This meant that it was impossible to measure the Danube in our territory, the whole of the Váh, Bodrog and Ipeľ or the Dunajec.

Input data on time series of total precipitation, discharge, air temperature, relative air humidity, cloud cover and wind speed were provided for the project from databases of the Slovak Hydrometeorological Institute. It covered the time series from the start of calendar year 1981 to the end of 2012.

Potential evapotranspiration was calculated using the Schendel equation (Hölting, 1980, adjusted for daily totals):

if $T > 0$, then:

$$E_{max} = 16\,\frac{T}{H} \tag{4.3.2.1}$$

where: E_{max} – potential evapotranspiration (mm.day^{-1})
T – daily average air temperature (°C)
H – relative air humidity (%).

Maps from the archive of the Department of Hydrogeology of the Faculty of Natural Sciences of Comenius University in Bratislava were used for the input spatial map for the digital elevation model with a 200 m raster and stream network on the scale 1:10,000, landscape use (CORINE 2006) and maps of soil types (Landscape atlas of the Slovak Republic, 2002).

4.3.2.1. Most frequent problems in hydrological model calibration

No method for the spatial distribution of measured meteorological values can reliably determine values for cells if there are not enough measurement stations or if they are not optimally distributed (location, altitude). There was a shortage of stations in nearly every Slovak basin, especially at higher altitudes.

To supplement precipitation totals, the project used the relationship between records from the missing and supplementing stations from periods when measurements were taken at both. The supplementing station is usually the one that is located closest to the station with missing data. A power dependency between station altitude and total precipitation was used. In the case of large altitude differences, the difference for lower totals is proportionally higher while with very large totals, there is assumed to be an insignificant difference. A deficiency that is hard to eliminate is the fact that at higher altitudes it not only rains more heavily but also more often. It is nearly always necessary to supplement a higher-altitude station with one at a lower elevation. In this case, the supplemented number of days with precipitation will be the same, however.

For air temperature, a table is generated of the relationship at each °C (each row is a step of 1°C) and the missing values are added from the table using the average values for dependences between stations and the given value measured for the supplementing station.

An important step is the creation of "virtual" stations, a few strategic points usually on the highest peaks and at the lowest point in the final profile of the basin. Capturing the values for the highest and lowest points in the basin makes it possible to create a more realistic vertical gradient for every time step. These few points can be checked more easily than all the cells in the basin. Values are entered using average annual values at the given altitude and given location. For total precipitation, vertical gradients are produced from the supplementing stations for each month and used to compute the precipitation that would fall at the given station if it was at the same altitude as the virtual station. The final value is computed by a weighted average based on the inverse distance of the supplementing stations from the virtual one. For air temperature, vertical gradients are produced from the supplementing stations for each time step and used to compute the value the given supplementing station would record if it were at the same altitude as the virtual station; a table is generated as in the previous case (each row representing a step of 1°C); the final value is computed by a weighted average of the values from the supplementing stations. The values from the virtual stations are checked and they can be partly adjusted based on the measured discharge. Precipitation is the most important input to the models and therefore the data must be prepared with due care. In Slovakia melting snow is the most important instantaneous addition of water to the system and it is therefore necessary to pay attention to air temperature, especially when its value is close to the temperature at which snow changes to water; an error in the estimate of air temperature of just 1°C when the temperature is close to 0°C makes it impossible to produce an acceptable calibration for the given simulation period. The virtual stations in the Nitra Basin can be taken as an example.

In Slovakia there are just 9 meteorological stations located at an elevation greater than 1,000 m a. s. l. Stations with an altitude around 2,000 m a. s. l. cannot supply adequate supplementary values for stations in lowlands and valleys because there is not usually a reliable relationship between them because of the change in conditions at altitudes around 1,500 m a. s. l. (Lapin, 2004, oral information). Based on these and other limiting criteria, e.g. large distance, the only source of supplementary data is the station on Krížna (1,570 m a. s. l.), though no measurements have been taken there since 2001.

4.3.2.2. The water balance in the modelled river basins

The modelled basins differ significantly in area. The smallest basin was the upper Ipeľ with 650 km^2, and the largest was the Hron with an area of 5,460 km^2. Basins with a relatively low average altitude included the Ondava, Ipeľ, Bodva and Rimava. At the other end of the scale, the Poprad, Hornád and Hron the highest average altitude. The steepest basins are the Hron to Brehy and the Slaná, the least steep are the Bodva, Ipeľ and Ondava basins.

The proportion of clay in the soil is very similar. Grain size distribution varies mainly in terms of the proportion of sand and silt. The lowest proportion of sand in the soil is in the Slaná, Ipeľ and Hornád Basins and the highest is in the basins of the Hron, Ondava, Poprad and Torysa.

To simplify comparison, land use was divided into three categories: (1) unfavourable surfaces (impermeable surfaces), (2) favourable surfaces (forests, scrub and meadows) and (3) agricultural land. All the basins have relatively little urbanised land, no more than 4%. Only the Poprad Basin has a relatively significant amount of bare soil, 3%, and elsewhere the value is less than 1%. Forest, scrub and meadows make up the majority of land in all the basins, with their occurrence ranging from 58% in the Bodva Basin to 86% in the Hron Basin to Brehy. The largest proportions of agricultural land are in the basins of the Bodva (38%) and the Ipeľ (36%) and the lowest are in the basins of the Laborec (13%) and the Hron to Brehy (11%). In all the basins, surface water flows to the basin outlet within 1 day, the longest time being 17 hours for the Hron and the shortest being less than 6 hours for the Ipeľ and the Laborec. The fastest average travel time is 3 hours in most basins though it is up to 9 hours in the Hron Basin.

The water balance was calculated on 3 levels: the surface, the unsaturated zone and the saturated zone. The resulting parameters for the water balance of all the modelled basin in the period 1981–2012 are summarised in Table 4.3.2.2.1.

Tab. 4.3.2.2.1 Hydrological balance of evaluated basins for the period 1981–2012, output of the Frier model

Parameter	**Myjava**	**Váh**	**Kysuca**	**Nitra**	**Hron total**	**Hron to Brehy**	**Ipeľ**	**Rimava**	**Slaná**	**Poprad**	**Torysa**	**Hornád**	**Topľa**	**Ondava**	**Laborec**	**Bodva**
Surface																
Precipitation	569	938	1054	574	858	939	680	685	835	913	765	784	831	844	976	943
Infiltration	485	809	906	496	768	837	599	599	729	794	670	670	736	745	880	850
Evaporation	60	110	112	60	78	91	65	72	91	91	94	94	81	79	79	79
Overland flow	25	19	37	22	13	13	17	17	18	30	23	23	18	23	17	17
Change in interception storage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Change in retention storage	-1	0	0	0	0	0	-1	-2	-2	-1	-1	-3	-3	-2	-1	-1
Change in snow storage	-1	0	-1	-4	-3	-4	-2	-2	-2	-3	-3	-2	-2	-2	0	-2
Soil																
Infiltration	485	809	906	496	768	837	599	599	729	794	670	670	736	745	880	850
Evapotranspiration	342	248	333	326	432	431	442	424	457	398	437	418	465	477	506	500
Percolation	126	317	291	150	265	290	141	151	223	259	198	207	217	224	246	235
Interflow	18	244	281	16	71	117	16	23	48	136	34	44	54	44	130	115
Change in soil moisture	-1	0	1	4	0	0	0	1	1	0	0	1	0	0	-2	0
Saturated zone																
Percolation	126	317	291	150	265	290	141	151	223	259	198	207	217	224	246	235
Transpiration	34	33	46	50	96	87	60	66	80	56	71	70	68	76	53	52
Baseflow	92	279	244	102	167	202	81	86	143	204	128	138	150	150	192	182
Change in groundwater storage	0	4	1	-2	2	1	0	0	0	0	-1	-1	-1	-1	1	0

The most precipitation per year on average fell in the basins of the Kysuca (1,054 mm), Laborec (976 mm), Váh (938 mm), followed by the Bodva, Hron and Poprad (all over 900 mm), and the least fell in the basins of the Myjava (569 mm), Nitra (574 mm), Ipeľ (680 mm) and Rimava (685 mm). The maximum difference between basins was nearly 500 mm (485 = 1,054 - 569). The highest totals, up to 1,764 mm, fell on the peaks of the Tatry Mountains in the Poprad basin (Fig. 4.3.2.2.1).

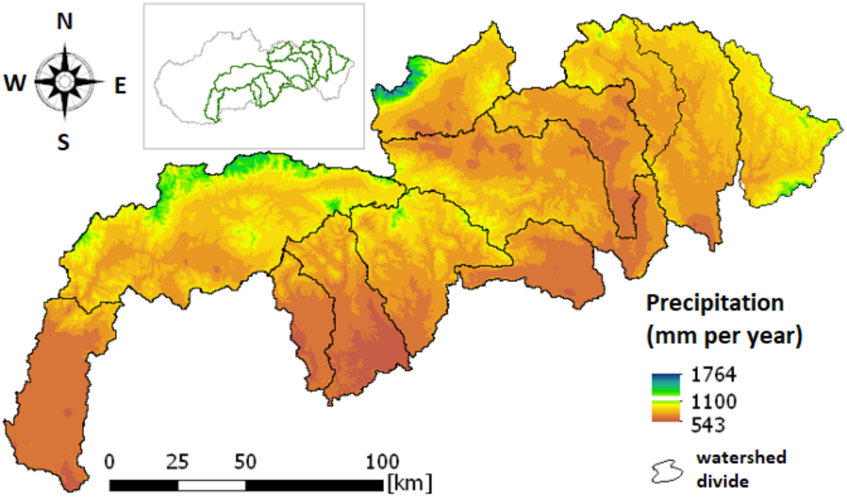


Fig. 4.3.2.2.1 Precipitation amounts in central and eastern Slovakian basins in 1981–2012

Infiltration reflects precipitation conditions and is similarly distributed. Evapotranspiration was highest in the basins of the Kysuca (112 mm), Váh (110 mm) and Hornád (94 mm) and lowest in the basins of the Myjava, Nitra (both 60 mm) and Ipeľ (65 mm). Surface runoff was highest in the basins of the Kysuca (37 mm) and Poprad (30 mm), and lowest in the basins of the Hron (13 mm), Ipeľ, Rimava, Laborec and Bodva (all 17 mm). Changes in interception storage over this time period were zero everywhere. Changes in retention storage and storage in snow in the basins were zero or negative, because there were high values at the start of 1981 and low values at the end of 2012.

The highest values for evapotranspiration were in calculated for the basins of the Laborec (506 mm) and Bodva (500 mm), while the lowest were in the Váh Basin (248 mm). Soil moisture decreased in the Myjava and Laborec Basins, while in other basins it was unchanged or increased usually by 1 mm; the largest increase was 4 mm in the Nitra Basin. In the saturated zone, the highest value for evaporation from the water table – transpiration – was computed for the basins of the Hron (96 mm – full basin, 87 mm to Brehy) and Slaná (80 mm) and the lowest values were for the basins of the Váh (33 mm) and Myjava (34 mm).

The ratios of the runoff components reveal differences in the character of the basins. While surface runoff in the basins of the Váh, Kysuca, Hron, Laborec, Poprad, Slaná and Topľa is below 10%, it is 18% in the Myjava Basin and 20% in the Bodva Basin (Tab. 4.3.2.2.2). The highest share of interflow was found in the basins of the Myjava (51%), Poprad, Laborec (37%) and Hron (35%), and the lowest in the basins of the Nitra (11%), Ipeľ and Bodva (14%).

The highest values for groundwater runoff (baseflow) were calculated for the basins of the Váh (279 mm), Kysuca (244 mm) and Poprad (204 mm), while the lowest were in the basins of the Ipeľ (81 mm) and Rimava (86 mm). Baseflow was the largest runoff component in all basins but contributed the least in the basins of the Váh (46%), Kysuca (47%), Poprad (55%) and Laborec (58%). In other basins baseflow's share of total runoff was in the range 61–73% with the highest values being in the Nitra Basin. Overall, the highest runoff of water was in the basins of the Kysuca (599 mm), Váh (542 mm) and Poprad (370 mm), while the lowest was in the basins of the Bodva (104 mm) and Myjava (135 mm). The highest ratio for interflow runoff occurs in the basins of the Poprad and Laborec (37%), and the Hron (28%, or 35%); the lowest is in the Ipeľ and Bodva Basins (only 14%).

Baseflow predominates in all basins but least in the basins of the Poprad (55%) and Laborec while in others it is 66–71%, with its highest percentage being in the Ipeľ Basin. Overall, the most water runs off in the Poprad Basin (370 mm) and the least in the Bodva Basin (104 mm).

The highest maximum discharges were recorded at Žďaňa on the Hornád (772 $m^3.s^{-1}$) and at Brehy on the Hron (753 $m^3.s^{-1}$), whereas the lowest values were close to zero on the Myjava, the Kysuca, the Ipeľ, the Rimava and the Bodva. The highest achieved average discharge was 44 $m^3.s^{-1}$ on the Hron at Kamenín and the lowest were on the Ipeľ at Holiša (2 $m^3.s^{-1}$), on the Myjava at Šaštín-Stráže (2.5 $m^3.s^{-1}$) and on the Bodva at Hosťovce (3 $m^3.s^{-1}$) (Tab. 4.3.2.2.2).

Tab. 4.3.2.2.2 Evaluation of the runoff components in the modelled basins

	Overland flow	Interflow	Baseflow	Total runoff	Runoff ratio OF:IF:BF	Minimum discharge	Maximum discharge	Average discharge
Unit	(mm)	(mm)	(mm)	(mm)	(%)	($m^3.s^{-1}$)	($m^3.s^{-1}$)	($m^3.s^{-1}$)
Myjava	25	18	92	135	18:13:69	0,2	72	2,5
Váh	19	244	279	542	03:51:46	4,2	260	19
Kysuca	37	281	244	599	06:47:47	0,3	286	8
Nitra	22	16	102	140	16:11:73	2,5	308	18
Hron total	13	71	167	251	05:28:66	7	684	44
Hron to Brehy	13	117	202	331	04:35:61	8	753	41
Ipeľ	17	16	81	114	15:14:71	0	80	2
Rimava	17	23	86	126	14:18:68	0	160	5
Slaná	18	48	143	210	09:23:68	1	284	12
Poprad	30	136	204	370	08:37:55	2	447	15
Torysa	23	34	128	185	12:19:69	1	292	7
Hornád	23	44	138	205	12:21:67	4	772	27
Topľa	18	54	150	222	08:24:67	1	220	7
Ondava	23	44	150	217	11:20:69	2	420	20
Laborec	17	115	182	314	05:37:58	1	323	13
Bodva	21	15	69	105	20:14:66	0	92	3

Because the FRIER model provides significantly better possibilities for more detailed study of water balance elements in a basin than the Bilan model, only the FRIER model was used in the prognosis of hydrological drought occurrence.

4.4. CHARACTERISTICS OF SELECTED EPISODES OF METEOROLOGICAL AND HYDROLOGICAL DROUGHT IN THE 21ST CENTURY

Slovakia is amongst the countries that have suffered from several episodes of drought in the 21st century. Three of them, in 2003, 2011–2012 and 2015 were episodes when there was meteorological and hydrological drought on the pan-European level. In general, it can be said that all three of the studied periods were amongst the warmest years on Earth in terms of average global air temperature since systematic weather measurements began. As Table 4.4.1 shows, 2015 was the second warmest year in history so far, 2012 was the tenth warmest and 2003 together with 2006 and 2007 take 11th to 13th place. Table 4.4.1 shows temperature deviations in °C from the average global air temperature in the period 1901–2000, which was 13.9°C.

Tab. 4.4.1 Ranking of 12 warmest years on the Earth within the observation period 1880–2017 (adopted according to NOAA, 2018)

Ranking*	Year	Deviation (°C)
1	2016	0.94
2	2015	0.90
3	2017	0.84
4	2014	0.74
5	2010	0.70
6	2013	0.67
7	2005	0.66
8	2009	0.64
9	1998	0.63
10	2012	0.62
11 (tie)	2003	0.61
11 (tie)	2006	0.61
11 (tie)	2007	0.61

Remark * 1 – the warmest year

An important factor affecting air temperature is change in the ocean surface temperature in the El Niño area. The parameter used for evaluation is a three-month moving average calculated for a three-month period made up of three consecutive months of the year (DJF – December-January-February, JFM – January-February-March, … NDJ – November-December-January). The threshold value is a value +/- 0.5°C compared to the ONI index (an anomaly in the three-month moving average of the ocean surface temperature in the El Niño region 3.4: 5°N – 5°S, 120–170°W compared to the 30-year reference period). The current reference period is 1986–2015. A positive anomaly with a value ≥ 0.5 is an El Niño effect, a negative anomaly with a value ≤ -0.5 is a La Niña effect. The values for 2003, 2012 and 2015 are shown in Table 4.4.2 with significant anomalies highlighted in bold. The table shows also the years preceding or following the evaluated year if their ONI values were significant for the development of air temperature.

The data in Table 4.4.2 shows that 2003 was under the influence of an El Niño effect, which had been at its peak in the previous year 2002. The year 2012 was under the influence of a La Niña effect, which had been strongest in the two preceding years, 2010 and 2011. The strongest El Niño effect was in 2015 but it began at the end of 2014 and continued nearly until the middle of 2016.

Tab. 4.4.2 Values of the deviations of ONI index in 2014–2016 compared to long-term period (http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_change.shtml)

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2002	-0.1	0.0	0.1	0.2	0.4	**0.7**	**0.8**	**0.9**	**1.0**	**1.2**	**1.3**	**1.1**
2003	**0.9**	**0.6**	0.4	0.0	-0.3	-0.2	0.1	0.2	0.3	0.3	0.4	0.4
2010	**1.5**	**1.3**	**0.9**	0.4	-0.1	**-0.6**	**-1.0**	**-1.4**	**-1.3**	**-1.7**	**-1.7**	**-1.6**
2011	**-1.4**	**-1.1**	**-0.8**	**-0.6**	**-0.5**	-0.4	**-0.5**	**-0.7**	**-0.9**	**-1.1**	**-1.1**	**-1.0**
2012	**-0.8**	**-0.6**	**-0.5**	-0.4	-0.2	0.1	0.3	0.3	0.3	0.2	0.0	-0.2
2014	-0.4	-0.4	-0.2	0.1	0.3	0.2	0.1	0.0	0.2	0.4	**0.6**	**0.7**
2015	**0.6**	**0.6**	**0.6**	**0.8**	**1.0**	**1.2**	**1.5**	**1.8**	**2.1**	**2.4**	**2.5**	**2.6**
2016	**2.5**	**2.2**	**1.7**	**1.0**	**0.5**	0.0	-0.3	**-0.6**	**-0.7**	**-0.7**	**-0.7**	**-0.6**

The drought in 2003 affect the whole of western, northern, central and southern Europe and the combination of heat wave and drought in 2003 is still considered one of the natural hazards with the most economically severe effects on Europe. From a climatological perspective the summer of 2003 was characterised by exceptionally high temperatures in many parts of central and eastern Europe with average daily temperatures being 2–3°C higher than the long-term average for 1970–2000. Atmospheric indicators such as the standardised precipitation and evapotranspiration index (SPEI) showed a dipolar structure with a precipitation deficit and extreme drought in central and southern Europe on the one hand and high total precipitation over part of the Scandinavian peninsula, Great Britain and Ireland (Laaha et al., 2017).

In 2012 the value of global average annual temperature calculated as a combination of land and ocean surface temperatures was 0.62°C higher than the average for the period 1880–2016 and 0.57°C higher than the average for the 20th century. As regards precipitation, 2012 followed two of the wettest years in the history of observation and the values for precipitation on land were close to the long-term average.

The last evaluated year, 2015, was the second warmest year in the period 1880–2017, as shown in Table 4.4.1. this year had a positive deviation of +0.9°C compared to the long-term average for 1901–2000. Global temperatures were significantly affected by the strong El Niño effect which began to develop at the end of 2014 and continued through the whole of 2015 to the middle of 2016, when it gave way to a weak La Niña phase. Air temperature on land in 2015 was 1.33°C higher than the average for the 20th century, the deviations for individual months ranged from +0.94°C in June to +1.89°C in December. In terms of total global annual precipitation, 2015 was slightly below the long-term average for the period 1961–1990 with a deviation of -22.5 mm compared to the average 1,033 mm. The year 2015 was dry not only in central Europe but also in southern Africa, Mongolia, the eastern part of Brazil and the parts of south-east Asia.

4.4.1. Meteorological drought in Slovakia in 2003, 2011–2012 and 2015

In Slovakia average air temperatures in summer 2003 were above the long-term average for 1951–2015 in all parts of the territory. As the data reported in Section 3.1.3 show, the year 2003 was characterised as dry in 97.2% of the territory of Slovakia, and from that, very dry in 74.4% of the territory. Total precipitation in the territory of Slovakia was 573 mm on average, which represents 74.5% of the normal. Although 57 mm of precipitation fell on the territory of Slovakia in the month of January (124% of the normal), the other early months of the year (February to April) were very dry or dry (43%, 28% and 78% of the normal). The month of May had normal precipitation (103%) but June was again very dry (44%). July's total (109%) mitigated the adverse situation but August and September were once again very dry or dry months (44%, 70%). After a slightly wetter October (130%), the remaining months of the year were once again dry and 2003 had an overall precipitation deficit for the territory of Slovakia amounting to 189 mm (www.shmu.sk). The deficit in soil moisture for all the monitored stations in Slovakia was over 30 mm.

The year 2012 was one of the warmest years in Slovakia since the start of meteorological observations. The average annual temperature at Hurbanovo was 11.7°C, which is +1.9°C above the long-term average for the period 1901–2000. It was the same in other parts of the territory. The temperature through the year was mostly above normal with the summer having the largest upward deviation. Only two months in the whole year had below-normal temperatures and the rest all ended with a positive temperature deviation. In terms of precipitation, 2012 was mostly normal (in 64% of the territory of Slovakia) and 33.8% of the territory was dry. There had, however, been drought in 2011 in which 88.6% of the territory had precipitation conditions that could be classified as dry and 56.8% of the territory could be characterised as very dry. Although 74 and 42 mm of precipitation fell on the territory of Slovakia in January and February 2012 (161% and 100% of the normal), the spring months from March to May were very dry or dry (28–78% of the normal). The month of June had normal precipitation, June was a wet month but these months were followed by a dry August with a total of 59 mm (27% of the normal) and September (75% of the normal). The adverse situation was improved by a very wet October (169% of the normal) but then there was a dry November. Precipitation at the end of the year was normal. Although 2012 was classified overall as having normal precipitation, there was an overall precipitation deficit of 49 mm, with August being the month with the deepest deficit (www.shmu.sk).

The year 2015 had significantly above-normal temperatures in Slovakia. 100% of climatological stations recorded an above-normal average annual air temperature with above-normally warm months in January, the whole period from June to September and November and December. Most of these months had temperatures much above normal (see Chapter 3.1.2). In terms of precipitation, 2015 was classified as a normal year overall (www.shmu.sk) with 719 mm of precipitation (94% of the long-term normal). It was evaluated as a dry year (Chapter 3.1.3), however, in 56.4% of the territory of Slovakia and drought occurred in several parts of the territory, especially in Eastern Slovakia. The first dry month was February (31 mm, 74% of the normal) and April was dry too (55% of the normal). The peak precipitation deficit was in the very dry June when precipitation was 47 mm (45% of the normal) and the months of July and August were also dry (53 and 57 mm, 59 and 70% of the normal). After an autumn with normal or above-normal precipitation, December was very dry (18 mm, 34% of the normal). The year 2015 ended with a precipitation deficit of 43 mm.

Meteorological drought in the period 1981–2016 was evaluated using the Standardised Precipitation Index (SPI) and the Standardised Precipitation and Evapotranspiration Index (SPEI).

Analysis of the values in SPI-12 show that the period 1981–2015 can be divided into two parts and this division applies to most of the studied basins. In the 1980s and the first half of the 1990s, most of the territory of Slovakia experienced dry conditions but the most extreme droughts occurred in the river basins of Northern Slovakia. The basin of the upper Váh can be used an example (Fig. 4.4.1.1) but the Poprad and Kysuca were similar. Long-lasting intense periods of drought were interrupted by only short periods of wetter conditions.

As Fig. 4.4.1.1 shows, normal to wet conditions developed from the mid-1990s culminating in the extremely wet year 2010. This period was interrupted by just three clear periods of drought: 2003–2004, 2011–2012 and 2015. The drought of 2003–2004 lasted for a relatively short time but the large deficit volume means that it can be considered the most intense drought of the 21st century in the Váh River Basin.

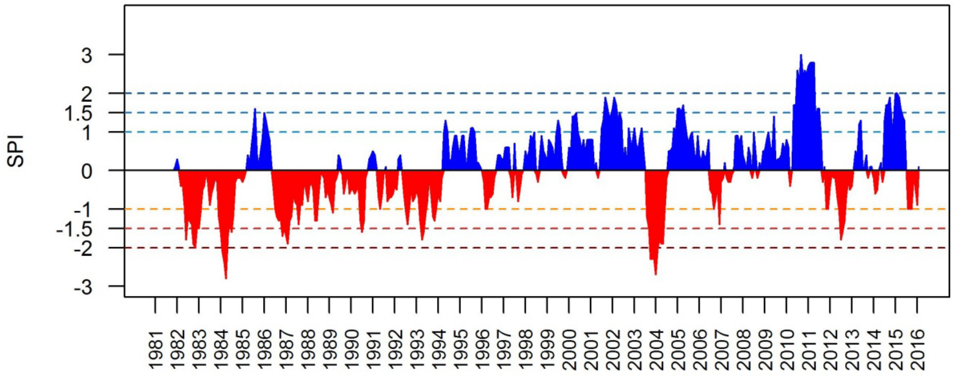


Fig. 4.4.1.1 Development of the SPI-12 index in the Váh River basin up to the Liptovský Mikuláš gauging profile (Labudová in Fendeková, Poórová and Slivová Eds., 2017)

Water conditions in the valley of the Myjava reflected the general development of the situation and the first half of the studied period there were many compact dry periods, especially in between 1988 and 1994, while the second half was dominated by normal or wet years. The picture of drought development did not change significantly after incorporating the effect of evapotranspiration determined using the SPEI-12 index.

Water conditions developed differently in the Kysuca River Basin in the 21st century, as documented in Fig. 4.4.1.2. The last five years in this river basin were very dry. The SPI-12 values fell to -2 or lower. Unlike other river basins in Northern Slovakia the wet periods here were much more moderate and were unable to balance the large precipitation deficits that developed especially after 2011.

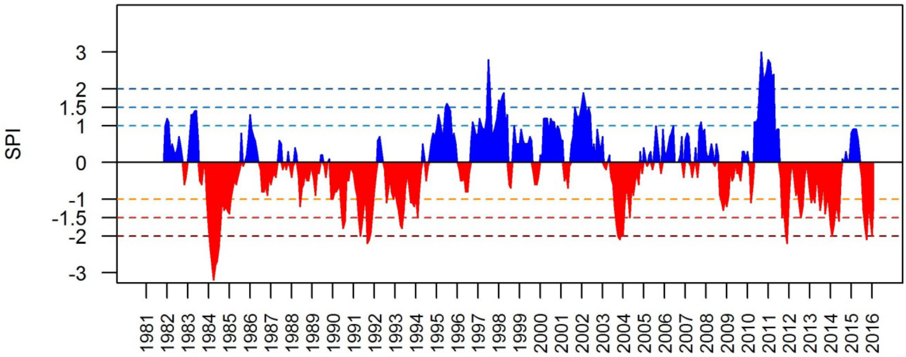


Fig. 4.4.1.2 Development of the SPI-12 index in the Kysuca River basin up to the Kysucké Nové Mesto gauging profile (Labudová in Fendeková, Poórová and Slivová Eds., 2017)

If the water balance is considered only in terms of precipitation, the last years in Southern and Eastern Slovakia were not extremely dry. The situation appears quite different, however, when temperatures are taken into consideration, which is possible when evaluating drought using SPEI. The sharpest difference can be seen when comparing the SPI and SPEI values for the Topľa River Basin to Hanušovce nad Topľou, as shown in Fig. 4.4.1.3. SPEI-12 shows that the droughts in 2011–2012 and 2015 were very intense, with values of -3 or lower.

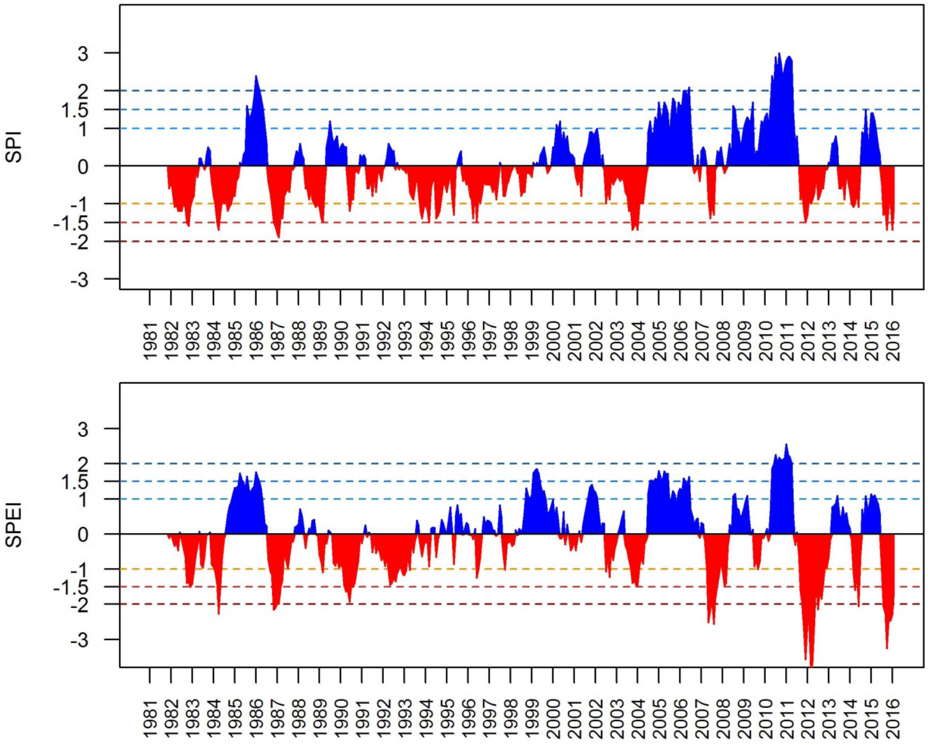


Fig. 4.4.1.3 Development of the SPI-12 index in the Topľa River basin up to the Hanušovce nad Topľou gauging profile (up) and SPEI-12 for the Čaklov station (down) (Labudová in Fendeková, Poórová and Slivová Eds., 2017)

4.4.2. Hydrological drought in Slovakia in 2003, 2011–2012 and 2015

The parameters of hydrological drought in the years 2003, 2012 and 2015 were computed by Dr Tobias Gauster at BOKU in Vienna (Gauster, 2016). The hydrological drought in discharges was evaluated using the Sequent Peak Algorithm (SPA) method using as a limit value the fixed flow Q_{80} calculated for the reference period 1981–2010. The limit value was set as the 80th percentile of the flow duration curve for the whole reference period and all discharges below the limit value were considered discharges indicating drought (Tallaksen and van Lanen Eds., 2004). The statistical analysis included identification of minimum values and the days of occurrence of the minimum annual discharge were identified based on the threshold value and using a 7-day moving average (AM7). The analysis also identified the start and end dates of the longest period of drought in a given year and the drought's duration, and also identified the occurrence of multi-year droughts (droughts extending beyond the end of one calendar year into another).

The period with the largest deficit volume was identified in each and this period was analysed in detail from the perspective of drought parameters. A theoretical frequency distribution was used to identify the return period of the drought parameters for the identified periods in all three evaluated years. The drought parameters were the value of annual minimum discharge ($m^3.s^{-1}$), the maximum annual value of deficit volume (m^3), its duration (day) and intensity ($m^3.d^{-1}$). The same parameters were also calculated as average values for each year and for the reference period.

The return period of the minimum annual discharge value was calculated using Weibull's theoretical frequency distribution, which is the method used most frequently for the analysis of minimum values in hydrology. Weibull's frequency distribution can be considered a generalised exponential distribution (Sachs, 1984) with three parameters (α, β, γ) that permit the distribution to approximate both normal and asymmetric distributions of series frequencies, whereas discharge series with predominantly low discharge values very often have an asymmetric distribution with positive asymmetry. The cumulative distribution function for the Weibull distribution is:

$$F(x) = 1 - e^{-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}} \qquad (4.4.2.1)$$

where: for $x > 0$ and $\alpha, \beta > 0$,
α – location parameter
β – scale parameter
γ – shape parameter.

Maximum deficit volume and its duration and intensity were analysed using the generalized extreme value (GEV) distribution for maximum values (Maidment Ed., 1992). This distribution incorporates Gumbel's type 1, 2 and 3 distributions for maximum values. The GEV distribution is also based on three parameters (ξ, α and κ), which are most frequently computed using L-moments (Hosking, Wallis, 1997). The cumulative distribution function for the GEV distribution (Sachs, 1984) is:

$$F(x) = e^{-\left[1-\frac{\kappa(x-\xi)}{\alpha}\right]^{1/\kappa}} \qquad (4.4.2.2)$$

where: for $\kappa \neq 0$
ξ – location parameter

α – scale parameter
$\varkappa$ – shape parameter.

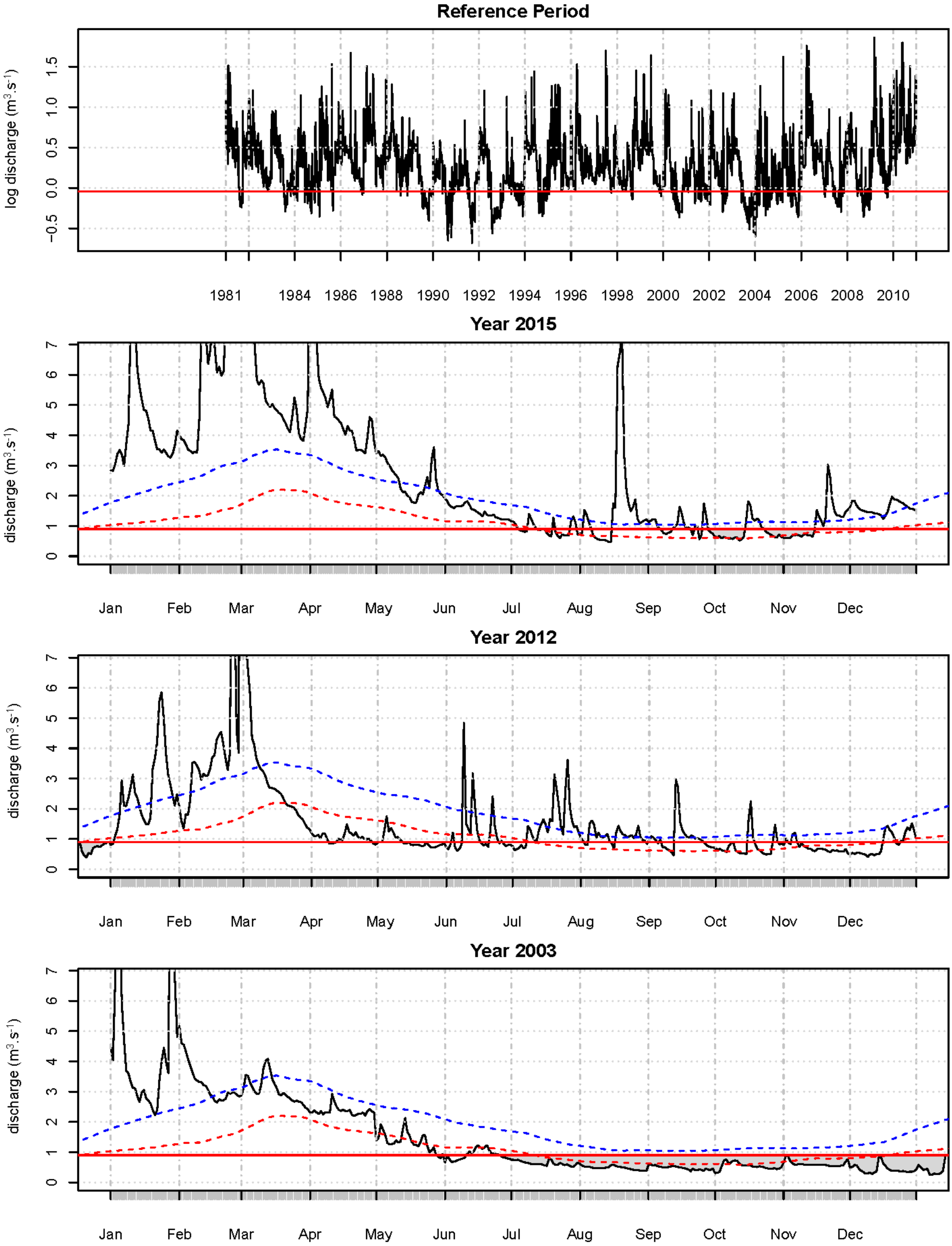
The match between the empirical and theoretical distributions was tested using the *L*-moments method.

The differences between the occurrence and course of the longest dry periods in the evaluated years can be clearly seen in the course of discharges in each of the studied river basins when they are compared against the threshold value Q_{80}. Fig. 4.4.2.1 shows the discharges in the Myjava – Šaštín - Stráže profile, Fig. 4.4.2.2 shows discharges in the Nitra - Nitrianska Streda profile and Fig. 4.4.2.3 shows discharges in the Kysuca - Kysucké Nové Mesto profile.

In Figures 4.4.2.1 – 4.4.2.3, the full black lines show surface discharges both for the reference period 1981–2010 and in the individual years 2015, 2012 and 2003. Discharges for the reference period are shown on a logarithmic scale so that it is possible to include all values; discharges for 2015, 2012 and 2003 are shown on a linear scale but maximum flows are cut off to provide a better resolution for the minimum values. The full horizontal red line in all figures corresponds to discharge Q_{80} calculated for the reference period 1981–2010, which represents the limit value below which all discharge values represent drought. The dashed blue line represents the seasonally variable value for the 30-day moving average of the quantile Q_{50} with probability of exceedance 0.5 (50%) and the dashed red line represents the seasonally variable 30-day moving average of the quantile Q_{80} with probability of exceedance 0.8 (80%). These lines are used as comparison values and express the long-term average value (blue) or drought conditions (red). The grey area represents the deficit volume during a period of drought.

Fig. 4.4.2.1 shows that the longest period of drought in the Myjava River Basin was in 2003, in the Nitra River Basin it was in all three years, with the longest being in 2003 and in the Kysuca River Basin it was in 2015.

The results of the evaluation of the return period for the drought parameters were as follows.



Reference Period

Year 2015

Year 2012

Year 2003

Fig. 4.4.2.1 Assessment of droughts in a discharge time series for the Myjava River at the Šaštín-Stráže station by the SPA method with a fixed threshold value and development of the 2015, 2012 and 2003 droughts (Gauster, 2016)

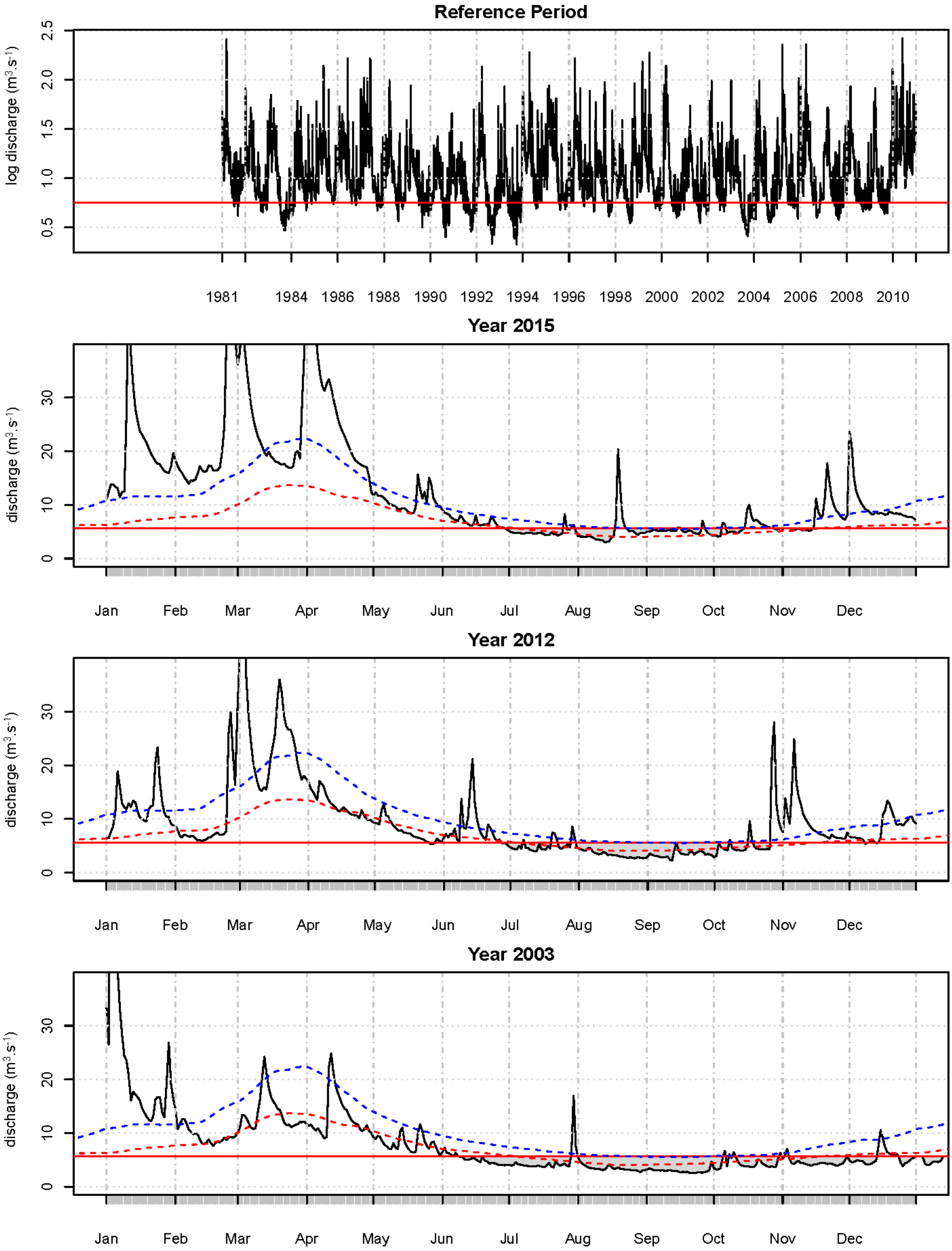


Fig. 4.4.2.2 Assessment of droughts in a discharge time series for the Nitra River at the Nitrianska Streda station by the SPA method with a fixed threshold value and development of the 2015, 2012 and 2003 droughts (Gauster, 2016)

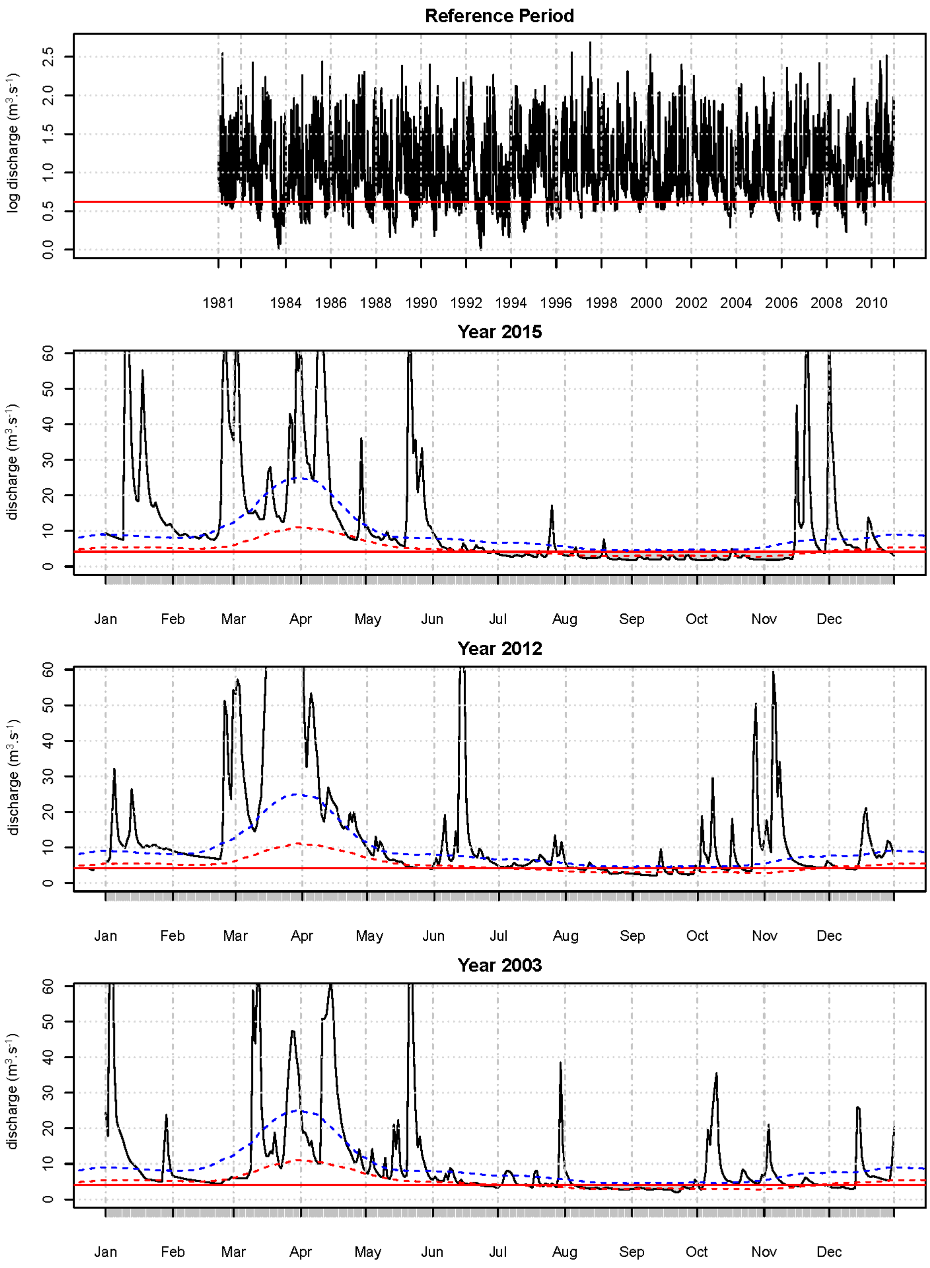


Fig. 4.4.2.3 Assessment of droughts in a discharge time series for the Kysuca River at the Kysucké Nové Mesto station by the SPA method with a fixed threshold value and development of the 2015, 2012 and 2003 droughts (Gauster, 2016)

The highest deficit volumes in most river basins were in 2003 and 2012. These deficit volumes were also higher than the average maximum deficit volumes in the reference period 1981–2010. This situation occurred in the basins of the Váh, Nitra (Fig. 4.4.2.4), Hron, Ipeľ, Rimava and Poprad. There was a significantly different situation in the Kysuca Basin where the highest deficit volume was in 2015 (Fig. 4.4.2.5).

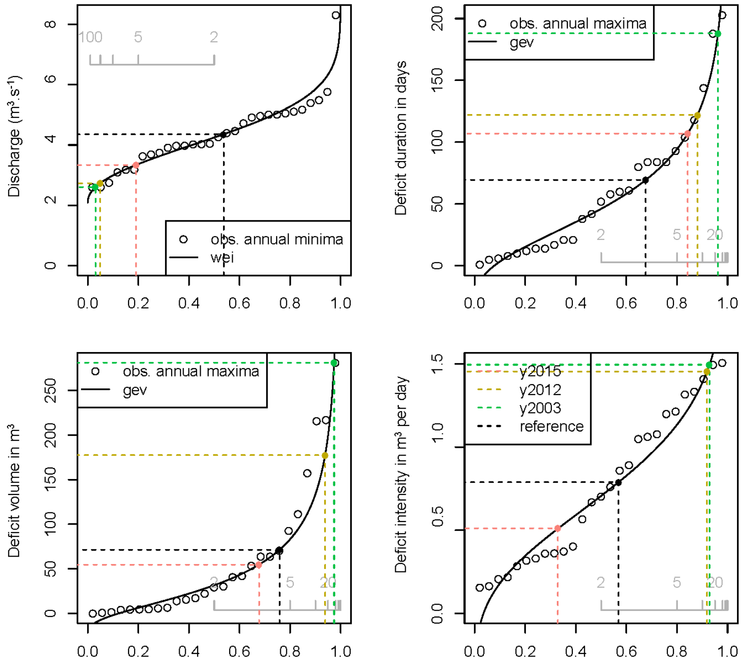


Fig. 4.4.2.4 Estimation of drought parameter return periods for the Nitra River (Gauster, 2016)

Drought intensity was most extreme in 2003 in the Myjava and Topľa Basins, in 2012 in the Váh and Poprad Basins and in 2015 in the Kysuce and Rimava Basins. Maximum drought intensity was nearly the same in 2003 and 2012 in the Nitra, Hron and Ipeľ Basins. In the Torysa Basin, drought intensity was nearly the same in all three years 2003, 2012 and 2015.

The highest return periods for the studied drought periods were as follows: (1) over 100 years for minimum AM7 discharge on the Torysa during the drought in 2012; (2) over 60 years for the duration of the longest drought period on the Hron in 2003; (3) over 50 years for the maximum deficit volume on the Kysuca in 2015 and (4) nearly 20 years for the intensity of drought on the Torysa in 2012. In general, the return period for drought parameters was highest in 2003 and 2012, with the return periods in the basins of the Myjava, Váh and Torysa being higher than the average return periods in the reference period. The only exception was the return period for the Kysuca, where the highest return periods for all parameters were in 2015 (Fig. 4.4.2.5).

To identify regional similarities linking the studied river basins, factor analysis was used in a version using the principal factor method and orthogonal rotation using the Varimax method. The input communalities for the calculation of factor loadings were calculated using the square of the coefficient of multiple correlation of every variable with all the other variables. After orthogonal rotation, the resulting communality had high values for all the input variables in the range 0.91–0.99; the resulting model with four extracted factors explained 98.99% of total variability in the input data.

Factor 1 (Tab. 4.4.2.1) is a common factor that covers the river basins of western, southern and eastern Slovakia, including the Myjava, Kysuca, Nitra, Ipeľ, Rimava, Torysa and Topľa River Basins. Factor 2 is another common factor that covers the river basins of central Slovakia, including the Váh, Nitra and Hron River Basins, and factor 3 affects the river basins of northern Slovakia, including the Váh and Poprad Basins. Factor 4 was a specific factor with a high factor loading for the Kysuca Basin.

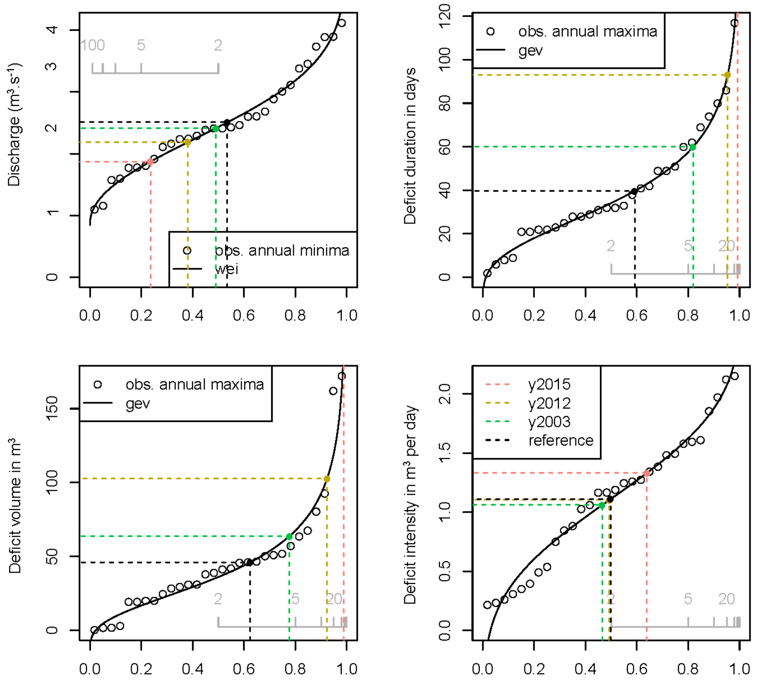


Fig. 4.4.2.5 Estimation of drought parameter return periods for the Kysuca River (Gauster, 2016)

Table 4.4.2.1 also shows that the Kysuca, Nitra and Váh had high factor loading in two different factors. The Kysuca River Basin was influenced by factors 1 and 4, the Nitra River Basin by factors 1 and 2 and the Váh River Basin by factors 2 and 3. This points to the borderline character of these river basins, which is probably the result of their location combined with their physiographical conditions, in particular their altitude, which is a determining factor for precipitation and temperature conditions.

Tab. 4.4.2.1 Results of drought parameters factor analysis

	Factor 1	Factor 2	Factor 3	Factor 4
Myjava	**0.949**	0.212	0.116	0.049
Váh	0.026	**0.710**	**0.665**	-0.046
Kysuca	**0.736**	0.194	0.157	**0.624**
Nitra	**0.668**	**0.668**	0.279	0.128
Hron	0.293	**0.919**	0.156	0.098
Ipeľ	**0.911**	0.109	0.160	0.147
Rimava	**0.944**	0.191	0.273	0.024
Poprad	0.181	0.481	**0.869**	0.069
Torysa	**0.822**	0.475	0.156	0.075
Topľa	**0.865**	0.351	0.211	0.225

A more detailed study of drought occurrence in the studied river basins identified other differences in the drought parameters also between neighbouring basins such as the Ipeľ and Rimava, or the Torysa and Topľa. These have been documented in another publication (Fendeková et al., 2017a).

4.5. ANALYSIS OF DROUGHT IN THE REFERENCE PERIOD 1981–2012

4.5.1 Evaluation of the occurrence of meteorological and hydrological drought

The FRIER model was used to obtain the parameters of meteorological and hydrological drought in the period 1981–2012 as shown in Tables 4.5.1.1 – 4.5.1.4. From the results, it is clear that the number of periods of hydrological droughts is decreasing in accordance with the drought propagation pattern and it is highest for drought in surface flow and lowest for drought in the saturated zone. Periods of meteorological drought are most frequent, which may be the result of the slightly different criteria for their occurrence. In the parameter of drought duration, the longest periods of drought occur in the saturated zone. The longest period was in the Myjava River Basin – 671 days, which is nearly 2 years. Such droughts were also frequent at times when flows on the surface and in the unsaturated zone had normal levels. An interesting statistical variable is the ratio of number of days of drought to the total number of days.

Tab. 4.5.1.1 Selected meteorological drought parameters for the period 1981–2012

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of meteorological drought		
				number of days	from	to
Myjava	**2.7**	85	26	177	04/02/2003	30/07/2003
Kysuca	2.4	74	24	135	02/05/1992	13/09/1992
Váh (upper)	2.5	83	27	156	05/02/1982	10/07/1982
Nitra	2.4	87	27	181	24/06/1983	21/12/1983
Hron (total)	**2.6**	87	26	195	17/12/1996	29/06/1997
Ipeľ (upper)	2.4	**93**	**30**	**270**	18/12/1992	13/09/1993
Poprad	2.5	82	26	208	26/10/1983	20/05/1984
Hornád	2.4	82	24	180	09/12/2001	06/06/2002
Slaná	2.3	**91**	28	**270**	17/12/1992	12/09/1993
Rimava	2.3	85	28	**270**	18/12/1992	13/09/1993
Bodva	2.1	**92**	26	217	17/12/1992	21/07/1993
Ondava	2.5	70	22	200	23/02/2003	10/09/2003
Laborec	2.4	74	23	158	25/01/2011	01/07/2011

Meteorological drought lasting at least one month (Table 4.5.1.1) occurred the most frequently in the basins of the Myjava and Hron (2.6 times per year) and least in the basin of the Bodva (2.1 times per year). The most days of meteorological drought per year were in the basins of the Ipeľ, Bodva and Slaná (91–93 days per year). The longest average duration of meteorological drought was in the basins of the Ipeľ, Rimava and Slaná (28–30 days) and the longest continuous period of meteorological drought, 270 days, occurred concurrently in the Ipeľ, Rimava and Slaná River Basins from 17/12/1992 to 13/09/1993.

Tab. 4.5.1.2 Selected surface stream hydrological drought parameters for the period 1981–2012

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the stream network		
				number of days	from	to
Myjava	0.3	4	6	58	13/02/1998	11/04/1998
Kysuca	0.7	10	**11**	81	15/06/1992	03/09/1992
Váh (upper)	0.8	15	9	118	30/10/2011	24/02/2012
Nitra	0.4	5	6	70	20/12/1989	27/02/1990
Hron (total)	0.9	13	9	96	22/04/1993	26/07/1993
Ipeľ (upper)	0.8	20	8	97	10/11/1989	14/02/1990
Poprad	0.9	19	9	166	31/08/1986	12/02/1987
Hornád	0.8	20	8	118	21/10/1986	15/02/1987
Slaná	0.9	**24**	9	**158**	21/10/1986	27/03/1987
Rimava	0.8	20	8	142	17/12/2011	06/05/2012
Bodva	0.8	15	7	82	23/11/1986	12/02/1987
Ondava	0.7	12	7	117	21/10/1986	14/02/1987
Laborec	0.9	17	9	**168**	30/08/1986	13/02/1987

The lowest frequency of hydrological droughts in the stream network lasting over one month (Table 4.5.1.2) were found in the Myjava and Nitra River Basins (0.3 – 0.4 times per year) and the highest frequencies were in the Hron, Poprad, Slaná and Laborec River Basins (0.9 times per year). The longest average drought length was in the Kysuca River Basin (11 days) and the shortest was in the Myjava and Nitra River Basins (just 6 days). The longest period of drought was 168 days, from 30/08/1986 to 13/02/1987 in the Laborec River Basin.

Hydrological processes in the unsaturated zone last longer than on the surface (max. 311 days in the Ipeľ River Basin vs. 168 days in Laborec River Basin) and have a greater delay. Drought is no exception to this rule. For example, the drought that began in the stream network of the Kysuca River Basin on 15/06/1992 was followed by drought in the unsaturated zone 8 days later. The average occurrence of periods of drought in the unsaturated zone lasting more than 31 days (Table 4.5.1.3) ranged from 0.8 times per year (Kysuca, Poprad, Hornád, Ondava) to 1.1 times per year (Myjava, Rimava). The average duration of periods of drought in the unsaturated zone reached a maximum of 25 days in the Bodva River Basin and just 11 days in the Kysuca and Váh River Basins. The longest identified period of drought was 311 days, from 04/09/2011 to 10/07/2012 in the Ipeľ River Basin.

Tab. 4.5.1.3 Selected hydrological drought parameters in the unsaturated zone for the period 1981–2012

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the unsaturated zone		
				number of days	from	to
Myjava	**1.1**	29	18	150	08/11/1989	06/04/1990
Kysuca	0.8	18	11	172	13/09/2005	25/03/2006
Váh (upper)	0.9	21	11	135	12/10/1988	23/02/1989
Nitra	1.0	34	19	**231**	07/07/1983	22/02/1984
Hron (total)	0.9	24	15	144	31/08/2011	21/01/2012
Ipeľ(upper)	1.0	**49**	**23**	**311**	04/09/2011	10/07/2012
Poprad	0.8	17	12	159	14/09/1986	19/02/1987
Hornád	0.8	32	17	226	01/09/2011	13/04/2012
Slaná	1.0	37	19	225	04/09/2011	15/04/2012
Rimava	**1.1**	43	**23**	**238**	30/08/2011	23/04/2012
Bodva	0.9	**56**	**25**	**238**	30/08/2011	23/04/2012
Ondava	0.8	23	14	182	27/08/2011	24/02/2012
Laborec	1.0	26	14	157	16/09/1986	19/02/1987

Periods of hydrological drought in the saturated zone exhibit less fluctuation and a smaller and more delayed response, while on the other hand they last longer. As can be seen in Table 4.5.1.4, the longest duration of drought in the saturated zone was 671 days between 26/01/1989 and 27/11/1990 in the Myjava River Basin.

Tab. 4.5.1.4 Selected hydrological drought parameters in the saturated zone for the period 1981–2012

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the saturated zone		
				number of days	from	to
Myjava	1.2	136	90	**671**	26/01/1989	27/11/1990
Kysuca	1.3	51	32	207	26/05/1983	18/12/1983
Váh (upper)	0.7	72	50	348	09/06/1983	21/05/1984
Nitra	1.2	134	79	**607**	07/03/1989	03/11/1990
Hron (total)	1.2	107	62	398	27/09/2011	28/10/2012
Ipeľ (upper)	1.3	**142**	81	465	02/09/2006	10/12/2007
Poprad	1.2	84	52	290	23/07/1983	07/05/1984
Hornád	1.2	111	70	301	20/09/2011	16/07/2012
Slaná	1.0	126	**95**	335	21/04/2003	20/03/2004
Rimava	1.0	**142**	**104**	432	06/10/2006	11/12/2007
Bodva	1,0	**149**	**104**	420	16/06/2001	09/08/2002
Ondava	**1.5**	97	54	330	02/05/1986	27/03/1987
Laborec	**1.5**	74	41	282	15/05/1986	20/02/1987

There was a slightly shorter drought at the same time in the Nitra River Basin. The average duration of periods of drought ranged from 104 days in the Rimava and Bodva River Basins to just 32 days in the Kysuca River Basin. Drought was most frequent in the Ondava and Laborec River Basins (1.5 times per year) and least frequent in the Váh River Basin (0.7 times per year).

4.5.2. Propagation of drought in the reference period 1981–2012

The propagation of drought in the water system can be illustrated with data from the Kysuca River Basin. The two largest periods of drought in the Kysuca Basin during the studied period 1981–2012 were the droughts in 1983–1984 and 2005–2006. Both began with meteorological drought. In Fig. 4.5.2.1, drought in each type of environment is represented by a red area. The meteorological drought lasted longer and was larger in 1983 than in 2005–2006 but the hydrological drought situation was reversed and was longer in 2005–2006, mainly because of the severe winter that extended it. Only the hydrological drought in the unsaturated zone was larger in 1983, but it was not longer. In 1983 the hydrological drought began after the snow melt ended whereas in 2005–2006 it began in the autumn after low precipitation. The meteorological drought in 1983 was interrupted by several precipitation events, one of which ended the hydrological drought in the unsaturated zone in October, though the drought in the stream network and the saturated zone ended only in December when snow melted prematurely. The hydrological drought in 2005–2006 ended with the melting of snow after a severe winter with long-lasting low air temperatures.

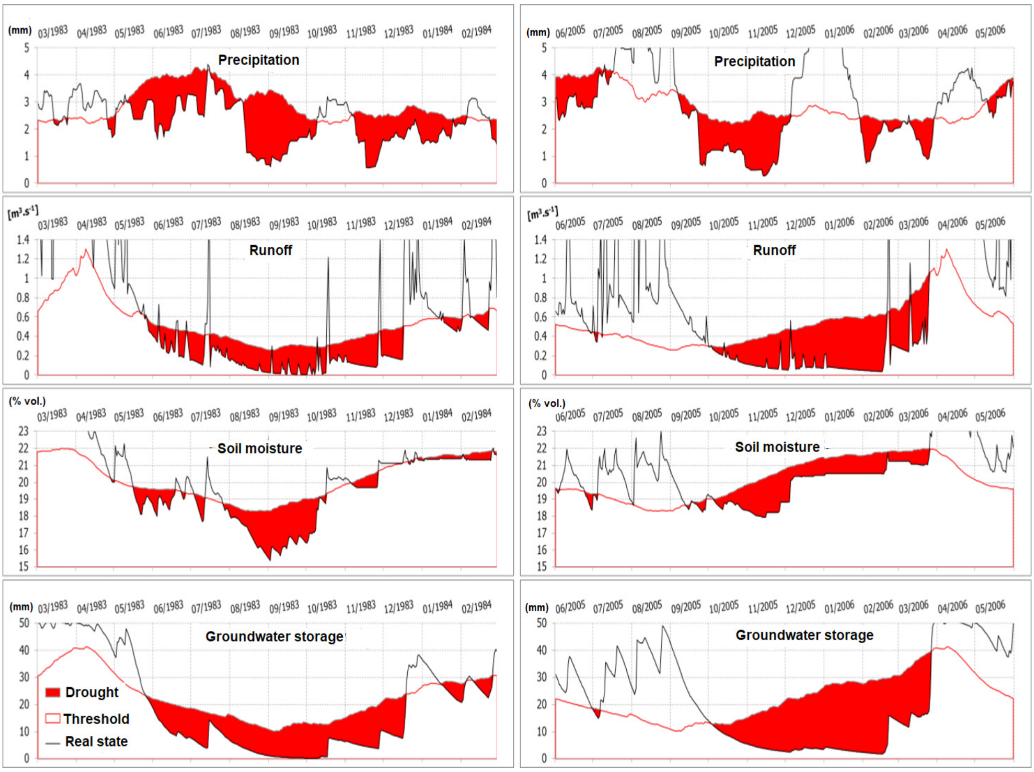


Fig. 4.5.2.1 Droughts in the Kysuca River basin in 1983–1984 and 2005–2006. Droughts are indicated in red. Upper panel: meteorological drought, second panel – streamflow drought, third panel – unsaturated zone drought, lower panel – saturated zone drought

4.6. ANALYSIS OF DROUGHT OCCURRENCE BASED ON CLIMATE CHANGE SCENARIOS FOR THE PERIOD 1981–2100

A period of occurrence of meteorological drought was determined by comparing total scenario precipitation for the preceding 31 days with a long-term average value for total precipitation for the 31-day reference period based on a day precisely in the middle of these days (e.g. for the date 16/1/2100, total scenario precipitation for the period 17/12/2099 to 16/01/2100 was compared with average total precipitation in Januaries (1/1–1/1) in the years 1981–2012. If the total precipitation calculated by the scenario was lower than the long-term average, the day was classified as dry. A consecutive series of at least 31 such dry days was classified as a period of drought.

The threshold value method was used to identify hydrological drought in surface flows, in the unsaturated zone (interflow) and the saturated zone (baseflow) computed using the FRIER model for each river basin. The threshold was set to the 90th percentile on a monthly basis. Separate monthly threshold values were smoothed using a 31-day centred moving average. To eliminate short periods of drought, a minimum duration of 31 days was set.

4.6.1. Characteristics of drought parameters in the period 1981–2100

The results obtained from the scenarios (Comenius University in Bratislava, Faculty of Mathematics, Physics and Computer Science, 2016, 2017) indicate that there will be less frequent meteorological droughts with shorter durations but that there will be greater water shortages during droughts. Hydrological drought will occur more frequently in the stream network, last longer and have greater water deficits. Hydrological drought in the unsaturated zone will last longer in future with a larger water deficiency while the frequency of drought in the saturated zone will be the same but it will last much longer and have a greater water deficit, as can be seen by comparing the values in Tables 4.5.1.1–4.5.1.4 with those in Tables 4.6.1.1–4.6.1.4, which show selected drought parameters forecast for the period 1981–2100.

Tab. 4.6.1.1 Selected meteorological drought parameters for the period 1981–2100 from the KNMI 2 and MPI 1 scenarios

KNMI 2 Scenario						
Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of meteorological drought		
				number of days	from	to
Myjava	2.3	72	24	232	05/02/1989	24/09/1989
Kysuca	2.1	76	24	216	28/03/2036	29/10/2036
Váh (upper)	2.2	81	27	274	08/12/2007	06/09/2008
Nitra	2.2	80	27	214	29/03/2036	28/10/2036
Hron (total)	2.2	87	29	270	12/12/2007	06/09/2008
Ipeľ (upper)	2.2	93	30	297	28/11/2087	19/09/2088
Poprad	2.2	82	27	270	12/12/2007	06/09/2008
Hornád	2.4	139	39	325	19/10/2007	07/09/2008
Slaná	2.2	91	30	332	29/10/2087	24/09/2088
Rimava	2.2	94	30	302	28/11/2087	24/09/2088
Bodva	2.2	93	30	269	28/11/2087	22/08/2088
Ondava	2.3	86	28	191	15/03/1999	21/09/1999
Laborec	2.1	81	25	200	23/03/2055	08/10/2055

MPI 1 Scenario						
Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of meteorological drought		
				number of days	from	to
Myjava	2.2	84	27	204	02/04/2036	22/10/2036
Kysuca	2.1	67	22	206	06/01/1992	29/07/1992
Váh (upper)	2.2	65	22	263	25/12/2007	12/09/2008
Nitra	2.2	68	25	168	01/04/2018	15/09/2018
Hron (total)	2.3	69	24	164	12/07/2071	22/12/2071
Ipeľ (upper)	2.3	76	25	207	01/12/2087	24/06/2088
Poprad	2.0	69	23	265	24/12/2007	13/09/2008
Hornád	2.5	124	33	284	26/12/2031	04/10/2032
Slaná	2.2	76	24	306	05/03/2032	04/01/2033
Rimava	2.3	82	26	270	13/12/2007	07/09/2008
Bodva	0.8	14	14	147	06/07/2071	29/11/2071
Ondava	2.1	72	23	215	05/03/2032	05/10/2032
Laborec	2.2	74	24	263	26/03/2071	13/12/2071

Tab. 4.6.1.2 Selected surface streams hydrological drought parameters for the period 1981–2100 using data of KNMI 2 and MPI 1 scenarios

KNMI 2 Scenario

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the stream network		
				number of days	from	to
Myjava	0.4	6	6	90	03/12/2041	02/03/2042
Kysuca	0.9	19	10	133	29/03/2099	08/08/2099
Váh (upper)	1.3	40	14	221	11/04/2055	17/11/2055
Nitra	0.6	8	7	93	11/02/2033	14/05/2033
Hron (total)	1.4	39	12	232	30/03/2055	16/11/2055
Ipeľ (upper)	1.1	20	10	219	10/11/2087	15/06/2088
Poprad	1.3	32	12	180	17/08/1993	12/02/1994
Hornád	2.2	63	13	275	06/09/1997	07/06/1998
Slaná	1.4	29	12	248	10/11/2087	14/07/2088
Rimava	1.1	20	10	228	10/11/2087	24/06/2088
Bodva	0.9	15	9	105	12/03/2099	24/06/2099
Ondava	0.9	19	10	121	25/02/2088	24/06/2088
Laborec	1.3	26	12	121	11/09/1989	09/01/1990

MPI 1 Scenario

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the stream network		
				number of days	from	to
Myjava	0.5	8	7	107	13/11/2036	27/02/2037
Kysuca	0.8	18	9	143	26/07/2071	15/12/2071
Váh (upper)	1.0	29	11	271	09/04/2032	04/01/2033
Nitra	0.5	8	6	100	13/02/2041	23/05/2041
Hron (total)	1.2	27	10	170	14/08/2071	30/01/2072
Ipeľ (upper)	0.8	15	8	185	10/11/2087	12/05/2088
Poprad	1.0	32	11	172	01/09/2048	19/02/2049
Hornád	1.8	69	12	257	08/10/2055	20/06/2056
Slaná	1.0	23	9	210	03/10/2041	30/04/2042
Rimava	0.8	16	8	131	03/11/2043	12/03/2044
Bodva	2.4	100	16	384	18/12/2031	04/01/2033
Ondava	0.8	19	8	150	16/01/2056	13/06/2056
Laborec	1.3	29	11	152	18/07/2071	16/12/2071

Tab. 4.6.1.3 Selected hydrological drought parameters in the unsaturated zone for the period 1981 – 2100 using data of KNMI 2 and MPI 1 scenarios

KNMI 2 Scenario

Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the unsaturated zone		
				number of days	from	to
Myjava	1.1	38	19	248	04/08/2071	07/04/2072
Kysuca	1.4	43	16	222	14/03/2055	21/10/2055
Váh (upper)	1.3	41	17	236	19/03/2099	09/11/2099
Nitra	1.2	54	23	287	12/03/2055	23/12/2055
Hron (total)	1.2	50	19	238	17/03/2099	09/11/2099
Ipeľ (upper)	1.4	76	31	433	20/07/2087	24/09/2088
Poprad	1.3	47	18	248	22/03/2099	24/11/2099
Hornád	0.3	10	16	153	23/09/2030	22/02/2031
Slaná	1.3	76	29	311	31/05/2043	05/04/2044
Rimava	1.3	77	31	460	23/06/2087	24/09/2088
Bodva	1.,2	63	29	374	09/06/2030	17/06/2031
Ondava	1.3	63	22	360	07/03/2055	29/02/2056
Laborec	1.3	58	21	264	16/03/2055	04/12/2055

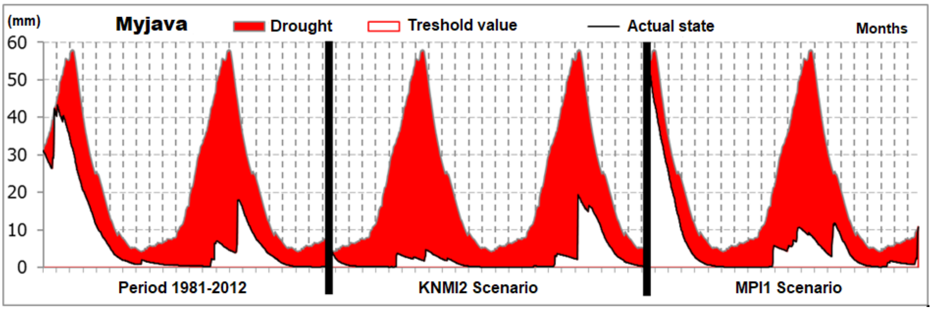
MPI 1 Scenario

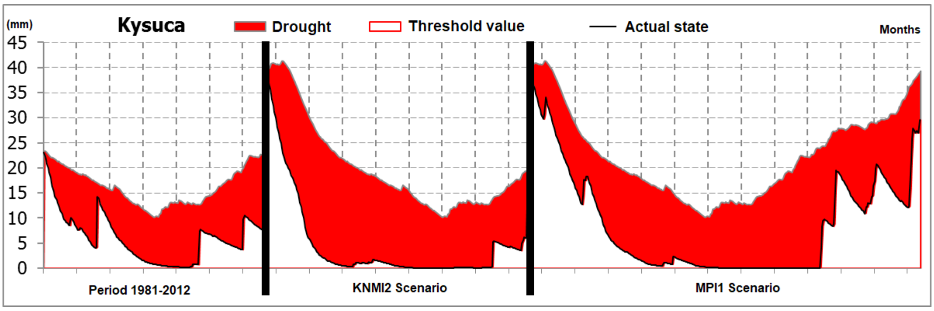
Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the unsaturated zone		
				number of days	from	to
Myjava	1.2	50	22	305	03/05/2036	03/03/2037
Kysuca	1.5	47	17	223	17/08/2032	27/03/2033
Váh (upper)	1.1	32	13	232	18/05/2032	04/01/2033
Nitra	1.2	44	20	308	21/05/2032	24/03/2033
Hron (total)	1.1	36	15	297	22/05/2032	14/03/2033
Ipeľ (upper)	1.1	55	24	348	20/05/2032	02/05/2033
Poprad	1.0	38	15	223	14/08/2032	24/03/2033
Hornád	0.3	8	20	158	28/08/2071	01/02/2072
Slaná	1.0	57	23	316	03/08/2030	14/06/2031
Rimava	1.1	62	25	325	22/05/2032	11/04/2033
Bodva	0.2	4	12	116	23/08/2071	16/12/2071
Ondava	1.1	54	20	306	21/05/2032	22/03/2033
Laborec	1.4	59	21	309	19/05/2032	23/03/2033

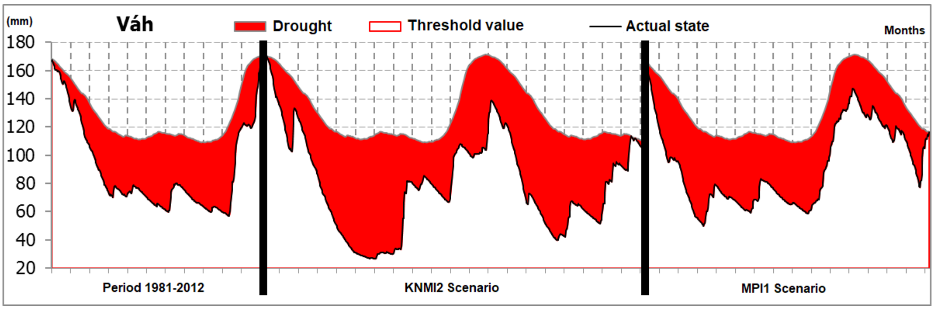
Tab. 4.6.1.4 Selected hydrological drought parameters in the saturated zone for the period 1981 – 2100 using data of KNMI 2 and MPI 1 scenarios

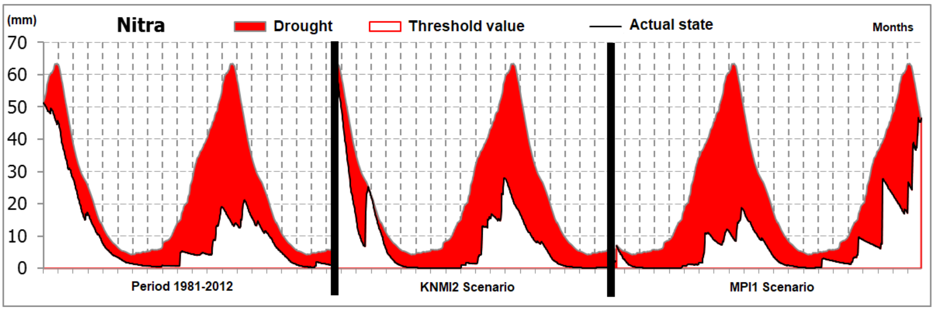
KNMI 2 Scenario						
Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the saturated zone		
				number of days	from	to
Myjava	1.1	131	86	734	05/09/2071	07/09/2073
Kysuca	1.3	67	39	245	26/03/2055	25/11/2055
Váh (upper)	1.0	130	89	620	27/05/2032	05/02/2034
Nitra	1.1	126	91	641	04/04/1997	04/01/1999
Hron (total)	1.1	130	87	648	01/04/1997	08/01/1999
Ipeľ (upper)	1.3	146	91	633	16/03/2032	08/12/2033
Poprad	1.2	116	68	627	29/06/2030	16/03/2032
Hornád	0.9	274	201	1 686	06/11/2029	18/06/2034
Slaná	1.1	141	99	647	08/04/1997	14/01/1999
Rimava	1.1	146	99	659	27/03/1997	14/01/1999
Bodva	1.0	154	125	877	02/04/2055	25/08/2057
Ondava	1.2	126	75	1 165	29/07/2030	05/10/2033
Laborec	1.4	101	55	332	23/03/2055	17/02/2056
MPI 1 Scenario						
Basin	Number of periods of drought per year with duration ≥ 31 days	Number of days in drought period (≥ 31 days)	Average drought duration in days	The longest duration of hydrological drought in the saturated zone		
				number of days	from	to
Myjava	1.1	131	95	633	18/03/2032	10/12/2033
Kysuca	1.3	65	36	364	27/03/2032	25/03/2033
Váh (upper)	1.0	106	67	499	05/12/2002	16/04/2004
Nitra	1.1	133	90	634	04/08/2071	28/04/2073
Hron (total)	1.1	125	88	774	23/10/2040	05/12/2042
Ipeľ (upper)	1.3	146	87	767	25/10/2040	30/11/2042
Poprad	1.2	101	58	384	14/03/2032	01/04/2033
Hornád	1.0	281	195	1 153	16/07/2001	10/09/2004
Slaná	1.1	134	93	750	16/11/2040	05/12/2042
Rimava	1.1	151	101	938	09/09/2001	03/04/2004
Bodva	1.5	70	35	407	15/02/2032	27/03/2033
Ondava	1.2	125	72	580	30/08/2002	31/03/2004
Laborec	1.4	107	56	385	31/05/2030	19/06/2031

Comparison of the data in Tables 4.5.1.1 – 4.5.1.4 and 4.6.1.1 – 4.6.1.4 gives an overview of the potential development of meteorological and hydrological drought in the studied river basins of Slovakia under two scenarios – KNMI 2 and MPI 1. Regarding drought in the saturated zone, the KNMI 2 scenario forecasts a significant extension in its duration in river basins east of the Nitra except the Laborec, which will be especially significant in the Hornád River Basin, where the longest period of continuous drought was estimated to be 1,686 days, which is 5 times longer than the longest drought in the reference period 1981–2012 (301 days), and likewise in the basins of the Ondava (1,165 days vs. 330 days) and Bodva (877 vs. 420 days). The largest extension of average drought length will also be in the Hornád River Basin (201 vs. 70 days). The MPI 1 scenario also predicts the longest drought in the Hornád River Basin (max. 1,153 days, average 195 days). In the basins of the Kysuca, Hron, Ipeľ, Slaná, Rimava and Laborec, the scenario forecasts longer periods of extreme drought than the KNMI 2 scenario but otherwise in the case of the Váh, Poprad, Hornád, Bodva and Ondava River Basins. The average duration of drought is unchanged in the basins of the Poprad, Rimava and Slaná. In the Bodva River Basin it even forecasts a significant reduction in drought duration (104 vs. 35 days).





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Nitra
Drought
Threshold value
Actual state
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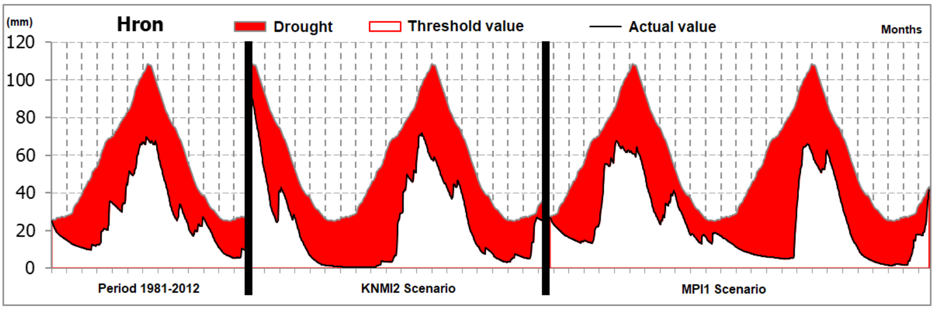
Period 1981-2012
KNMI2 Scenario
MPI1 Scenario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Drought
Threshold value
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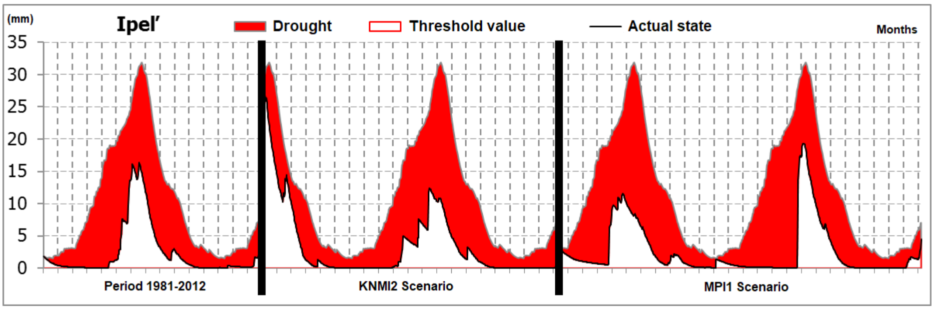
Period 1981-2012
KNMI2 Scenario
MPI1 Scenario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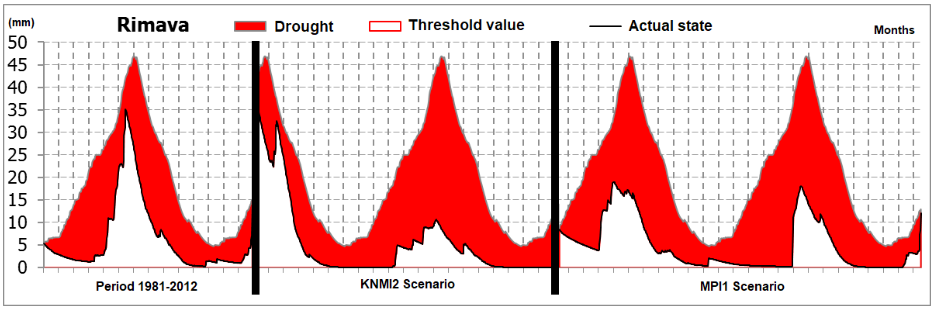
Period 1981-2012
KNMI2 Scenario
MPI1 Scenario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Drought
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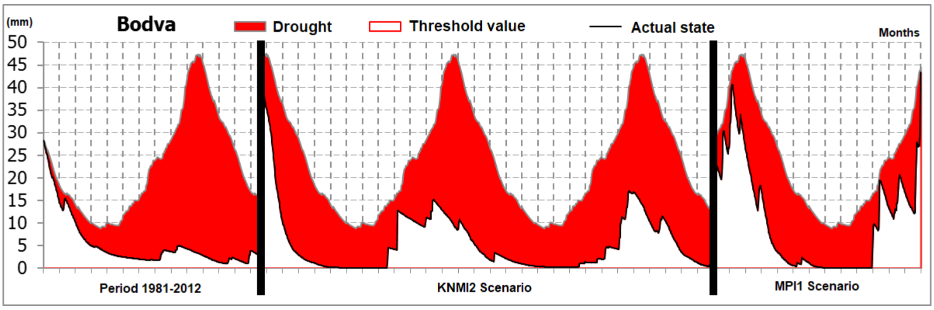
MPI1 Scenario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Bodva
Drought
Threshold value
Actual state
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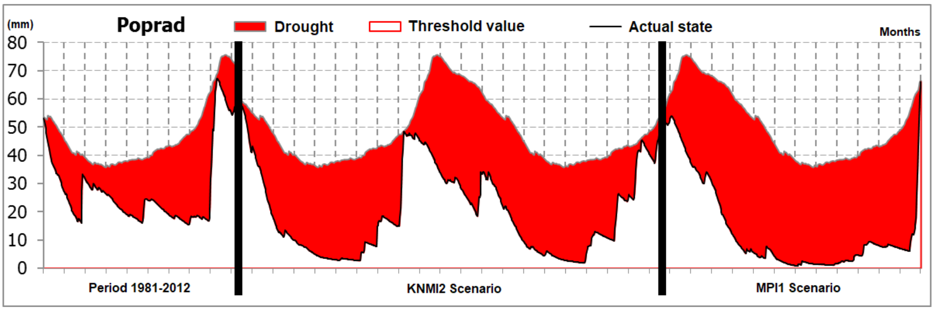
KNMI2 Scenario
MPI1 Scenario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Poprad
Drought
Threshold value
Actual state
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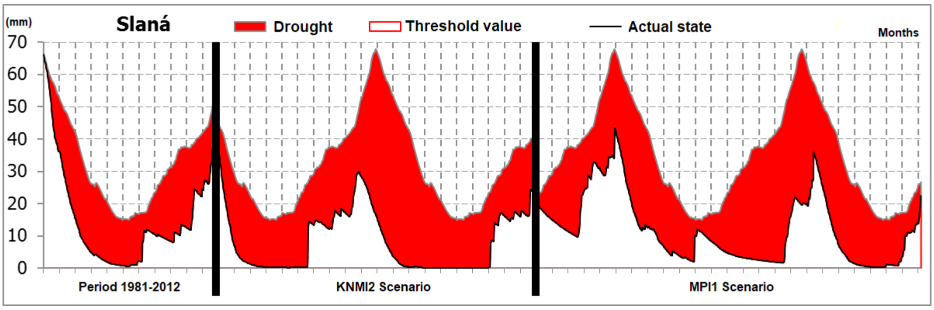
KNMI2 Scenario
MPI1 Scenario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Slaná
Drought
Threshold value
Actual state
Months
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40
30
20
10
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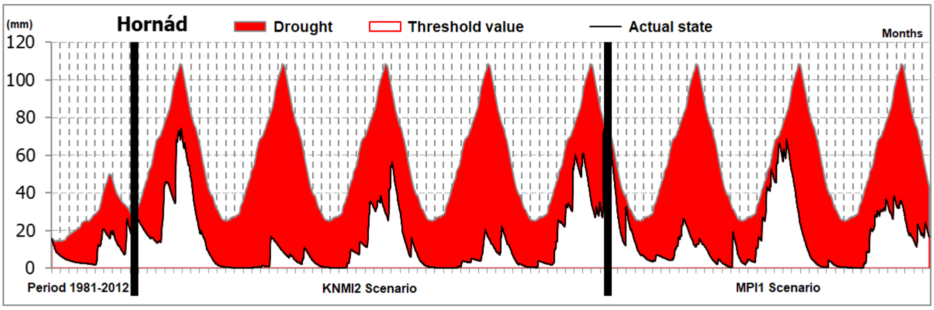
Period 1981-2012
KNMI2 Scenario
MPI1 Scenario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Hornád
Drought
Threshold value
Actual state
Months
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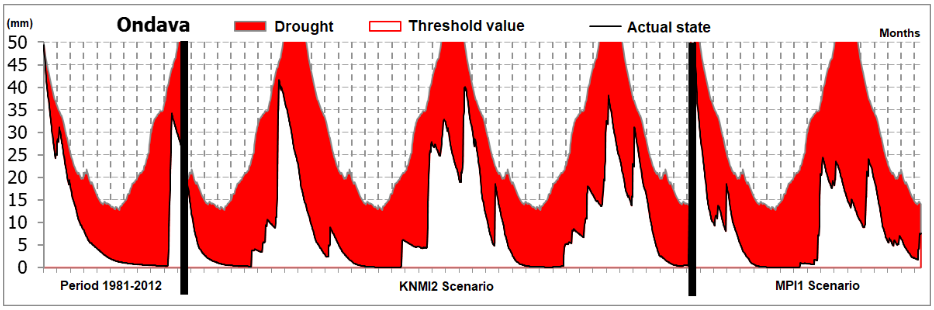
Period 1981-2012
KNMI2 Scenario
MPI1 Scenario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Ondava
Drought
Threshold value
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Period 1981-2012
KNMI2 Scenario
MPI1 Scenario

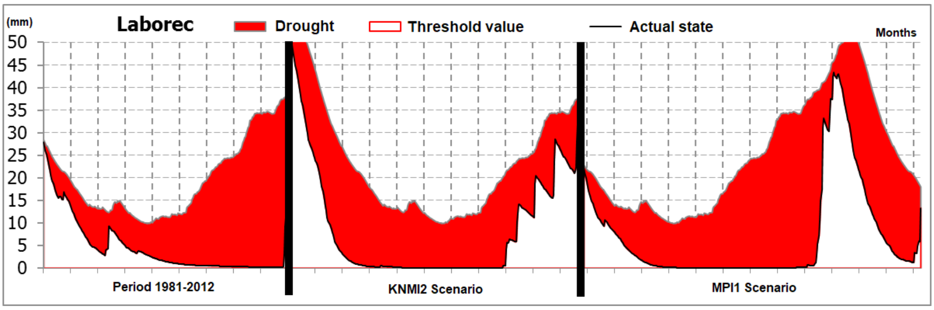


Fig. 4.6.1.1 Comparison of the present and future longest drought periods in the saturated zone in the evaluated river basins: from the left – reference period 1981–2012; climate change scenario KNMI 2; climate change scenario MPI 1. Drought is indicated in red.

Fig. 4.6.1.1 shows a comparison of the largest droughts in the studied basins in the compared periods. The reference period 1981–2012 is compared with the results of hydrological modelling using the FRIER model and climate parameters from the KNMI 2 and MPI 1 scenarios.

4.6.2. Prognosis of changes in the annual course of selected components of the hydrological balance in evaluated river basins

The hydrological modelling carried out in the FRIER model included a comparison of the annual course of total precipitation, total runoff, soil moisture and water storage in groundwater for the average modelled scenario values for the years 2069–2100 and for the reference period 1981–2012.

The results of modelling for both the scenarios used, KNMI 2 and MPI 1, were very similar. The scenarios mostly forecast larger total precipitation for our river basins, the movement of the largest precipitation from July to September, reduced total precipitation between May and July and higher temperatures, especially in winter. This will mean less accumulation of snow in winter, greater runoff in winter after snow melts, an increase in dry periods with low precipitation, high evapotranspiration, low runoff and reduced water storage throughout the growing season.

The most significant change in climate conditions forecast by both models is in the annual course of evapotranspiration. The differences between months will be smaller because from May to June, when evapotranspiration totals are highest, it will be warmer but there will be significantly less precipitation. In autumn and winter, which will be both warmer and have more precipitation, evapotranspiration will increase.

Myjava River Basin

The forecast changes in the regime of the basic balance components for the Myjava River Basin to Šaštín - Stráže are shown in Fig. 4.6.2.1.

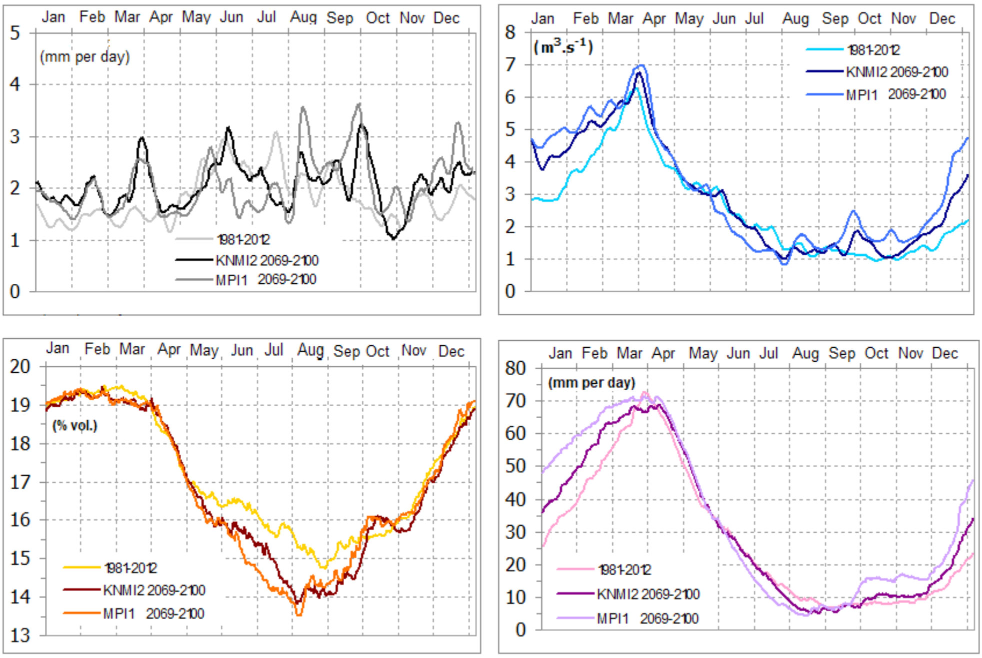


Fig. 4.6.2.1 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Myjava basin

Under the KNMI 2 scenario (Fig. 4.6.2.1), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that lower totals will occur only in May and July. Total runoff will be higher, runoff from melting snow will occur at the same time with a higher maximum runoff in the year, lower runoff is forecast only in July and August, the most significant difference will be in December, when runoff will increase more than 2-fold because milder winters will have less accumulation of snow and higher runoff during the winter. Soil moisture will be lower, especially in the growing season. The available water in groundwater storage will increase slightly thanks to greater accumulation between October and March.

Under the MPI 1 scenario (Fig. 4.6.2.1), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from June and July to August and September and that lower totals will occur only from May to July. Total runoff will be significantly higher, runoff from melting snow will occur at the same time with a higher maximum runoff in the year, lower runoff is forecast only in the summer. The most significant difference will be at the turn of the calendar years, when runoff will increase 1.5-fold because milder winters will have less accumulation of snow and higher runoff during the winter. Soil moisture will be lower, especially in the growing season. The available water in groundwater storage will increase thanks to greater accumulation between October and March.

Váh River Basin to Liptovský Mikuláš

The forecast changes in the regime of the basic balance components for the upper basin of the Váh to Liptovský Mikuláš are shown in Fig. 4.6.2.2.

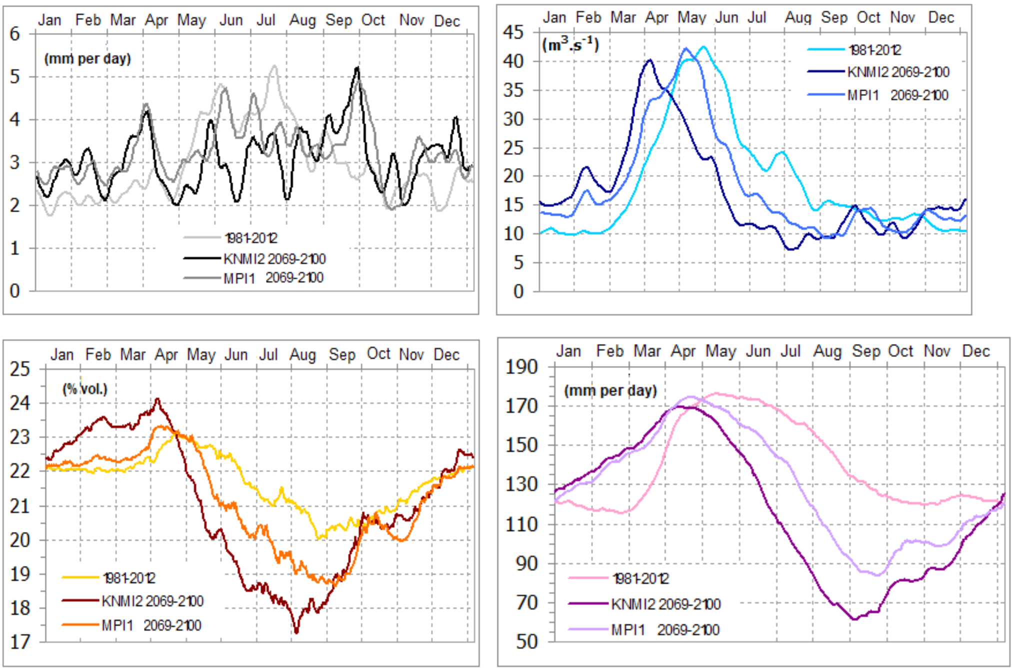


Fig. 4.6.2.2 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the upper Váh basin

Under the KNMI 2 scenario (Fig. 4.6.2.3), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be higher totals in winter and lower totals from May to July. Total runoff will be lower, runoff from melting snow will happen a month and a half sooner with a lower maximum runoff in the year. There will be significantly less runoff from melting snow and it will decrease by more than half between May and September followed by balanced runoff until the end of the year. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season, though amounts are forecast to be higher in the winter until April. Water in groundwater storage will decrease very significantly and will fluctuate significantly with the largest deficiency between May and December and larger amounts from January to April.

Under the MPI 1 scenario (Fig. 4.6.2.3), it is forecast that overall total precipitation will be higher, that the largest precipitation totals will move from summer to autumn, that there will be higher totals in winter and lower totals from May to July. Total runoff will be slightly lower, runoff from melting snow will happen 10 days later with a lower maximum runoff in the year. After the snow melts, there will be less runoff between May and September followed by balanced runoff until the end of the year. Milder winters will mean less accumulation of snow and more runoff in January and February. Soil moisture will be lower, especially in the growing season. Water in groundwater storage will decrease significantly and will fluctuate significantly with the largest deficiency between May and December and larger amounts from January to April.

Kysuca River Basin

The forecast changes in the regime of the basic balance components for the Kysuca River Basin to Kysucké Nové Mesto are shown in Fig. 4.6.2.3.

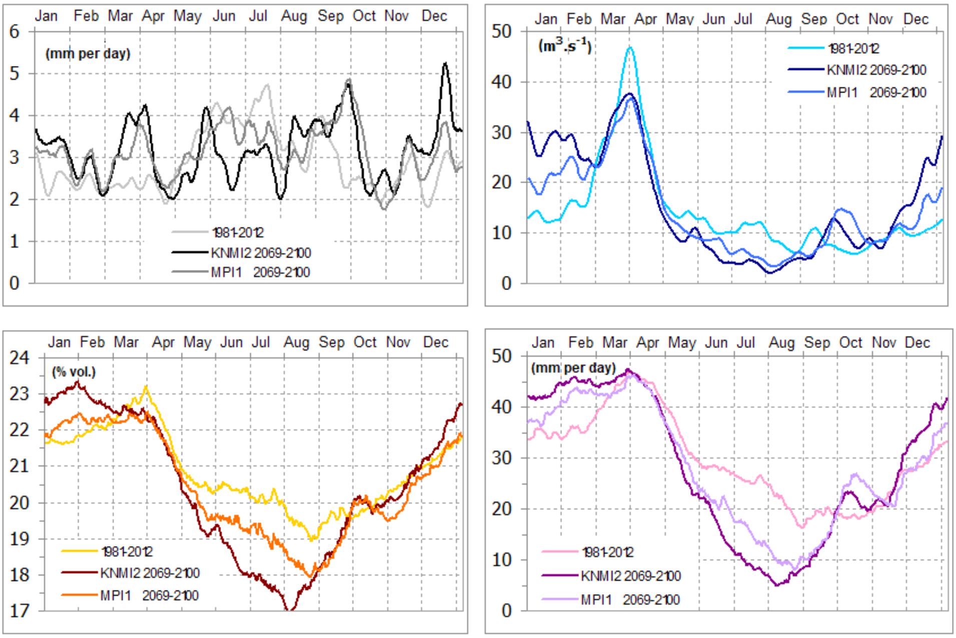


Fig. 4.6.2.3 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Kysuca basin

Under the KNMI 2 scenario (Fig. 4.6.2.3), it is forecast that overall total precipitation will be higher, that the largest precipitation totals will move from July to September and December, that there will be higher totals in winter and lower totals from May to July. Total runoff will be higher, runoff from melting snow will happen at the same time with a lower maximum runoff in the year after the snow melts, a lower runoff is forecast from May to September. Higher total precipitation in September will increase runoff, milder winters will cause less accumulation of snow and significantly higher runoff during the winter, nearly 3-fold higher runoff is forecast for the turn of the year. Soil moisture will be significantly lower, especially in the growing season. Water in groundwater storage will decrease slightly and significant fluctuation is forecast with the largest deficiency in the growing season and higher amounts in winter.

Under the MPI 1 scenario (Fig. 4.6.2.3), it is forecast that overall total precipitation will be higher, that the largest precipitation totals will move from July to September, that there will be higher totals in winter and lower totals from May to July. Total runoff will be higher, runoff from melting snow will happen at the same time with a higher maximum runoff in the year. After snow melts, there will be less runoff between May and August. Higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be lower, especially in the growing season. The amount of water in groundwater storage will not change significantly; deficiencies will be largest in the growing season and there will be higher amounts in winter.

Nitra River Basin

The forecast changes in the regime of the basic balance components for the Nitra River Basin to Nové Zámky are shown in Fig. 4.6.2.4.

Under the KNMI 2 scenario (Fig. 4.6.2.4), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to September and December, and that lower totals will occur only in May and July. Total runoff will be higher, runoff from melting snow will happen at the same time with a higher maximum runoff in the year. After snow melts, there will lower runoff from May to August, higher total precipitation in September will increase runoff and milder winters will lead to less accumulation of snow and higher runoff during the winter. Soil moisture will be significantly lower, especially in the growing season. The available water in groundwater storage will increase thanks to greater accumulation between October and March, but there will be less stored in the summer.

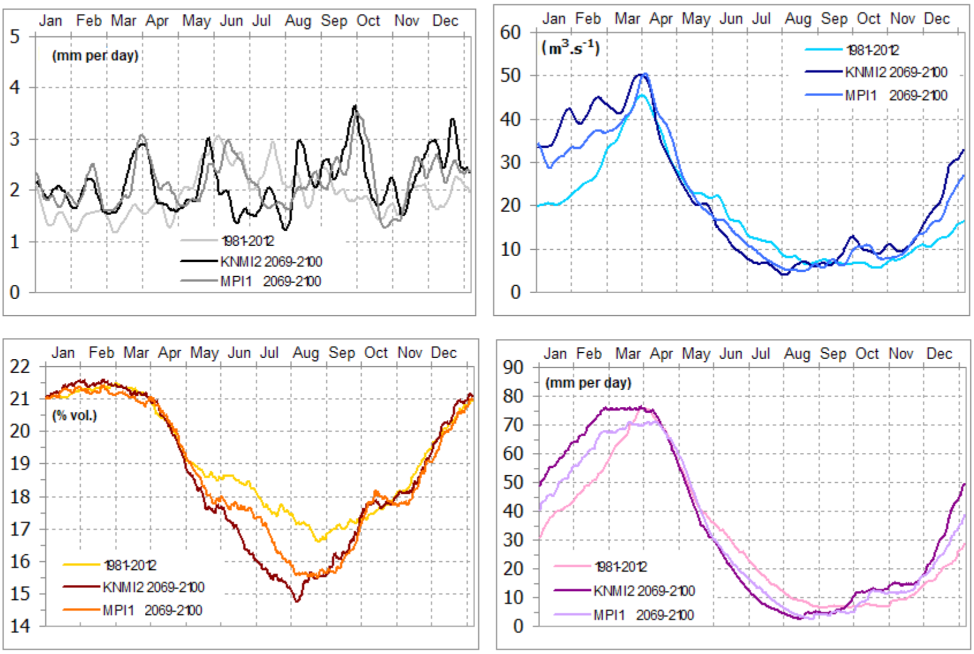


Fig. 4.6.2.4 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Nitra basin

Under the MPI 1 scenario (Fig. 4.6.2.4), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that lower totals will occur only in May and July. Total runoff will be higher, runoff from melting snow will happen at the same time with a higher maximum runoff in the year. After snow melts, there will be less runoff between May and August, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be lower, especially in the growing season. The available water in groundwater storage will increase thanks to greater accumulation between October and March, but there will be less stored in the summer.

Hron River Basin

The forecast changes in the regime of the basic balance components for the Hron River Basin to Kamenín are shown in Fig. 4.6.2.5.

Under the KNMI 2 scenario (Fig. 4.6.2.5), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that there will be significantly less precipitation only from May to July. Total runoff will be slightly higher, runoff from melting snow will happen at approximately the same time with a higher maximum runoff in the year. After snow melts, there will be less runoff between April and September, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. The amount of water in groundwater storage will decrease; the largest deficiencies will occur in the growing season and there will be higher amounts in winter.

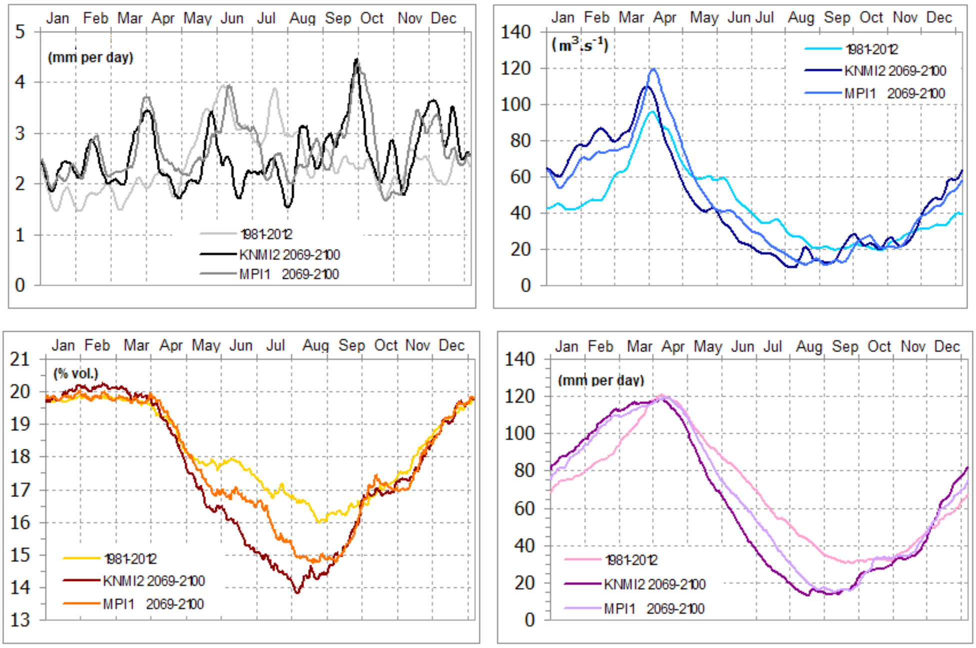


Fig. 4.6.2.5 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Hron basin

Under the MPI 1 scenario (Fig. 4.6.2.5), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that less precipitation will occur only in May and July. Total runoff will be slightly higher, runoff from melting snow will happen at approximately the same time with a significantly higher maximum runoff in the year. After snow melts, there will be less runoff between April and September, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially from May to November. The course and quantity of groundwater storage will be the same as in the KNMI 2 scenario, there will be less water in groundwater storage, with the largest deficiencies in the growing season and more stored water in the winter.

Ipeľ River Basin

The forecast changes in the regime of the basic balance components for the upper basin of the Ipeľ to Holiša are shown in Fig. 4.6.2.6.

Under the KNMI 2 scenario (Fig. 4.6.2.6), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be higher totals in winter and lower totals from May to July. Total runoff will be higher, runoff from melting snow will happen a month earlier with a higher maximum runoff in the year. After snow melts, there will be less runoff between April and August, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. The amount of water in groundwater storage will not change; deficiencies will be largest in the growing season and there will be higher groundwater amounts in winter.

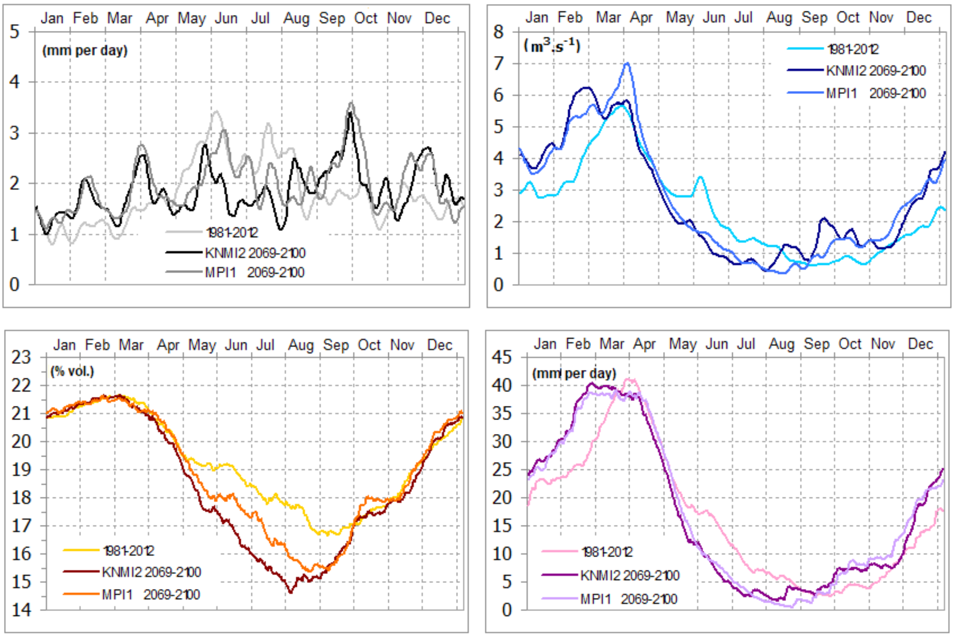


Fig. 4.6.2.6 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Ipeľ basin

Under the MPI 1 scenario (Fig. 4.6.2.6), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that a slight decrease will occur only from May to July. Total runoff will be higher, runoff from melting snow will happen at the same time with a higher maximum runoff in the year. After snow melts, there will be less runoff between April and September, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be lower, especially in the growing season. The course and quantity of groundwater storage will be the same as in the KNMI 2 scenario, the quantity of water in groundwater storage will not change, deficiencies will be largest in the growing season but there will be more stored water in the winter.

Rimava River Basin

The forecast changes in the regime of the basic balance components for the Rimava River Basin to Vlkyňa are shown in Fig. 4.6.2.7.

Under the KNMI 2 scenario (Fig. 4.6.2.7), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be higher totals in winter and lower totals from May to July. Total runoff will be slightly higher, runoff from melting snow will begin a month earlier and will last longer with a higher maximum runoff in the year. After snow melts, there will be less runoff between April and August, higher totals in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. The amount of water in groundwater storage will not change; deficiencies will be largest in the growing season and there will be higher amounts in winter.

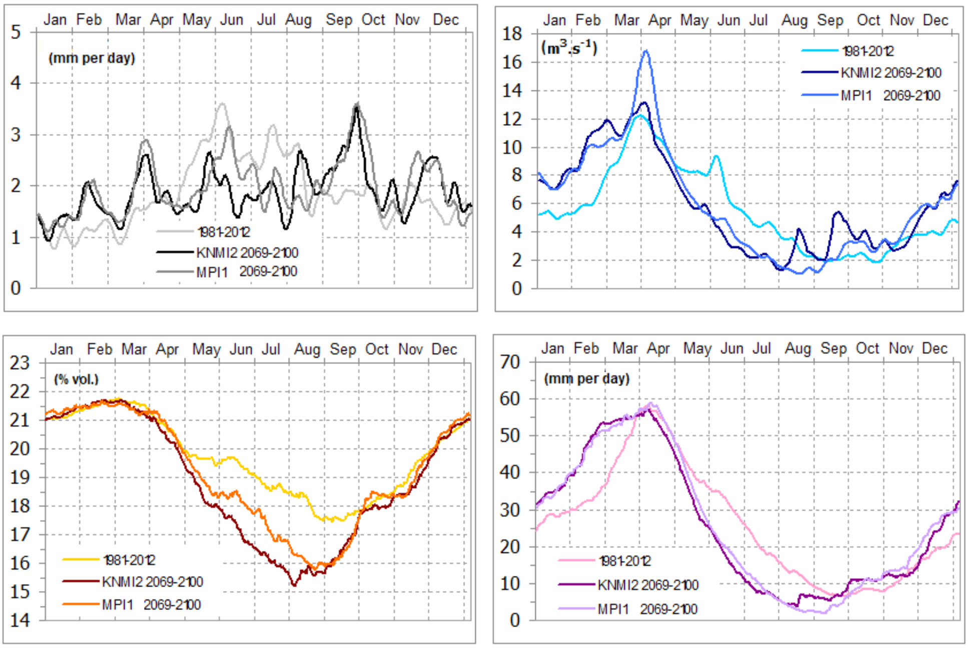


Fig. 4.6.2.7 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Rimava basin

Under the MPI 1 scenario (Fig. 4.6.2.7), it is forecast that overall total precipitation will be higher, that the highest precipitation totals will move from summer to autumn and that lower totals will occur only in May and July. Total runoff will be slightly higher, runoff from melting snow will happen at the same time with a higher maximum runoff in the year. After snow melts, there will be less runoff between April and August, higher totals in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be lower, especially in the growing season. The course and quantity of groundwater storage will be the same as in the KNMI 2 scenario, the quantity of water in groundwater storage will not change, deficiencies will be largest in the growing season but there will be more stored water in the winter.

Hornád River Basin including the Torysa Sub-Basin

The forecast changes in the regime of the basic balance components for the Hornád River Basin to Ždaňa, including the Torysa River Basin to Košické Olšany are shown in Fig. 4.6.2.8.

Under the KNMI 2 scenario (Fig. 4.6.2.8), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be higher totals in winter and lower totals from May to July. Total runoff will remain approximately the same, the quantity and timing of runoff from melting snow will remain approximately the same, after the snow melts there will be less runoff from April to August but higher precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. The amount of water in groundwater storage will decrease; the largest deficiencies will occur in the growing season though there will be higher amounts in winter.

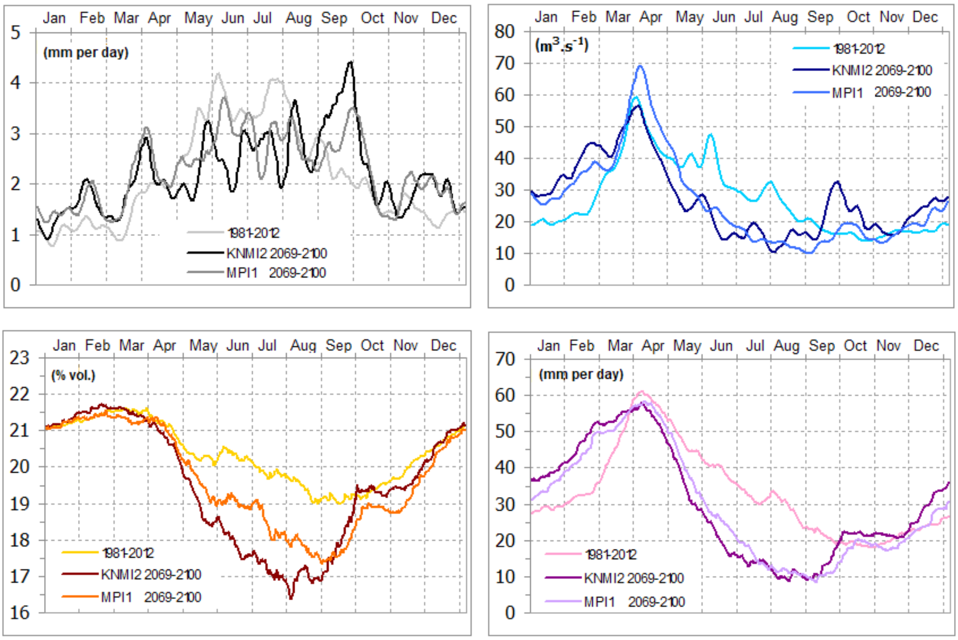


Fig. 4.6.2.8 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater stage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Hornád basin including the Torysa sub-basin

Under the MPI 1 scenario (Fig. 4.6.2.8), it is forecast that overall total precipitation will be higher and more balanced than in the KNMI 1 scenario and that there will be a slightly lower total only from May to July. Total runoff will be slightly lower with extremes; runoff from melting snow will be higher and will last longer, then decrease significantly from May to September followed by slightly higher levels in winter. Soil moisture will be significantly lower, especially from May to November. The course and quantity of groundwater storage will be the same as in the KNMI 2 scenario, there will be less water in groundwater storage, with the largest deficiencies in the growing season and more stored water in the winter.

Ondava River Basin including the Topľa Sub-Basin

The forecast changes in the regime of the basic balance components for the basin of the Ondava River to Horovce, including the Topľa River Basin to Hanušovce nad Topľou are shown in Fig. 4.6.2.9.

Under the KNMI 2 scenario (Fig. 4.6.2.9), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be slightly higher totals in winter and lower totals from May to July. Total runoff will be the same, runoff from melting snow will begin a month and a half earlier and will last long without a more pronounced maximum runoff; maximum runoff in the year will be significantly lower. After snow melts, there will be less runoff between April and September, higher total precipitation in September will increase runoff. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. The amount of water in groundwater storage will decrease; the largest deficiencies will occur in the growing season though there will be higher groundwater amounts in winter.

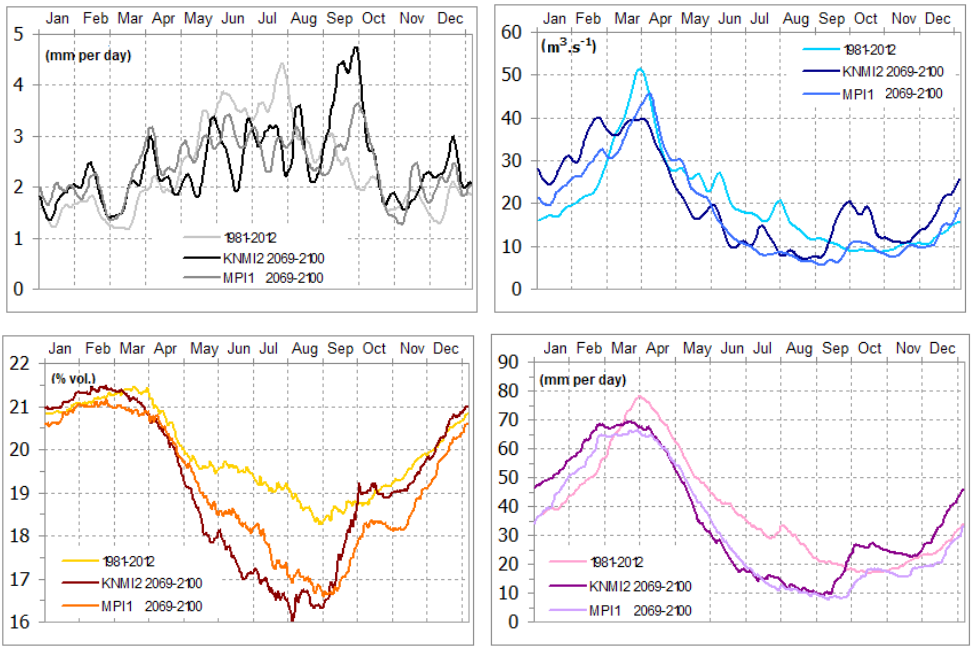


Fig. 4.6.2.9 Comparison of the course of precipitation (upper left), total runoff (upper right), soil moisture (lower left) and groundwater storage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Ondava basin including the Topľa sub-basin

Under the MPI 1 scenario (Fig. 4.6.2.9), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be slightly higher totals in winter and lower totals from May to July. Total runoff will be lower, runoff from melting snow will happen around 10 days later, with a lower maximum runoff in the year. After the snow melts, there will less runoff between May and September followed by balanced runoff until the end of the year. Milder winters will mean less accumulation of snow and more runoff in January and February. Soil moisture will be significantly lower, especially from May to November. The amount of water in groundwater storage will decrease significantly; the largest deficiencies will occur in the growing season and only in January and February will amounts be slightly higher.

Poprad River Basin

The forecast changes in the regime of the basic balance components for the Poprad River Basin to Chmeľnica are shown in Fig. 4.6.2.10.

Under the KNMI 2 scenario (Fig. 4.6.2.10), it is forecast that overall total precipitation will be the same, that the largest precipitation totals will move from summer to autumn, that there will be slightly higher totals in winter and lower totals from May to July. The total runoff will be lower, the original long-lasting runoff from melting snow from April to June will change to a much shorter period of runoff in April with a larger maximum runoff in the year. After the snow melts there will be significantly less runoff from May to September. Milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be significantly lower, especially in the growing season. Water in groundwater storage decrease slightly and significant fluctuation is forecast with the largest deficiency in the growing season and higher amounts in winter.

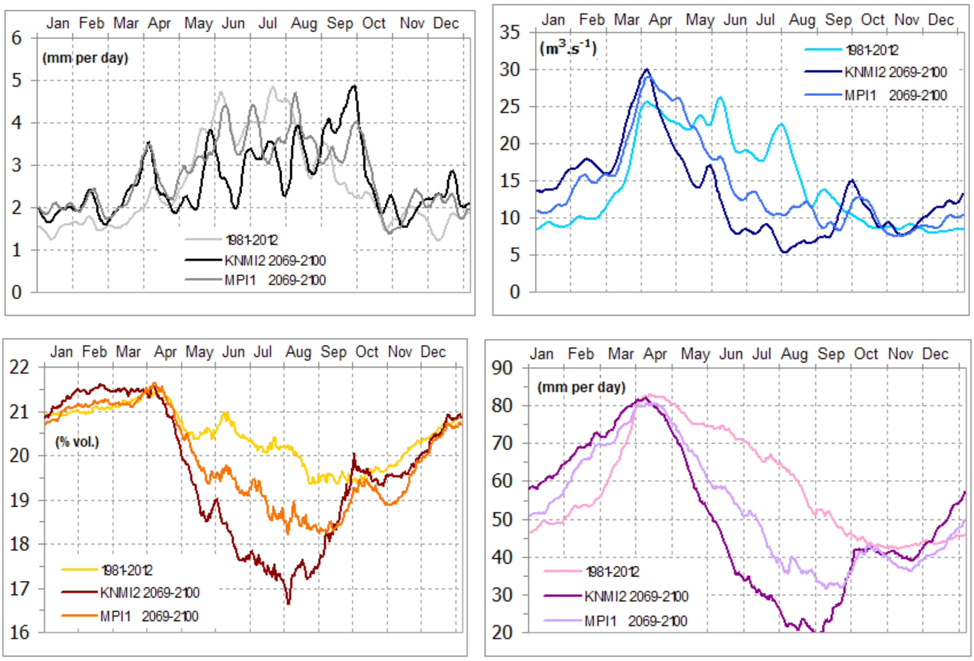


Fig. 4.6.2.10 Comparison of the course of precipitation (upper left), total runoff (upper right),

soil moisture (lower left) and groundwater stage (lower right) predicted by the KNMI 2 and MPI 1 scenarios with the values for the reference period 1981–2012 in the Poprad basin

Under the MPI 1 scenario (Fig. 4.6.2.10), it is forecast that overall total precipitation will be higher, with fluctuations in the summer; there will be slightly lower totals only in May and July. The total runoff will be slightly lower, the original long-lasting runoff from melting snow from April to June will change to a much shorter period of runoff in April, with a larger maximum runoff in the year. After the snow melts there will be significantly less runoff from May to September and milder winters will mean less accumulation of snow and more runoff in the winter. Soil moisture will be lower, especially from May to November. The amount of water in groundwater storage will decrease; the largest deficiencies will occur in the growing season and there will be higher amounts in winter.

4.7. PROGNOSIS OF AREAL CHANGES IN INDIVIDUAL COMPONENTS OF THE WATER BALANCE

The results of the forecasts for components of the water balance permitted the computation of spatial prognoses for most of the territory of Slovakia. The analysis covered the forecast spatial changes in the components of the water balance that could be quantified in every raster: changes in water storage, total precipitation, actual evapotranspiration, total runoff, surface runoff, interflow, baseflow and soil moisture. Figures 4.7.1 to 4.7.8 show the forecast change in annual totals for the components under scenarios KNMI 2 and MPI 1 in the period 2069–2100 compared to their values in the reference period 1981–2012. The spatial visualisation includes another three modelled river basins: the Slaná (south central Slovakia), the Bodva (south-eastern Slovakia) and the Laborec (north-eastern Slovakia).

The two scenarios each gave different results. The KNMI 2 scenario forecasts more extreme changes to the water balance in the river basins. The greatest loss of water storage is in central Slovakia, especially around the headwaters of the Hron and Hornád, whereas more storage will remain in lowlands, valleys and basins, but also in the Vysoké Tatry Mountains. The reason for the increase in the Vysoké Tatry Mountains is the presence of bare surfaces (rock). This component is strongly affected by the type of land use and soil granularity. The MPI 1 scenario forecasts greater loss of water storage than KNMI 2 with the highest losses being in the upper parts of the Hron, Slaná and Rimava River Basins and the highest gains in storage in the upper parts of the Hornád, Poprad, Váh River Basins and the lowest-lying territories in the Rimava, Hron and Ondava River Basins. The most extreme changes are forecast for the Hornád River Basin where there will be more storage at higher elevations, less storage at medium elevations and again more storage in the lowest-lying part of the basin (Fig. 4.7.1).

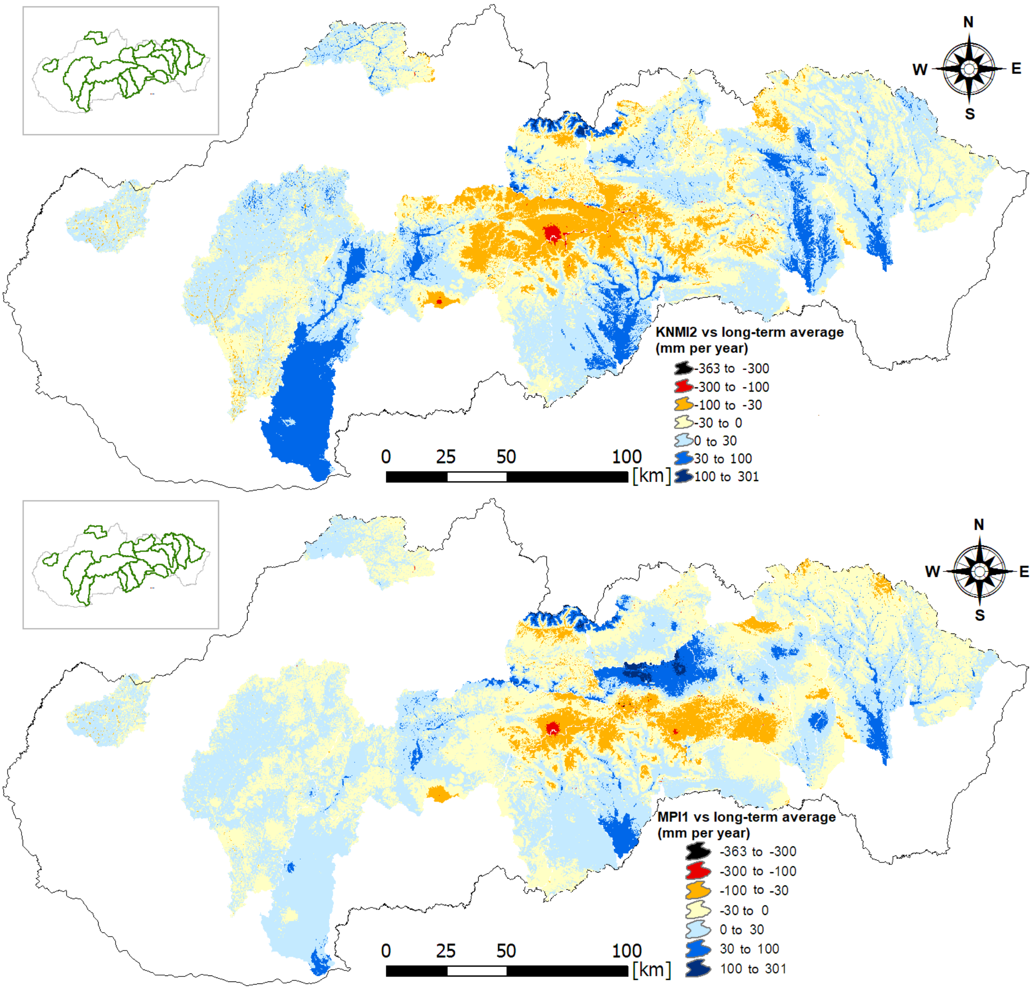


Fig. 4.7.1 Comparison of the differences in basin´s average water storage according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

Annual total rainfall in Slovakia increases under both scenarios. The KNMI 2 scenario forecasts a 50–150 mm increase in total precipitation in the west and the north-east affecting the basins of the Myjava, Kysuca, Nitra, Hron, Laborec and Ondava. Annual total precipitation in the centre and the east will not change. Only two stations have lower precipitation, which could be classified as an error and does not significantly influence the results. The MPI 1 scenario forecasts more precipitation than the KNMI 2 scenario, with the largest increase, up to around 300 mm, to be expected at higher altitudes particularly in the Hornád, Hron, Poprad and Váh River Basins. The east - the Ondava, Laborec, Bodva and much of the Rimava River Basins - will remain without changes (Fig. 4.7.2).

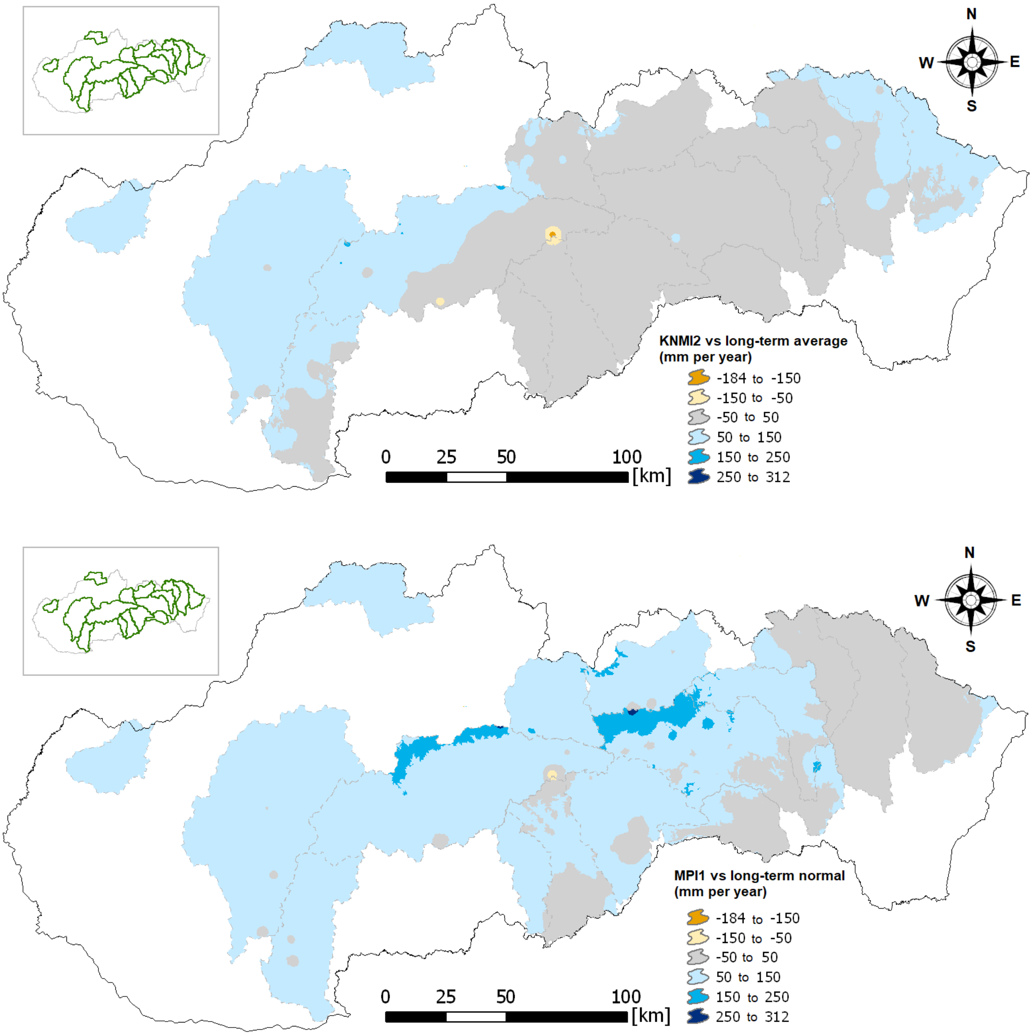


Fig. 4.7.2 Comparison of the differences in average precipitation according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

Annual total actual evapotranspiration in Slovakia increases under both scenarios. The KNMI 2 scenario forecasts an increase in total annual evapotranspiration of 50–150 mm in the west and north-east, logically in those places where there is increased total precipitation, with a larger increase at higher altitudes. The largest increases are in the basins of the Kysuca, the upper Váh and the Myjava. Actual evapotranspiration will remain unchanged in southern areas such as the basins of the Ipeľ, Rimava, Bodva, Slaná and Hornád. The MPI 1 scenario forecasts a more significant increase in actual evapotranspiration than the KNMI 2 scenario, with the largest increase, in places 150–250 mm, occurring at higher altitudes. Actual evapotranspiration increases in every basin, the most in the basins of the upper Váh, the Poprad, the Hornád and the Hron. It only decreases at the Domaša Reservoir and scenario probably anticipates frequent water shortages in this reservoir (Fig. 4.7.3).

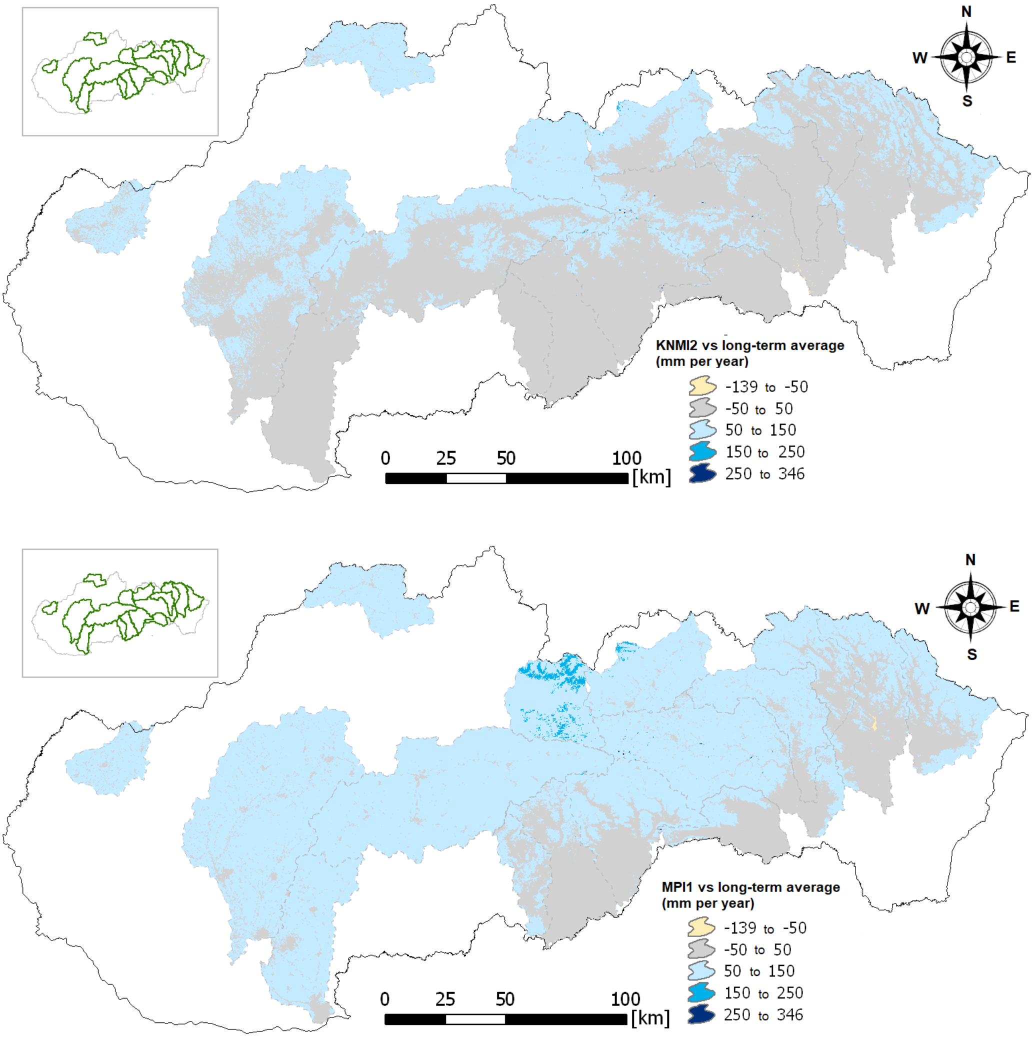


Fig. 4.7.3 Comparison of the differences in average real evapotranspiration according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

In the maps of annual total runoff, it was not possible to link together the results for individual river basins into an integrated picture; there are differences at the watershed divides but these are not as large as they look at first sight because the colour scale is not evenly distributed. The map is a good illustration of the complexity of the topic and the reason for inaccuracy is explained at the start of this section.

Annual total runoff in Slovakia increases under both scenarios but is unevenly distributed. Under the KNMI 2 scenario, the largest increase in overall runoff will be in the west, in the the Kysuca, Myjava, Nitra, upper Hron and Ipeľ River Basins. In contrast, total runoff will decrease in the upper Váh, Poprad, Hornád and lower Hron River Basins. Under the MPI 1 scenario, the largest increase in total runoff will be in central Slovakia, affecting the upper Hron, Hornád, Ipeľ, Rimava, Slaná and Nitra River Basins. Total runoff will decrease in the north and south, especially in the upper Váh, Laborec, Ondava, Poprad, Bodva and lower Hron River Basins. Under both scenarios, the most extreme effects will be in the Hron River Basin because it is forecast to have increased runoff in its upper section and reduced runoff in its lower section (Fig. 4.7.4).

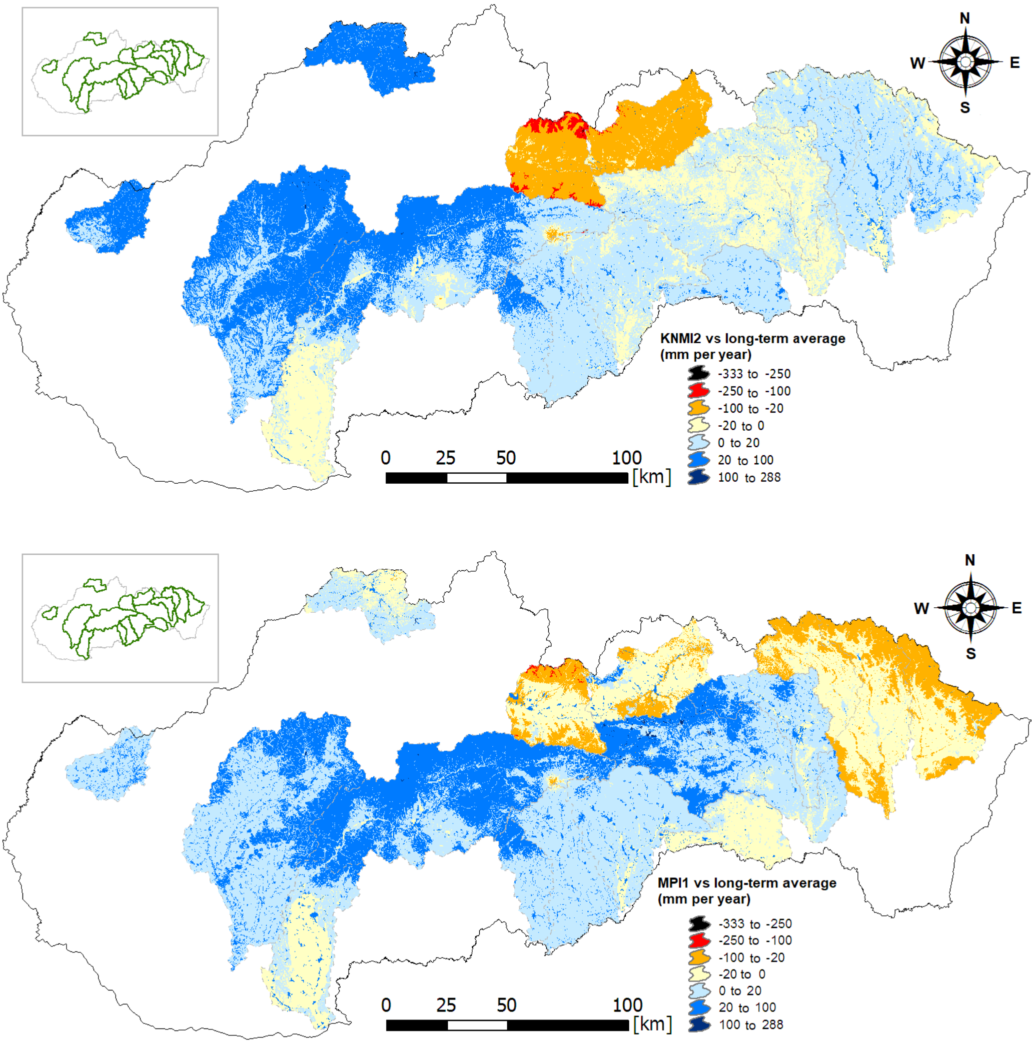


Fig. 4.7.4 Comparison of the differences in average annual total runoff values according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

Annual total surface runoff in Slovakia increases under both scenarios. Maps of surface runoff are most strongly influenced by the initial map of land use. The largest increase is forecast in urban areas and water bodies where it is expected that everything will run off the surface. If there is forecast to be an increase in precipitation then there will also be an increase in surface runoff from such areas. On other surfaces, surface runoff is close to zero, so differences are not significant (Fig. 4.7.5).

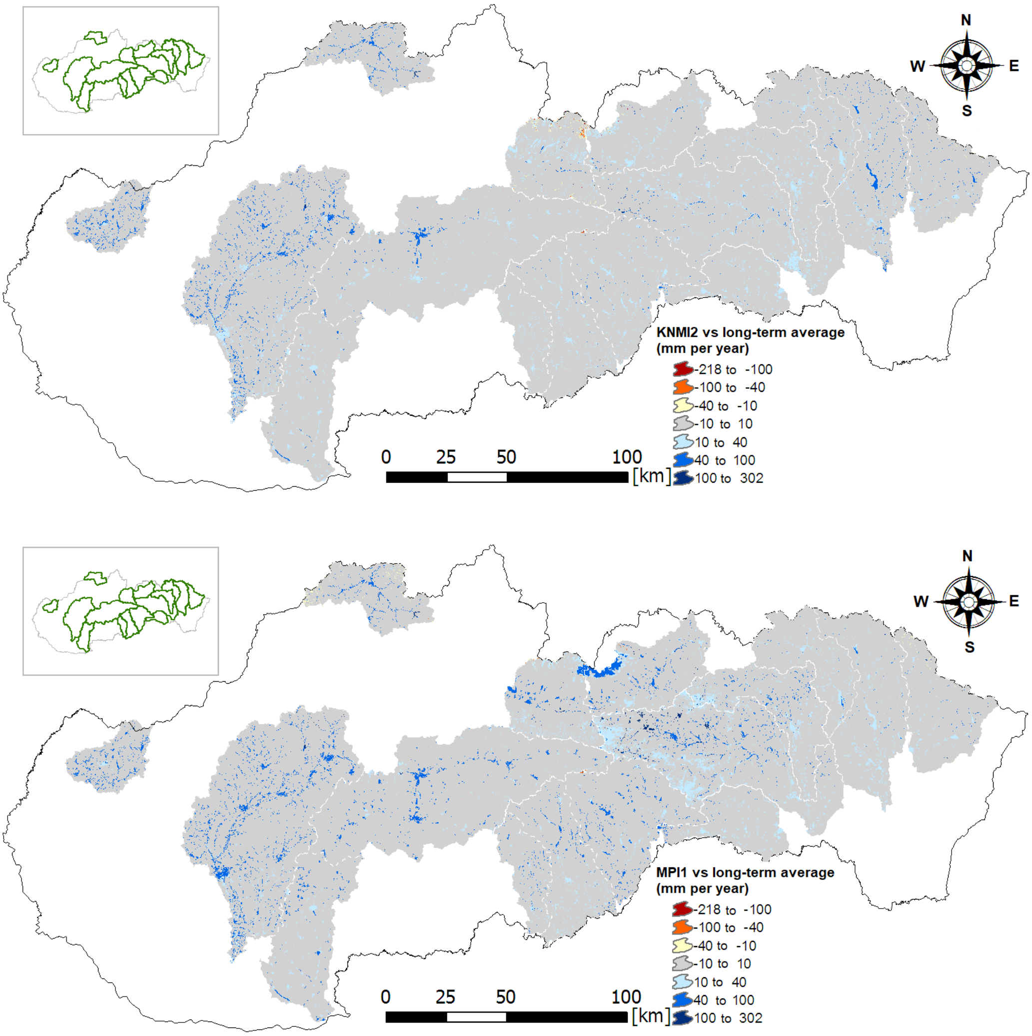


Fig. 4.7.5 Comparison of the differences in average annual surface runoff values according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

Annual total interflow in Slovakia increases under both scenarios. Under the KNMI 2 scenario, the largest increases in interflow will be in the Kysuca, Hron, Laborec and Ondava River Basins. In contrast, interflow will decrease in the upper Váh and Poprad River Basins. Under the MPI 2 scenario, the largest increases in interflow will be in the Hron, Hornád and Kysuca River Basins. Interflow will decrease in the upper Váh River Basin. Under both scenarios, the most extreme effects will be in the upper Váh River Basin because it is forecast to have reduced interflow in its upper section and increased interflow in lower-lying areas (Fig. 4.7.6).

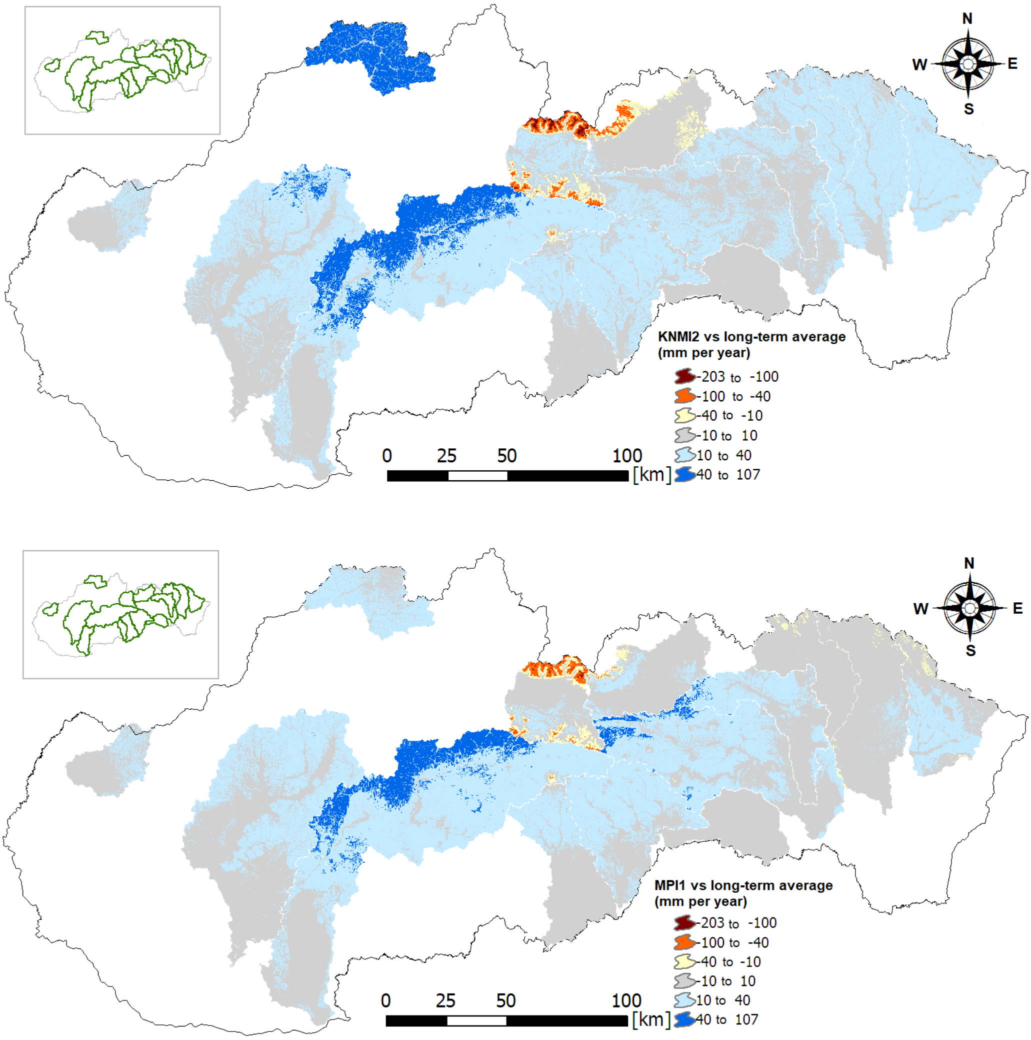


Fig. 4.7.6 Comparison of the differences in average annual lateral flow (subsurface runoff) values according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

In the model, baseflow is calculated as an average for the whole basin and is not calculated for every cell. Annual total baseflow in Slovakia increases under both scenarios but is unevenly distributed. Under the KNMI 2 scenario, baseflow will increase significantly in the Myjava and Nitra River Basins and significantly decrease in the upper Váh and Poprad River Basins. Under the MPI 1 scenario there will be a relatively significant increase in baseflow only in the Myjava River Basin and there will be relatively significant decreases in the upper Váh, Poprad, Ondava and Laborec River Basins (Fig. 4.7.7).

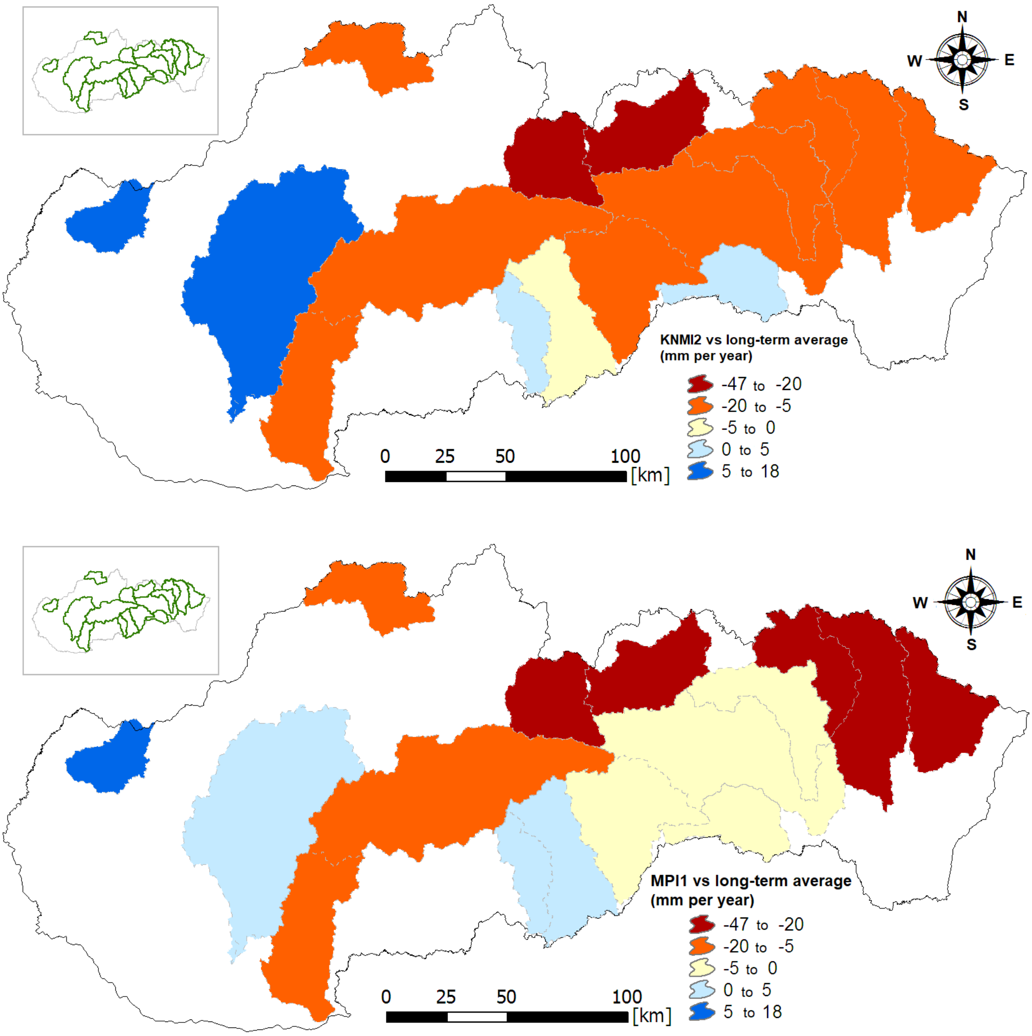


Fig. 4.7.7 Comparison of the differences in average baseflow (groundwater runoff) values according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

Soil moisture in Slovakia will decrease under both scenarios (Fig. 4.7.8). Under the KNMI 2 scenario, the most significant decrease in soil moisture will be in the centre, south and east of Slovakia, in the upper Hron, Ipeľ, Rimava, Slaná and Hornád River Basins. The smallest decrease will be in the Kysuca River Basin. The decrease under the MPI 1 scenario will be smaller than under the KNMI 2 scenario, with the largest decrease in eastern Slovakia, especially in the Hornád, Ondava and Laborec River Basins. In both scenarios, the most extreme effect on soil moisture is in the Poprad and Hornád River Basins.

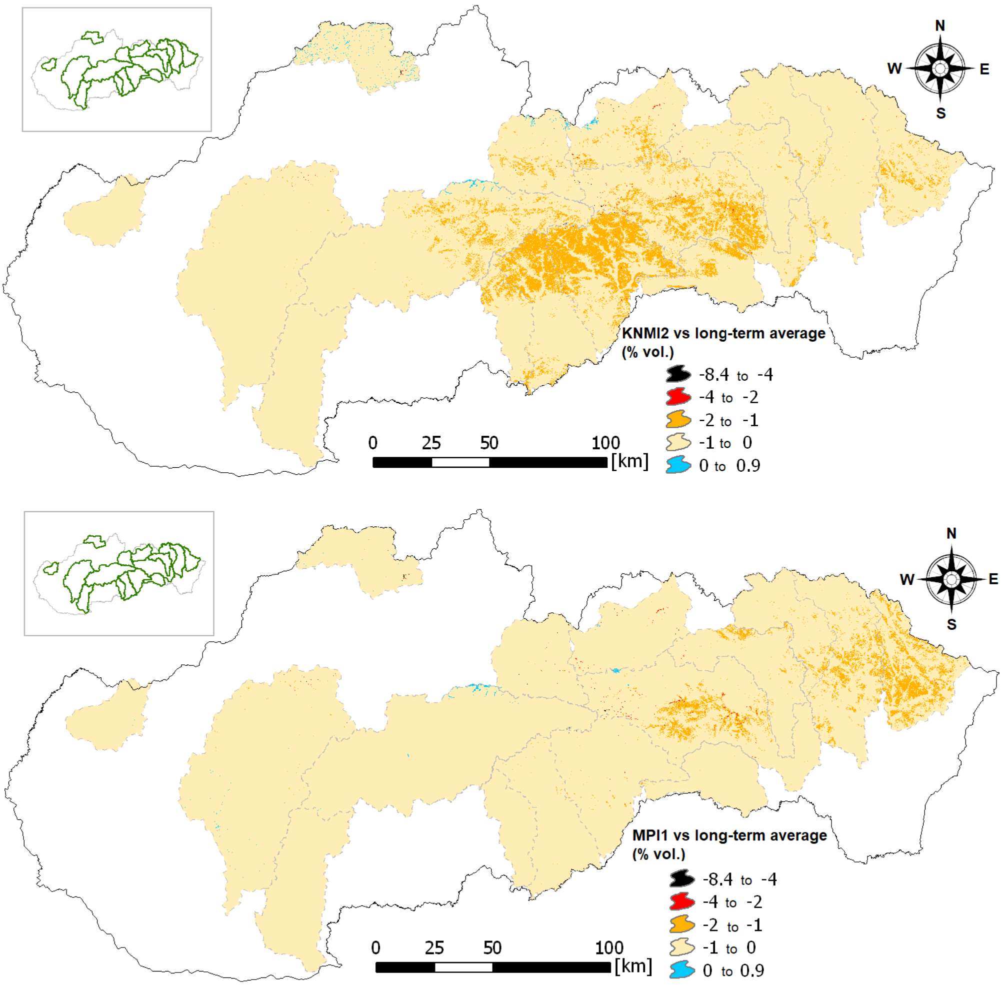


Fig. 4.7.8 Comparison of the differences in average soil moisture values according to the KNMI 2 and MPI 1 scenarios in 2069–2100 vs reference period 1981–2012

4.8. PROGNOSIS FOR THE OCCURRENCE OF HYDROLOGICAL DROUGHT BASED ON THE NAO INDEX

Recently, researchers have found a growing number of links between long-term variation in precipitation, air temperature and stream flow in Europe and the North Atlantic Oscillation. According to Hurrell et al. (2003), the **NAO Index** (NAOI) can be defined as the pressure gradient between the high pressure zone at the latitude of the Azores (Ponta Delgada) or Lisbon and the low pressure zone over Iceland (Stykkisholmur/ Reykjavik) – Fig. 4.8.1. If the pressure gradient between the Azores and Iceland is low (the negative phase of the NAO), the movement of warm and moist ocean air over Europe is slowed. There are more wet years in southern Europe. Positive values of the NAO index are usually linked to more intense meteorological systems over the North Atlantic and wetter weather over northern and western Europe (Hurrrell and Deser, 2009). The basis of the NAO phenomenon is deep ocean currents (thermohaline circulation) originating in the Southern Hemisphere and around Indonesia.

Data on the winter North Atlantic oscillation index (NAOIw) can be used in long-term forecasting of drought or low flow in rivers. Previous statistical analysis has shown that if the value of the winter NAO index is positive, discharges in Slovak streams are usually below-normal. Years with a low winter NAO index are significantly wetter.

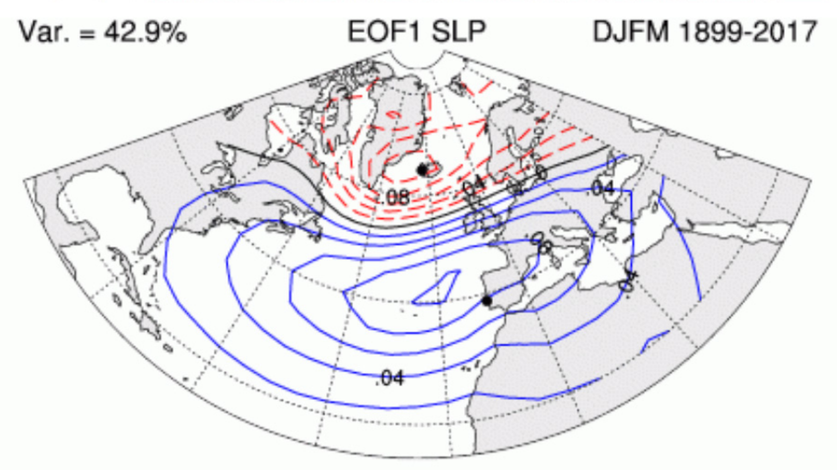


Fig. 4.8.1 Winter (December through March) index of the NAO based on the differences in normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864. The SLP values at each station were normalized by removing the long-term mean and dividing by the long-term standard deviation. Both the long-term means and standard deviations are based on the period 1864–1983 (Hurrel et al., 2017)

4.8.1. Data and methods

The relationship between climate modes in the Northern Hemisphere and stream discharges in Slovakia was analysed using several indexes of the North Atlantic Oscillation and series of average river discharges in selected Slovak rivers drawn from the database of the Slovak Hydrometeorological Institute.

NAO Index

Forecasts of the development of hydrological and climatic conditions in a given year are based on the series of average NAO indexes for the winter months (the averages for the months from December of the previous year to March of the given year).

There are several series of NAO indexes, e.g.:

- based on Jones et al. (1997) from 1824 (Gibraltar – Iceland, NAOIJ Fig. 4.8.2; 4.8.3), https://crudata.uea.ac.uk/~timo/datapages/naoi.htm;
- Based on Hurrell and the National Center for Atmospheric Research Staff (Eds), from 1856 (Lisbon-Reykjavik – NAOIH), https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based;

- or based on the US NOAA, National Weather Service Center for Weather and Climate Prediction), which run from 1951, http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml.

Fig. 4.8.2 shows the one-year and ten-year values for the winter North Atlantic Oscillation Index (NAOIw) based on Jones. The course of the annual values shows that the NAO operates in multi-year cycles with clusters of higher and lower values lasting 5–7 years. The thirty-year averages also point to long-term cycles lasting 70–80 years. Several methods were used to determine the length of these cycles: graphical methods, autocorrelation analysis and spectral analysis.

Looking at the period 1824–2017, there is no increase or decrease in the winter NAO index based on Jones et al. (1997). As can be seen from Figures 4.8.2 and 4.8.3, the years 1989–1995 have above-average values for the winter NAO index. Low flow was recorded in Slovak streams during this period. The NAOIw also had above average values in the years 1920–1925 and Slovakia and the whole Danube Basin were struck by a historic drought in 1921.

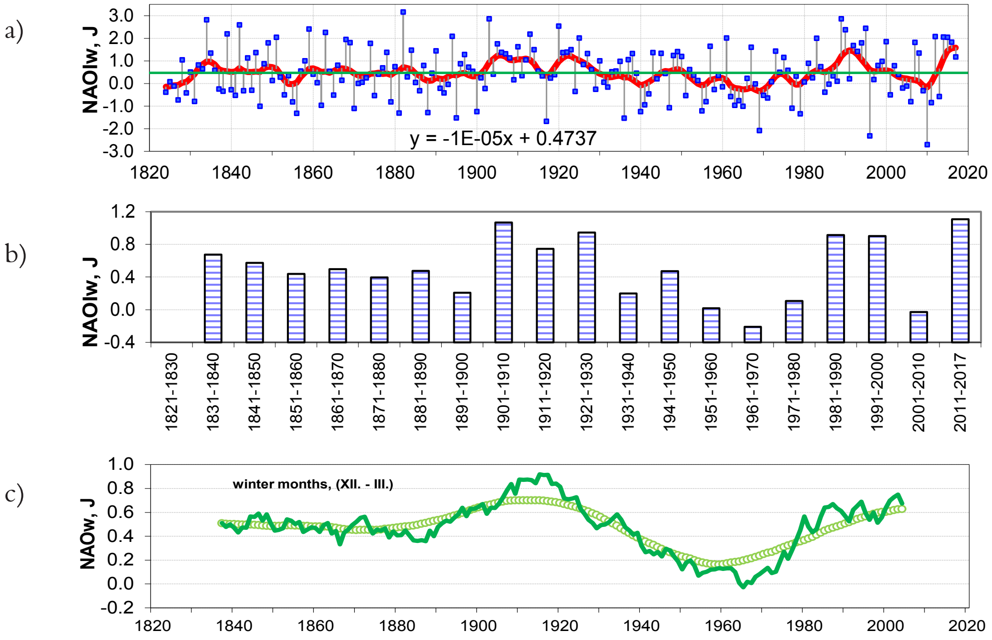


Fig. 4.8.2 a) Annual values of the winter NAO index NAOIw according to Jones (blue points) and filtered data (5-year moving averages, red line); b) Decadal averages; c) 30-year moving averages of the NAOIw phenomena

There are also interesting correlations in the other direction based on the NAOw index for 2009/2010 and 2005/2006. In 2009/10 Jones' index recorded its lowest value in 190 years (Osborn, 2011). The year 2010 was extremely wet in Slovakia. It was a year of catastrophic floods all over central Europe.

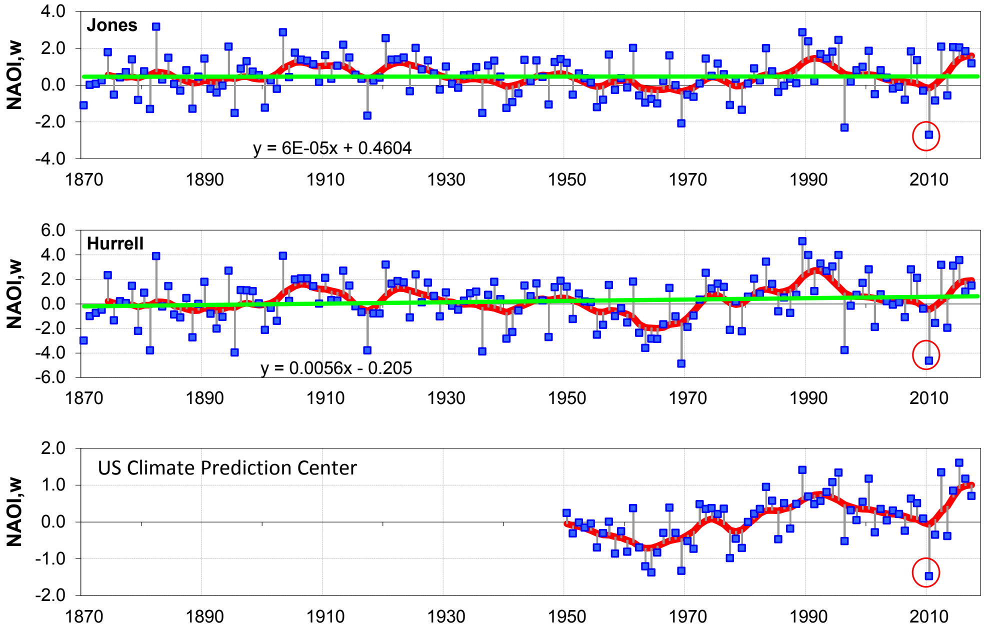
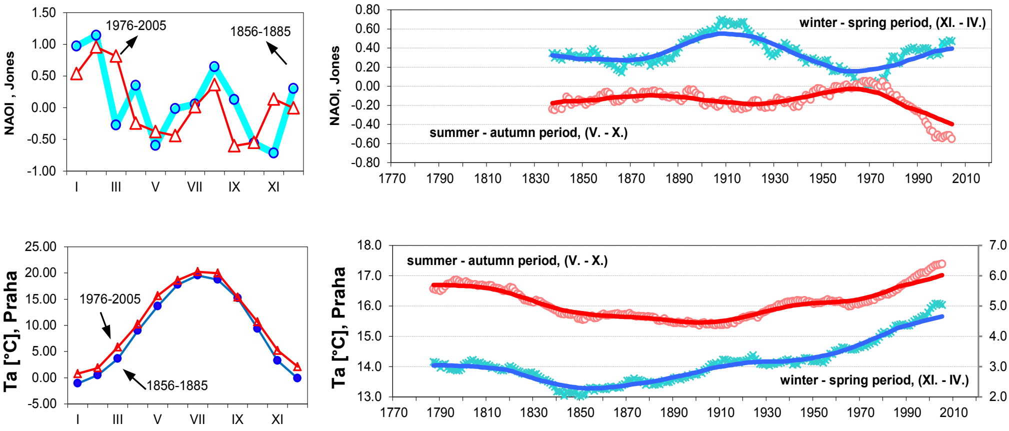


Fig. 4.8.3 Winter NAO indexes, periods 1871–2017 and 1950–2017

The monthly course of the NAO index and its course in the summer–autumn and winter–spring seasons are interesting. While the winter–spring index naturally fluctuates, the summer–autumn index has had a clear downward trend since 1970.

Figure 4.8.4 shows that the rising air temperature in central Europe (station Prague - Klementinum, http://portal.chmi.cz/historicka-data/pocasi/praha-klementinum) and the NAO phenomenon are not correlated. The NAO has its own long-term cycle.



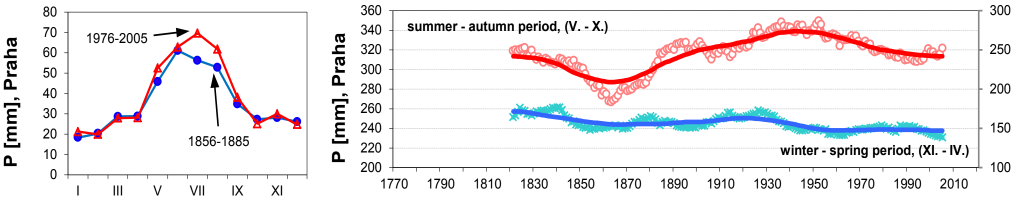


Fig. 4.8.4 30-year monthly averages of the NAO indexes, air temperature and precipitation totals for two periods (left). Course of 30-year moving averages of winter spring and summer – autumn periods (right)

Data from the Prague - Klementinum station was used for the presentation because of its unique duration and quality of observation. It is known that while the long-term air temperature trend at one station can represent the temperature trend of a broad region (including Slovakia), the same does not apply to precipitation. The long-term trends in air temperature in central Europe were that they fell in the period 1775–1850 and have been increasing since 1850. This increases evaporation (evapotranspiration), which has a negative effect on water runoff from river basins – runoff is decreasing.

Stahl et al. (2001) studied the relationship between monthly, two-monthly and seasonal values of the NAOI and the occurrence of drought in several river basins in Europe over the period 1962–1990. The river basins in Europe were divided into 18 regions. The river basins of central Slovakia were included in region 15. The central European region was found to have a low dependency on NAO phenomena, but Norwegian, English and Spanish rivers showed a strong dependency of flow on the NAOI. Shorthouse and Arnell (1997) likewise studied the relationship between intra-year climate variability – expressed by the NAOI – and the spatial distribution of runoff in Europe. The analysis was based on regional data on monthly discharges in 477 small river basins in the period 1961–1990 which was provided from the FRIEND European archive. The authors showed that runoff from European rivers is correlated with NAOI values (especially in winter) and that the dependency has a spatial distribution. Northern European rivers show a positive dependency on NAOI values while rivers in southern Europe have a negative dependency on the NAO index.

The imaginary boundary between north-west and south-east Europe passes through the territory of Slovakia (Adler et al., 1999). This boundary moves from year to year. The effect of the NAO phenomenon on precipitation (and thus on runoff) is varied and therefore there is a special need for further research on the relationship between the winter NAO index and runoff in the various river basins of Slovakia.

4.8.2. Results

Long-term trends in discharge time series

The statistical analysis of long-term development in discharges was based on data on average daily discharges as described in Chapter 4.1.3. In the case of six rivers – the Váh, Kysuca, Hron, Topľa, Nitra and Ipeľ – the evaluated period was extended to 85 years, from 1931 to 2015. The basic characteristics and descriptions of the river basins are given in Chapter 2. The hydrological characteristics of the studied river basins to the selected profile are shown in Table 4.8.1. Data on runoff height *R* indicate, amongst other things, that at their chosen profiles the Váh and the Kysuca have more than three times the runoff of the studied profile of the Ipeľ and more than two times the runoff of the studied profiles of the Topľa and Nitra. Figure 4.8.5 shows the results of various statistical analyses of average daily discharges at the Ipeľ – Holiša gauging station. This gauging station, like those at Váh – Liptovský Mikuláš, Kysuca – Kysucké Nové Mesto, Hron – Brehy, Nitra – Nitrianska Streda and Topľa – Hanušovce nad Topľou, has a long, uninterrupted series of observations. Another five gauging stations with long time series were also evaluated. The top part of Figure 4.8.5 shows the course of average daily discharges and the value of the four-year moving average of discharges. The central part shows the courses of average annual discharges and the annual values for Q_{300d} and Q_{360d} in the studied years. In the bottom left of the figure are the average long-term values for the percentiles $Q_{10\%}$, $Q_{50\%}$ and $Q_{90\%}$ for each day of the year and on the right is part of the flow duration curve representing low flow from the value Q_{300d} ($Q_{80\%}$).

Tab. 4.8.2.1 Basic characteristics of the water gauges

River	Gauging station	Basin size (km$^{2)}$	Water gauge zero (m a.s.l.)	Long-term average annual discharge Q_a (m^{3}s^{-1})	Runoff *R* (mm)
1931–2015					
Váh	Liptovský Mikuláš	1107	568	20.4	581
Kysuca	Kysucké Nové Mesto	955	346	16.23	536
Hron	Brehy	3821	195	46.7	385
Topľa	Hanušovce	1050	160	8.13	244
Nitra	Nitrianska Streda	2094	158	14.6	220
Ipeľ	Holiša	686	172	3.08	142
1981–2015					
Myjava	Šaštín-Stráže	645	164	2.62	128
Rimava	Vlkyňa	1377	151	5.74	132
Poprad	Chmeľnica	1262	507	14.93	373
Torysa	Košické Olšany	1298	186	7.53	183

Based on the evaluation of discharges from the six gauging stations, the following conclusions can be drawn:

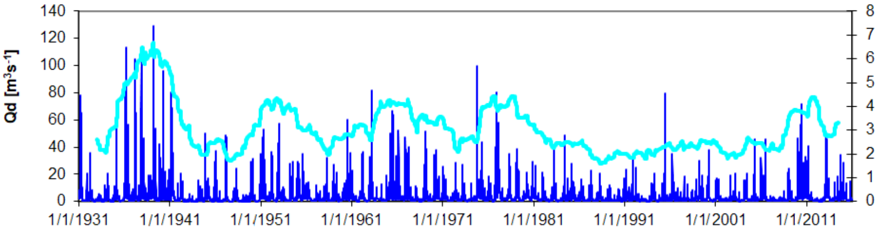
- The course of the 4-year moving averages of average daily discharges shows a clear decrease in discharges in the period covering approximately 1986–2005, except in the Kysuca River Basin
- Discharges at the selected gauging stations have a slight decreasing trend, with steepest decrease at the Ipeľ - Holiša gauging station (Fig. 4.8.5)
- The long-term development of low flow characteristics is interesting: during the period 1931–2015 there was no significant decrease in the values Q_{300d} and Q_{360d}.

Daily discharge **Ipeľ: Holiša**

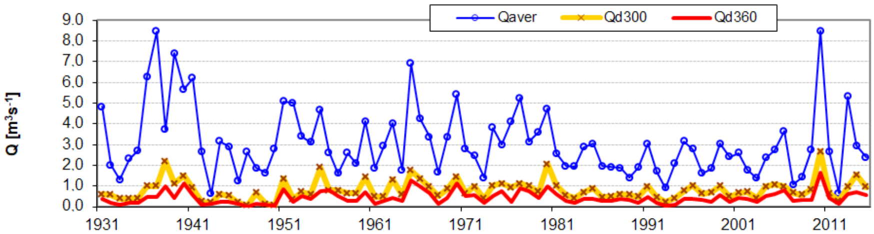
Basin size	686	km^2
Starting year	1931	
Ending year	2005	

Basic hydrological parameters of average daily discharges

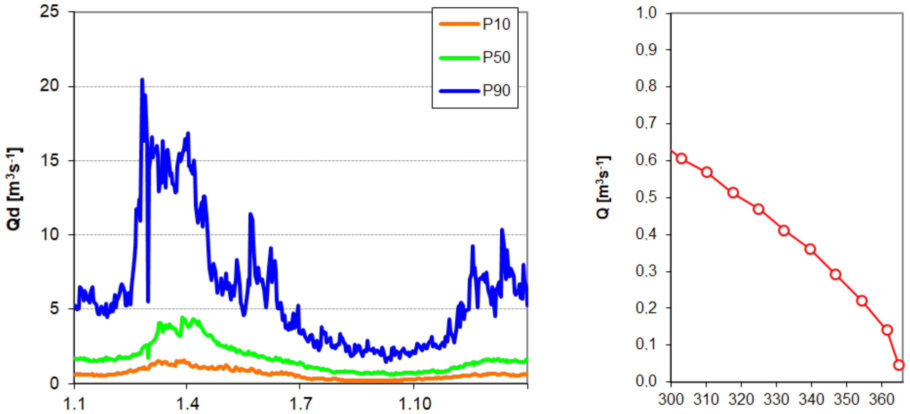
	mean	min	max	330-day	30-day	cs	cv
Q $[m^3s^{-1}]$	3,08	0,010	129,0	0,43	7,6	6,88	1,84
q $[l.s^{-1}km^{-2}]$	4,49	0,015	188,1	0,63	11,1		
R [mm]	141,5						



Average daily discharges and their 4-year moving averages



Course of average annual discharges and linear trend, course of 300- and 360-days discharges



Long-term percentiles of average daily discharges

M-day discharges

Fig. 4.8.5 Panel of the basic statistical and graphical evaluation of discharges at the Ipeľ – Holiša gauging profile (Q – annual discharge in $m^3.s^{-1}$, Q_d – average daily discharge in $m^3.s^{-1}$, q – specific annual discharge in $m^3.s^{-1}.km^{-2}$, R – runoff in mm)

Autocorrelation and spectral analysis

All the series of average annual discharges, the series of annual total precipitation on the surface of the territory of Slovakia and Jones’ series of winter NAO indexes (NAOIw) underwent spectral and autocorrelation analysis to detect hidden cycles. Spectral analysis based on the combined periodogram method (Pekárová et al., 2003) identified cycles with lengths of around 3.65; 5–6; 7; 10–11; 13.5; 22 years (and their higher harmonic multiples). Fig. 4.8.6 shows examples of the combined periodograms for selected series. The cycle of 2.4 years in the series of discharges means that in addition to the 12-month cycle determined by the Earth's movement around the Sun, there another 28–29-month cycle.

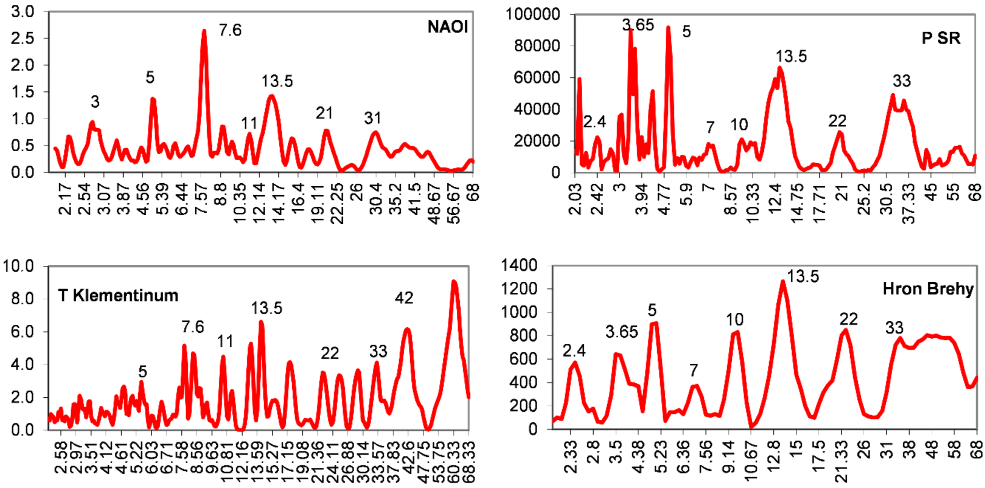


Fig. 4.8.6 Combined periodogram of: the winter NAO index time series, precipitation totals on the Slovakia territory series, air temperature – Praha Klementinum series, annual discharge of the Hron: Brehy series. The periods are on the x-axis.

All the series have a cycle with a length of 5–6 years. This means that discharges in a given year are dependent on the discharges five years before. The periodogram does not indicate wither this dependency is positive (direct) or negative (indirect). The type of dependency can be identified with the help of an autocorrelation plot. Fig. 4.8.7 presents examples of autocorrelation plots of average annual discharges in the Hron and the Kysuca.

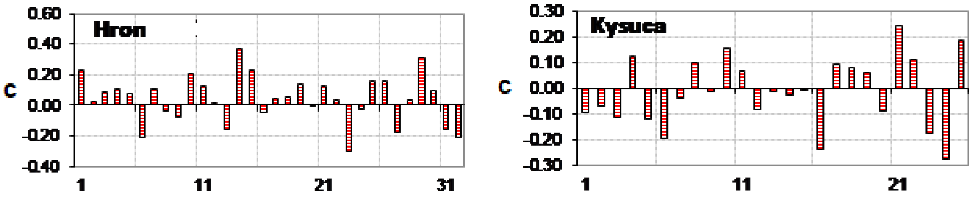


Fig. 4.8.7 Auto-correlograms of the annual discharges of the Hron and Kysuca Rivers

The autocorrelation coefficients *c* for a time lag of 5–6 years are negative, which means that the base cycle is 11 years. This analysis indicates that five to six years after the occurrence of a year with above-normal discharges, a dry year will occur. This cycle could be related to solar activity and the thermohaline circulation of sea water. Several scholars have looked for the causes of these cycles but they have not yet been fully clarified. Several interesting works have considered the effect of the Sun's movement around the barycentre of the Solar System on solar activity and thus on the Earth's climate (Charvátová and Střeštík, 1995; Charvátová, 2000, Garric and Huber, 2003; Liritzis and Fairbridge, 2003).

Forecast of the occurrence of a dry year based on the winter NAO index

As shown above, the series of the winter NAO index and the discharge series have the same length of their fluctuation cycles. There is however a time lag of several months between these two series which makes it possible to forecast a dry year based on the NAO index for the preceding winter months.

Cross-correlation was used to identify the time lag between the two series and assess the closeness of the relationship between them. In the first case, cross-correlation analysis was used to calculate the correlation coefficients c and identify the time lag between the winter NAO index (NAOIw, cpc) and the annual series of discharges in selected Slovak rivers (Q_a). An example of results for the Ipeľ – Holiša gauging station is shown in Figure 4.8.8.

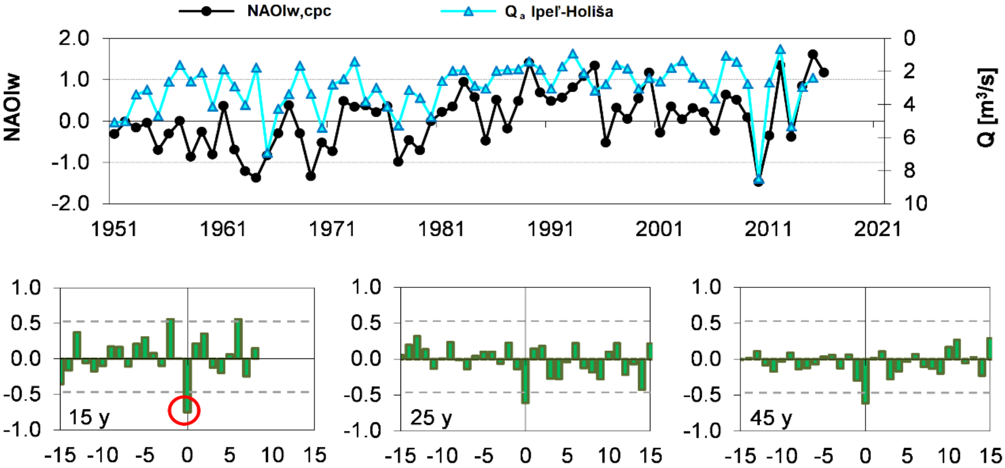


Fig. 4.8.8 Course of the values of NAOIw,cpc and annual discharges Q_a (up), and cross-correlograms of the winter NAO indexes and average annual discharges of the Ipeľ River for three periods: 15-, 25- a 45-years

In general, Slovak rivers are strongly affected by the North Atlantic Oscillation. As the present work concerns low flows, correlation coefficients and time lags were identified between NAOIw,cpc and the series of values Q_{330d}. A graphical presentation of the relationship for the Ipeľ – Holiša gauging station is shown in Figure 4.8.9. The results of the calculation are given in Table 4.8.2.2.

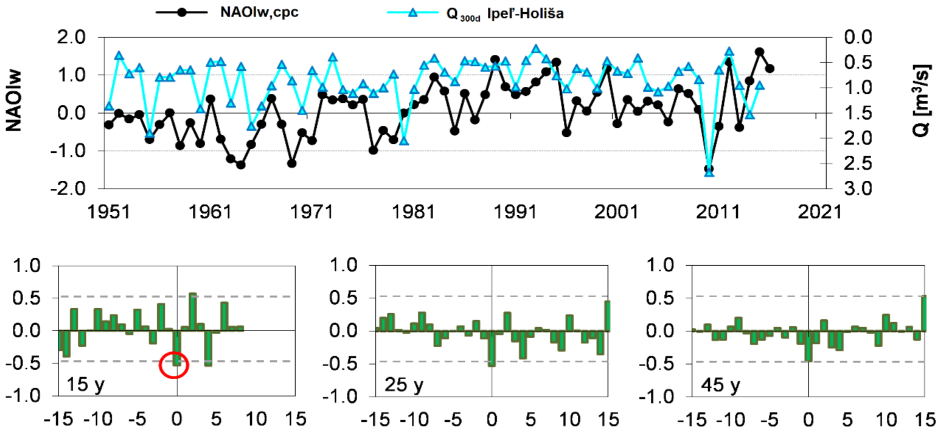


Fig. 4.8.9 Course of the values of NAOIw,cpc and Q_{300d} discharges (up), and cross-correlograms of the winter NAO indexes and Q_{300d} discharges of the Ipeľ River for three periods: 15-, 25- a 45-years ending in 2015

Tab. 4.8.2.2 Cross-correlation coefficients among NAOIw, cpc vs. Q_a and NAOIw,cpc vs. Q_{330} with a lag of 0 – 5 years

Stream	Gauging station	Q_a						Q_{330d}					
		lag						lag					
		0	-1	-2	-3	-4	-5	0	-1	-2	-3	-4	-5
Váh	Liptovský Mikuláš	**-0.5**	-0.1	*0.2*	-0.3	0.1	0.4	-0.2	0.0	*-0.1*	-0.4	0.1	**0.6**
Kysuca	Kysucké Nové Mesto	**-0.5**	-0.3	***0.5***	-0.1	-0.4	0.3	**-0.4**	0.0	*0.2*	-0.2	-0.1	**0.5**
Hron	Brehy	**-0.7**	0.0	***0.6***	-0.2	0.0	0.3	-0.3	0.1	*0.3*	-0.3	0.2	0.4
Topľa	Hanušovce	**-0.7**	-0.3	*0.3*	-0.1	0.0	-0.1	**-0.4**	-0.4	*0.0*	-0.2	0,2	0.1
Nitra	Nitrianska Streda	**-0.6**	-0.1	***0.5***	-0.2	-0.2	0.2	**-0.4**	0.1	*0.2*	-0.3	0.3	0.3
Ipeľ	Holiša	**-0.6**	-0.1	***0.5***	-0.2	-0.2	0.2	**-0.4**	0.0	*0.3*	-0.2	0.3	0.3
Myjava	Šaštín-Stráže	**-0.7**	-0.1	***0.4***	0.0	-0.1	0.4	**-0.6**	0.0	***0.5***	-0.1	-0.2	0.4
Rimava	Vlkyňa	**-0.7**	-0.1	***0.4***	0.0	-0.1	0.4	**-0.6**	0.0	***0.5***	-0.1	-0.2	0.4
Poprad	Chmeľnica	**-0.6**	-0.1	*0.2*	-0.2	0.0	0.2	-0.2	-0.2	*-0.1*	-0.3	0.0	**0.6**
Torysa	Košické Olšany	**-0.6**	-0.2	*0.3*	-0.1	0.0	-0.1	**-0.4**	-0.2	*0.1*	-0.2	0.1	0.1

If the correlation coefficient with a zero time lag is equal to or less than -0.5, it means that there is a significant negative dependency between the series (Table 4.8.2.2). In years with a high winter NAO index (NAOIw), it can be expected that the year will be dry. The closest dependency, with a correlation coefficient of -0.7 was found between NAOIw and the average annual discharge Q_a in the Hron, Topľa, Myjava and Rimava River Basins and the correlation coefficients for the remaining river basins were a little weaker: -0.6 for the Nitra, Poprad and Torysa River Basins and -0.5 for the Váh and Kysuca River Basins. All the coefficients are significant on the significance level $\alpha=0.05$. The test of the relationship between NAOIw and Q_{300} achieved lower values, which were statistically significant only for the Kysuca, Topľa, Nitra, Myjava, Rimava and Torysa River Basins.

With time lags of two and five years, there was mainly a positive dependency between NAOIw and average annual discharges. These results indicate that the values of the winter North Atlantic Oscillation index (NAOIw) can be used to estimate river flow levels in the following year. The positive correlation coefficients for a 5–6 year time lag are caused by the cyclical character of the series. This means that five–six years after an extremely low NAOIw, the annual total precipitation in southern Slovakia and average annual discharges should be lower. In other words, a period of drought can be expected.

5. OCCURRENCE OF HYDROLOGICAL DROUGHT IN GROUNDWATER

In Slovakia groundwater is both one of the most important and also the most economical sources of drinking water in terms of its capture, exploitation, quality requirements and protection. The systematic detection and evaluation of the occurrence and condition of surface and groundwater in the territory of the Slovak Republic is vital to ensuring adequate information for the development of blueprints for sustainable development, the provision of public services and for public information (Škoda et al., 2009). Knowledge of spring yield regimes is important especially in mountain areas where the population is not supplied for large water sources and has to rely on local sources, above all springs.

The occurrence of extreme hydrological phenomena caused by climate change has an impact on the sustainability of water sources. There are more frequent reports of problems with shortages of drinking water such as at the village of Žakarovce near Gelnica, but also in the village of Prihradzany in Revúca District (in 2012) and the villages of Zákamenné and Markušovce (in 2015), where drought caused a shortage of drinking water because the local springs dried up almost completely.

5.1. CHARACTERISTICS OF THE HYDROLOGICAL SITUATION IN GROUNDWATER IN SLOVAKIA IN THE YEARS 1981 TO 2015

The occurrence of drought in groundwater was evaluated using the SANDRE method. The evaluation included 123 sites in the state hydrological monitoring network for groundwater operated by the Slovak Hydrometeorological Institute. The selection of sites had to satisfy the following criteria:

- uniform coverage of the whole territory of Slovakia,
- an uninterrupted 30-year series of measurements,
- no interference in the data.

The evaluated period covered the hydrological years 1981–2015 and the hydrological years 1981–2010 were used as a reference period. The evaluation used monthly time steps. The evaluation of the individual hydrological years from a long-term perspective is shown Table 5.1.1.

Tab. 5.1.1 Evaluation of hydrological years wetness from the groundwater point of view

Hydrological year	Evaluation
1981	*above average*
1982	around average
1983	around average
1984	**below average**
1985	*above average*
1986	around average
1987	around average
1988	around average
1989	**below average**
1990	**below average**
1991	**below average**
1992	**below average**
1993	**below average**
1994	around average
1995	around average to slightly above average
1996	around average to slightly above average
1997	around average
1998	around average
1999	*above average*
2000	*above average*
2001	around average
2002	around average to slightly below average
2003	**below average**
2004	**below average**
2005	around average to slightly above average
2006	*above average*
2007	**below average**
2008	around average to slightly below average
2009	around average
2010	*above average*
2011	*above average*
2012	**below average**
2013	*above average*
2014	around average
2015	around average

A general observation is that most of the dry years in the studied period occurred before 1993, even with the five-year drought from hydrological year 1989 to 1993. Within these five studied years, the most intense periods of drought were in the hydrological years 1990 and 1993. In the hydrological year 1990, drought mainly affected the western part of Slovakia and the southern part of central Slovakia, where the level of groundwater and spring yields were significantly lower than the long-term average of the reference period (Fig. 5.1.1, red colour).

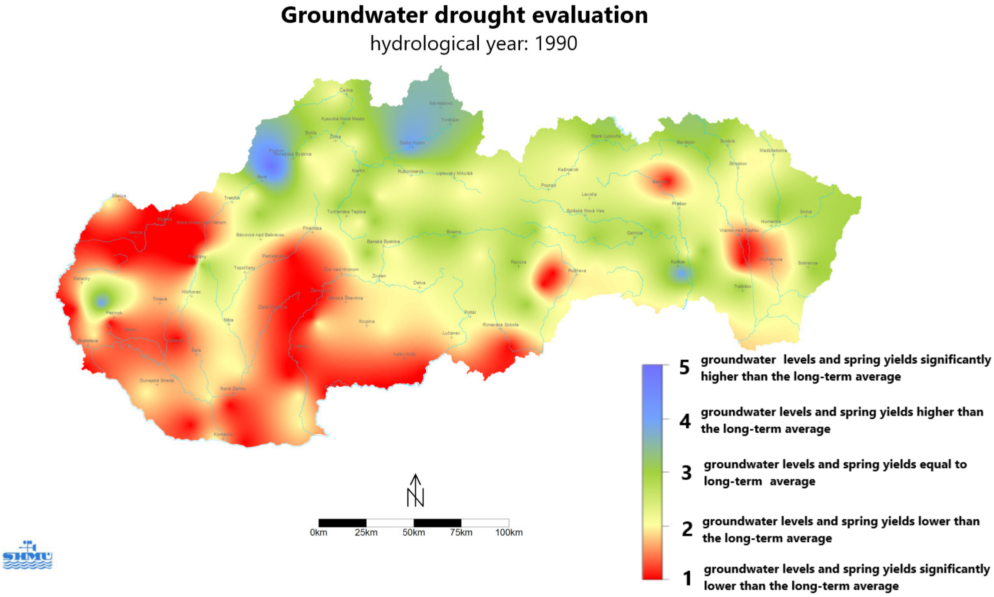


Fig. 5.1.1 Evaluation of the hydrological year 1990 in groundwater

After the hydrological year 1993, droughts occurred in 2003, 2004, 2007 and 2012. The year from this group with the most intense drought was 2012 (Fig. 5.1.2), which was affected by earlier meteorological conditions in 2011. The drought had its strongest effects in the north-west and centre (the Kysuca and Orava River Basins, a large part of the Hron River Basin) and in the east of Slovakia (the Topľa and Hornád River Basins and in the far east). In the west, the Váh and Myjava River Basins were affected by drought.

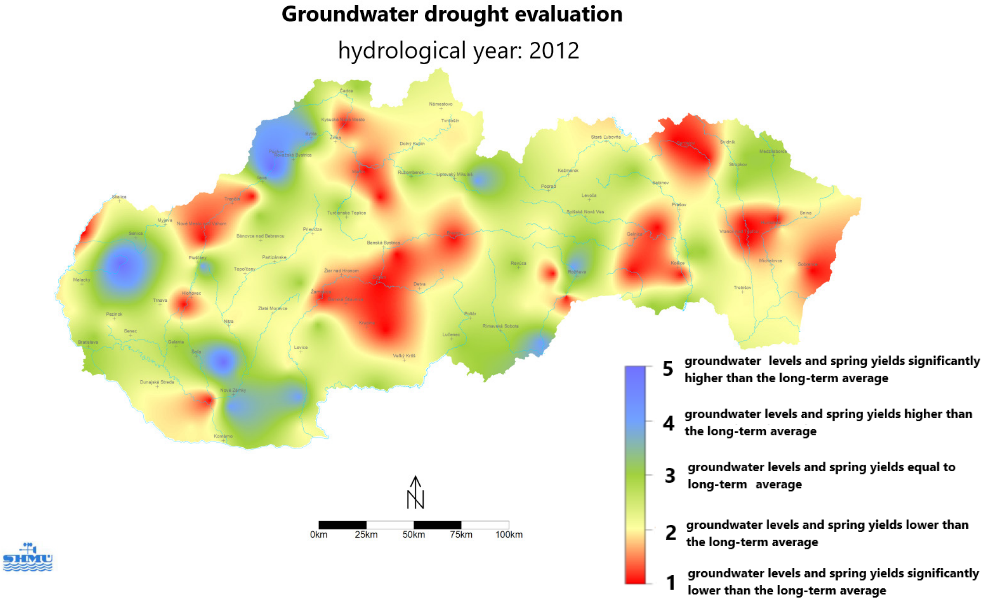


Fig. 5.1.2 Evaluation of the hydrological year 2012 in groundwater

5.2. SEASONALITY OF MINIMUM SPRING YIELDS

Spring yields are of fundamental importance for supplying drinking water to the inhabitants of mountain regions of Slovakia. When capturing a spring, it is important to consider not only the stability of its yield but also its ecological function. The stability of a spring is determined by the amplitude of its yield, and therefore also by its minimum yield. The minimum yield of a spring is one of the factors in the calculation of the usable volumes for spring capture under Slovak law. To be able to quantify usable volumes of groundwater and local ecological limits related to spring yields, it is necessary to know how the spring yield changes over time – the seasonal course of yields and especially the seasonal minimum values.

5.2.1. Results of the statistical evaluation of seasonality in minimum spring yields

Statistical analysis of average monthly yields found that the average monthly yields of the studied springs ranged from 30.67 $l.s^{-1}$ (spring 1312 in Dolná Lehota) to 0.33 $l.s^{-1}$ (spring 1725 in Vyšný Komárnik). An exception is spring 328 in Vyšná Boca, where the mean yield is 115.3 $l.s^{-1}$ and the median is 63.12 $l.s^{-1}$. The status of this spring is complicated, however, because it is influenced by surface water in the spring months. As regards extreme values, as in the case of average values, the highest maximum yield was from spring 328 in Vyšná Boca – 888.8 $l.s^{-1}$. The lowest yields were equal to 0.00 $l.s^{-1}$. Such minimum yields were observed at springs in Slovenská Ľupča (1265), Dobšinská ľadová jaskyňa (2153) and Lučiná (2292).

Nearly half the studied springs have a variation coefficient greater than 50%, which points to data inconsistency and indicates that it is better to use the median than the mean. The distribution type for set frequencies is significantly different from a normal distribution and for most of the studied springs there is an asymmetric distribution. Data set homogeneity was tested using a normal probability plot for frequency. Based on the results of this test, the yield series for individual springs can be considered homogeneous.

The minimum spring yield below Q_{90} was set for the long-term period based on the empirical flow duration curve. The yields of individual spring naturally vary. The lowest values for Q_{90} were found for the springs at Dobšinská ľadová jaskyňa (2153) with a value of 0.00 $l.s^{-1}$, and at Lučiná (2292) with a yield of 0.08 $l.s^{-1}$. The highest value for the Q_{90} yield was at Vyšná Boca (328), with a value of 19.5 $l.s^{-1}$. Values for Q_{90} were also determined for each decade and season.

5.2.2. Results of the evaluation of seasonality in minimum spring yields

The seasonality of minimum spring yields was evaluated based on the **occurrence dates** of yields below the $\mathbf{Q_{90}}$ value for long-term yields (1980–2012). Seasonality was also calculated based on the occurrence dates of yields below Q_{90} for the long-term **summer -** $\mathbf{Q_{90S}}$ (months 4–10) and **winter -** $\mathbf{Q_{90W}}$ (months 9–3) periods. Since the value of Q_{90} was determined from the overall empirical flow duration curve for weekly yields in the hydrological years 1980–2012, seasonality was also evaluated for the decades **1980–1989** ($\mathbf{Q_{90\,1}}$), **1990–1999 (**$\mathbf{Q_{90\,2}}$**)**, **2000–2009 (**$\mathbf{Q_{90\,3}}$**)** and for the period **2000–2012 (**$\mathbf{Q_{90\,4}}$**)**. Seasonality was also evaluated for the dates of absolute annual minimum yields $\mathbf{Q}_{Amin}$ (1980–2012) and absolute minimum yields for summer $\mathbf{Q}_{AminS}$ (months 4–10) and winter $\mathbf{Q}_{AminW}$ (months 11–3).

The first parameter of seasonality evaluated using Burn's method, (1997) based on the timing (θ) and regularity (*r*) of extreme phenomena, were the occurrence dates of minimum yields below Q_{90} (1980–2012). The average occurrence date was in the months between August and March (Fig. 5.2.2.1).

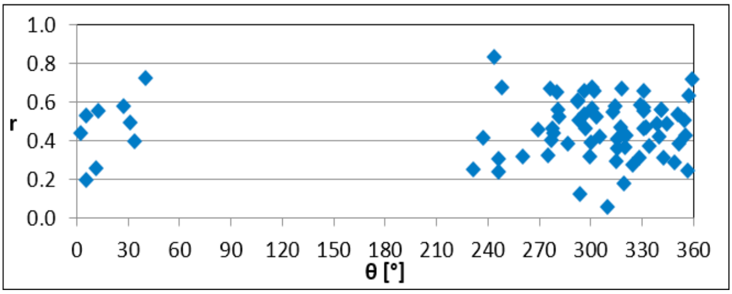


Fig. 5.2.2.1 Average angle date of minimum yields occurrence (θ) and seasonal concentration index (*r*) for yields lower than Q_{90}

Figure 5.2.2.2 shows Burn's vector calculated for yields below Q_{90}. The direction of the arrows on the map indicates the month in which the minimum yields were observed and the size of the arrow represents the probability of occurrence of a minimum yield on the calculated date.

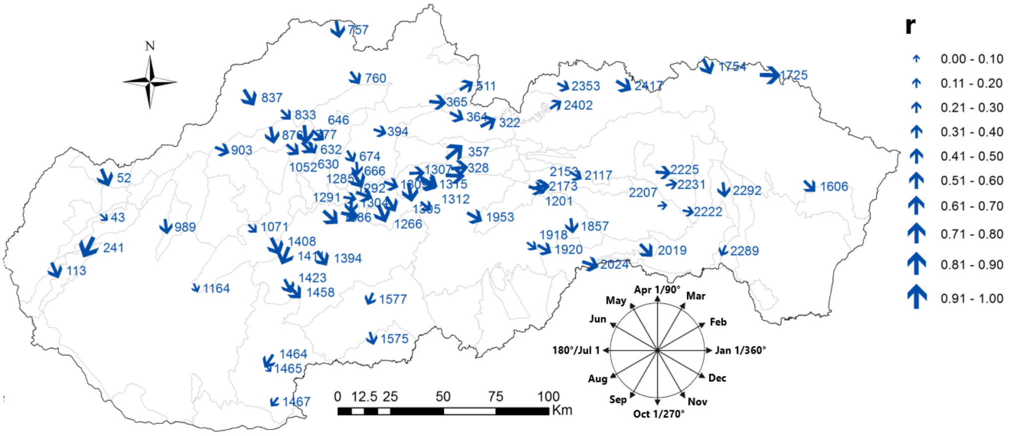


Fig. 5.2.2.2 Burn´s vector calculated for yields lower than Q_{90}

Minimum values occur most frequently in the months of November (21), December (20) and October (17). Less frequently they also occur in January (6), February (3) and at the end of the summer, in August (2) or September (6). The second parameter for the evaluation of the seasonality of minimum yields was the date of occurrence of the absolute annual minimum yield Q_{Amin} for the whole studied period, which as in the case of Q_{90}, fell in the period from September to February. There was a difference in the value for seasonal concentration *r*, which is usually higher for Q_{Amin}.

If we compare the seasonal development in individual decades with the long-term seasonality of minimum yields below Q_{90}, seasonality usually moves one month forward or backward in the course of each decade. The relationship between the decrease or increase in the values of $Q_{90(1,2,3,4)}$ in each decade compared to the long-term value of Q_{90}, and the size of the change in the average occurrence date of minimum yields is not statistically significant. Comparison of the individual decades with the long-term value of Q_{90} shows that in the years 1980–1989 there was a decrease in the value of minimum yield and later occurrence of minimum yields in the hydrological year relative to the long-term period. The trend in 1990–1999 was mainly in the opposite direction towards an increase in minimum yields and earlier occurrence of the minimum relative to long-term values. The development of minimum yields from the studied springs in the years 2000–2009 and 2000–2012 was very similar to the long-term values. In most cases in both periods there was a decrease (41 springs) or no change (48 springs) in minimum spring yields. Half the springs had either earlier or later occurrence of minimum yields compared to the long-term yields.

When individual decades are compared with each other, the largest changes in minimum yields and their average occurrence dates occurred between 1990 and 1999 compared to the previous decade 1980–1989 (Fig. 5.2.2.3).

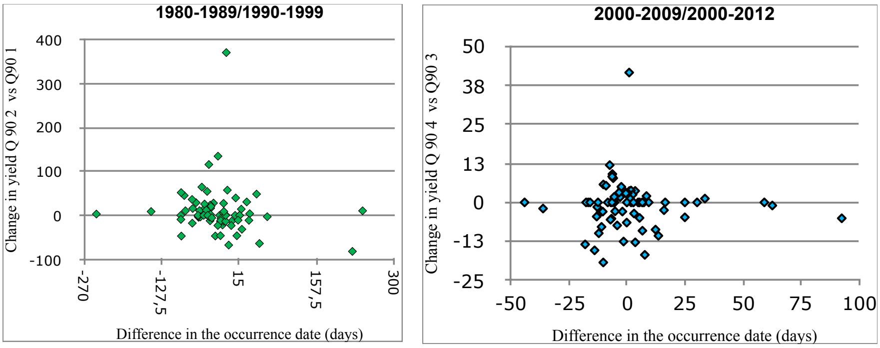


Fig. 5.2.2.3 Change in minimum yields and average occurrence dates of the decade 1990–1999 vs 1980–1989 (left) and 2000–2009 vs 2000–2012 (right)

In the 1990s compared to the 1980s, minimum yields got lower for most springs and some springs had significant changes in the average occurrence date. The changes in yield between the last decade 2000–2009 and the period 2000–2012 are not very large. The effect of the dry years in 2011 and 2012 wiped out the effect of the above-normally wet year in 2010 and there was probably a slight decrease in minimum yields over the last 13 years compared to the decade 2000–2009 (Fig. 5.2.2.3). Although there were significant changes in the average occurrence date of minimum yields for springs 2222, 2289, 2231, 1164 and 394, they had low values for seasonal concentration.

The seasonality of annual minimum yields was complemented by the seasonality of minimum yields for the summer period lasting from April to October and for the winter period lasting from November to March. The average occurrence date of summer minimum yields below Q_{90S} was mainly in August and September while the absolute lowest summer yields Q_{AminS} were mainly in September and October. In the winter period, both minimum yield parameters (Q_{90W} and Q_{AminW}) occurred most frequently in December and January, and in a few cases in February.

Figure 5.2.2.4 shows the relative frequency histogram for the dates of annual absolute minimum yields Q_{Amin} during the hydrological year for all the studied springs.

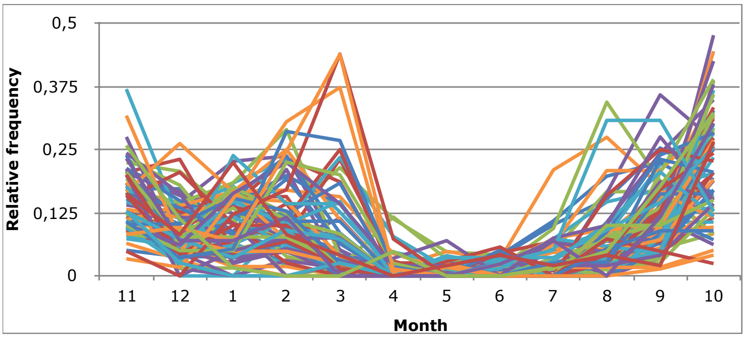


Fig. 5.2.2.4 Histogram of the relative frequency of dates with the absolute minimum yields Q_{Amin} within a hydrological year for all evaluated springs

From the course of the frequency histogram (Fig. 5.2.2.4) it is clear that minimum yields are most frequent in the autumn–winter period.

5.2.3. Regionalisation of the seasonality of minimum spring yields

After the analysis of seasonality of individual parameters of minimum spring yields in each time period, the next step was regionalisation with the help of a cluster analysis. The input data for regionalisation were the parameters of seasonality represented by **Burn's vector** and **frequency histogram** values for spring yields below **Q_{90} (1980–2012)** and for absolute annual minimum yields **Q_{Amin} (1980–2012),** physiographical parameters and their mutual combinations.

The values for the Burn's vector expressed as the average angle θ and the value for seasonal concentration *r* cannot be entered into a cluster analysis, so these values were converted to cartesian coordinates *x, y* using the formula: $x = r \,.\, \cos(\theta)$; $y = r \,.\, \sin(\theta)$ (Burn, 1997) and were then used in the cluster analysis.

The regional types created based on the parameters for seasonality of minimum yields were compared with each other. The most similar are regions created based on the Burn's vector and relative frequency of absolute annual minimum yields Q_{Amin} (Fig. 5.2.3.1). Based on the occurrence dates of absolute annual minimum yields, it is possible to identify three types of minimum yield regime:

- A winter regime, which is represented in region 4, where the minimum yields occur most frequently between December and February inclusive
- An autumn region, represented mainly in regions 1 and 2, where the lowest yields occur in the months October and November
- A summer regime, for which there are the fewest cases, in which minimum yields occur mainly in August and September. The best results for regionalisation were obtained using a combination of physiographical parameters and the Burn's vector for yields Q_{90} a $Q_{Amin,}$ with both regionalisation results being similar to each other because of the dominant role of altitude above sea level.

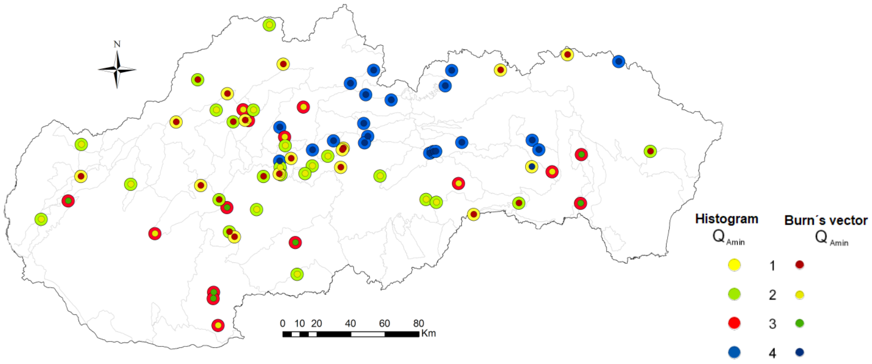


Fig. 5.2.3.1 Comparison of regions based on Burn´s vector and relative frequency of the absolute annual minimum yields

Three regions were identified with minimal differences in the classification of individual springs to the same region. The first region type (Fig. 5.2.3.2) is characterised by the occurrence of the spring outflow at an altitude of 100–460 m a.s.l., occasionally up to 550 m. Minimum yields occur most frequently in between the month of August and the first of November. Springs in the west are concentrated mainly in the Malé Karpaty, Považský Inovec, Tribeč, Vtáčnik, Štiavnické Vrchy Mountains, the Danube Uplands and the South Slovakia and Zvolen Basins. In the eastern part of the territory they occur mainly in the Slovak Karst and the Slanské Vrchy Mountains. The second region type is concentrated mainly in northern parts of the territory in the Vysoké and Nízke Tatry Mountains, the Podtatranská Kotlina Basin, the Veľká Fatra Mountains and the Spiš-Gemer Karst. The altitude of the spring outflows is 700 m a.s.l. and higher. From the perspective of seasonality, minimum yields occur in the months from December to February. The last region type has outflow at altitudes from 300 m to 800 m a.s.l. and is found in Kysuce, the Malá Fatra and Veľká Fatra Mountains, the Kremnické Vrchy Mountains, the upper Hron Valley, the Veporské Vrchy Mountains and in the east in the Čierna Hora Mountains, the Šarišská, Laborecká and Ľubovnianska Vrchovina Highlands and the Spišská Magura Mountains.

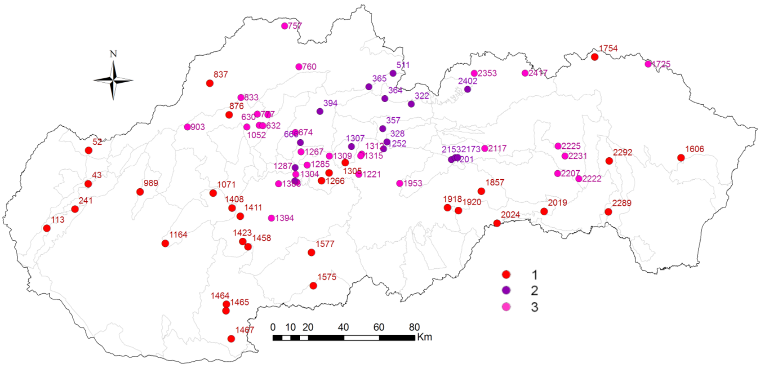


Fig. 5.2.3.2 Spatial plot of springs belonging to the relevant regional type according to physical-geographical parameters and Burn´s vector calculated for spring yields lower than Q_{90}

6. DISCHARGE VULNERABILITY MAP OF SLOVAKIA WITH REFERENCE TO MINIMUM DISCHARGES

6.1. METHOD USED TO DRAW UP THE MAP

In the first decade of the 2000s, the reference period for both meteorological and hydrological data was changed from 1931–1980 to 1961–2000. This change was preceded by detailed analysis and comparison of the data for both periods. The map of vulnerability and sensitivity of the territory of Slovakia (Fig. 6.1.1) expresses an estimate of which parts of a basin (territory) have experienced certain changes in runoff based on the values calculated for the basic components of the annual water balance (precipitation, runoff). The results allow the territory of Slovakia to be divided into (1) territory where there is an increasing or balanced trend in average runoff (low sensitivity and vulnerability); (2) river basins in which there is a balanced or slightly decreasing trend in runoff (medium sensitivity and vulnerability) and (3) river basins in which there is a decreasing or sharply decreasing trend in runoff (high sensitivity and vulnerability).

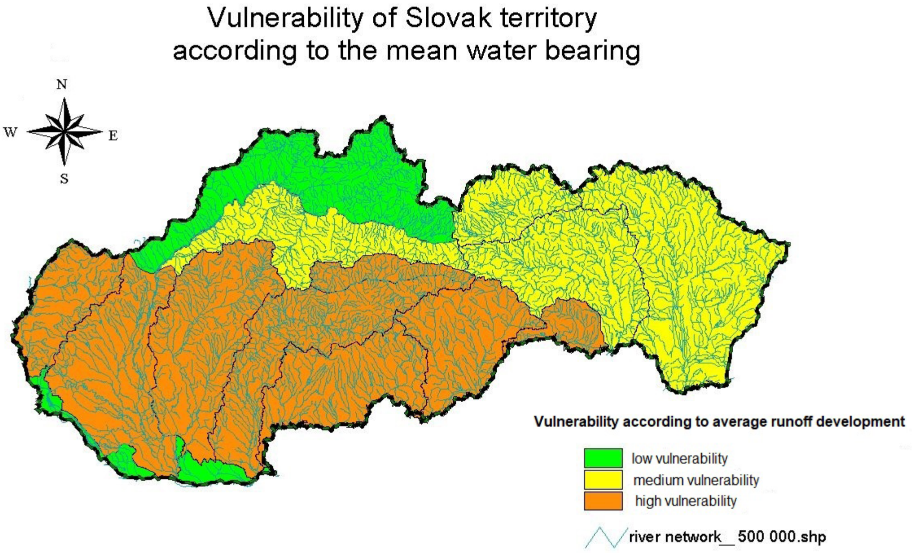


Fig. 6.1.1 Vulnerability of the Slovak territory according to annual flow development

The first group includes the Danube, the basin of the Dunajec, the high mountain parts of the Váh River Basin and basins in upper Orava and Kysuce. The second group includes the Poprad River Basin, the upper part of the Váh River Basin, the Bodrog River Basin and the Hornád River Basin. Other river basins (the Slovak part of the Morava River Basin, the basin of the Danube and the Little Danube, the lower part of the Váh River Basin and the basins of the Nitra, Hron, Ipeľ, Slaná and Bodva) belong to the third group.

In specific terms this means that runoff in some areas classified as highly sensitive decreased by up to 20% in the period 1961–2000. It should also be noted that the distribution of runoff in the year (the percentage of annual runoff occurring in each month of the year) has not changed significantly in any area.

In the following period, several years hydrologically classified as dry years confirmed these estimates for sensitivity, e.g. the hydrologically very dry year 2012 (Fig. 6.1.2).

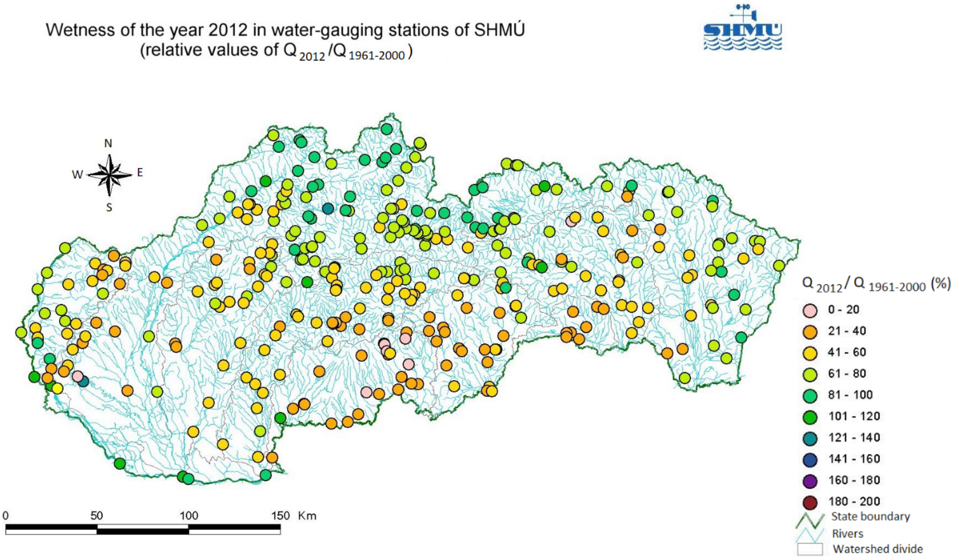


Fig. 6.1.2 Wetness of the year 2012 (relative values of $Q_{2012}/Q_{1961\text{-}2000}$) in evaluated discharge gauging stations (SHMÚ, 2013)

The same procedure used to make the map of vulnerability based on the development of mean runoff was also used to map of vulnerability based on the development of annual minimum discharges (Fig. 6.1.3)

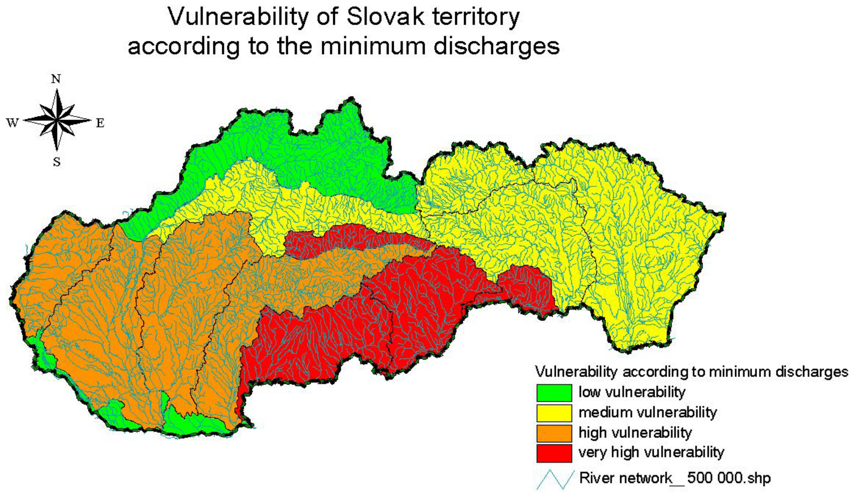


Fig. 6.1.3 Vulnerability of the Slovak territory according to minimum discharge development

6.2. EVALUATION OF TRENDS IN DISCHARGE CHANGES IN THE PERIOD 1981–2012

The trends of changes in discharges were evaluated using the Mann-Kendall test, which is used to detect significant trends in time series. The advantage of the Mann-Kendall nonparametric test is that it is not affected by the current distribution of data and it is also less sensitive to extreme values in the time series. The test is particularly suitable for larger statistical sets with more than 40 data points (WMO, 2008). The sign of statistic $\boldsymbol{Z}$ indicates whether a trend is increasing ($Z > 0$) or decreasing ($Z < 0$), but the test is not able to determine an estimate of the size of the obtained trends. With a significance threshold of 95%, a value of $Z > 1.96$ indicates an increasing trend while a value of $Z < -1.96$ indicates a decreasing trend.

Trend evaluation was carried out for discharge gauging stations selected from across the whole territory of Slovakia based on criteria of length of observation period and the smallest possible influence on the discharge regime from human activity (abstraction, emissions, manipulation via reservoirs). In view of the need for a more even distribution of territorial representation and representation of different stream types (smaller and larger streams and rivers, profiles in mountain and lowland areas), the evaluation included several influenced profiles. For the evaluation of trends in annual minimum discharges, the significance level was set as alpha = 0.05. In the studied period 1981–2015 increasing trends were found among the selected discharge gauging stations (Fig. 6.2.1) in discharge gauging stations in the Poprad River Basin and the upper parts of the Hornád and Váh River Basins. Decreasing trends were identified in a few discharge gauging stations on tributaries in the Orava region (Polhoranka, Veselianka), tributaries of the Váh (e.g. Jalovčianka, Suchý potok in Liptov; Rajčianka, Petrovička, some streams in the Malé Karpaty Mountains – Račiansky potok, Vištucký potok) and the upper Nitra.

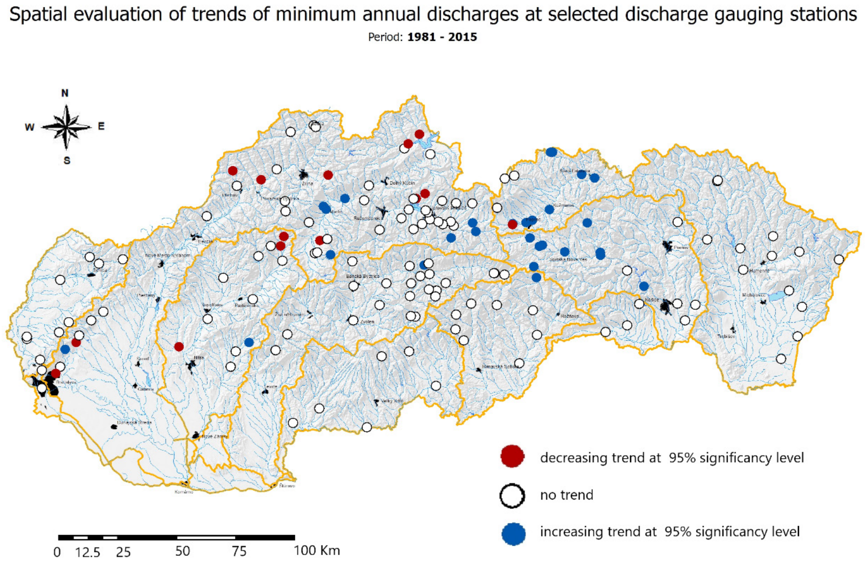


Fig. 6.2.1 Spatial evaluation of trends of minimum annual discharges in the period 1981–2015 at selected discharge gauging stations

This is confirmed by the analysis of runoff development (Fig. 6.2.2) which clearly shows the occurrence within the period 1981–2012 of a dry period from 1987 to 1993.

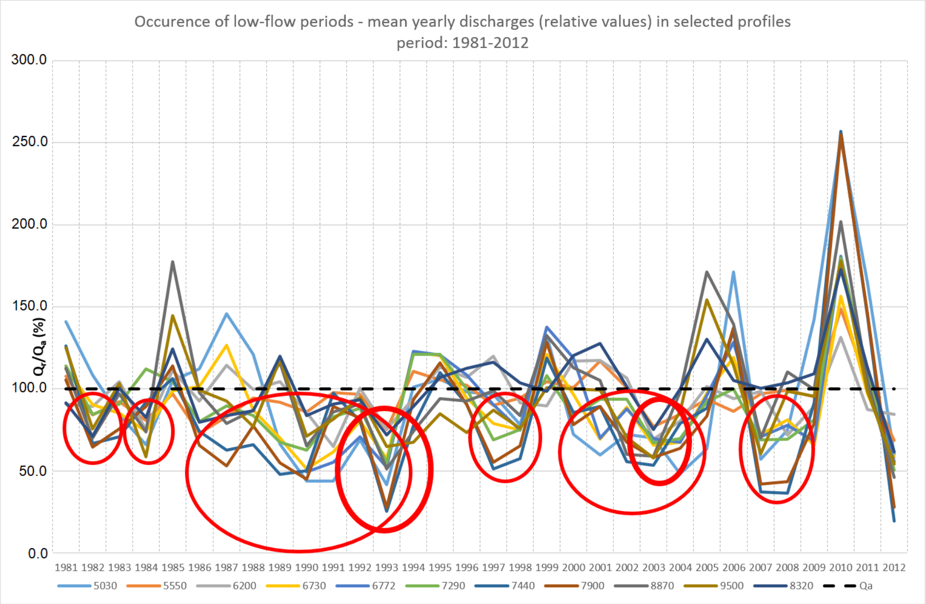


Fig. 6.2.2 Development of relative wetness (ratio of the average annual discharge Q_r to the long-term average Q_a) in selected discharge gauging stations in the period 1981–2012

Trend analyses are very sensitive to the period chosen for evaluation. Using a longer time period covering the period 1961–2015 (55 years), the trends in average annual discharges (Fig. 6.2.3) match relatively well with the set maps for vulnerability of the territory of Slovakia.

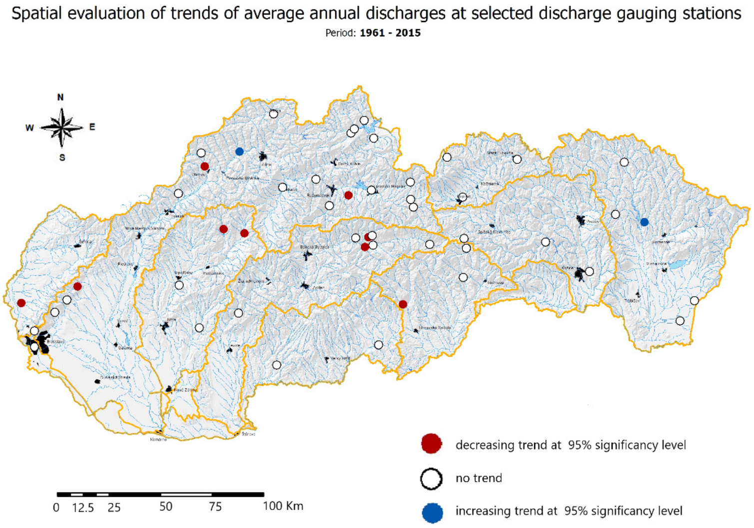


Fig. 6.2.3 Spatial evaluation of trends of average annual discharges in the period 1961–2015 at selected discharge gauging stations

The evaluation of trends in minimum annual discharges in this period did not confirm decreasing trends in minimum discharges at many of the studied gauging stations in areas classified as highly vulnerable. Initial analyses of linear trends pointed to decreasing trends in a larger number of gauging stations but the Mann-Kendall statistical test did not prove many of them to be statistically significant with a 95% level of significance. Dry years repeat in certain cycles. Although the period 2001–2015 includes some dry years (e.g. 2003, 2007, 2012), there have not been longer (multi-year) periods of continuous drought on the level of 1987–1993, and therefore the period does fundamentally change the evaluated long-term trend.

CONCLUSION

The present monograph, ***Prognosis of hydrological drought development in Slovakia,*** publishes the results of the pilot project in hydrological modelling of future drought occurrence and intensity in Slovak territory. The ***Hydrological drought and prognosis of its development in Slovakia*** project financed by the Slovak Research and Development Agency (APVV) was undertaken between October 2013 and June 2017. Two organisations were involved in the project; The Comenius University in Bratislava, and the Slovak Hydrometeorological Institute. The Comenius University was the coordinating organisation with Professor Miriam Fendeková as principal investigator leading the research team of the Department of Hydrogeology in the Faculty of Natural Sciences. The Comenius University second partner was drawn from researchers in the Department of Astronomy, Physics of the Earth and Meteorology of the Faculty of Mathematics, Physics and Informatics led by Professor Milan Lapin, and the research team of the Slovak Hydrometeorological Institute was headed by Ing. Zuzana Danáčová, PhD. The specialist from the BOKU University of Vienna – dr. Tobias Gauster and specialist from the Institute of Hydrology of the Slovak Academy of Sciences – Dr. Pavla Pekárová also contributed to the research results.

Drought as a global phenomenon still requires further research despite the great number of successful projects and studies published annually world-wide. Many approaches and methods of assessing drought have been developed, depending on the type of drought.

The World Meteorological Organization (WMO, 2012) recommended utilisation of the Standardized Precipitation Index (SPI) in various time steps for meteorological drought assessment. While this proved a useful tool, the Standardized Precipitation and Evapotranspiration Index (SPEI) performed much better in lower altitude river basins with higher average annual temperature. The climate-change-induced increase in air temperatures evoke much higher water demand because of increased evapotranspiration, and therefore established precipitation amounts no longer provide relevant description of the meteorological drought generation processes. Meteorological drought is best described as a lack of water from insufficient precipitation and increased evapotranspiration.

The main goal of this research is to assess Slovak drought occurrence between 1981 and 2012 and use models to predict drought development to 2100. Research is based on daily discharge data from ten main river basins approximately equally distributed throughout Slovak territory in the differing climatic, hydrological and hydrogeological conditions which form the mutual interrelationship of the hydrological balance equation elements. The river basins were: the Myjava up to the Šaštín-Stráže gauging profile (western Slovakia), the upper Váh up to Liptovský Mikuláš and the Kysuca up to the Kysucké Nové Mesto gauging profile (north-western Slovakia), and the Poprad up to Chmeľnica gauging profiles (northern Slovakia), the Hron up to Brehy and the Nitra up to Nitrianska Streda gauging profiles (central Slovakia), the Ipeľ up to Holiša and the Rimava up to Vlkyňa gauging profiles (southern Slovakia) and the Torysa up to Košické Oľšany and the Topľa up to Hanušovce nad Topľou gauging profiles (eastern Slovakia). The hydrological conditions and drought occurrence were evaluated in detail in daily, monthly and annual steps, with hydrological data correlated with data on meteorological conditions in the evaluated river basins; and hence throughout Slovakia.

The Frier spatially distributed physical model was the main tool used in prognosis of future drought development. The above list of evaluated river basins modelled by the Frier model was complemented by: (1) the Slaná up to Lenartovce (southern Slovakia), the Hornád up to Ždaňa (including the Torysa sub-basin), the Bodva up to Hosťovce, the Ondava up to Horovce (including the Topľa sub-basin) and the Laborec up to Humenné gauging profiles in Eastern Slovakia and (2) the Nitra and Hron River Basins were also investigated up to the Nové Zámky and Kamenín gauging profiles.

Detailed analysis of 1981–2012 meteorological and hydrological conditions established meteorological and hydrological drought occurrence. However, it was first necessary to prepare the climatic scenarios data. The Netherlands KNMI and German MPI regional climatic models (RCMs) were both used in two different scenarios. The latest observations have confirmed that predicted climate change progress presents quite realistic alternatives for future Slovak climate development. These have indicated that future climate development is not very favourable for Slovakia; with negative consequences outweighing the positive. Moreover, climate change scenarios anticipate further aridity in southern Slovakia and climate zone shift to higher altitudes in the north.

There is visible moderate linear increase in long-term annual precipitation in Slovakia with concurrent moderate decrease in runoff depth. The runoff coefficient is calculated as the ratio between runoff and precipitation depths, and this highlights a decreasing trend. While the long-term runoff coefficient value approximates the 32.3% value established for 1961–2000, this decreased to 29.8% for 1981–2015; and even 27.9% between 2001 and 2015. The decreasing runoff depth coefficient value is an explicit consequence of greater losses in the hydrological balance equation caused by increased evapotranspiration from rising air temperature.

The relative values–ratio of the average annual discharge ($\boldsymbol{Q_r}$) compared to the long-term discharge value for 1961–2000 ($\boldsymbol{Q_a}$) at discharge gauging stations evaluated the annual discharges ($\boldsymbol{Q_r}$) for 1981–2012. The evaluation identified dry periods with drought in consecutive months and the effect on river basins. These occurred in 1983/1984, 1986/1987, 1992/1993, 1995/1996, 1997/1998, 2000/2001, 2003/2004, 2007/2008 and 2011/2012. Average daily discharge evaluation showed that the highest number of low flow periods with $\boldsymbol{Q_d < Q_{330d}}$ (average daily discharge lower than that registered in 330 days a year ($\boldsymbol{Q_{90\%}}$)) was identified in the Hron River Basin with 51 such periods for a total of 1,658 days. The highest number of low flow periods with average daily discharge value below $\boldsymbol{Q_{355d}}$ ($\boldsymbol{Q_{97\%}}$) and $\boldsymbol{Q_{364d}}$ ($\boldsymbol{Q_{99.7\%}}$) was also recorded in the Hron River basin with a total 612 days and 93 days, respectively. The lowest number of such periods was found for the Torysa River Basin up to gauging profile Košické Olšany, with $\boldsymbol{Q_d < Q_{330d}}$ in 22 periods for a total of 718 days and $\boldsymbol{Q_d < Q_{355d}}$ was observed during 106 days, and there was no day the discharge lower than the $\boldsymbol{Q_{364d}}$ value.

Detailed analysis of drought occurrence and parameters was performed in 2003, 2012, and 2015; and the 2003 drought occurrence was obvious throughout Europe. The SPI12 results for Slovakia highlight that the 1981–2012 evaluated period can be divided into two parts according to meteorological drought occurrence. This is valid for almost all evaluated river basins, with dry conditions prevailing in most river basins in the 1980's and the first half of the 90's. The most extreme dry conditions were documented for the northern part of Slovakia where the upper Váh, Poprad and Kysuca River basins had long-term dry periods interrupted only by short periods of more humid conditions. The normal to wet conditions then prevailed from the second half of the 1990's until 2015, peaking in the extremely wet 2010 year. This period was interrupted only by three pronounced drought periods in 2003–2004, 2011–2012 and 2015.

The three drought periods had different intensity and the hydrological drought was evaluated using four parameters; minimum discharge expressed as AM7 value, drought duration, drought deficit volume and intensity. The drought period with the highest intensity in each evaluated year was then selected and studied in greater detail. The most extreme drought parameter values were recorded in the same year in seven of the ten evaluated river basins – in the Kysuca River basin in 2015, in the Ipeľ River basin in 2012 and in the Myjava, Nitra, Hron, Torysa and Topľa in 2003; with the remaining river basins experiencing these extreme values in different years. The highest drought intensity was not followed by either (1) the lowest value of the minimum discharge in the Rimava River Basin, (2) drought duration in the Poprad River basin or (3) deficit volume in the Váh River basin. While the highest deficit volumes were recorded in most river basins in 2003 and 2012, they were still higher than those in the 1981–2010 reference period in the Váh, Nitra, Hron, Ipeľ, Rimava and Poprad River basins. The only exception was the Kysuca River basin where the highest deficit volume occurred in 2015, and this was accompanied by the most extreme values of the three other drought parameters. The factor analysis applied to drought parameters resulted in classification of the evaluated river basins in the following three groups: (1) the Myjava, Kysuca, Nitra, Ipeľ, Rimava, Torysa and Topľa river basins in south, west and east Slovakia; (2) the Váh, Hron, and Nitra River basins in central Slovakia and (3) the Poprad and Váh River basins in northern Slovakia. Analysis highlighted that some river basins have transient character according to drought parameters; with the Nitra River Basin in the first and the second groups above and the Váh River in the second and the third groups.

The hydrological balance equation elements were subjected to two different models. The Bilan model is the 'lumped parameter' model compiled at the T.G. Masaryk Water Research Institute in Prague in the Czech Republic. The Frier model is a physically based spatially distributed model programmed by Oliver Horvat and based on the WetSpa model. The Bilan model was calibrated on the base-flow values estimated by Kille and BFI and this provided conformity in all evaluated basins, with the highest agreement noted in the Myjava River Basin seasonal course of modelled and observed runoff. The Frier model was then applied in further research because it provides the best prognosis of water balance elements on the spatial level.

Frier model evaluation of 1981–2012 hydrological drought showed that the number of drought periods with duration of 31 days or more in one year was highest at 0.9 value in the Hron, Poprad and Slaná River basins. This conformed to the average drought duration estimated by analysing average daily discharges; especially in the Hron River Basin.

Frier model prediction of development of the hydrological balance elements provided the following results: (1) while we can anticipate less meteorological drought periods for 1981–2100, greater water deficits are predicted; (2) the future unsaturated zone drought should last longer with greater deficit volumes and (3) although the saturated zone droughts should last approximately as long as at present, the drought duration could also be much longer and deficit volumes much larger.

The KNMI 2 scenario shows that the future saturated zone droughts should be longer, especially in all river basins east of the Nitra River Basin except for the Laborec. The most critical situation should occur in the Hornád River Basin where the longest predicted drought should last 1,686 consecutive days; five-times longer than the 301-day longest drought in the 1981–2012 reference period. A similar situation was predicted for the Ondava River Basin (1,165 days vs. 330) and the Bodva (877 days vs. 420). The average drought duration should extend mainly in the Hornád River Basin (201 days vs. 70). Moreover, similar results were obtained with the MPI 1 prognosis which anticipates the longest drought in the Hornád River Basin at 1,153 days maximum and 195 day average. KNMI 2 estimates longer extreme drought duration for the Kysuca, Hron, Ipeľ, Slaná, Rimava, and Laborec River basins, while MPI 1 predicts shorter drought duration in the Váh, Poprad, Hornád, Bodva, and Ondava River basins. In addition, the average drought duration should not change in the Poprad, Rimava and Slaná River basins but should be shorter in the Bodva River Basin (104 days vs. 35).

Both KNMI 2 and MPI 1 models gave similar seasonality change prognosis. They predict a general increase in precipitation amounts, shifts in the highest precipitation amounts from July to September and less precipitation from May to July. Air temperature should increase; mainly during the winter period and this could cause less snow accumulation and increased winter snow-melt runoff. While the onset of dry periods should be more frequent, with low precipitation, low runoff and less water storage, the most pronounced seasonality change is expected to evapotranspiration. The expectation of change to spatial distribution in hydrological balance elements from the 1981–2012 reference period to 2069–2100 includes the KNMI 2 scenario forecast of more extreme water storage changes; with central Slovakia losing the highest amount of water storage in the eastern Slovak Hornád River Basin and most especially in the Hron River Basin. However, increased storage should be retained in the lowlands, valleys, intra-mountainous depressions and the High Tatra Mts. Meanwhile, the MPI 1 projects higher water storage losses in the upper parts of the Hron, Slaná, and Rimava River Basins, but storage should increase in the upper parts of the Hornád, Poprad, Váh and at lower altitudes in the Rimava, Hron and Ondava River basins.

Further drought prognosis is provided by the winter North Atlantic Oscillation Index (**NAO-Iw**). This highlights statistically significant negative correlation between discharge time series and the **NAOw** index. In addition, dry years are expected in years with high winter NAO index and the positive correlation prevails in a time shift of 2 to 5 years. Therefore, **NAOIw** values provide prediction of annual "wetness". The tightest dependencies were found between the **NAOIw** values and $\mathbf{Q}_a$ average annual discharge in the Hron, Topľa, Myjava and Rimava river basins with -0.7 correlation coefficients, while the slightly lower -0.6 values were estimated for the Nitra, Poprad and Torysa river discharges. The lowest, but still statistically significant correlation coefficient value, was established for the relationship between **NAOIw** estimate and average annual Váh and Kysuca river discharges. Interestingly, the extraordinary low NAO index predicted a further dry period in Slovakia within 5 to 6 years.

Groundwater drought occurrence evaluation showed that most dry years in the evaluated 1981–2012 period occurred before 1993; even allowing for the five-year drought between 1989 and 1993. The most intense droughts in these five years were in 1990 and 1993. The groundwater drought evaluation results correspond well with the established discharge trends, and this evaluation documents the important percentage of identified decreasing discharge trends before 2001. Finally, following the 1993 wet spell, droughts occurred only in 2003, 2004, 2007, and also in 2012 which was the most intense event.

Detailed study was also performed on the seasonality of yields from 78 springs in mountainous Slovak areas; with emphasis on minimum yields. These parameters were determined by $\boldsymbol{Q_{90\%}}$ and $\boldsymbol{Q_{Amin}}$ where: (1) $\boldsymbol{Q_{90\%}}$ presents the yield calculated from the long-term flow duration curve which denotes yields attained and exceeded over 90% of the entire 1980–2012 experimental period and (2) $\boldsymbol{Q_{Amin}}$ gives the absolute minimum spring yield in the evaluated period.

Minimum spring yields were evaluated for the 1980–1989, 1990–1999, 2000–2009 ten-year periods, and also for the 2000–2012 thirteen years and the European winter and summer periods. The average and minimum spring yield seasonality was then evaluated by Burn vector and frequency histograms. These evaluations were followed by minimum spring yield regionalisation based on the combined physical-geographical factors of precipitation, air temperature, spring discharge area altitude, slope orientation and the rock hydraulic properties expressed as transmissivity coefficient. The Burn vector values and the frequency histogram values were determined, and the best results were obtained using the physical-geographical parameters and the Burn vector for both $\boldsymbol{Q_{90\%}}$ and $\boldsymbol{Q_{Amin}}$. The regionalisation results for these minimum spring yield parameters were similar, thus reflecting the dominant influence of spring discharge area altitude. The following three regions were delineated: (1) all springs with discharge altitude between 100 and 460 m; and to 550 m in a few instances. Minimum yields mostly occurred from August to the first half of November; (2) springs at 700 m and above. Here, the minimum spring yields were recorded in December to February winter months and (3) the third regional springs stretch spatially between the first two regional areas and these are typical spring discharge areas between 300 and 800 m with minimum discharges during the summer-autumn period. They range from the strip of mountains stretching from the Kysuce region through the Malá and Veľká Fatra Mts, the Kremnické vrchy Mts, the upper Hron valley and the Veporské vrchy Mts up to the eastern Slovakian mountains of Čierna Hora, Šarišská, Laborecká and Ľubovnianska vrchovina highlands and the Spišská Magura Mts.

The discharge development trends for 1981–2012 were evaluated and compared with the discharge vulnerability map of Slovakia. With Mann-Kendall 0.05 significance, this confirmed an increasing 1981–2015 trend in minimum annual discharges at discharge gauging stations in the Poprad River Basin and upper parts of the Váh and Hornád Rivers. In contrast, decreasing trends were identified at the Polhoranka and Veselianka discharge gauging stations in the Orava region, at the Jalovčianka, Suchý potok, Rajčianka and Petrovička upper Váh River tributaries, at the small Račiansky and Vištucký potok small brooks on the eastern slopes of the Malé Karpaty Mts. and also in the upper Nitra region. While these were not identified in the 2001–2015 period, the decreasing trends established in the 1981–2015 experimental period almost certainly have their origin prior to 2001.

Models compiled within the project simplify the actual natural hydrological processes and although we are not able to reproduce them precisely at this point in time, our experimental methodology remains extremely valid for hydrological modelling. A further uncertainty in actual development of climatic conditions is acknowledged in scenario prediction of future development in climatic elements up to 2100. Therefore, we stress that the prognostic results are accurate only to the extent that the scenario values of climate elements match real future climate development. While acknowledging these limitations, our predicted values certainly depict the likely future development of hydrological drought on Slovak territory in accordance with current state-of-art analytic technology.

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