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Interactions of natural and anthropogenic drivers and hydrological processes on local and regional scales: A review of main results of Slovak hydrology from 2019 to 2022

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The need to increase understanding of the impacts of changing natural and anthropogenic drivers on hydrological processes on local and regional scales is an essential prerequisite for advancing hydrology and a precondition for solving water resources management tasks. Slovakia exhibits abundant spatial and temporal variability of hydrological processes complicating the generalisation of runoff regimes. Changing climate and recent extreme floods and droughts put additional pressure on improving the observing, monitoring, describing, and modelling of hydrological processes. This paper reviews the response of hydrologic research in Slovakia to these challenges published in international journals from 2019 to 2022. It continues the practice of publishing the review part of the Slovak National Reports to IUGG on behalf of the IAHS (Szolgay, 2003; 2007; 2011; 2015; 2019), which follows the custom of National IUGG Committees to prepare a Quadrennial Report for the IUGG General Assemblies containing comprehensive summaries of national activities in geodesy and geophysics (Szolgay, et al., 2023).

KEY WORDS: climate change, hydrological processes, runoff regimes, hydrological research, Slovakia

Introduction

It is internationally recognized that the need to increase understanding of the impacts of changing natural and anthropogenic drivers on hydrological processes on local and regional scales is an essential prerequisite not only for the advance of the science of hydrology but a necessary precondition for addressing practical water resources management problems (Blöschl et al., 2019; Blauhut et al., 2022; Dolejš et al., 2022). The abundance of spatial and temporal variability of climatic drivers and regional and local runoff generation controls in Slovakia (Lehotský et al., 2022; Lehotský and Boltižiar, 2022) results in various runoff regimes. That complicates the attempts to arrive at generalized descriptions of the genesis of particular types of regimes and events. The same applies to hydrological extremes, which generally exhibit specific patterns of regional and local hazards (Blöschl et al., 2019), complicating thereby the design of generally applicable mitigation schemes (Lun et al., 2021; van Loon et al., 2022). In this respect, understanding the local, catchment and regional scale of hydrological processes became imperative in addressing science and practical water resources management questions. Specifying ecosystem services (Kaletová et al., 2019; Pastor et al., 2022) requires studying fundamental drivers that alter patterns and processes across spatial and temporal dimensions in catchments and streams (Allen et al., 2020). New data sources (such as remote sensing (Kuban et al., 2022), radar meteorology (Nechaj et al., 2019; Méri et al., 2021), Lidar measurements (Vorobyeva et al., 2019) experiments on hillslopes, and tracer studies have offered unique opportunities to develop and compare different models of the same type (e.g., distributed) or different types of models (e.g., distributed vs lumped, process-based vs conceptual) on a local and regional basis. The confrontation of catchment experiments with results from catchment modelling has become popular in recent years in the region (Szolgay et al., 2020). This report continues the tradition of the Slovak National Reports to the International Union of Geodesy and Geophysics (IUGG) on behalf of the International Association of Hydrological Sciences (IAHS), (see Szolgay, 2003; 2007; 2011; 2015; 2019). It contains the part of the 2019 – 2022 report which reviews the response of hydrologic research in Slovakia from 2019 to 2022 to these challenges (Szolgay et al., 2023). The main research focuses are referenced in the bibliography of selected research papers with a short description of the paper.

Soil-water-plant-atmosphere interactions on point and plot scales

The need to develop an increased understanding of the erosion and transport processes on the plot and catchment scales under the specific physiographic conditions of Slovakia was stressed. Research on water

and material transport in the soil-water-plant-atmosphere system has been partly focused on quantifying the water balance components in the unsaturated zone of soils in natural, agricultural and forested catchment ecosystems. Field research was conducted, and methodological aspects of modelling were tested and verified under lowland conditions and in forested experimental mountainous catchments. Estimation of the components of the water balance (including water content of the snowpack), the interpretation of infiltration, evaporation, transpiration, capillary inflow and the seepage of water into lower horizons using monitoring and mathematical modelling resulted in an advanced quantitative analysis of the elements of the water balance equation. The spatial and temporal variability of the soil's hydraulic conductivity were also studied. Soil water repellency was studied at several sites on actual natural soils. Laboratory and field research on the shrinking and swelling processes in heavy soils was focused on the East Slovakian Lowland.

Botyanszká et al. (2022) investigated the effect of the microplastics in silty loam soil on selected soil properties and the growth of radishes. Still, the measured values of the soil characteristics have not shown significant changes. Czachor et al. (2020) investigated how sample geometry affects the water retention curve by simulation and experimental proof. A 3D virtual network was numerically constructed from particles of various sizes, and the drainage process was simulated. The resulting moisture retention curves suggested that the sample geometry affects the drainage. Dulovičová et al. (2022) assessed the hydraulic conductivities from 14 empirical formulas. They developed a simple method to estimate hydraulic conductivities for clayey sand sediments using sediment samples extracted from irrigation canals in Žitný Ostrov, Southern Slovakia. Gluba et al. (2021) studied the effect of fine-size-fractionated sunflower husk biochar on water retention properties of sandy arable soil and explained the water retention effects as the interplay between the dose, the size of biochar particles, and the porous properties of biochar fractions. Gomboš et al. (2021) studied the winter water refill of the soil profile of heavy clay soils, lighter clay-loam-silty soils and the lightest loam soils from three localities of East Slovakian Lowland. The soil water storage, vertical scatter of soil profile moisture volume, temporal and spatial moisture regime changes and soil water availability for plant cover during the 2015 extreme drought period were analysed.

Gomboš et al. (2022) presented results of theoretical approaches and experimental measurements of the settling rate of soil microparticles from laser diffraction measurements on soil samples taken in the East Slovakian Lowland. The results were compared with the results calculated by the Stokes equation. Hlaváčiková et al. (2019a) presented results of quantification of the number of macropores, their relative volume and the ratio of water infiltrating through the macropores for five study sites with stony soils located in a mountain catchment of northern Slovakia. Hlaváčiková et al. (2019b) investigated the effect of two types of biochars on the water retention of clay, loamy soil and silica sand. Despite the positive effect on soil water retention, a statistically significant increase in available water capacity was identified only in the loam soil.

Jančo et al. (2021) investigated the effect of mature spruce forests on canopy interception in subalpine conditions during three growing seasons. Throughfall and gross precipitation measurements were carried out at an elevation of 1,420 m a.s.l. in the Western Tatra Mountains and evaluated with respect to the interception process during the growing season from May to October 2018–2020. Kidron et al. (2022) reviewed mechanisms for biocrust-modulated runoff generation concerning mechanisms for runoff generation due to water repellency, pore-clogging, soil texture and structural features, including surface roughness. Oravcová and Vido (2022) aimed to evaluate the risk of drought from a meteorological point of view and the subsequent response in soil hydrology throughout the hydrological years 2015 and 2016 in beech forests in Central Slovakia. The drought lasted longer in deeper layers and retreated only after long-lasting rainfall. Sudden heavy rainfall has proven ineffective at moistening the entire soil profile, impacting only the upper few centimetres while the main root zone suffers from water shortage. Rončák et al. (2021) analysed and statistically confirmed the relationship between the computed daily values of the effective precipitation index and the measured moisture content of the topsoil of a research site near Nitra, Slovakia. Sándor et al. (2021) considered the impact of climate, soil properties and grassland cover on soil water repellency. They showed an area of land is more likely to be water-repellent if it has a sandy soil texture and a high frequency of prolonged drought events. To study the separate and combined effects of soil texture, climate, and grassland cover type, four sites from different climatic and soil regions were selected in Italy, Hungary, United Kingdom and Slovakia.

Tall et al. (2019) studied the influence of soil texture on the course of volume changes of soil on 172 soil samples with different textures collected from 11 sites in the Eastern Slovak Lowland. These were used to measure dependencies between soil volume changes and soil moisture changes under laboratory conditions. Ten mathematical models were created to estimate the relationship between volume changes of soil and soil moisture content and texture. Tall et al. (2019) and Tall and Pavelková (2020) dealt with the development and comparison of individual soil water balance components in two different soil profiles from the Easter-Slovakian-Lowland using two lysimeters filled monolithically with sandy soil profile and silty-loam soil maintaining a constant groundwater level of 1 m below ground. The level was maintained in both soil profiles. Under the same meteorological conditions, all differences in the development of water balance components were caused only by the differences in soil profiles. The actual evapotranspiration and water flow at the bottom of the soil profiles were compared. Under the specific conditions of this experiment, it was shown that the silty-loam soil profile was more prone to drought than the sandy soil profile.

Catchment scale surface, subsurface and groundwater flow processes and mathematical modelling of runoff and water quality

With a particular interest in surface, subsurface and groundwater runoff, runoff components were estimated by experimental research, mathematical rainfall-runoff models, water balance studies, and runoff separation methods. Tracer techniques were used to study water movement in the soil and bedrock and the mean transit times in catchments. Modelling was used to estimate the relationship between surface waters and groundwater in the weathered zone of stony soils, where rapid runoff and the reaction of groundwater were studied. Remote sensing was used when describing the spatial distribution components of the hydrological cycle in mountainous catchments. The overall trends in the spatial and temporal distributions of snow density, height and water equivalent in several mountainous catchments were analysed. Snowmelt components hydrologic models used both energy-based and temperature-index approaches in general. The validation of snow models using satellite images was tested.

Cisty et al. (2021a) presented a study dealing with the similarity of catchments, which may be utilised in estimating river flows in catchments without flow measurements. A penalisation method of evaluating similarity was proposed, which helps to identify hydrological similarity, i.e., finding the most similar catchment to a given catchment in the rainfall-runoff process. Kaya et al. (2021) studied the capabilities of soft computing techniques for estimating daily evapotranspiration in Košice. Daily solar radiation, relative humidity, air temperature, and wind speed were the meteorological variables considered in different combinations of multilayer perceptron MLP, support vector regression, and multilinear regression models and are compared with each other and with the Hargreaves-Samani, Ritchie, and Turc empirical equations. Model results showed that the MLP model performed better than the other soft computing techniques. Kuban et al. (2022) investigated the effects of satellite soil moisture data on the parametrisation of topsoil and root zone soil moisture in a conceptual hydrological model in those catchments, which in the validation of the dual-layer conceptual semi-distributed model showed improvement in the runoff simulation efficiency compared to the single objective runoff calibration. The runoff simulation efficiency of three multi-objective calibration approaches was separately considered. Inferences about the specific location and the physiographic properties of the catchments where the inclusion of ASCAT data proved beneficial were made. Lukasová et al. (2019) and Lukasová et al. (2020) investigated the potential of phenological metrics from moderate resolution remotely sensed data to monitor the altitudinal variations in phenological phases of European beech and phenological response to drought. Phenological metrics were derived from the NDVI annual trajectories fitted with a double sigmoid logistic function. Ground observations of phenological phases from twelve beech stands along the altitudinal gradient were employed. The effect of altitude was evaluated through differences in local climatic conditions, especially temperature and precipitation, from the last 30 years in 12 study stands. The approach presented in this paper contributes to a more explicit understanding of satellite data-based beech phenology along the altitudinal gradient. It will be useful for determining the optimal distribution range of European beech under changing climate conditions in hydrological modelling.

Mačejná et al. (2021) hydro-bio-chemical balance of total mercury at former cinnabar mining locality. The most important fluxes of total mercury in two small forested catchment areas with different anthropogenic loads in the Kremnické vrchy Mountains. The study highlighted the importance of forest areas to the biogeochemical cycle of Hg and the influence of areas close to cinnabar mining, even inactive ones. Mezei et al. (2019) combined yearly Landsat-derived bark beetle infestation spots from 2006 to 2014 and meteorological data to identify the susceptibility of forest stands to beetle infestation. Digital elevation model-derived potential radiation loads predicted beetle infestation, especially in the peak phase of the beetle epidemic. indicating that bark beetles prefer sites with higher insolation during outbreaks. Solar radiation, easily determined from the DEM, better identified beetle infestations than commonly used meteorological variables and can be used in hydrological models in beetle infestation prediction sub-models.

Tátošová et al. (2021) evaluated the extent of changes in land use in Nitra from 1954 to 2017. The growth of areas with minimal infiltration capacity in the Slovak University of Agriculture area was identified. The possibilities of using rainwater and its accumulation in the monitored area were discussed. Varga and Velísková (2021) assessed the time course of water and air temperature in the locality of the Turček reservoir during its operation from 2005–2019. The analysis confirmed that it is impossible to determine a significant trend despite the rise in annual air temperature during the study period.

Experimental research in snow hydrology has a long tradition in Slovakia. Systematic measurements resulted in a large database of field measurements which started in 1960 in the Low Tatra Mountains and were later extended to the West Tatra Mountains by the Institute of Hydrology of the Slovak Academy of Sciences (Holko et al., 2021). The snow regime of forested sites received particular attention (Bartík et al., 2019). The estimation of snow redistribution by the wind was also outlined, and the spatial and temporal variations of snow water equivalent and the water balance were also documented (Holko et al., 2021). The impact of the changing climate on the snow water using isotopic data, trend and attribution analyses were studied (Holko et al., 2020b). Snow accumulation and melt modelling were practically oriented recently (Holko et al., 2022). Ways were explored how to constrain the parameters of the snowmelt components of an HBV-type model and improve its performance (Sleziak et al., 2020). Studies focusing on the distribution of snow cover in the forests and ski slopes in Central Slovakia were also conducted, and implications for ecosystem services

were defined (Mikloš et al., 2020a; Mikloš et al., 2020b).

Erosion, sediment transport, river morphology and hydro-ecology

Qualitative and quantitative investigations of the effect of river morphology on ichthyological fauna in both natural and regulated segments of selected rivers were conducted (e.g., fish species composition, species diversity, the abundance and biomass of particular species, the mean individual weight and the ichthyomass were monitored during the spring and autumn seasons, etc.). Factors affecting fish population density were also specified. In a natural stream segment, the number of species, the diversity of species and equitability indices were higher than in regulated ones. Several projects focused on studying river and floodplain processes (flow regime, development of river channels and floodplains, sediment transport) using numerical and physical models to analyse the impacts of human interventions on the river's environmental quality and the adjacent areas. Morphologically stable and environmentally sensitive river training measures were also sought to support creating a natural range of instream and bankside habitats for fisheries, flora and fauna and to protect the wetland ecosystems.

Cisty et al. (2021b) set out options for modelling suspended sediment concentrations for ungauged periods on the Danube River profile in Bratislava. Regression using least absolute selection and shrinkage operator, support vector regression and deep learning neural network were compared using various data sources. A significant increase in the precision of modelling suspended sediment concentrations over the standard rating curve method was achieved. Hlavčová et al. (2019) estimated the effectiveness of crop management on sediment transport on hilly agricultural land in the Myjava region. Field experiments with a rainfall simulator on experimental plots estimated surface runoff and the mass of sediments transported and were used to parameterise the SMODERP physically-based hydrological model. The hydrological modelling of the surface runoff on the selected slope profile quantified the protective effect of various soil covers on reducing surface runoff and sediment transport. Honek et al. (2020) estimated and compared sedimentation rates in small reservoirs by three empirical models (USLE, RUSLE and USPED) applied to two small catchments taking advantage of real measured and modelled sedimentation during 2012 and 2017. The study emphasised the importance of the R-factor value, which quantifies the ability of precipitation to cause soil erosion and is a key component of the above-mentioned empirical models. The authors identified the correlation ($R > 0.7$) between observed sedimentation, the R-factor, and precipitation, and concluded that the supposed rise of precipitation in Central Europe due to climate change will lead to an increase in the levels of stored sediment in reservoirs. The USPED model was recommended to estimate the modelling of the siltation rate in small reservoir maintenance projects.

Kaletová et al. (2019), Kaletova et al. (2021), and Pastor et al. (2022) considered the temporal flow variability of non-perennial rivers and the relevance of intermittent rivers in an agricultural landscape in assessing their ecosystem service provision for three different hydrological phases: flowing conditions, isolated pools, and dry streambeds. They also discussed the spatial variability of flow regimes. Kidová et al. (2021) evaluated the impact of river training works on the braided-wandering Belá River in the Slovakian Carpathians. Decreasing geodiversity in managed river reaches, a rapid increase in flow velocity during an extreme flood in trained river reaches, and increasing erosive force in the channel zone was confirmed.

Lehotský et al. (2022) reconstructed the history of the Danube Plain (Podunajská rovina), the largest fluvial system in Slovakia. They showed that in the past, the territory of the Danube Plain has operated as a dynamic fluvial system (inland delta) with its anastomosing, migrating, meandering and braided river channel patterns and the development of several fluvial terraces, levees, abandoned channels and aeolian landforms. Okhravi et al. (2022) addressed the problem of flow resistance in lowland rivers impacted by distributed aquatic vegetation by hypothesising that a fixed value for the bed roughness coefficient in lowland rivers (mostly sand-bed rivers) is deemed practically questionable in 45 cross-sections in four lowland streams. They showed that bed forms and aquatic vegetation were significant sources of boundary resistance in lowland rivers. The study ended with two new flow resistance predictors, which connected the dimensionless unit discharge to flow resistance factors, Darcy-Weisbach and Manning coefficients.

Rodríguez-González et al. (2022) stressed the role of Riparian zones as the paragon of transitional ecosystems, providing critical habitat and ecosystem services that are especially threatened by global change. Following consultation with experts, they identified ten key challenges which must be addressed for riparian vegetation science and management improvement. Using a sediment cascade approach, Rusnák et al. (2020) studied channel and cut-bluff failure connectivity in the braided-wandering Belá River. A terrestrial laser scanning time series was generated by systematically monitoring the cut-bluff slope surface. Volume changes were estimated, and the conceptualisation model of coupling of cut-bluff slope based on spatial and temporal analyses of channel hydrology, a gravity-conditioned transformation of matter and detailed sediment budget calculations was developed. Rusnák et al. (2019) monitored a chute cutoff in the meander bend, the avulsion channel evolution and river morphology changes using UAV photogrammetry on the gravel bed of the Ondava River in Outer Western Carpathians after the 2010 flood events. The mechanism of evolution and post-cutoff avulsion channel adjustment using photogrammetry and field survey was described. Sokáč et al. (2019) presented new approaches to simulating 1D substance transport and tested them on tracer experiments in three small streams in Slovakia with dead zones. Evaluation of the proposed methods, based on different probability distributions, confirmed that they

approximate the measured concentrations significantly better than those based upon the commonly used Gaussian distribution.

Štefunková et al. (2020) evaluated a methodology to assess the influence of hydraulic characteristics on habitat quality from the Riverine Habitat Simulation model, which represents the quality of the aquatic habitat by the weighted usable area using brown trout as the bioindicator. The influence of flow velocity and water depth as basic abiotic characteristics that determine the ratio of the suitability of the instream habitat on the objective evaluation of the habitat quality was targeted. Three methods for assessing the habitat quality were tested. Štefunková et al. (2021) evaluated the relationship between abiotic flow characteristics and habitat quality in mountain streams of Slovakia, which was assessed using the Instream Flow Incremental Methodology (IFIM), which uses bioindication. Brown trout was selected as a bioindicator because of its sensitivity to morphological changes, and its occurrence in sufficient reference reaches. Fifty-nine reference reaches of fifty-two mountain and piedmont streams in Slovakia were analysed. Valent et al. (2019) performed a joint sedimentation-flood retention assessment of a small water reservoir in Slovakia. They presented an analysis of changes in the retention capacity over eight years based on a detailed reservoir bathymetry conducted using an acoustic Doppler current profiler. The possibility of strengthening the reservoir's role in flood protection was also investigated.

Pekárová et al. (2020) analysed the long-term development of runoff and nitrates nitrogen concentrations in the Parná River at Horné Orešany water gauge station during the period 1991–2018. Discharges in the Parná River decreased slightly; nitrate concentrations markedly decreased in this river basin. The relation between discharge and nitrate concentration was used to derive exponential empirical relations for estimating the nitrate-nitrogen concentrations in the stream based on mean daily discharge. Siman and Velísková (2020) presented results of the comparison of yearly total nitrogen emissions and the contribution of different emission pathways on these emissions into surface streams for three river catchments in Slovakia territory with a contrasting proportion of agricultural land to the total area of the river catchment using the numerical MONERIS model. Results indicated that in river catchments with a higher proportion of agricultural land, higher contribution of nitrogen emission was carried out mainly via groundwater (especially in lowland) and agricultural erosion and drainage systems.

Groundwater

The quantitative aspects of groundwater formation and regimes were studied regionally. Research is also oriented towards the influence of human activities on the natural groundwater regime and surface-groundwater interactions. Research on the impact of human activities on the recharging groundwater amounts and water quality under different hydrologic conditions was conducted. Numerical groundwater models were used to analyse, predict and control groundwater levels at several water structures in Slovakia. The conditions under which technical measures could improve groundwater regimes, even in extreme hydrologic conditions, were also sought. Abd-Elaty et al. (2019) contributed to groundwater protection techniques based on changing boundary conditions, installing a cut-off wall and using linings for polluted drains. They presented a possible way forward to treat contaminated stream networks. It was concluded that technical measures could improve the groundwater regime. Abd-Elaty et al. (2020) presented simulation-based solutions for reducing soil and groundwater contamination from fertilisers in arid and semi-arid regions by installing drainage networks, which can decrease the groundwater and soil contamination from nonpoint contamination. Baroková et al. (2020) assessed the impact of cut-off walls on the regime of groundwater levels during extreme hydrological conditions in the broader area for both steady and unsteady scenarios. Červeňanská et al. (2021) reconstructed in a case study concerning the May and June 2010 flood the groundwater level rise in the Žitný ostrov region and established the basis for the construction of flood hazard maps and flood risk management plans. Pekárová et al. (2022) aimed to analyse and model the groundwater temperature at the water table in different regions of Slovakia by a simple groundwater temperature model based on a one-dimensional differential Fourier heat conduction equation. It can estimate future groundwater temperature trends using regional air temperature projections for different greenhouse gas emission scenarios. Šoltész et al. (2020) presented a hydraulic assessment of groundwater flow in the area affected by the realisation of the hydraulic gate on a river branch. A 3D mathematical model was created to simulate groundwater flow by changing boundary conditions of surface water flows during flood periods.

Hydrological extremes

Recent extreme events in Europe have also stimulated public discussion on the issue of whether the frequency and severity of these have been increasing in Europe and Slovakia and if such changes could be attributed to anthropogenic influence. Large floods and droughts occurred in some regions of Central Europe also during the period covered by this report. That increased interest in the flood and drought formation in catchments from various areas of Slovakia. Statistical analysis was used to study past extreme events. Knowledge of the genesis of extreme precipitation and floods and data on rare events was needed to develop regional generalizations of the flood and drought regime. Several extreme events were individually investigated, and the formation of these in ungauged basins was reconstructed using data from at-site hydrological surveillance and available data from the hydrological and meteorological network, together with radar and satellite data. An assessment of the historical extremes floods in several rivers

complemented characteristics of measured and historical extreme flows. The various risks associated with flooding and droughts were characterized.

Almikaeel et al. (2022b) used a machine to learn hydrological drought forecasting. The assessment of hydrological drought was carried out by indexing dry, normal, and wet hydrological situations. Artificial neural networks and support vector machine models were applied to predict the hydrological drought based on daily average discharges. Bačová Mitková et al. (2021) stressed the need to harmonize design flood assessment methods along long international rivers in the example of the Danube River. Using the Log-Pearson type III distribution, the regionalization of the Log-Pearson type III distribution skew parameter, they also analysed the effect of the inclusion and exclusion of the historical extremes. Bartok et al. (2022b) applied a novel approach in using machine learning-based fog nowcasting for aviation. Various machine learning algorithms (support vector machine, decision trees, k-nearest neighbours) were adopted to predict fog with visibility below 300 m for a lead time of 30 min. Beyond the standard meteorological variables as predictors, the forecast models also used information on visibility obtained through remote camera observations. These were also applied by Bartok et al. (2022a) to assess visibility conditions.

Blöschl et al. (2019) and Blöschl et al. (2020), with the participation of Slovak hydrologists, analysed a comprehensive dataset of flood observations in Europe. They showed that the changing climate has increased river flood discharges in some regions of Europe but decreased in others. They also showed that the past three decades were among the most flood-rich periods in Europe in the past 500 years. The flood changes were broadly consistent with climate model projections for the next century, suggesting that climate-driven changes are already happening. This period differs from other past flood-rich periods in terms of its extent, air temperatures and flood seasonality. The results support calls for considering climate change in flood risk management. The same dataset was used by Lun et al. (2021) to provide a performance baseline for more local flood studies by assessing the estimation accuracy of regional multiple linear regression models for estimating flood moments in ungauged basins.

Čubanová et al. (2019), Šoltész et al. (2021), Mydla et al. (2021), Šoltész et al. (2022), and Čubanová et al. (2022) proposed several management solutions for mitigating flood and drought risk in smaller municipalities based on hydrological-hydraulic assessment. Markovič et al. (2021) investigated extreme heavy precipitation events in the Slovak Republic in the period 1951–2020 in terms of their spatial and temporal distribution. The goal was to create a dynamic-climatological analysis of atmospheric circulation patterns that can eventually lead to extreme multi-day precipitation events. Onderka and Pecho (2021) evaluated the sensitivity of total rainfall kinetic energy, 15-min peak intensities, and total event depth concerning pre-event atmospheric conditions in the northern part of the Pannonian Plain. The analyses revealed strong responsiveness of rainfall kinetic energy and 15-minute peak rainfall intensities to dew point temperature.

Solín and Rusnák (2020) presented a methodological approach to preliminary flood risk assessment conceptually based on the regional typing and integrated flood risk assessment. The basic spatial unit was defined as the municipality district. The flood risk potential index was determined as aggregating the flood hazard and flood consequences. Šurda et al. (2020) aimed to determine the monthly values of the meteorological drought indices of the Nitra region in 2014–2018 and to analyse their sensitivity based on comparing the determined droughts frequency. Vojtek et al. (2022) mapped and assessed the riverine flood potential in municipalities of Slovakia using vector-based spatial multi-criteria analysis and geographic information systems. The flood potential index in municipalities was computed based on eight flood factors, and sensitivity analysis using the modelling approaches was proposed.

Raška et al. (2022) focused on the empirical evidence of the effects of nature-based solutions in flood risk mitigation across various fragmented settings, and their implementation faces a series of institutional barriers. A community expert perspective was used to identify barriers and their cascading and compound interactions. A comprehensive set of 17 barriers affecting the implementation of 12 groups in both urban and rural settings in five European regional environmental domains were identified, and avenues for further research, connecting hydrology and soil science, on the one hand, and land use planning, social geography and economics, on the other suggested. Solín (2019) and Solín and Sládeková Madajová (2019) identified regional types of flood hazards in mountainous regions resulting from the physiographic characteristics. It has been shown that the soil texture permeability and the forest cover are the basin attributes that influence the spatial variability of flood hazards. Based on their combination, several physical geographic classes were created. A framework of integrated flood risk assessment was taken into account.

Vojtek et al. (2019) reported a sensitivity analysis of flood inundation mapping in small and ungauged basins using the event-based approach for small and ungauged basins and a one-dimensional in terms of simulated flood area and volume to different combinations of input parameters. Hydrologic modelling results highlighted the great variety of design peak discharges, which strongly influence the modelled area and volume. Vojtek et al. (2021) identified areas with different levels of riverine flood potential in the Nitra River basin using multi-criteria evaluation, hierarchical analytical process, geographic information systems, and seven flood conditioning factors. Zeleňáková et al. (2019) presented a case study of flow modelling focusing on the open channel of the Slatvinec stream running through the north-east Slovakian village of Kružlov for identifying flood risk areas in the village. Cost analysis for evaluating flood damage to property supplemented the modelling.

Runoff fluctuations and anthropogenic impacts on hydrological processes

Time series of precipitation, air temperature and runoff were analysed in several studies to detect and attribute climate change signals using statistical methods. The long-term variability of extremes of Slovak rivers, as well as rivers in the temperate zone of the Northern Hemisphere, were also analysed. The analysis detected a time shift in the occurrence of runoff extremes in the regions studied. Studies of groundwater runoff changes in different geological conditions in the last four decades showed a decrease in groundwater runoff in most of the assessed catchments in Slovakia. Studies of spring yields in the karstic areas of Slovakia showed decreasing trends in almost all the evaluated cases. Local and regional hydrological droughts and the water balance of the sensitive regions, such as agricultural land and wetlands, were studied, too. Intermittency was observed recently in several rivers, and the phenomenon started to be explored. Several RCM and GCM-based climate change scenarios were used, and the construction of physically plausible downscaled scenarios of daily, monthly and annual time series for air temperature, precipitation and air humidity was also attempted. Attempts to design scenarios of extreme short-term precipitation totals began. According to these scenarios, a significant increase in air temperature, small changes in long-term precipitation totals, and a remarkable rise in short-term precipitation extremes are expected in Slovakia in the warm half-years. On the other hand, more frequent and extended periods of drought may occur, mainly in the Slovak lowlands, because higher precipitation and a warmer climate in winter will significantly affect the winter runoff and snow regime on most of the territory of Slovakia. Therefore, the whole territory of Slovakia could become more vulnerable to drought in the summer and autumn.

Almikaeel et al. (2022a) investigated flow rate fluctuations in two different streams in Slovakia to investigate the low and peak flow periods and to identify the trends in monthly and annual mean flows for both rivers. Analysing daily mean discharge data from two different types of streams has required using a robust normalisation approach to verify the comparability between the chosen streams. Blaškovičová et al. (2022a) and Blaškovičová et al. (2022b) focused on the assessment of river drought in Slovakia. Low-flow characteristics and their changes in the 2001–2015 period compared with the 1961–2000 reference period were evaluated with two methods at selected representative water-gauging stations. The results show significant changes in the compared periods. Differences in individual regions of Slovakia were also described.

Csáki et al. (2020) described a multi-model climatic water balance prediction in the Zala River Basin using a modified Budyko framework. The research included validating models and predictions of the main components of the water balance (evapotranspiration and runoff) and using precipitation and temperature results of 12 regional climate model simulations. The mean annual evapotranspiration rate is expected to increase slightly during the 21st century, and for runoff, a substantial decrease can be anticipated. Danáčová et al. (2021) studied the occurrence of areal droughts from 2011 to 2020 in Slovakia based on the data from 164 water gauging stations. The mean monthly discharges were compared with the long-term mean monthly discharges for the baseline period 1961–2000. Trend detection analysis of the mean monthly discharges in 1961–2020 was conducted. The months of April, June, July, August and October were detected as the months with the highest occurrence of mean monthly discharges below 40% of the long–term mean monthly discharges for the reference period.

Halmová et al. (2022) evaluated changes in the hydrological balance of the Krupinica River for the entire 90-year period of observations and three 30-year subperiods. Changes in water resources in the river basin over the three mentioned time subperiods were analysed, and a simple regression relationship between runoff, precipitation and the air temperature was derived to estimate the future development of the annual runoff from the basin. Holko et al. (2020a) Analysed changes in the hydrological cycle of a pristine alpine mountain catchment by isotopic data, trend and attribution analyses. δ18O in precipitation has remained constantly higher since 2014, which might be related to greater evaporation in the region of origin of the air masses bringing precipitation to the studied part of Central Europe. The seasonality of δ18O became less pronounced since 2014. Linear regressions between the drivers and supposedly changed data series explained only about 31% to 36% of the variability.

Lukasová et al. (2021) dealt with regional and altitudinal aspects of summer heatwave intensification in the Western Carpathians for various elevations. The percentile threshold-based calculation of heatwaves was used, which, compared to those using absolute thresholds, allows for revealing the possible threats of climate warming extremes at the range of altitudes. The greatest intensification of heatwaves was evident, particularly in the last decade. Minďaš et al. (2020) evaluated the long-term changes in the chemical composition of precipitation in the mountain forests of Slovakia in a forty-one-year period (1987 to 2018). Two stations with long-term measurements of precipitation quality were selected, all basic chemical components were analysed, and changes in the individual components were statistically evaluated. The results showed significant declining trends for almost all components, which can significantly affect element cycles in mountain forest ecosystems.

Onderka et al. (2020) evaluated the efficiency and reliability of water harvesting systems in dependence on the local climate in Slovakia using 84 rainfall records from climatologically distinct regions. A considerable spatial and seasonal variability has been observed in the statistics of rainfall events. Inter-event times decrease with elevation, whereas event volume and annual incidence of rainfall events increase with elevation. The applicability of the derived rainfall statistics was illustrated by simulations for a typical residential house using the analytical probabilistic approach. Empirical

relationships between tank size and site elevation have been developed to estimate tank sizes for ungauged locations. The simulations show that rain barrels in the southern parts of Slovakia require larger storage capacities than those located in the mountainous regions. The presented annual and seasonal estimates of rainfall characteristics are published for the first time.

Škvareninová et al. (2022) stressed that the onset and duration of phenological events are key indicators of the ecological impact of climate change on vegetation. During 1987–2016, they analysed the occurrence and intensity of frosts during May. Results indicate that recent climate change caused the beginning of flowering to start significantly earlier; thus, the risk of late frost damage to flowers is highly probable, particularly at 160, 300 and 500 m a.s.l., where the flowering and frosts co-occur. Decreased risk of frost damage was found at 400 and 700 m a.s.l., Vido and Nalevanková (2020) stressed that the West Carpathian region forms a transitional zone for drought patterns, which are complicated because of the geomorphologically complicated landscape and analysed drought occurrence and trends indices at available climatological stations of the Slovak Hydrometeorological Institute in the upper Hron region within the 1984–2014 period. They found that drought incidence decreased with increasing altitude, and increasing air temperature increased the difference in drought trends between lowlands and mountains. Abrupt changes in the time series of drought indices, which could indicate some signals of changing atmospheric circulation patterns, were not revealed.

Conclusion

Changing climate, recent extreme events and the requirements of implementing the European Water Framework Directive have stimulated public and scientific discussion in Slovakia on improving observing, monitoring and modelling hydrological processes describing these (Szolgay et al., 2020). This report reviewed the response of hydrologic research in Slovakia to the challenges of global hydrologic research between 2019 and 2022. It follows previous reports from 1999, 2004, 2007, 2011 and 2015, and 2019. It summarizes the results and outcomes of the leading research programs in hydrology in Slovakia. The short review and the selected annotated bibliography on hydrological research in Slovakia showed how research reflected the need to investigate the effects of changing natural drivers and new societal pressures on water resources and hydrological processes.

Recent extreme flood and drought events in Slovakia, along with indications of a changing climate, have sparked debate in the scientific community and among the general public about whether the frequency and severity of these events have been rising, how much of these changes may be attributable to human activity, and how best to observe, track, and model the processes that describe them. A thorough understanding of the effects of changing land use and management practices on runoff processes in general and those of extremes in particular, is still desperately needed, despite the substantial amount of research that has been done to explore the primary sources of natural drivers and societal pressures of hydrological phenomena in Slovakia.

It was challenging to come up with generalized explanations of the genesis of particular types of hydrological regimes and events because of Slovakia's rich spatial and temporal heterogeneity of climatic drivers, regional and local control conditions, and the variety of active flow processes during specific seasons and events. This also holds true for particular local and regional hazards of extremes. In this regard, answering scientific and real-world water resource management issues still requires a regional grasp of watershed hydrological dynamics and their modeling. Opportunities provided by new data sources, based on the most recent advancements in radar meteorology, hillslope experiments, and catchment tracer investigations, will allow hydrologists in Slovakia to compare various models on a local and regional scale. Improved process representations in both stochastic and deterministic models in various hydrological settings will be made possible by the additional data sources, which will also make predictions in ungauged basins more trustworthy. It will become crucial to compare the findings of catchment modeling with those of catchment experiments.

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