Proc. IAHS, 369, 25–30, 2015
proc-iahs.net/369/25/2015/
doi:10.5194/piahs-369-25-2015

A Tri-National program for estimating the link between snow resources and hydrological droughts

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Received: 14 April 2015 – Accepted: 14 April 2015 – Published: 11 June 2015

Abstract. To evaluate how summer low flows and droughts are affected by the winter snowpack, a Tri-National effort will analyse data from three catchments: Alpbach (Prealps, central Switzerland), Gudjaretis-Tskali (Little Caucasus, central Georgia), and Kamenice (Jizera Mountains, northern Czech Republic). Two GIS-based rainfall-runoff models will simulate over 10 years of runoff in streams based on rain and snowfall measurements, and further meteorological variables. The models use information on the geographical settings of the catchments together with knowledge of the hydrological processes of runoff generation from rainfall, looking particularly at the relationship between spring snowmelt and summer droughts. These processes include snow accumulation and melt, evapotranspiration, groundwater recharge in spring that contributes to (the) summer runoff, and will be studied by means of the environmental isotopes ^{18}O and ^{2}H. Knowledge about the isotopic composition of the different water sources will allow to identify the flow paths and estimate the residence time of snow meltwater in the subsurface and its contribution to the stream. The application of the models in different nested or neighbouring catchments will explore their potential for further development and allow a better early prediction of low-flow periods in various mountainous zones across Europe. The paper presents the planned activities including a first analysis of already available dataset of environmental isotopes, discharge, snow water equivalent and modelling experiments of the (already) available datasets.

1 Introduction

Seasonal low flows are important for sustaining ecosystems and supplying human needs during the dry season (Godsey et al., 2014). In mountainous areas, a substantial fraction of winter precipitation is typically stored aboveground in seasonal snowpacks which persist beyond the end of the winter precipitation season. Furthermore snowmelt contributes to about 40 % of the total annual runoff in Switzerland. Seasonal snowpacks usually melt in late spring or early summer, depending mainly on the site's topography (elevation, aspect, slope, exposure), meteorology (net solar radiation, wind) and vegetation (Lundquist and Dettinger, 2005). Snowmelt sustains flow through the spring and early summer, and infiltrates into the ground to recharge groundwater. Some of this stored groundwater then slowly feeds low flows later in the season (Van Loon et al., 2014).

The relationship between snow cover/snowmelt and summer low flow is highly complex and remains poorly understood. The spring/summer snowmelt typically can be expected to yield different amounts of net recharge due to (1) the timing and intensity of the arrival of the liquid (infiltrating) phase, (2) differing antecedent soil moisture – and thus the conductivity and infiltration capacity, and (3) a variation in the immediate evapotranspiration losses of near-surface water (Godsey et al., 2014). As the climate change is expected to affect the volume and timing of snowmelt, the projected decrease in snowpack volume may be caused by: (1) more frequent melt events throughout the winter, (2) warmer temperatures that shift the phase of winter precipitation from snow to rain, or (3) lower total precipitation (Dettinger et al., 2004).

Two approaches to predict properties of low streamflow events in the longterm are available: stochastic approach and coupled rainfall-runoff modelling. The stochastic approaches relate the current state of a catchment and potential predictors to what has been observed in the past, inferring the likelihood of low streamflow within the prediction period (Jörg-Hess et al., 2014). On the other hand, the main challenge in rainfall-runoff modelling with emphasis on the linkages between snowmelt and droughts lies in the difficult parameterization of snow input (Parajka and Bloeschl, 2008) and the related groundwater recharge and discharge that supply the streams during low flows (Kuras et al., 2008). There is a substantial potential in supporting models with more experimental results to allow an improved parameterization of the models. Knowledge gaps also remain in the understanding of how the model approaches should address the hydrological droughts and their control by snow resources in mountainous catchments. To close the gap between the physical understanding of water movement through catchments and its parameterization in rainfall-runoff catchment models, environmental isotope approaches have been used since the 1970's. Isotopic analysis tracks processes more reliably than traditional monitoring techniques, yet there is scope for improvement for their successful simulation in rainfall-runoff models. For instance, Dincer et al. (1970) published the first analysis of snowmelt contribution to streamflow in mountainous catchments based on environmental isotopes in 1970. Many experimental studies then ensued to distinguish the critical runoff components and their travel times through the subsurface from recharge to discharge with an emphasis on snowmelt (Holko, 1995; McGuire et al., 2002; Rodgers et al., 2005). Moreover, Seibert and McDonnell (2002) have highlighted the rationale for a better parameterization of catchment models through incorporation of experimental results ("soft data") such as runoff contributions to total streamflow or the travel times of groundwater from recharge to streams.

The objective of the Tri-National SREP-DROUGHT project (**S**now **R**esources and the **E**arly **P**rediction of hydrological DROUGHT in mountainous streams) is to evaluate and predict the relationship between winter snowpack and summer low flows in three mountainous streams in central Switzerland (northern Prealps), central Georgia (Little Caucasus) and the northern Czech Republic (Jizera Mountains). SREP-DROUGHT first focuses on the parallel application of the two distributed hydrological rainfall-runoff models PREVAH (Viviroli et al., 2009) and GSSHA (Downer and Ogden, 2004). Secondly, environmental isotope methods in the three catchments will be used to identify the runoff generation from snow accumulation, snowmelt and groundwater recharge. Third, the relationships between anomalies in air temperature, aridity index, potential evapotranspiration and the runoff generation processes will be parameterized to allow a better simulation of low flows and mitigation of hydrological droughts.

Figure 1. Location of the study areas in Switzerland, Georgia and Czech Republic.

2 Study areas

In each country of this Tri-National project nested basins have been identified (Fig. 1):

2.1 Switzerland

The small Erlenbach catchment (0.7 km^2) is situated within the larger Alp catchment (46.4 km^2). This basin is located in the Alptal, a north-south oriented valley in Central Switzerland. Annual precipitation in the basins might range between 1500 and 2500 mm at elevations between 1100 and 1550 m a.s.l. In years with cold winters, up to 40 % of that amount falls as snow. In the summer, thunderstorms are frequent and intensive rains produce short but pronounced peaks in streamflow with elevated rates of suspended sediment and bed load transport. The hydrological research topics and facilities in the Alptal area are described in Hegg et al. (2006) which include state-of-the-art hydrometeorological monitoring, evaluation of nitrogen storage and leakage in the forested catchments. Biweekly water sampling for hydrochemical analyses, established by the National River Monitoring and Survey Programme Switzerland (NADUF), is now complemented by sampling for environmental isotope (^{2}H and ^{18}O) analyses (Fischer et al., 2013).

2.2 Georgia

The study area is situated in the south western part of Georgia, in the Little Caucasus Mountains, the Adjara-Trialeti range, in which the larger catchment Gudjareti (catchment area 316 km^2) and the smaller catchment Mitarbi (ca. 10 km^2) are located. Mean annual air temperature is 8.3 °C in Borjomi (altitude 794 m a.s.l.) and 4.4 °C in Bakuriani (altitude 1703 m a.s.l.). Mean annual precipitation in the area varies from 650 to 950 mm in Bakuriani. Apart from the routine hydrological (Kura River) and meteorological (Bakuriani) observations, most of the monitoring and environmental isotope analytical facilities were established after 2000, dominantly under the auspices of the International Atomic Energy Agency (IAEA).

2.3 Czech Republic

The experimental headwater catchment Uhlířská (1.78 km^2) and the larger catchment of Kamenice (145 km^2) are located in the northern part of the Czech Republic in the Jizera Mountains. The average altitude of the headwater catchment is 822 m a.s.l. with gentle convex-concave slopes, whereas the larger catchment reaches down to 450 m a.s.l. into a sparsely populated area. Two dams in the larger Kamenice catchment supply water for a nearby agglomeration. Annual precipitation in the area ranges between 930 and 1800 mm. The average air temperature (1961–1997) in the headwater catchment is 4.7 °C (Hrnčíř et al., 2010). First hydrological data in the Uhlířská catchment were collected in 1982 and a monitoring and sampling network was subsequently developed, primarily aimed at studying extreme flood events as a consequence of deforestation. Further research objectives in this area also included hillsope preferential flow (Šanda and Císlerová, 2009; Sněhota et al., 2010). Hrnčíř et al. (2010) concluded that, similarly to many other headwater catchments the antecedent wetness of hillslope soils is a key factor governing the magnitude and duration of runoff events. Šanda et al. (2014) also demonstrated that meltwater and winter precipitation are the prevailing source of the perennial groundwater recharge.

3 Methods

3.1 Field data

All the study areas are already equipped with facilities for collecting hydrological and meteorological data, including precipitation, air temperature, air humidity, snow height and water level or discharge. Particular innovation emphasis in all three countries will be given to water sampling for isotopic analysis. Snow resources are measured by in-situ measurements including snow depth and snow water equivalent (SWE).

Hydrological data in the Alptal in Switzerland have been collected through the WSL since 1968. Isotopic monitoring was established in 2010 through the University of Zurich (Fischer et al., 2013). Manual biweekly water sampling for isotopes at 5 sites will be changed to a weekly interval in 2015. Extension of the monitoring program includes the installation of Palmex-rain collectors for rainwater (Gröning et al., 2012) and ISCO sampling devices for automatic regular sampling of streamwater and composited rainfall. Snow samples from field campaigns will be melted and decanted in the laboratory to analyse the isotopic composition of the snow pit. Snow meltwater samples will be taken monthly within the Alptal area at 17 forested or open land sites at different altitudes, aspects and slopes, four of these originating in the Erlenbach catchment (Stähli and Gustafsson, 2006).

Georgia has a hydrological and isotope monitoring network in the study area since the early 2010's. Monthly isotope sampling was established at 4 locations in streams, precipitation, groundwater and springs in the larger Gudjareti catchment, and at one location at its outflow at Likani where the catchment contributes to the river Kura (Melikadze et al., 2009). Regular monthly ^{18}O and ^{2}H isotopic data in rainwater (meteorological station Bakuriani) and river water (stream gauge at the Kura river in Likani) are collected in the framework of the IAEA Global Network of Isotopes in Precipitation and Global Network of Isotopes in Runoff - GNIP and GNIR (Vitvar et al., 2007). The smaller Mitarbi catchment draining into the Gudjareti river is monitored at the Didi Mitarbi profile where weekly isotope sampling has started in September 2014 at 6 sites in precipitation and river water. Regular snow campaigns are operated in the study area with snow samples collected at four different locations within the Gudjareti and one location within the Mitarbi catchment which are either forested or open land sites. Additionally, three measuring fields are equipped with snow lysimeters, an extended funnel gauge, passive sampler and partly passive samplers to facilitate snowmelt water sampling (Penna et al., 2014).

In the Czech Republic, hydrological monitoring in the Jizera Mountains was established in the 1980's. Water sampling for analyses of ^{18}O and ^{2}H started in 2006 in the experimental catchment Uhlířská (Šanda and Cislerova, 2009). Similar to the Georgian study area, the Uhlířská catchment is also equipped with one GNIP and one GNIR station for monthly isotope monitoring of rainwater and stream water. In addition, samples of rainwater and stream water are collected daily at two locations during vegetation season (May–October) and weekly during November-April period. At high flows stream water samples are collected with higher frequency. The experimental catchment is equipped with ten soil lysimeters which are sampled monthly. In the larger Plavy catchment, two streamflow sites are sampled manually, and one sub-catchment Jezdecká is sampled on a daily basis during vegetation period. Snow samples are collected weekly at two locations. Furthermore, one of the sites is monthly examined for different snow layers. Additional sampling of snowmelt probes is also planned. The Czech Republic has also established automatic weight systems to measure SWE. One of the systems is tailor made by the Czech Technical University in Prague, and is located at the GNIP site at the small catchment Uhlířská. Three sites in the Plavy catchment are designed by a local manufacturer. All sites are recali-

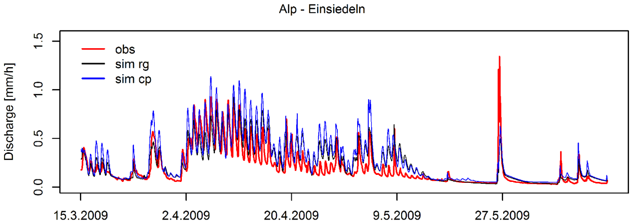

Figure 2. Application of the PREVAH model in the Swiss study are of the river Alp (gauge Einsiedeln, 46.4 km^2 area). Simulated (black and blue lines) and observed (red line) hourly discharge values are indicated for the snowmelt season in 2009. Black line (sim – rg) shows simulations forced with interpolated precipitation data, while the blue line (sim cp) shows a simulation forced by data obtained combining rainfall-radar with pluviometer observations (Sideris et al., 2014).

brated weekly by manual SWE sampling especially during the snowmelt.

Analyses of ^{18}O and ^{2}H in water samples from all three countries are performed with laser water isotope analyzers to minimize analytical differences.

3.2 Rainfall-runoff modelling

Distributed hydrological rainfall-runoff models will be employed to simulate and predict the runoff response in different geographical settings in two nested or neighbouring catchments: one small (1–2 km^2) and one larger (100–200 km^2). The model GSSHA (Gridded Surface/Subsurface Hydrologic Analysis; Downer and Ogden, 2004) is being widely applied by the project partner Czech Technical University in Prague (David et al., 2013; Strouhal and David, 2013), whereas the model PREVAH (Viviroli et al., 2009) is well established in Switzerland (Fundel et al., 2013, for a drought-forecasting application). In particular, the first application of both models in the Caucasus will provide a potential to improve the parameterization of the model components in different mountainous catchments across Europe. The runoff simulation with PREVAH and GSSHA will cover a period of 10 years or longer, which will require an extended compilation and pre-processing of spatial and temporal data particularly in the Georgian study areas. Figure 2 presents a current application of the PREVAH model in the study area of the river Alp in Switzerland (larger catchment) during the snowmelt season in the year 2009 which was followed by a dry period of three weeks.

4 First achievements

4.1 Environmental isotopes

Figure 3 shows values of δ^{18}O and δ^2H in samples collected in 2010–2013 in various water types in the larger catchment Gudjareti (Georgia). All values are concentrated along the Meteoric Water Line, suggesting modern recharge as opposed to very old palaeowaters or waters affected by significant water-rock interactions. Figure 3 reveals that the heaviest isotopic values occur in summer rainwater, while the values of the snow cover are the lowest. Values of isotopically more depleted winter rainfall and snowfall are close to those of the groundwater's (δ^{18}O about -12 per mil SMOW). In turn, the groundwater values are similar to the streams', indicating a common recharge for both sources. The composition of snow meltwater covers a large range of isotopic compositions, ranging from δ^{18}O values -22 per mil SMOW up to about -10 per mil SMOW. This shows that snowmelt and winter precipitations are an important recharge source for groundwater and stream water (Melikadze et al., 2013).

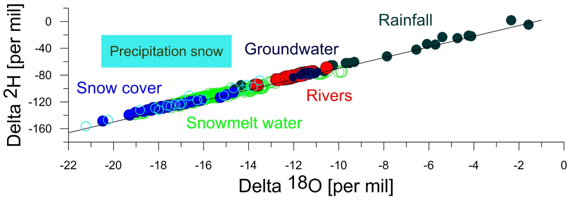

Figure 3. ^{18}O-^{2}H relationship in monthly samples in the test sites of Gudjaretis in Georgia for the period, 2010–2013. Different colors and circles relate to different water types.

Figure 4 right shows the ^{18}O composition of rainwater, stream water and groundwater in the Uhlířská catchment, Czech Republic, during the winter and spring 2009–2010. Isotopically depleted winter rainfall values are manifested by the isotopically depleted stream water during the following spring snowmelt period. The groundwater maintains a nearly constant isotopic composition. Figure 4 left demonstrates that the spring snowmelt runoff is substantially supplied by a baseflow component, originating from subsurface water recharged from autumn rainfalls and recent meltwater infiltration.

4.2 Snow resources

In the Alptal catchment the high heterogeneity of the SWE is due to effects of topography, vegetation and exposition (Stähli and Gustafsson, 2006). The range of altitudes of the Alp catchment between 1000 and 1500 m a.s.l. is critical, because the transition process of rain to snow is strongly influenced by altitude.

Figure 5 shows a first approach to relate snow resources and low-flows for the Erlenbach catchment (data 1981–2012) and the Alp catchment (data 1991–2012) adopting the methodology introduced by Jörg-Hess et al. (2014). Gridded SWE values were calculated for the whole catchment with respect to the calibrated SWE on 15 April (Jörg-Hess et al., 2014). Additionally, the daily-minimum of the discharge of the Erlenbach was extracted from the database. The scatter plot in Fig. 5 shows the correlation between the log trans-

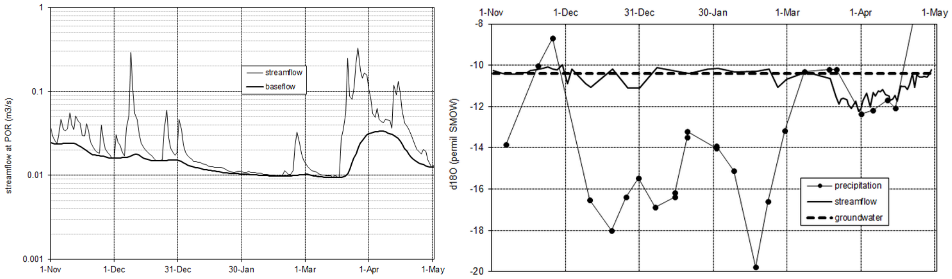

Figure 4. ^{18}O – Streamflow and baseflow at the catchment outlet (left) composition of rainwater, streamwater and groundwater (right) in the Uhlířská catchment, Czech Republic, 2009–2010.

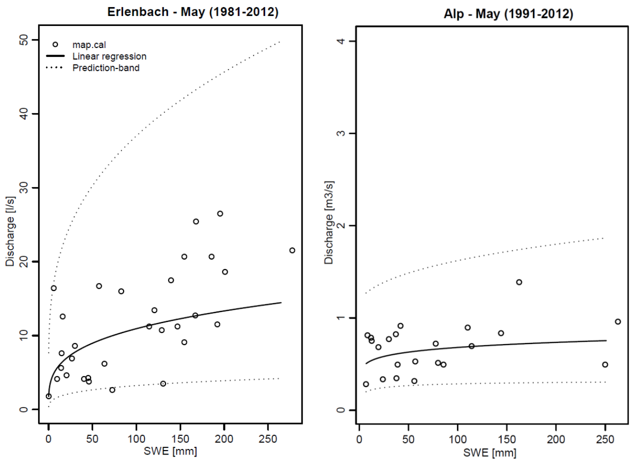

Figure 5. The minimum runoff of the Erlenbach (left) and the Alp River gauge in May (right), explained by the SWE on 15 April (black circles). The linear regression (black line) is computed from the log-transformed runoff and SWE variables and is then back-transformed to the non-logarithmic space as described in Jörg-Hess et al. (2014). The dotted lines represents the uncertainty of the prediction band.

formed variables SWE and daily-minimum of the discharge values in May. The calculated prediction interval was different for the two catchments, and 95 % of the predicted low flows were considered. Also significant is the higher uncertainty of the 95 % prediction-band for the smaller Erlenbach catchment compared to the larger Alp catchment. The lower prediction-band represents the worst-case of the low flow scenarios in May only depending on the gridded SWE values, thus it mainly characterizes low flows during cold periods with small amounts of precipitation.

5 Conclusions

The first achievements discussed above show a significant potential for further analysis of the data sets of the three catchments with different methods. Isotope data of Georgia and Czech Republic reveal that the catchments show significant differences in isotopic composition of water types contributing to streamflow. This will allow a more sensitive quantification of the runoff components and therefore a better parameterization of the rainfall-runoff models.

Concerning the snow water resources, the approach presented was applied to represent low flows within the study catchments in Switzerland by only considering SWE. Additional information about isotopic composition and residence times of the runoff components will give further knowledge about all water sources contributing to low-flow discharge.

Synchronizing the sampling methodology and collection as well as the pre-processing of spatial and temporal datasets for the different background conditions in the project countries will substantially enhance the quality of this undertaking. This will in turn improve the application of the models and broaden their performance to different geographical settings.

Acknowledgements. This project is supported by the Swiss National Science Foundation SNF through the Joint Research Projects (SCOPES) Action (Grant IZ73Z0_152506). We are indebted to Stefanie Jörg-Hess for her R-Scripts and to James Kirchner (ETH and WSL) and Jan Seibert team (University of Zürich) for the ongoing support concerning isotope sampling in the Alptal basin. We are also indebted to Alena Kulasová and Jakub Jankovec for fieldwork assistance in the Czech Republic, and Mariam Todadze and Sophio Vephkvadze in Georgia for laboratory work.

References

David, V., Davidova, T., and Strouhal, L.: Land use related parameters as an input for the estimation of flood characteristics in small catchments, in: 13th International Multidisciplinary Scientific Geoconference SGEM 2013, Water Resour. Forest, Mar. Ocean Ecosyst., 189–196, doi:10.5593/sgem2013, 2013.

Dettinger, M. D., Cayan, D. R., Meyer, M. K., and Jeton, A. E.: Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American river basins, Sierra Nevada, California, 1990–2099, Clim. Change, 62, 283–317, 2014.

Dincer, T., Payne, R., and Florkowski, T.: Snowmelt Runoff from Measurements of Tritium and Oxygen-18, Water Resour. Res., 6, 110–124, 1970.

Downer, C. W. and Ogden, F. L.: GSSHA: A model for simulating diverse streamflow generating processes, J. Hydrol. Eng., 9, 161–174, 2004.

Fischer, B., Rinderer, M., Schneider, P., and Seibert, J.: The terroir of prealpine headwaters – spatial patterns of water chemistry, Geophys. Res. Abstracts, Vol. 15, EGU2013-481-1, 2013.

Fundel, F., Jörg-Hess, S., and Zappa, M.: Monthly hydrometeorological ensemble prediction of streamflow droughts and corresponding drought indices, Hydrol. Earth Syst. Sci., 17, 395–407, doi:10.5194/hess-17-395-2013, 2013.

Godsey, S. E., Kirchner, J. W., and Tague C. L.:. Effects of changes in winter snowpacks on summer low flows: case studies in the Sierra Nevada, California, USA, Hydrol. Process., 28, 5048–5064, doi:10.1002/hyp.9943, 2014.

Gröning, M., Lutz, H. O., Roller-Lutz, Z., Kralik, M., Gourcy, L., and Pöltenstein, L.: A simple rain collector preventing water reevaporation dedicated for δ^{18}O and δ^{2}H analysis of cumulative precipitation samples, J. Hydrol., 448, 195–200, 2012.

Hegg, C., McArdell, B. W., and Badoux, A.: One hundred years of mountain hydrology in Switzerland by the WSL, Hydrol. Process., 20, 371–376, doi:10.1002/hyp.6055, 2006.

Holko, L.: Snowmelt runoff generation in a mountainous catchment. Tracer Technologies for Hydrol. Systems (Proceedings of a Boulder Symposium, 1995), IAHS Publ. No. 229, 1995.

Jörg-Hess, S., Fundel, F., Jonas, T., and Zappa, M.: Homogenisation of a gridded snow water equivalent climatology for Alpine terrain: methodology and applications, The Cryosphere, 8, 471–485, doi:10.5194/tc-8-471-2014, 2014.

Kuras, P. K., Weiler, M., and Alila, Y.: The spatiotemporal variability of runoff generation and groundwater dynamics in a snow-dominated catchment, J. Hydrol., 352, 50–66, doi:10.1016/j.jhydrol.2007.12.021, 2008.

Lundquist, J. D. and Dettinger, M. D.: How snowpack heterogeneity affects diurnal streamflow timing, Water Resour. Res., 41, W05007, doi:10.1029/2004WR003649, 2005.

McGuire, K. J., DeWalle, D. R., and Gburek, W. J.: Evaluation of mean residence time in subsurface waters using oxygen-18 fluctuations during drought conditions in the mid-Appalachians, J. Hydrol., 261, 132–149, 2002.

Melikadze, G., Chelidze, T., Zhukova, N., Rozanski, K., Dulinski, M., and Vitvar T.: Using nuclear technology for environmental safety and sustainable development of water resources in Borjomi region (Southern Georgia). Journal of Georgian Geophysical Society, Issue (A), Phys. Solid Earth, 13a, 17–25, 2009.

Melikadze, G., Kapanadze, N., and Todadze, M.: Assessment the role of snow in hydrological cycle of the Borjomula-Gudjareti-Tskali rivers basin. Journal of Georgian Geophysical Society, Phys. Solid Earth., 16a, 19–24, 2013.

Seibert, J. and McDonnell, J. J.: On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration, Water Resour. Rese., 38, 1241, doi:10.1029/2001WR000978, 2002

Hrnčíř, M., Šanda, M., Kulasová, A., and Císlerová M.: Runoff formation in a small catchment at hillslope and catchment scales, Hydrol. Proc., 24, 2248–2256, doi:10.1002/hyp.7614, 2010.

Parajka, J. and Bloschl, G.: The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models, J. Hydrol., 358, 240–258, doi:10.1016/j.jhydrol.2008.06.006, 2008.

Penna, D., Engel, M., Mao, L., Dell'Agnese, A., Bertoldi, G., and Comiti, F.: Tracer-based analysis of spatial and temporal variations of water sources in a glacierized catchment, Hydrol. Earth Syst. Sci., 18, 5271-5288, doi:10.5194/hess-18-5271-2014, 2014.

Penna, D., Stenni, B., Šanda, M., Wrede, S., Bogaard, T. A., Gobbi, A., Borga, M., Fischer, B. M. C., Bonazza, M., and Chárová, Z.: On the reproducibility and repeatability of laser absorption spectroscopy measurements for δ^{2}H and δ^{18}O isotopic analysis, Hydrol. Earth Syst. Sci., 14, 1551–1566, doi:10.5194/hess-14-1551-2010, 2010.

Rodgers, P., Soulsby, C., Waldron, S., and Tetzlaff, D.: Using stable isotope tracers to assess hydrological flow paths, residence times and landscape influences in a nested mesoscale catchment, Hydrol. Earth Syst. Sci., 9, 139–155, doi:10.5194/hess-9-139-2005, 2005.

Šanda, M. and Císlerová, M.: Transforming hydrographs in the hillslope subsurface. J. Hydrol. Hydromech., 57, 264–275, doi:10.2478/v10098-009-0023-z, 2009.

Šanda, M., Vitvar, T., Kulasová, A., Jankovec, J., and Císlerová, M.: Runoff formation in a humid, temperate headwater catchment using a combined hydrological, hydrochemical and isotopic approach (Jizera Mountains, Czech Republic), Hydrol. Proc., 28, 3217–3229, doi:10.1002/hyp.9847, 2014.

Sideris, I. V., Gabella, M., Erdin, R., and Germann, U.: Real-time radar rain-gauge merging using spatio-temporal co-kriging with external drift in the alpine terrain of Switzerland, Q. J. Roy. Meteorol. Soc., 140, 1097–1111, 2014.

Snĕhota, M., Císlerová, M., Amin, M. H. G., and Hall, L. D.: Tracing the Entrapped Air in Heterogeneous Soil by Means of Magnetic Resonance Imaging, Vadose Zone J., 9, 373–384, 2010.

Stähli, M. and Gustafsson, D.: Long-term investigations of the snow cover in a subalpine semi-forested catchment, Hydrol. Process., 20, 411–428, 2006.

Strouhal, L. and David, V.: Role of Infiltration and Saturation Excess in Rainfall-Runoff Modelling in Small Catchments, in: Selected Scientific Papers, J. Civil Eng., 8, 5–12, doi:10.2478/sspjce-2013-0001, 2013.

Van Loon, A. F., Ploum, S. W., Parajka, J., Fleig, A. K., Garnier, E., Laaha, G., and Van Lanen, H. A. J.: Hydrological drought typology: temperature-related drought types and associated societal impacts, Hydrol. Earth Syst. Sci. Discuss., 11, 10465–10514, doi:10.5194/hessd-11-10465-2014, 2014.

Vitvar, T., Aggarwal, P. K., and Herczeg, A. L.: Global Network is launched to monitor isotopes in rivers, Eos Trans, AGU, 88, 325–326, 2007.

Viviroli, D., Zappa, M., Gurtz, J., and Weingartner, R.: An introduction to the hydrological modelling system PREVAH and it pre- and post-processing tools, Environ. Modell. Softw., 24, 1209–1222, 2009.