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REVIEW OF HYDROLOGICAL STUDIES CONTRIBUTING TO THE ADVANCEMENT OF HYDROLOGICAL SCIENCES IN SLOVENIA

PREGLED HIDROLOŠKIH ŠTUDIJ Z VIDIKA NAPREDKA HIDROLOŠKE ZNANOSTI V SLOVENIJI

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Abstract

In the last decade hydrological science in the world has changed significantly. Numerous new methods have been introduced and also the way how hydrological problems are approached has changed dramatically. That is true also for the hydrological science in Slovenia. The present review of selected hydrological studies contributing to the advancements of hydrology in Slovenia demonstrates that Slovenian hydrology follows the most recent trends in the world, including the “Panta Rhei” initiative dedicated to scientific research of interactions between hydrology and society in a changing world. Majority of the presented studies are in some way related to Professor Mitja Brilly, whose leadership of the group of hydrologists at the University of Ljubljana resulted in such impressive development.

Keywords: experimental river basins, field measurements, floods, hydrology, landslides, Slovenia.

Izvleček

Hidrologija kot veda se je v zadnjih desetletjih zelo spremenila. V uporabo je bilo vpeljanih veliko novih metod, način obravnave praktičnih hidroloških problemov pa se je izboljšal ter nadgradil. Te ugotovitve veljajo tudi za hidrološko znanost v Sloveniji. Pregled obstoječih hidroloških študij ter raziskav v Sloveniji, ki so prispevale tudi k razvoju mednarodne stroke, nakazuje skladnost slovenskih raziskav z mednarodnimi. Poleg tega je razvidno, da slovenska hidrološka znanost sledi “Panta Rhei” iniciativi, ki stremi k nadgradnji povezav med hidrologijo in družbo. Večina študij, ki so omenjene v prispevku, so tako ali drugače povezave s prof. Mitjo Brilly-jem. Njegovo vodenje skupine hidrologov v sklopu Univerze v Ljubljani je v veliki meri pripomoglo k napredku slovenske hidrološke znanosti.

Ključne besede: eksperimentalna porečja, terenske meritve, poplave, hidrologija, zemeljski plazovi, Slovenija.

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1. Introduction

New scientific decade (2013–2022) of the International Association of Hydrological Sciences (IAHS) named “Panta Rhei–Everything Flows” (Montanari et al., 2013) aims to improve interpretation and understanding of processes that define the hydrological cycle. The main focus of this initiative is to observe changing dynamics of hydrology and society. In order to improve our understanding of water cycle, interdisciplinary approach is needed to connect hydrology and society. Moreover, interactions between these two concepts are changing (Montanari et al., 2013). New concepts, models, assessments, and predictions are therefore needed to achieve the main goal of this international activity.

Figure 1: *General framework used to contribute to advancements in hydrological sciences. Extreme rainfall situations (upper left) can cause floods (upper right) and can initiate different types of slope instabilities such as landslides (bottom left). These extreme events cause economic damage or even human fatalities (bottom right). Measurements in experimental catchments are essential for enhancing the knowledge about hydrological processes.*

Slika 1: *Metodologija, ki je bila uporabljena za prispevek k razvoju hidrološke znanosti. Ekstremni padavinski dogodki (levo zgoraj) lahko povzročijo poplave (desno zgoraj) ter sprožijo različne oblike masnih premikov, kot so plazovi (levo spodaj). Omenjeni ekstremni dogodki lahko povzročijo veliko gmotno škodo ali celo ogrozijo človeška življenja (desno spodaj). Poleg tega za nadgradnjo znanja o hidroloških procesih nujno potrebujemo tudi meritve na eksperimentalnih porečjih.*

The general framework that was used for contributing to the advancement on hydrological sciences and that was mostly focused on Slovenian case studies is presented in Fig. 1. The scope runs from field measurements in experimental catchments such as Dragonja, Reka and Gradaščica rivers (e.g., Petkovšek and Mikoš, 2004; Brilly et al., 2006a; Rusjan et al., 2008a; Rusjan and Mikoš, 2008; Šraj et al., 2008a; 2008b; Rusjan and Mikoš, 2010; Bezak et al., 2016b), where different processes (e.g., precipitation, rainfall interception, soil erosion, sediment transport…) were measured over detailed analyses of different extreme hydrological events such as floods or droughts (e.g., Kobold in Brilly, 2006; Špitalar et al., 2014; Kobold et al., 2015; Šraj et al., 2015; Vidmar et al., 2015; Bezak et al., 2016b) to triggering factors and monitoring of landslides (e.g., Mikoš et al., 2004; Mikoš et al., 2005; Mikoš et al., 2006; Bezak et al., 2016c) for their better mitigation. The relationship between hydrology and society was also taken into account (e.g., Polič et al., 1998; Brilly and Polič, 2005; Špitalar et al., 2014). Thus, this short overview of some of the recent hydrological studies in Slovenia indicates that the Panta Rhei concepts (Montanari et al., 2013) have already been considered in previous hydrological studies in Slovenia that were mainly coordinated by professor Mitja Brilly (http://ksh.fgg.uni-lj.si/ksh_ang/predst/zaposleni/Brilly.html).
Moreover, these studies were not only focused on the area of Slovenia that covers approximately 20,000 km^2, but also extended to other countries such as USA (Bezak et al., 2014b; Špitalar et al., 2014; Trejo Rangel et al., 2016), Bosnia and Herzegovina (Kobold et al., 2015; Vidmar et al., 2015), Croatia (Hozjan et al., 2016), Austria, Slovakia and Serbia (Kryžanowski et al., 2014). Some of the studies also focused on specific large scale European catchments such as the Sava River catchment (e.g., Primožič et al., 2008) and the Mura River catchment (Šraj et al., 2011).

This review paper gives an extensive overview of previous hydrological studies in Slovenia that contributed to advancements in hydrological sciences with the aim of emphasizing some of the main achievements and conclusions that are also interesting from the international perspective. Firstly, the focus is on extreme hydrological events where floods were more frequently studied than droughts. Secondly, studies that connect hydrology, landslides and society are presented. In the third part, several original papers based on field experimental work are described, and in the last section some of the main achievements of the last two decades at UL FGG working on hydrological problems in Slovenia are stressed.

2. Extreme hydrological events

Extreme meteorological events such as intense summer storms (e.g., Fazarinc and Mikoš, 1992; Rusjan et al., 2009; Bezak et al., 2016b) or long-duration convective precipitation events (e.g., Kobold et al., 2015; Vidmar et al., 2015) can cause extreme hydrological events such as (flash) floods (e.g., Bezak et al., 2016b). On the other hand, significant shortage of rainfall can lead to droughts (e.g., Štravs and Brilly, 2007; Šebenik et al., 2017) that can also be regarded as an extreme event. These extreme events can cause large economic damage or even endanger human lives (e.g., Brilly and Polič, 2005; Špitalar et al., 2014). Flood frequency analysis (FFA) is an important part of the engineering practice whose aim is to obtain relationships between design variables corresponding to a chosen hydrologic risk (Bezak et al., 2014a; Šraj et al., 2015; Bezak et al., 2016a; Šraj et al., 2016). FFA is often used to design different hydro-technical structures such as dams or levees that can also be used to protect inhabitants of hazardous areas (e.g., Kjeldsen et al., 2014; Kryžanowski et al., 2014). In order to enhance the knowledge about these extreme events hydrological modelling can also be applied to specific case studies (e.g., Kobold and Brilly, 2006; Šraj et al., 2010; Kobold et al., 2015; Vidmar et al., 2015). One of the most important and frequently asked questions in today’s science is how climate change or climate variability will affect different processes in the water cycle. From this perspective studies that connect flood risk and climate change (e.g., Brilly et al., 2014a; Brilly et al., 2014b; Brilly et al., 2015; Kobold, 2009; Mediero et al., 2015; Šraj et al., 2016b) can be useful to effectively prepare the society for future decades.

One of the first studies in Slovenia that connect flood risk and society was conducted in 1998 (Polič et al., 1998) and also continued in the next decades (Brilly and Polič, 2005). The results of the study that focused on the Slovenian town Celje (large floods happened in 1990 and 1998 with return period larger than 100 and 50 years, respectively) revealed that floods present a large threat to inhabitants (Brilly and Polič, 2005). It was also interesting that to a certain degree this threat depends on the place of residence (Brilly and Polič, 2005). The extreme floods in 1990 and 1998 caused 4 of 74 fatalities due to floods in Slovenia between 1926 and 2014 (Fig. 2). Most of these fatalities can be connected with extreme events with flashy characteristics (http://ksh.fgg.uni-lj.si/ksh/strok_dej/Zrtve_poplav_SLO.html) such as the Železniki flash flood (e.g., Rusjan et al., 2009) or Log pod Mangartom debris flow (e.g., Mikoš et al., 2004). Moreover, recent study of human fatalities and injuries due to flash floods in the USA has stressed several interesting points such as that fatalities and injuries were less frequent in urban than rural areas (Špitalar et al., 2014). Furthermore, authors also found that events with duration of less than 1 hour lead to the largest number of injuries and fatalities. Furthermore, more than 60 % of injuries and fatalities were vehicle-related and a large percentage of these occurred when visibility was reduced after sunset. One of the potential effects of floods is also the influence on the real estate market. A comparison of flood impact in Ljubljana (Slovenia) and Boulder (Colorado, United States) showed that in Boulder real estate prices in the flood plain areas are lower than outside the flood plain areas (Trejo Rangel et al., 2016). Floods do not have much impact on the mean real estate prices but they do affect the number of sales, which decreased after the flood (Trejo Rangel et al., 2016). On the other hand, in Ljubljana the situation was somehow different because the number of contracts did not reduce significantly due to the flood. Moreover, there were also some changes in the prices inside and outside the flood plain areas. Furthermore, different models can also be used for the estimation of direct flood damage. One of such models was developed for Croatia where movable property was also included (Hozjan et al., 2016).

Fatalities, injuries and economic damage can sometimes be reduced with appropriate design of hydraulic structures. Reliable estimation of a design value and the corresponding chosen risk of flooding is an important part of engineering practice and water management and it is usually performed using flood frequency analysis (FFA). Most often FFA is carried out using a univariate approach, where only one variable, usually peak discharge value is considered (e.g., Bezak et al., 2014a; Bezak et al., 2016a). Hydrograph volume and duration are often given less attention (Bezak et al., 2015). Different procedures can be used to perform univariate flood frequency analysis, namely annual maximum method and peaks-over-threshold approach (e.g., Bezak et al., 2014a). The latter option is usually used in case of short data series when e.g., less than 10 or 15 years of data are available. Moreover, different distribution functions (e.g., Gumbel, Pearson type 3, log-Pearson type 3, log-normal, GEV) and parameter estimation techniques (e.g., method of moments, method of L-moments, maximum likelihood method) are available (e.g., Bezak et al., 2014a). Using statistical tests (e.g., Kolmogorov-Smirnov) and goodness-of-fit criteria (e.g., root-mean-square-error) the most suitable combination of distribution function and parameter estimation method should be selected in order to get reliable design values. Alternatively, multivariate FFA can be performed in order to consider more variables at the same time, e.g. hydrograph volume and/or hydrograph duration (e.g., Šraj et al., 2015). Copulas are a good alternative to the univariate FFA. They are a useful mathematical tool that can be applied to a large number of environmental problems (e.g., Bezak et al., 2014b; Šraj et al., 2015; Bezak et al., 2016c). By applying these functions one can construct the relationship among design variables and the multivariate return period concept. One of the first steps in multivariate FFA is dependence assessment among the investigated variables. An example of the dependence assessment for the trivariate case of Litija station on the Sava River is shown in Fig. 3. Different copula functions from several families are available and using statistical tests and goodness-of-fit criteria the most suitable copula should be selected (e.g., Šraj et al., 2015; Bezak et al., 2014b). Figure 4 shows an example of the graphical goodness-of-fit criteria for the trivariate *Q*-*V*-*T* case. Using the constructed copula model one can build the relationship between the return period and design variables. Moreover, in some cases for the design of hydro-technical structures also coincident frequency analysis of flood waves should be performed. Vihar et al. (2014) performed this kind of analysis for the confluence of the Soča and Vipava Rivers in Slovenia.

From the perspective of the next decades the question of non-stationarity in extreme hydrological events arises. Many studies show that the frequency of hydrological extremes is changing and will probably change also in the near future (Šraj et al., 2016b). Studies on this topic can be divided into two groups. In the first group are so-called data oriented studies that focus on the measured data and try to analyse differences between different periods of data collection (e.g., Bezak et al., 2016a; Šraj et al., 2016a; 2016b). In the other group are the studies that use ensembles of climate change models to forecast the situation in next decades (e.g., Brilly et al., 2014a; Brilly et al., 2014b; Brilly et al., 2015). The study of Šraj et al. (2016a) was performed using discharge data from 55 stations in Slovenia and results indicated that no uniform pattern (upward or downward trend) can be found in the flood risk in Slovenian streams. This conclusion was confirmed using flood frequency approach for different data periods that is shown in Fig. 5 and Mann-Kendall statistical test. Moreover, using the Mann-Kendall test, a statistically significant (significance level 0.05) positive trend was detected only for about 5% of stations. However, using a non-stationary approach of FFA applying GEV distribution with parameters dependent on annual precipitation, Šraj et al. (2016b) found for one of these stations that a 10% increase in annual precipitation translates into an 8% increase of the 10-year flood (station Škocjan on Radulja River). On the other hand, the results of the climate change impact study on the flood hazard in the Sava River basin (e.g., Brilly et al., 2015) showed that the peak discharge values with 100-year return period will increase until the year 2100 by 9–55%, depending on the location in the Sava River basin (Brilly et al., 2015). Fig. 6 shows the results for the Čatež station on the Sava River. In this procedure a calibrated hydrological model was used with precipitation input that was derived from climate change models (Brilly et al., 2015). We can summarize that for Slovenia there is some deviation between the results of the climate models and changes that can detected in the measured discharge data.

In order to perform this kind of climate change (variability) assessment a hydrological model has to be used. Several aspects of hydrological modelling were investigated in Slovenia in the last decade, namely the influence of effective rainfall on modelled runoff hydrograph (Šraj et al., 2010), applicability of HBV model for flash flood forecasting (Kobold and Brilly, 2006), modelling the hydrological processes in the Sava River basin (Primožič et al., 2008). HBV model was also used to model an extreme flood in Bosnia and Herzegovina in 2014 (Kobold et al., 2015; Vidmar et al., 2015). Moreover, machine learning algorithms were also applied to model low flows (Štravs and Brilly, 2007). Fig. 7 shows forecasted precipitation in May 2014 for the Balkan region that was heavily damaged by the 2014 flood (e.g., Kobold et al., 2015; Vidmar et al., 2015). For this event the return period for the peak discharge and precipitation sum exceeded the 100-year return period (Vidmar et al., 2015). However, a question arises about reliability of the estimated return period in the light of climate change (variability) and potential changes in the relationship between the design variables and the return period.

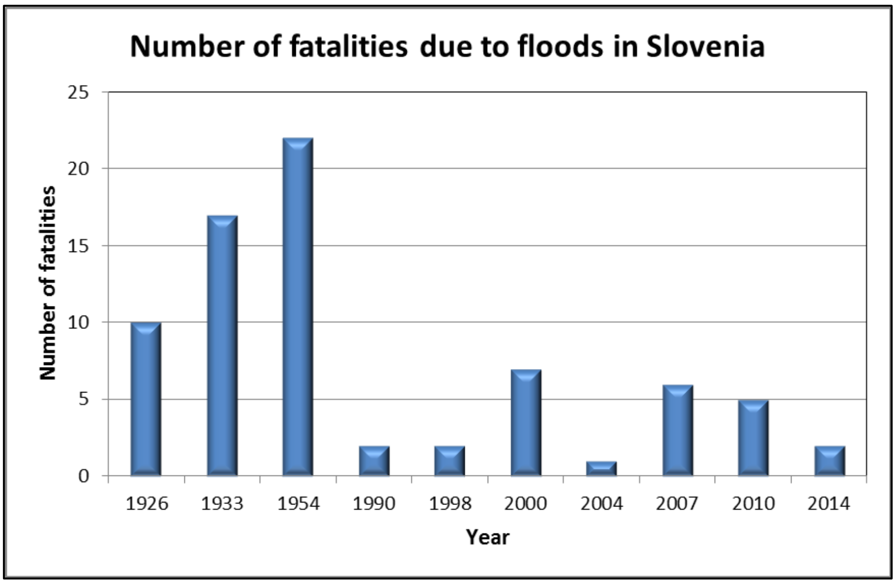

Figure 2: *Number of fatalities due to floods in Slovenia between the years 1926 and 2014. This chart was prepared using the data from: http://ksh.fgg.uni-lj.si/ksh/strok_dej/Zrtve_poplav_SLO.html.*

Slika 2: *Število žrtev zaradi poplav v Sloveniji v obdobju med letoma 1926 in 2014. Diagram je bil pripravljen z upoštevanjem podatkov na povezavi: http://ksh.fgg.uni-lj.si/ksh/strok_dej/Zrtve_poplav_SLO.html.*

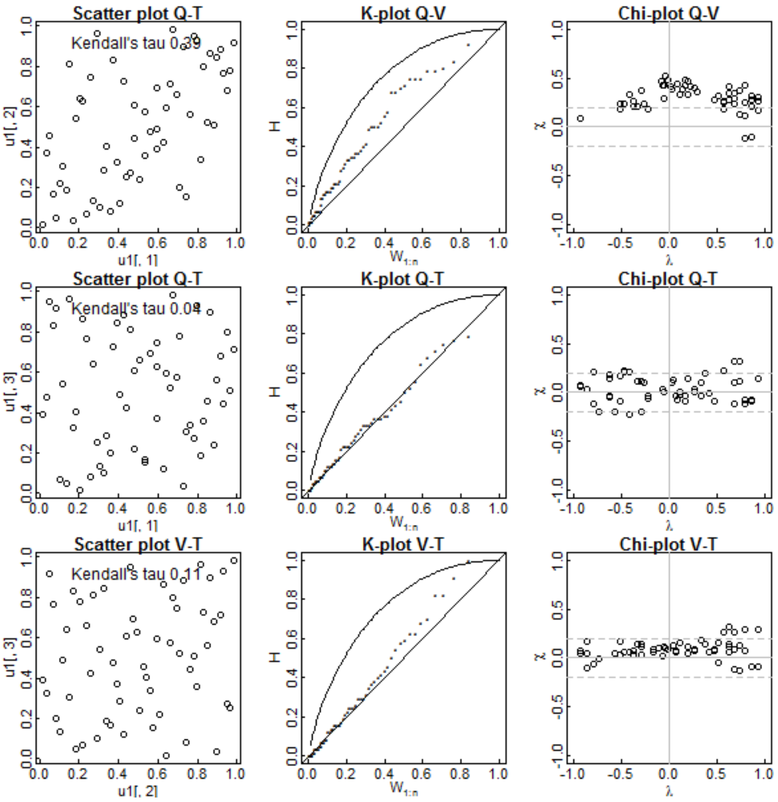

Figure 3: *Dependence assessment for the peak discharge (Q)–hydrograph volume (V)–hydrograph duration (T) analysis for the Litija station on the Sava River.*

Slika 3: *Ocena odvisnosti med konicami pretokov (Q), volumni visokovodnih valov (V) ter trajanji visokovodnih valov (T) za primer postaje Litija na reki Savi.*

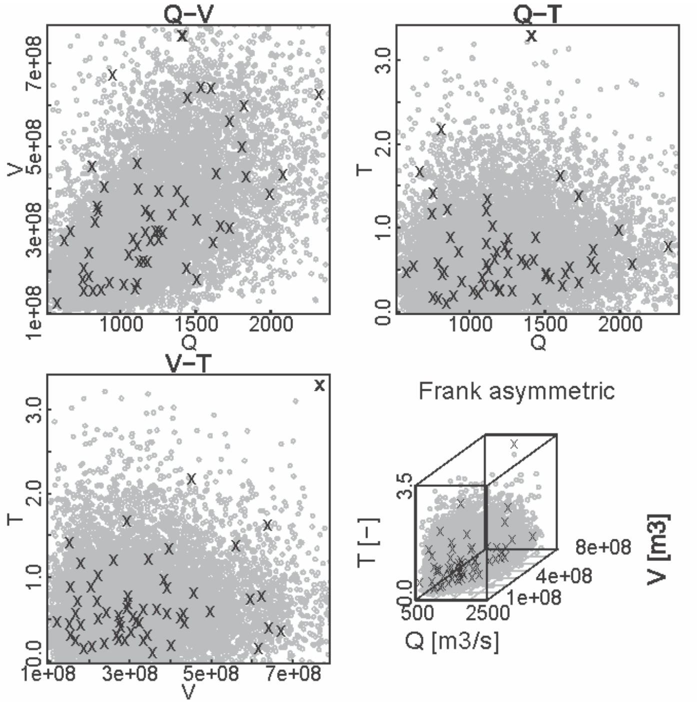

Figure 4: *Graphical goodness-of-fit selection criteria for the trivariate Q-V-T case study for the Litija station on the Sava river for the asymmetric Frank copula from the Archimedean family.*

Slika 4: *Grafični test ustreznosti ujemanja za trivariatni primer Q-V-T za podatke s postaje Litija na reki Savi z uporabo asimetrične kopule Frank iz Arhimedove družine kopul.*

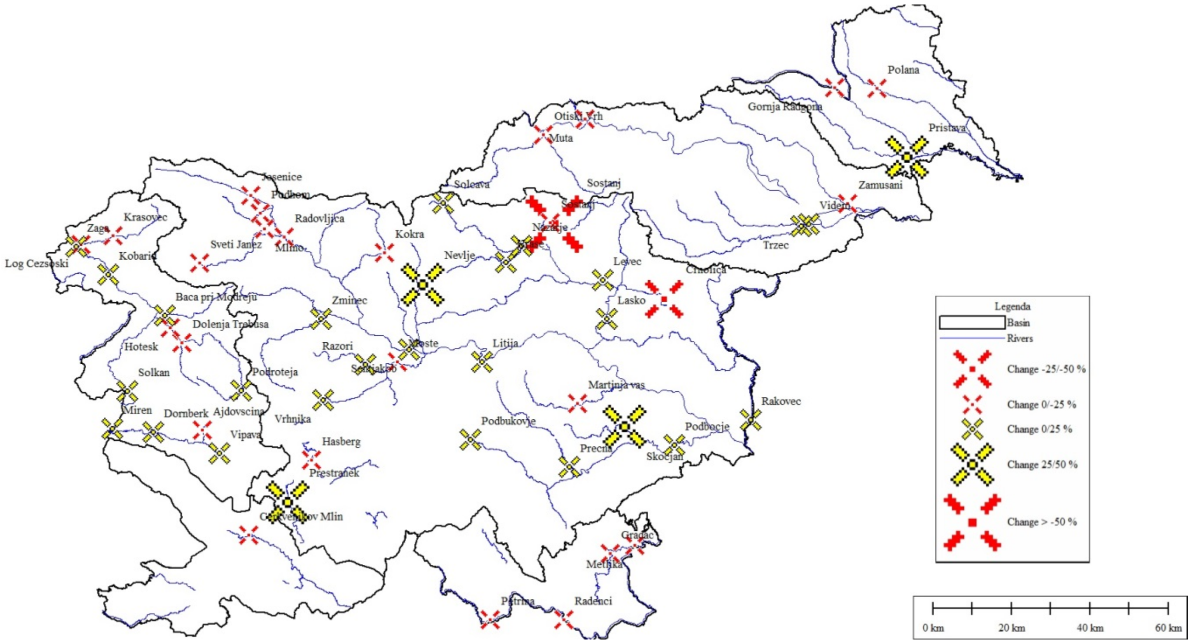

Figure 5: *Differences (in %) in the design discharge (T=100 years) for two time periods (1961-1990 and 1981-2010) (based on Šraj et al., 2016a).*

Slika 5: *Razlike (v %) v projektnih pretokih s povratno dobo 100 let za dve časovni obdobji (1961-1990 in 1981-2010) (prilagojeno po Šraj et al., 2016a).*

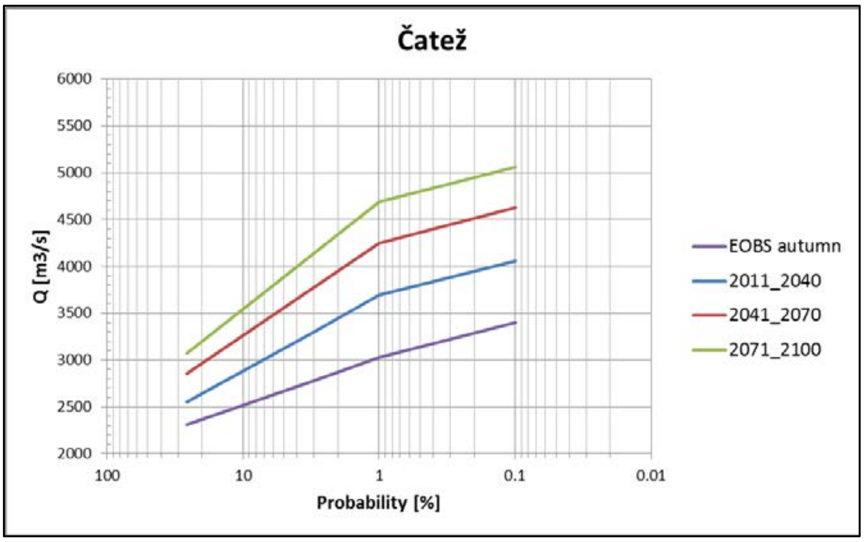

***Figure 6:** Probability function of peak discharges at the gauging station Čatež on the Sava River for different periods (2011-2040; 2041-2070; 2071-2100) of climate change forecast (based on Brilly et al., 2015).*

***Slika 6:** Verjetnostna funkcija konic pretokov za vodomerno postajo Čatež na reki Savi za različna obdobja (2011-2040; 2041-2070; 2071-2100) z uporabo modelov podnebnih sprememb (prilagojeno po Brilly et al., 2015).*

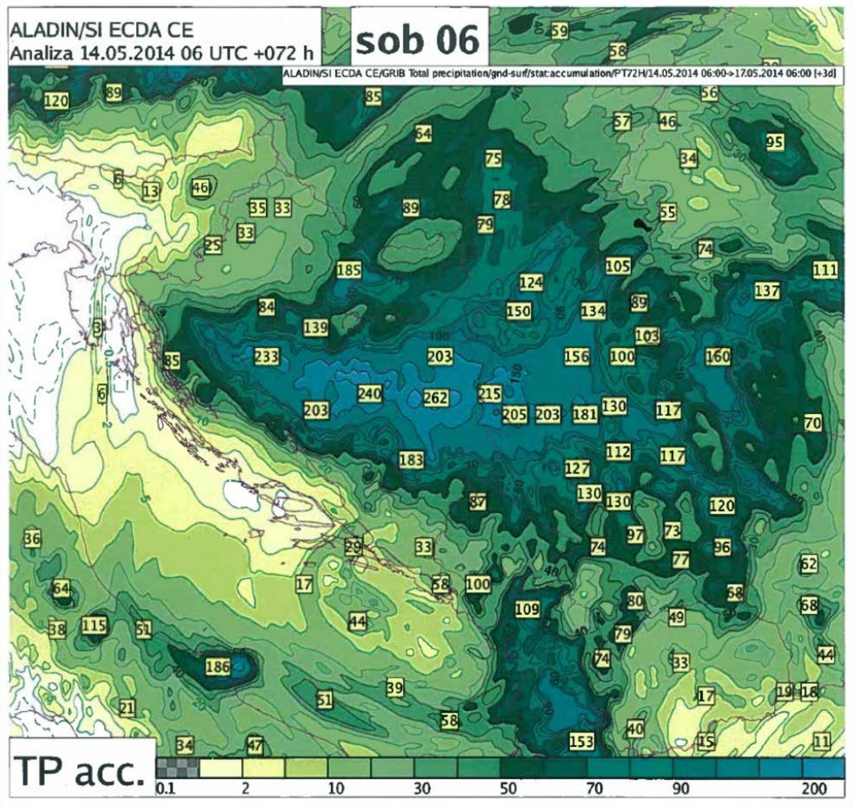

***Figure 7:** Total forecasted precipitation for the period 14.05.2014 06 UTC – 17.05.2014 06 UTC for the Balkan region (ARSO, 2014 and Kobold et al., 2015).*

***Slika 7:** Skupna napovedana količina padavin za obdobje od 14. 5. 2014 ob 06 UTC do 17. 5. 2014 ob 06 UTC za območje Balkana (povzeto po ARSO, 2014 in Kobold et al., 2015).*

3. Hydrology and landslide research

The most hazardous hydro-geologic phenomena in Slovenia are mass wasting processes, such as rainfall-induced shallow landslides (Fazarinc and Mikoš, 1992), quake-induced rock falls (Mikoš and Fazarinc, 2000; Mikoš et al., 2006b), and fluvial erosion caused by steep torrential streams in mountainous watersheds and by a dense river network (1.33 km/km^2; Mikoš et al., 2004b). In the last decades of the 20th century, smaller shallow rainfall-induced landslides prevailed, triggered during short but intense rainfalls (summer or early autumn thunderstorms), e.g. such as in 1989 in Kozarica and Lahomnica watersheds (on average 130 mm in less than 3 hours on August 19, 1989, causing specific discharges of around 10 m^3/km^2 for watershed areas of around 10 km^2; Fazarinc and Mikoš, 1992), where land use (meadows and infrastructure versus forest) was shown to have a decisive impact on the number of shallow slips (Fazarinc and Mikoš, 1992). After 1990, several deep-seated landslides were triggered by heavy and prolonged rainfalls (Mikoš and Majes, 2010), some of them also associated with debris flows (Stože and Strug landslides) as a “new” mass wasting phenomenon, not widely occurring in the past decades in Slovenia. It was obvious that hydro-meteorological field measurements and expertise were an important contribution to understanding causes and triggers of such hazardous natural phenomena. In the majority of the deep-seated landslides in the last two decades in Slovenia (since 1990), hydro-meteorological measurements were performed in the field for at least a short period.

On the Stože landslide, triggered in November 2000, discharges in the Mangart torrent were measured and an analysis was performed of the hydrogeological reservoir in the Stože slope that slipped on 15November 2000 into the Mangart torrential channel after prolonged rainfall in autumn of 2000 (1638.4 mm in 48 days before the landslide or 1.42 mm/h in 1152 h; Mikoš et al., 2004a). A hydrological analysis of the event showed that the increase in runoff coefficients during the wet and warm period in autumn of 2000 prior to the Stože landslide was as high as two- to threefold (Mikoš et al., 2002). Furthermore, an analysis using natural isotopes of δ^{18}O and tritium ^{3}H of water samples from the Stože landslide area showed permanent but slow exfiltration of ground waters from a large reservoir in the slope. During the low-intensity and long-lasting rainfall in autumn of 2000, morainic material of relatively low permeability (10^{-7} m/s) was nearly saturated but remained stable (average porosity 21 %, water content 20 %, liquid limit 25 %) until high artesian pressures of up to 100 m developed in the slope by slow exfiltration from the relatively highly permeable (10^{-5} m/s) massive dolomite (Fig. 8 and Fig. 9). The Stože landslide was triggered by high artesian pressures built in the Stože slope after a long-duration rainfall. The devastating debris-flow that hit the village of Log pod Mangartom and claimed 7 victims formed from the Stože landslide masses by infiltration of rainfall and surface runoff into the landslide masses deposited in the Mangart torrential channel and by their liquefaction. The Log pod Mangartom debris flow was extensively studied, among other studies also numerical modelling was performed using one- and two-dimensional numerical debris-flow modelling (Četina et al., 2006), where hydrologic expertise was needed to estimate the hydrograph and debris-flow peak discharge.

On the Strug complex landslide (a combination of a rock slide, rock fall, translational soil landslide, debris flows from rock fall masses; Fig. 10 above), initially triggered as a rock slide above the village of Koseč in December 2001 (Mikoš et al., 2006a), weather parameters (wind, air temperature, air pressure, air humidity, wind speed) were measured, and 5-min rainfall intensities (Fig. 11) using an automatic weather station, and soil infiltration was determined by using the Kopecky infiltrometer. In 2002, inside the Strug rock fall masses several smaller debris flows with clear pulses and a total magnitude of up to 1000 m^3 were triggered during rainfall events (Fig. 12). These events were mostly triggered during a rainfall event when the rainfall amount reached up to 30 mm in 3 to 4 hours. The debris flows were also numerically modelled using hydrologic expertise when determining debris-flow magnitudes from rainfall and the watershed area (Mikoš et al., 2006c). The debris flows were recognised as sediment-supply limited events that stopped in late 2002, when the rock fall intensity lowered and practically ceased. The limitation of sediment availability for triggering debris flows was confirmed by field measurements of the Strug rock fall source area and the morphological changes on the rock fall deposits (Fig. 10 below; Mikoš et al., 2005), using a medium-ranged high performance handheld reflectorless laser measurement system.

Different geological hazards such as debris flows (e.g., Strug) or shallow landslides can lead to economic damage and even endanger human lives. In order to warn people living in the hazard area different procedures can be applied. From physically based models that can give good time and location prediction but are relatively complex tools that need a lot of input data, to empirically based methods. As one of the latter options, empirical rainfall thresholds can be selected to be included as part of the early warning system (EWS) for shallow landslides and debris flows. A large number of empirical rainfall thresholds can be found in the literature (e.g., Guzzetti et al., 2007). Some of these thresholds were developed using debris-flow data, while others applied shallow-landslides data sets. Empirical rainfall threshold curves were also developed for Slovenia (Rosi et al., 2016). Moreover, in order to add additional information to these classical empirical rainfall threshold curves this method can be combined with intensity-duration-frequency (IDF) curves that can also be constructed using copula functions (Bezak et al., 2016c). This procedure was performed for several Slovenian case studies that occurred in the last 25 years and are shown in Fig. 13 (Bezak et al., 2016c). Bezak et al. (2016c) provided more information about these results. One of the aims of the study was also to perform evaluation of several empirical rainfall thresholds that are frequently used in the literature (Fig. 14) and the main conclusion was that rainfall conditions responsible for initiation of deep-seated and shallow landslides are different (Bezak et al., 2016c). Moreover, not all tested empirical rainfall thresholds were suitable for the Slovenian meteorological conditions and different thresholds should be applied for different parts of the country (Bezak et al., 2016c).

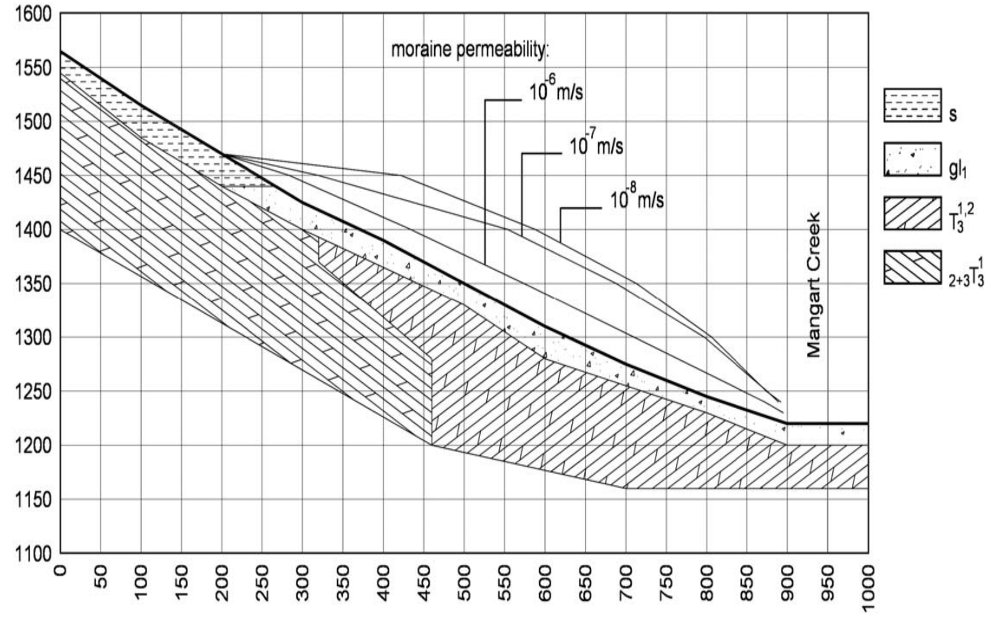

***Figure 8:** Results of computer modelling of steady ground water flow in the longitudinal profile of the Stože slope before the first event on 15 November 2000 (thick black line) showing artesian pressures (thin black lines) for three different moraine permeabilities (coordinates are given in metres) (from Mikoš et al., 2004a).*

***Slika 8:** Rezultati modeliranja toka podtalnice v longitudinalnem profilu pobočja Stože pred prvim dogodkom dne 15. 11. 2000 (debela črna črta) kažejo arteške pritiske (tanka črna črta) za tri različne morenske prepustnosti (koordinate so podane v metrih) (povzeto po Mikoš et al., 2004a).*

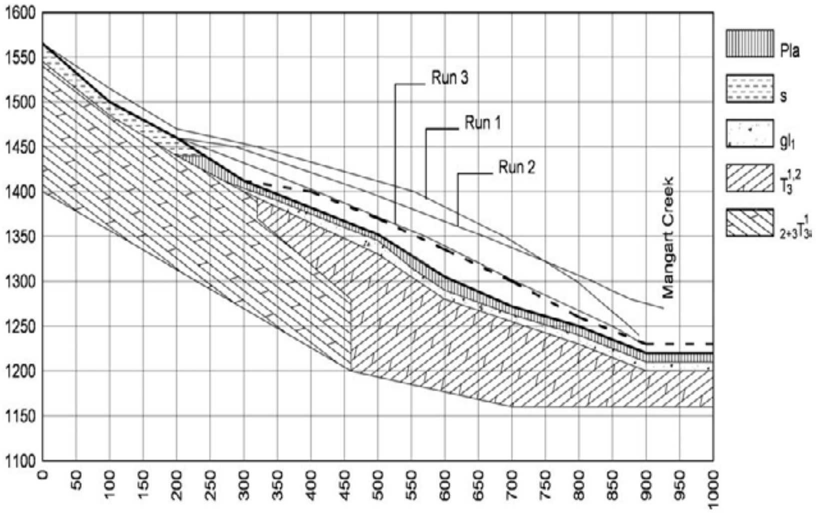

***Figure 9:** A comparison of computed artesian pressures (thin black lines) in a longitudinal profile for field situations on the Stože slope before the first event on 15 November 2000 (Run 1), after the first event (Run 2, slope surface is given in dashed thick black line), and after the second event on 17 November 2000 (Run 3, new slope surface is given in thick black line), respectively (coordinates are given in metres) (from Mikoš et al., 2004a).*

***Slika 9:** Primerjava izračunanih arteških pritiskov (tanka črna črta) v longitudinalnem profilu za situacijo na pobočju Stože pred prvim dogodkom dne 15. 11. 2000 (Run 1), po prvem dogodku (Run 2, teren je označen z debelo črno črtkano črto), ter po drugem dogodku dne 17. 11. 2000 (Run 3, nova linija terena je označena z debelo črno črto) (koordinate so podane v metrih) (povzeto po Mikoš et al., 2004a).*

***Figure 10:** The complex Strug Landslide: photo taken on 31 December 2001 (upper left); an upslope view of the rock fall source area towards the crown (upper right); a new gully was measured in May 2004 (bottom).*

***Slika 10:** Kompleksni plaz Strug: fotografija posneta 31. 12. 2001 (levo zgoraj); pogled na erozijsko žarišče (padajoče kamenje) (desno zgoraj); nov erozijski jarek, ki je bil izmerjen maja 2004 (spodaj).*

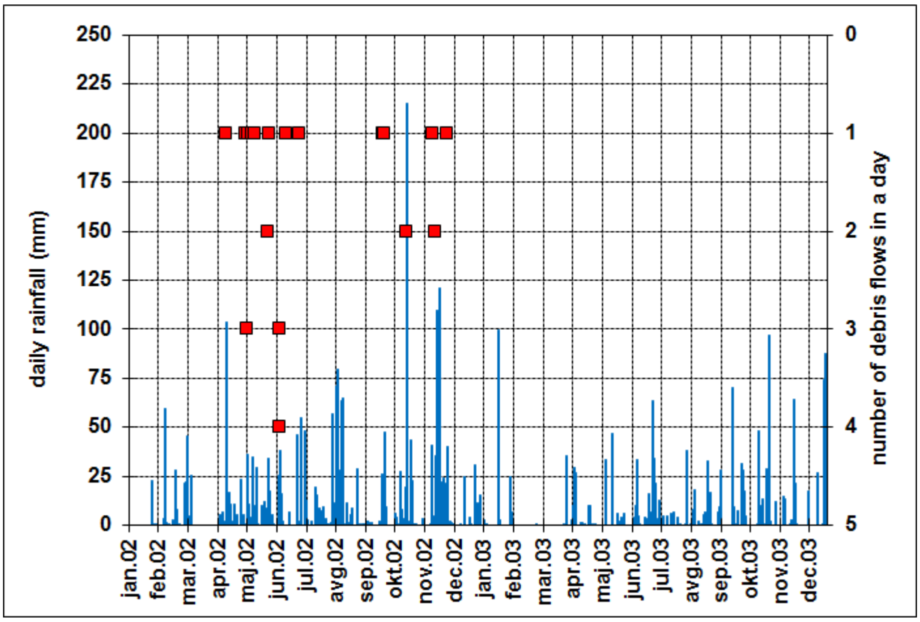

***Figure 11:** The daily rainfall totals measured on the rain gauge in Koseč. For the days with technical troubles with the weather station, correlation with measured rainfall in Kobarid was used instead (adapted from Mikoš et al., 2006a).*

***Slika 11:** Dnevne vrednosti padavin izmerjene z dežemerom v Kosečų. Pri dneh z manjkajočimi podatki je bila za dopolnitev podatkov uporabljena postaja v Kobaridu (prilagojeno po Mikoš et al., 2006a).*

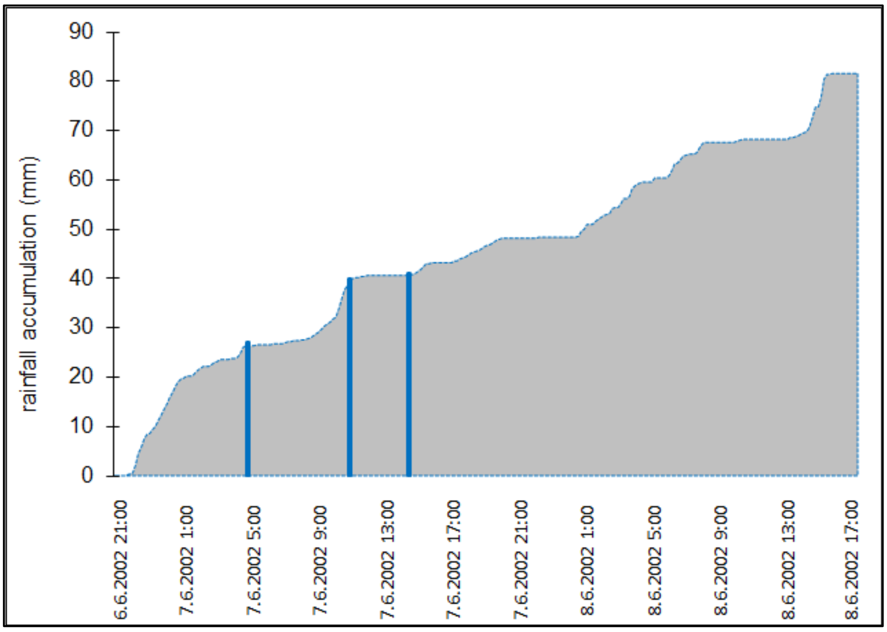

***Figure 12:** Timing of three debris flow events (vertical lines) observed on 7 June 2002, and measured cumulative rainfall in the Koseč rain gauge from 9 pm on 6 June 2002 to 5 pm on 8 June 2002 (adapted from Mikoš et al., 2006a).*

***Slika 12:** Čas nastopa treh drobirskih tokov (vertikalne črte), ki so se zgodili 7. 6. 2002 ter kumulativne vrednosti padavin za padavinsko postajo Koseč od 6. 6. 2002 ob 21:00 do 8. 6. 2002 ob 17:00 (prilagojeno po Mikoš et al., 2006a).*

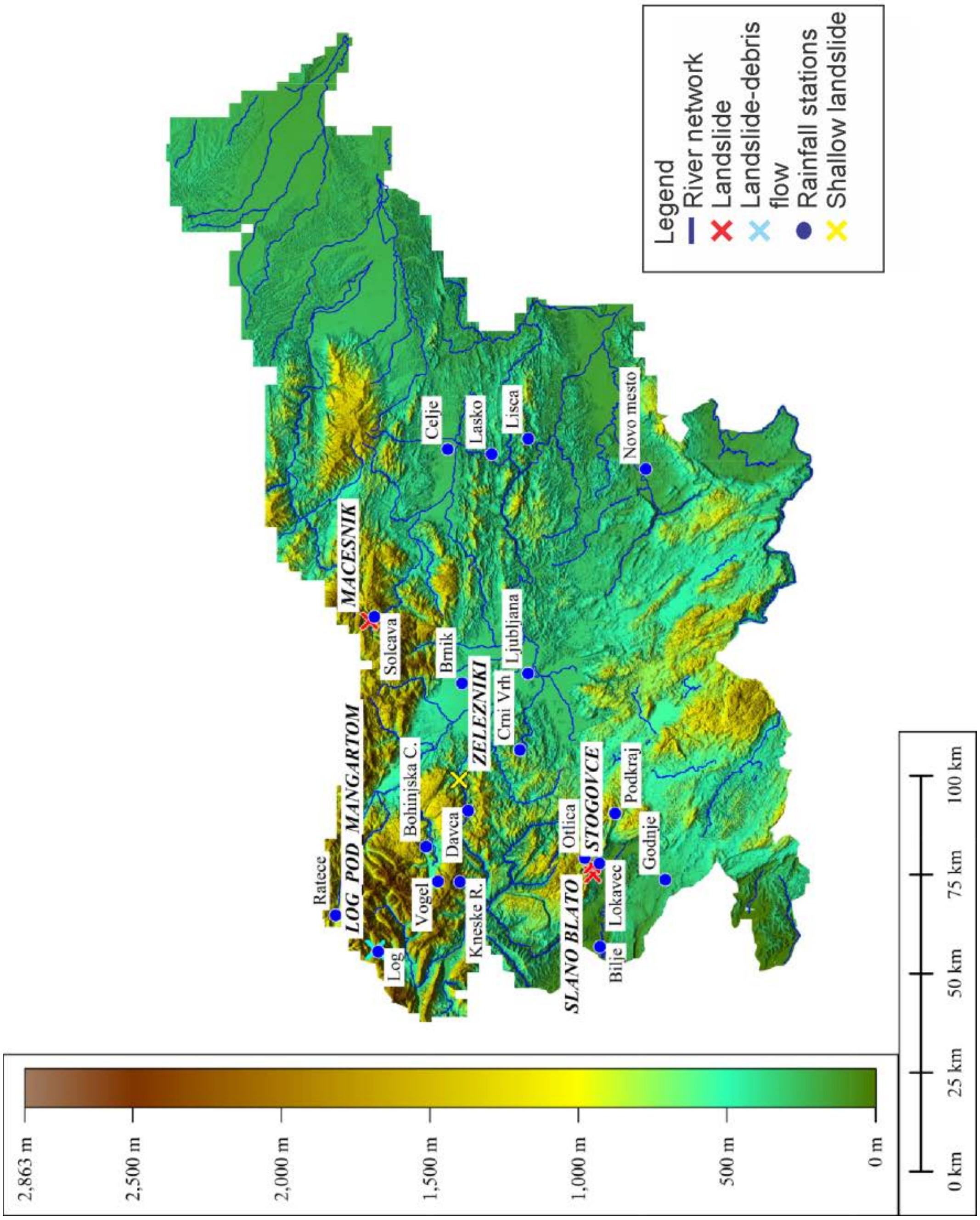

Figure 13: *Slovenian case studies and locations of the considered rainfall stations on a topographic map of Slovenia with main rivers included.*

Slika 13: *Prikaz študij slovenskih primerov in obravnavanih padavinskih postaj na topografski karti Slovenije s prikazanimi glavnimi vodotoki.*

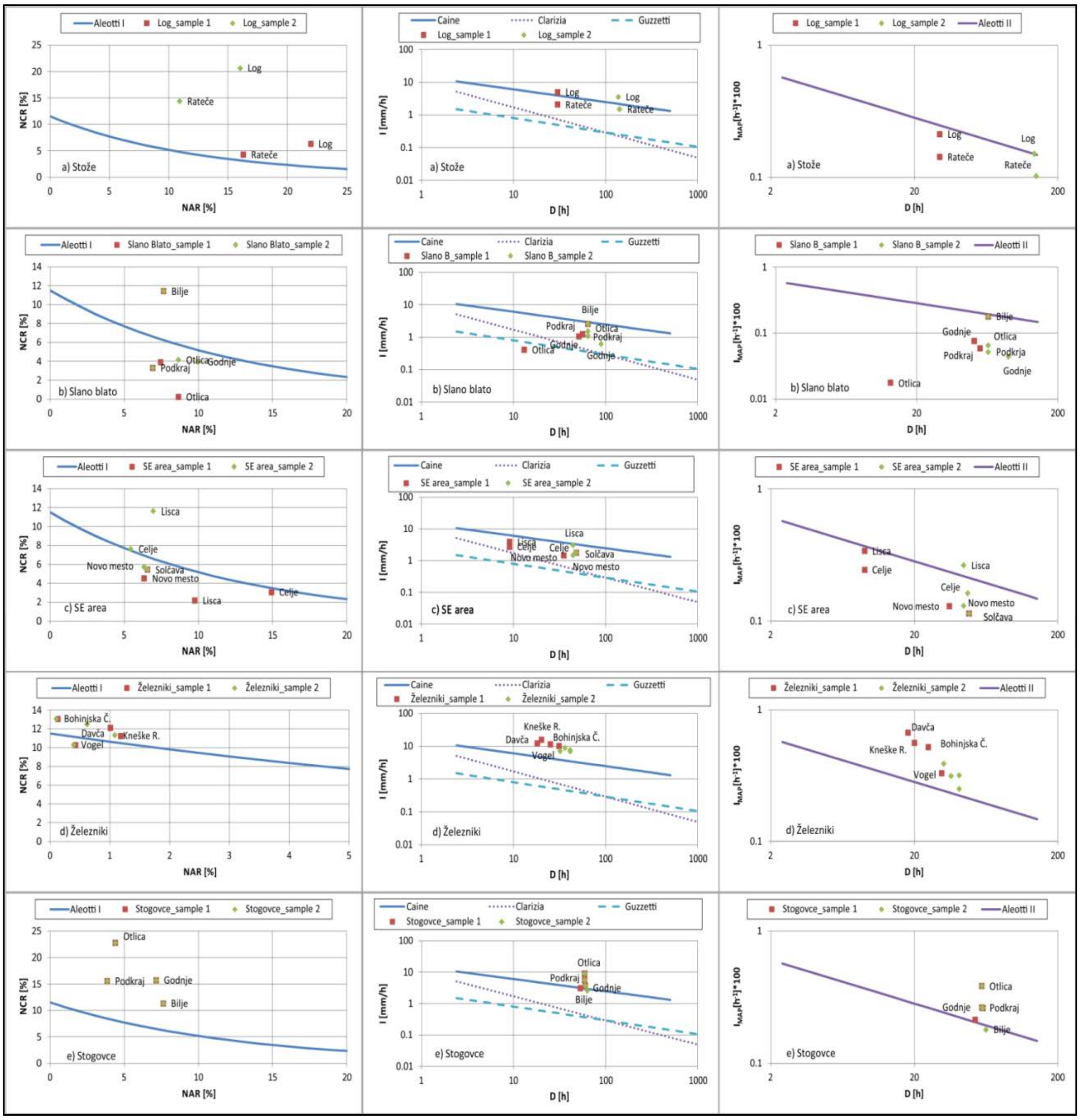

Figure 14: *Evaluation of several empirical rainfall thresholds for selected case studies (adapted from Bezak et al., 2016c).*

Slika 14: *Ocena ustreznosti različnih empiričnih krivulj za padavine izbranih ekstremnih dogodkov (prilagojeno po Bezak et al., 2016c).*

4. Experimental catchments

Experimental catchments proved to be crucial for the advancement of hydrological science, as evidenced by numerous investigations found in the literature. The experimental catchments of the rivers Dragonja, Reka river with Padež stream and Gradaščica with Glinščica stream (Fig. 15), which extend in different climatic regions, proved to be extremely valuable sources of information for studying different parts of the hydrological cycle and related biogeochemical and erosion processes in Slovenia. The experimental catchments are equipped with modern measuring equipment for precise measurements of precipitation, intercepted precipitation, discharges, erosion and water quality (Šraj et al., 2008b). These experimental measurements on major rivers in the experimental catchments are a direct extension and upgrade of the state hydrological monitoring system managed by the Slovenian Environment Agency (ARSO), which allows integration and extension of the data time series. This contemporary experimental base is further used for scientific research and at the same time provides support for teaching, studying and research on national and international levels.

4.1 The Dragonja River

The Dragonja river basin was chosen as an experimental catchment in 1999 (Globevnik, 2001). It is situated in SW Slovenia, the northern part of the Istrian Peninsula, on the border between Slovenia and Croatia (Fig. 15). The catchment area amounts to 91 km^2. In the past the area was mainly inhabited in the hilly ridge tops. In the 1960s and 1970s the region depopulated and this led to the abandonment of agricultural land use (Brilly and Globevnik, 2003). Combined with the anti-erosion vegetation stabilisation works, this caused natural reforestation of the land. The forest area has increased from 25% (in 1953) to more than 60% (Globevnik et al., 2004). The geological composition of the river basin is relatively simple and homogenous. Eocene flysch sediments predominate, mostly consisting of marl and sandstones. The bedrock is relatively soft and erodible. Soil is mostly carbonate rendzina, while some hill ridges have brown eutric soil. The Dragonja river basin belongs to the sub-Mediterranean climate region with average annual temperature of 14°C on the sea coast and 10°C on the eastern-most side. The total annual precipitation by the coast is on average 950 mm. This value increases further inland and reaches 1200 mm on the eastern end of the river basin.

Due to specific climatic conditions and extensive change in land use, extensive research on the effect of natural afforestation on hydrological conditions was carried out in cooperation with Vrije University of Amsterdam (Brilly and Globevnik, 2003; Šraj, 2004; Keestra et al., 2005; Brilly 2006b; Van der Tol et al., 2007; Šraj et al., 2008a). Gradual natural reforestation of the area resulted in a decrease in the minimum, median and maximum discharges of the Dragonja river. Two experimental forest plots were selected to research this phenomenon, one on the north-facing slope and the other on the south-facing slope. Some of the measuring equipment used in the research is shown in Fig. 16.

Figure 15: *Experimental catchments in Slovenia (1 – Dragonja river; 2 – Reka river; 3 – Gradaščica river).*

Slika 15: *Eksperimentalna porečja v Sloveniji (1 – reka Dragonja; 2 – reka Reka; 3 – reka Gradaščica).*

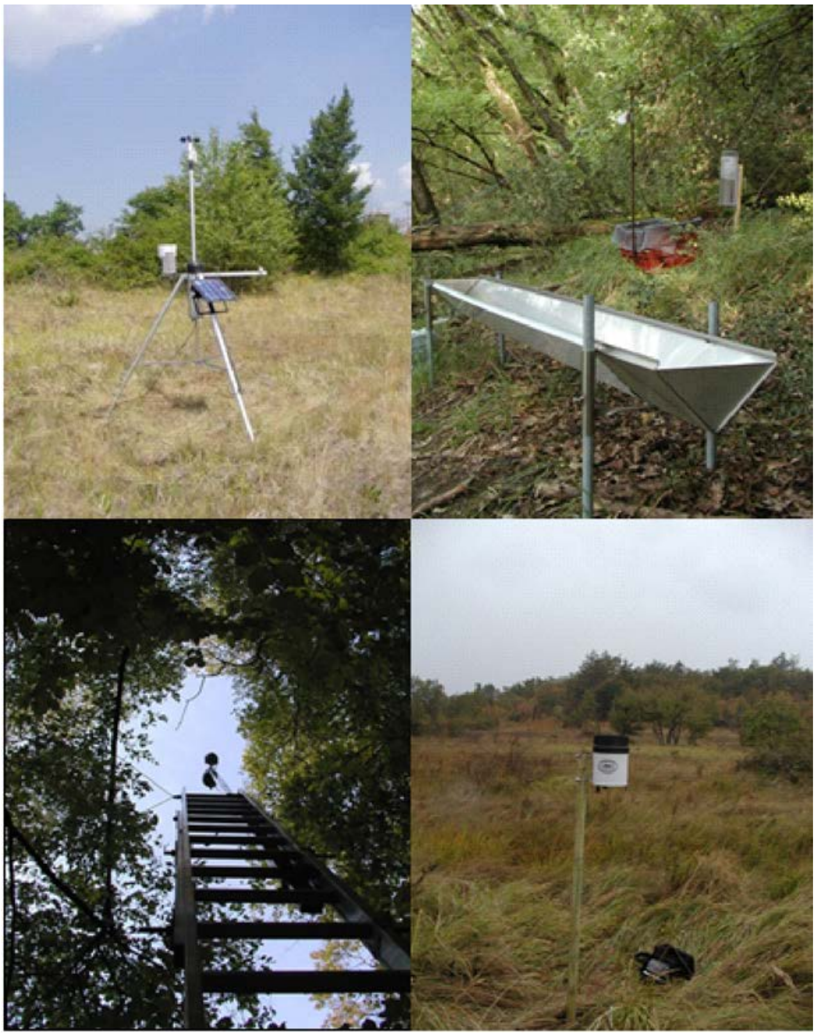

Figure 16: *Measuring equipment at the Dragonja river catchment.*

Slika 16: *Merska oprema na porečju reke Dragonje.*

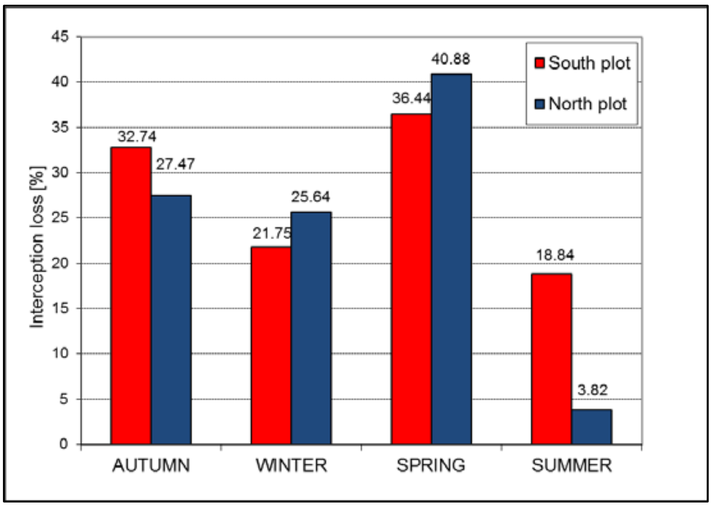

Figure 17: *Results of the interception loss by seasons for the two experimental forest plots (based on Šraj, 2008a).*

Slika 17: *Rezultati padavinskih izgub zaradi prestrezanja padavin po posameznih letnih časih na dveh eksperimentalnih gozdnih ploskvah (prilagojeno po Šraj, 2008a).*

According to the results of measurements and analysis of individual components of the forest hydrological cycle, the following conclusions could be made: the average values of throughfall amounted to 67.1 and 71.5% of the associated rainfall for the south and north research plot, respectively, while the average stemflow fraction was 4.5 and 2.9% for the south and north plot, respectively (Šraj et al., 2008a). The difference is a consequence of the different structure and characteristics of forests on both slopes (Šraj, 2004). On the basis of the measurements, water balance equation and models, it was calculated that the average annual interception losses amount to 28.4 and 25.4% for the south and north slope, respectively (Šraj et al., 2008a). The results of the interception loss measurements by seasons are shown in Fig. 17. The values are relatively high compared to other similar studies, which are usually between 15 and 25%. Such high loss of the deciduous forest of the Dragonja watershed is considerable and could be the reason for the reduction of surface water runoff.

The extension of forest cover strongly affected also the erosion processes in the Dragonja catchment headwater parts which were in the past one of the most active sites in terms of soil erosion. Petkovšek and Mikoš (2004) made initial estimation of the R factor from daily rainfall data. In 2006 and 2007 intensive soil erosion measurements were carried out at eight 1m^2 erosion plots with different land use (Petan et al., 2008). The results of the measurements show that interrill soil erosion in the forest is strongly connected with the vegetation period when the most intensive erosive events occur; the portion of the forest soil loss in the summer period, when the vegetation cover is adequately developed, is much lower than the soil loss on bare soil.

4.2 The Notranjska Reka River

The Notranjska Reka river (also called Reka River) was selected as experimental catchment by Slovenian IHP Committee in 1998 (Brilly et al., 2002). It has an area of 422 km^2 and a mean discharge of 8.26 m^3/s. The Reka river catchment is situated on the Brkini syncline Eocene flysch rocks surrounded by a large karstic region (Fig. 15). It is the widest known sinking stream of a classical karst area, and it has been studied since antiquity. The river sinks into the Škocjan Cave system, which was proclaimed by UNESCO as a World Heritage Site in 1986. Then the stream flows underground to the karst springs of the Timavo in Italy, and drains into the Adriatic Sea in the Trieste Bay. Initial experimental measurements of water velocity, water stage, suspended sediments concentration, chemical parameters and toxicity tests were carried out in 1999 and 2000 (Brilly et al., 2002). Intensive monitoring of hydrological cycle supplemented by continuous measurements of water chemistry and nutrients (nitrate) was initiated in 2004 in the Padež stream catchment, a tributary of the Reka river (Rusjan, 2006; Rusjan et al., 2008a; Rusjan et al., 2008b). Some of the measuring equipment used in the monitoring system is shown in Fig. 18.

The results of the measurements revealed interesting patterns of nitrate flushing during rainfall events in different seasons (Rusjan, 2006; Rusjan et al., 2008a; Rusjan et al., 2008b) and interesting hydrological behavior of the Padež catchment in different seasons (Rusjan and Mikoš, 2015). More than 15 recorded hydrographs which, in the hydrological and biogeochemical sense, differed substantially disclosed high variability. However, at the same time a strong linkage between hydrological and biogeochemical controls of nitrate exports from the spatial perspective of a catchment (Rusjan et al., 2008a) (Fig. 19). During most of the hydrographs, with the exception of early spring rainfall events, a positive relationship between nitrate concentration and discharge was observed with peak nitrate concentrations having a time delay of a few hours after the hydrograph peaks (Fig. 19). Peak nitrate concentrations in periods of rainfall events span from 3.5 mg/l-N in late spring to 14 mg/l-N in the case of the autumn hydrograph (Rusjan et al., 2008a). The role of specific hydrological events on nitrate mobilization proved to be important as the size of the accumulated nitrate pool available for mobilization was large throughout most of the hydrographs. Based on the extensive dataset, a model describing the flushing of nitrate was constructed using the regression tree data mining algorithm (Rusjan and Mikoš, 2008). The model was most successful in describing stream water concentrations in the range 1–4 mg/l-N, covering large proportion of the dataset. The model performance was little worse in the periods of high stream water nitrate concentration peaks during the summer hydrographs (up to 7 mg/l-N) and poor during the autumn hydrograph (up to 14 mg/l-N), which is related to highly variable hydrological conditions that would require a less robust regression tree model based on the extended dataset (Rusjan and Mikoš, 2008). Additionally, continuous measurements of water quality parameters disclosed interesting seasonal and daily patterns which disclose interesting ecohydrological functioning of the stream and its tight connection with the catchment area (Rusjan and Mikoš, 2010).

Figure 18: *Measuring equipment at the Reka river catchment.*

Slika 18: *Merska oprema na porečju reke Reke.*

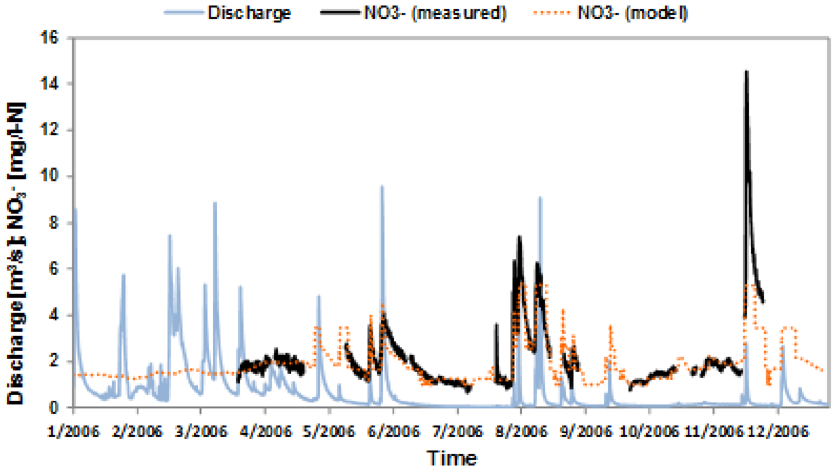

Figure 19: *Measurements of Padež stream discharge, nitrate concentration and results of the nitrate flushing modelling.*

Slika 19: *Meritve pretoka vodotoka Padež, koncentracije nitratnega dušika in rezultati modela spiranja nitratnega dušika.*

4.3 The Gradaščica River

The Gradascica river basin spreads in the transitional area from the Dinaric into Alpine region in the central part of Slovenia (Fig. 15). The headwater section flows through the varied mountain relief of the Dolomites, and is carved with numerous ravines and valleys. The Gradaščica river watershed comprises an area of 154.4 km^2, which reaches far into the Polhov Gradec mountainous area. Position of the Gradaščica catchment in the Alpine-Dinaric barrier results in high rainfall amounts (yearly averages between 1600 and 1800 mm). The highest rainfall totals are observed in autumn, and high rainfall amounts can also be observed during summer due to frequent storms. Steep slopes, fairly high altitudes and abundance of precipitation result in torrential response of the numerous tributaries in the headwater parts of the catchment and the Gradaščica river. The plain area of the Ljubljana basin widens on the eastern part of the catchment. The western part of the urban areas of the city of Ljubljana is heavily exposed to flooding of the Gradaščica River and its tributary in that region, the Glinščica stream (Brilly et al., 2006a). Some of the measuring equipment used to perform various measurements there is shown in Fig. 20.

The analysis of the impact of urbanization on hydrological and ecological conditions was the primary goal of the monitoring system established at the Glinščica stream catchment (Brilly et al., 2005; Brilly et al., 2006a). The watershed was equipped with three rainfall stations, a Doppler velocity meter and a water quality multi parameter probe. In a short period of time more than 10 thunderstorm events were recorded and analyzed. The hydrological response of the watershed was analyzed and, interestingly, it did not show the ‘‘typical’’ urban impact on the runoff processes. In the sense of decreased concentration time of the precipitation runoff, the hydrological response of the watershed has not changed considerably (Brilly et al., 2006a).

The main water quality parameters such as temperature, pH, TDS, ORP, conductivity, dissolved oxygen and especially the concentrations of nitrate and ammonium, were measured to obtain an insight into seasonal and short time dynamics of water quality (Brilly et al., 2004; Brilly et al., 2006a) (Fig. 21). The measurements showed substantial seasonal and along-the-channel variations of concentration of dissolved oxygen, nitrate and ammonium content due to biochemical processes in the channeled stream. The continuous tracing of nitrate and ammonium showed significant influence of stream regulation works on short time variations of the measured water quality parameters. The small stream with low flow and in-stream water content due to configuration of the regulated concrete channel is highly exposed to pollution and should be protected. The good conditions in the head part of the stream, which was moderately degraded through regulations, may provide a starting point for revitalization measures and subsequent removal of the concrete linings from the bottom and stream banks in the downstream section (Brilly and Rusjan, 2006).

Due to torrential response of the catchment and rather erodible geological formations, there is a huge sediment yield potential in the Gradaščica river headwaters; consequently the river transports large amounts of sediment. A significant proportion of the sediment is deposited in the Ljubljanica river channel. This could cause reduction of the Ljubljanica river channel conveyance and possible worsening of the flood situation.

In order to obtain an insight into the soil erosion processes in the headwater part of the Gradaščica catchment, a geomorphic change detection was performed using DTM of Difference approach (Bezak et al., 2016b) supported by continuous measurements of the suspended sediment concentration. During one extreme rainfall event in August 2014 with a return period exceeding 100 years causing extreme flash flood, erosion rates by an order of magnitude higher than average annual rates were calculated. Additionally, during another flood event in October 2014, according to the suspended sediment concentration measurements, approximately 20,000 t of suspended sediment material was transported through the Gradaščica river cross section at the water gauging station Dvor at the foothills of the Polhov Gradec mountainous area.

***Figure 20:** Measuring equipment at the Gradaščica river catchment.*

***Slika 20:** Merska oprema na porečju reke Gradaščice.*

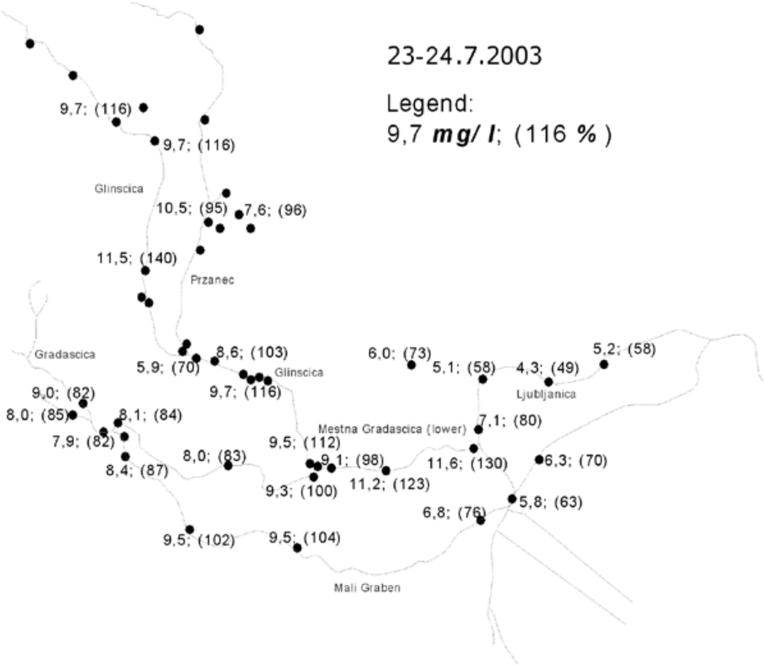

***Figure 21:** Measurements of dissolved oxygen concentrations in the Gradaščica and Glinščica rivers in the urban area of the city of Ljubljana (from Brilly et al., 2004).*

***Slika 21:** Meritve koncentracije raztopljenega kisika v reki Gradaščici in potoku Glinščica na območju urbanih površin mesta Ljubljane (povzeto po Brilly et al., 2004).*

5. Conclusions

Water is all around us on the Earth, but its cycling is not easy to understand. Field measurements and monitoring are essential for better understanding of the main hydrological processes, involving ground water and surface waters, their mutual interactions, and exchange with the atmospheric water. If much longer measured data sets of meteorological and hydrological variables of any kind were available, we would probably not even discuss climate change today, and would treat it to a large extent as climate variability. Among main tasks of contemporary hydrology are multidisciplinary approach (e.g. socio-hydrology), consideration of non-stationarity of the world, real-time learning through observations, modeling and management etc. (Wagener et al., 2010; Montanari et al., 2013).

This review of the selected hydrological studies shows that hydrology in Slovenia follows the contemporary trends in the world. As we look back, it is easy to see that Slovenian hydrology has indeed made incredible advances and contributions in the last two decades or so. A great contribution to the advancement of hydrological sciences in Slovenia can be attributed to Professor Brilly, his dedication to research and his laudable attitude to his friends and colleagues. At the occasion of his 70th Birthday, we would like to acknowledge his contributions to the advancement of hydrology in the world and specifically in Slovenia.

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