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RECENT ADVANCES IN FLOOD HYDROLOGY – CONTRIBUTIONS TO IMPLEMENTING THE FLOOD DIRECTIVE

NAJNOVEJŠI NAPREDEK V HIDROLOGIJI POPLAV – PRISPEVEK K IZVAJANJU POPLAVNE DIREKTIVE

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Abstract

Flood risk management has recently evolved from a focus on individual flood protection structures to a more integrated approach at the river basin scale that considers a diversity of management options. Suitable methods are needed to assist in the implementation of these options. This paper reviews new methodological developments on the following themes: hazard mapping, large scale interactions of floods, residual risk (flood prevention); retaining water in the landscape, linear protection measures, flood retention (flood protection); flood warning, flood awareness, long term trends (flood preparedness). The new methods are intended to contribute to even more reliable and more efficient management of flood risks. The paper is dedicated to Professor Brilly on the occasion of his 70th birthday.

Keywords: flood risk, flood management, flood hazard mapping, flood retention, flood warning, flood changes.

Izvleček

Obvladovanje poplavne ogroženosti se je nedavno preusmerilo s posameznih objektov za varovanje pred poplavami na izvajanje celovitejšega pristopa na ravni porečja, ki upošteva različne možnosti upravljanja. Za izvajanje teh možnosti potrebujemo ustrezno metodologijo. V članku podajamo pregled metodološkega napredka na naslednjih področjih: kartiranje ogroženih območij, obsežni medsebojni vplivi poplav, preostalo tveganje (preprečevanje poplav); zadrževanje vode v krajini, linearni zaščitni ukrepi, zadrževanje visokih voda (varovanje pred poplavami); opozarjanje na poplave, osveščenost o poplavah, dolgoročni trendi (pripravljenost na poplave). Namen novih metod je prispevati k še zanesljivejšemu in učinkovitejšemu obvladovanju poplavne ogroženosti. Članek posvečam profesorju Brillyju ob njegovi sedemdesetletnici.

Ključne besede: poplavna ogroženost, obvladovanje poplav, kartiranje nevarnosti poplav, zadrževanje poplavnih voda, opozarjanje na poplave, spremembe poplav.

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1. Floods in recent times and the EU Flood Directive

Numerous large floods have recently occurred in Europe. The 2013 flood in the Upper Danube was close to the August 1501 flood, the largest known event in history (Blöschl et al., 2013). Another example is the November 2012 flood in Southern Austria. The September 2010 flood in Slovenia was one of the worst floods in the country's history (Kobold, 2011).

While society has always had to deal with floods in some way, there has been a recent change in addressing this issue. In the past, the focus has often been on individual protective measures. More recently, the emphasis has shifted towards a combination of many different measures viewed from a river basin perspective in line with the more modern concept of "integrated flood risk management". This new view is also reflected in the EU Flood Risk Management Directive (EU, 2007) which establishes a framework for Europe to deal with flood risks. The framework stipulated by the Directive requires the implementation of flood risk management plans that involve a diverse set of measures broadly classified into

- flood prevention
- flood protection, and
- flood preparedness.

The purpose of this paper is to review recent advances in flood hydrology research conducted in Austria and put them into the context of some of the excellent flood research Professor Mitja Brilly from the University of Ljubljana has performed over the years. Mitja Brilly and colleagues reported that the total inundated area covered by extreme flood events (100 year floods) in Slovenia is 695 km² (Mikoš et al., 2004), and the potentially inundated area in Austria is even larger. Both Slovenia and Austria are therefore countries prone to severe floods. The advances in flood research reviewed in this paper are specifically intended to contribute to the implementation of the Flood Directive and are therefore organised into contributions to prevention, protection, and preparedness.

2. Flood prevention

Flood risk zoning to guide land use planning and thus flood prevention has traditionally been based on mapping observed flood events, but a more flexible and balanced method is using two-dimensional hydrodynamic models. Such models are computationally rather expensive, so a reduction in computation time is important. New numerical methods now make it possible to reduce computation times considerably by making use of graphic processors (GPUs). Horváth et al. (2015) introduced a new numerical scheme to solve the Saint-Venant system of shallow water equations that is specifically geared towards the use of GPUs, and is robust, particularly for dry-wet transitions that are numerically difficult to handle. Fig. 1 shows an example of the simulations in an urban area. The method allows large areas with millions of cells to be run within reasonable time frames, thus contributing to more reliable flood hazard maps.

One of the important objectives of flood risk management plans is to account for the regional interactions of floods in the process of identifying risk zones. New methods of Monte Carlo simulations based on stochastic rainfall models take such interactions into account in a statistically consistent way, both in terms of anthropogenic effects (such as retention basins) and in terms of the interactions of soil moisture and event precipitation. Rogger et al. (2012; 2013) demonstrated the benefits of this approach for a number of catchments in Tyrol. Such models are also particularly suited for estimating the financial damage (or residual risk) in case extreme floods exceed the protection level of, say, a 100 year flood (Apel et al., 2006).

In addition to the financial aspects, other preventive measures are needed such as flood-adapted building and emergency plans in case design floods are exceeded as, often, there is an additional element of surprise. Merz et al. (2015) developed a concept for dealing with the surprises of extreme floods and singled out two main causes of surprise: (1) the complexity of the flood risk system, due to non-linearities, interdependencies and non-stationarity and (2) cognitive biases in human perception and decision making. They used the metaphors of Terra incognita and Terra maligna to illustrate unknown and malicious flood situations from the perspective of the actors (e.g. flood managers) (Fig. 2). These concepts are intended to contribute to more robust flood risk management instruments that are effective irrespective of the exact causes and characteristics of extreme floods.

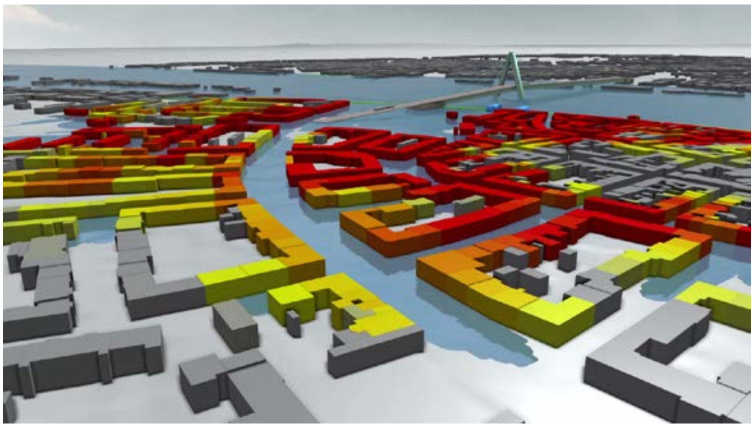

Figure 1: *Flooding simulations of a two-dimensional hydrodynamic model. The buildings are colour coded according to water depth. New technologies such as the use of graphic processing units and new numerical schemes allow massive reductions in computation times. After Horváth et al. (2015).*

Slika 1: *Simulacija poplavnega dogodka z uporabo dvo-dimenzijskega hidrodinamičnega modela. Barve stavb so določene glede na modelirane vrednosti vodne gladine. Razvoj novih tehnologij, kot je uporaba grafičnih procesorjev ter novih numeričnih shem, omogoča izrazito zmanjšanje računskih časov. Povzeto po Horváth et al. (2015).*

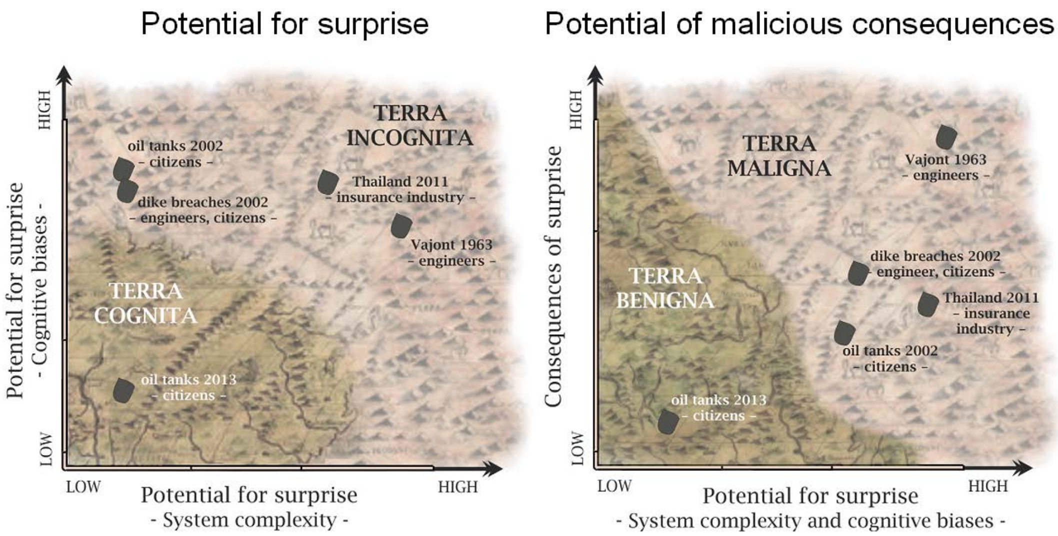

Figure 2: *Dealing with residual risks. Left: Potential for surprise illustrated by the metaphor of terra incognita. Each event is linked to the perspective of a specific group of stakeholders such as citizens or engineers. Right: potential of malicious consequences illustrated by the metaphor of terra maligna. From Merz et al. (2015).*

Slika 2: *Obravnava preostalega tveganja. Levo: Primer potenciala presenečenja, ki je prikazan z metaforo terra incognita. Vsak dogodek je povezan s perspektivo določene interesne skupine kot so prebivalci ali inženirji. Desno: Potencial neugodnih posledic, ki je prikazan z metaforo terra maligna. Povzeto po Merz et al. (2015).*

3. Flood protection

An important principle of the new flood risk management concept is to mitigate floods, if possible, where they are generated, i.e. in the headwaters. This is a concept known as "retaining water in the landscape", for example by afforestation. The effect of land use change on flooding can be simulated by numerical models (Blöschl et al., 2007). New methods take into account not only the sequence of events, but also other factors such as changes in evaporation and soil moisture at the beginning of the event. Typically, such studies find that land use change will only affect small floods, while large floods are mainly controlled by precipitation (e.g., Salazar et al., 2012). However, much uncertainty in the parameterisation of such models remains. The construction of levees remains an important part of the management portfolio and therefore accurate estimation of design floods is essential.

Mitja Brilly and colleagues contributed to the design flood issue in many ways. Šraj et al. (2012), for example, noted that flood frequency estimates strongly depend on the choice of method and therefore care must be exercised in selecting suitable distribution functions and parameter estimation methods. They provided guidance on method choice. While, in the past, design floods were often based on statistical methods and measured discharge series alone, Merz and Blöschl (2008) proposed the concept of "Flood Frequency Hydrology" that uses additional information. This additional information may be spatial (regional floods), causal (rainfall-runoff process), or temporal (historic floods). This concept also underpins the German flood estimation guidelines (DWA, 2012). Fig. 3 illustrates the value of the concept, implemented by the Markov chain Monte Carlo (MCMC) method. If one only uses the flood peak data, the credibility interval of the estimated 100 year flood is very wide and, depending on whether the extreme 2002 flood is considered or not, the estimates differ substantially. If additional information is included, the credibility interval becomes narrower and the 2002 event has hardly any effect on the results. Clearly, additional information strengthens the reliability of flood probability estimates.

Mitja Brilly and colleagues also contributed comprehensively to the issue of flood probability changes. Bezak et al. (2016) found a statistically significant increasing trend of floods for the Sava River. They also showed that the identified trends and their statistical significance depended on how the samples were defined. Brilly et al. (2015) projected peak discharge probabilities into the future and suggested that the 100 year floods will increase by between 9 % (in the headwaters) and 55% (in the lower river reaches) by the end of the twenty-first century. These Slovenian findings fit very well into a European context (Hall et al., 2014). Floods can be increased by three main factors: climate, land use and river works, and their influence depends on the size of the event and the catchment area (Blöschl et al., 2015). Similar to Brilly et al. (2015), Blöschl et al. (2011) projected floods in Austria into the future, and noted that changes will be particularly relevant for rain-on-snow events. Still, more work is needed on this issue.

As highlighted by Šraj et al. (2012), estimates of peak discharges associated with a given return period do not usually suffice for designing flood protection measures, and hydrograph shapes or volumes are needed. A key question in this context is how closely peaks and volumes are correlated, and whether this correlation varies with the size of the event. Gaál et al. (2015) found that this relationship depends on the flood generation mechanism. Flash floods showed a flatter slope of the peak-volume relationship than synoptic floods and snow melt floods, and flash floods showed the highest correlations between peaks and volumes. Mitja Brilly and colleagues identified suitable models for this relationship, and found one such model (Gumbel–Hougaard copulas) to be particularly well suited (Šraj et al., 2015).

The shape of the hydrograph will control the effectiveness of flood retention areas to reduce peak discharges. Skublics et al. (2016) showed that for the Bavarian Danube the timing of the filling of the retention areas is crucial too (Fig. 4). In the current situation, the retention effect increases strongly with the size of the event, but for the historical situation (in the year 1800 prior to the implementation of river training measures), this is not the case, and the damping of extreme floods was much smaller than today. This is because the available volume was exhausted at the beginning of the event, so no free volume was left at the time of the peak. These mechanisms need to be accounted for in designing and managing flood control polders.

4. Flood preparedness

In case a flood is immanent, flood warnings can substantially reduce damage and loss of life. Accurate flood forecasting methods are therefore needed, and any uncertainties in the forecasts need to be quantified. Kobold and Brilly (2006) evaluated the hydrological uncertainty from input precipitation in a flood forecasting system. They showed that a 10% error in precipitation will translate into a 17% error in the flood peak due to the non-linearities involved. In a similar vein, Blöschl (2008) developed an ensemble flood forecasting system that allows the dynamic estimation of forecasting errors due to precipitation and other factors. An example of such ensemble forecasts during the 2013 flood at the Salzach river, Austria, is shown in Fig. 5. The figure indicates that the forecasts are most accurate for short lead times that are based on flood routing of observed runoff, and least accurate for long lead times that are based on rainfall-runoff modelling of predicted precipitation. This kind of uncertainty information is essential for more robust decision making during flood situations.

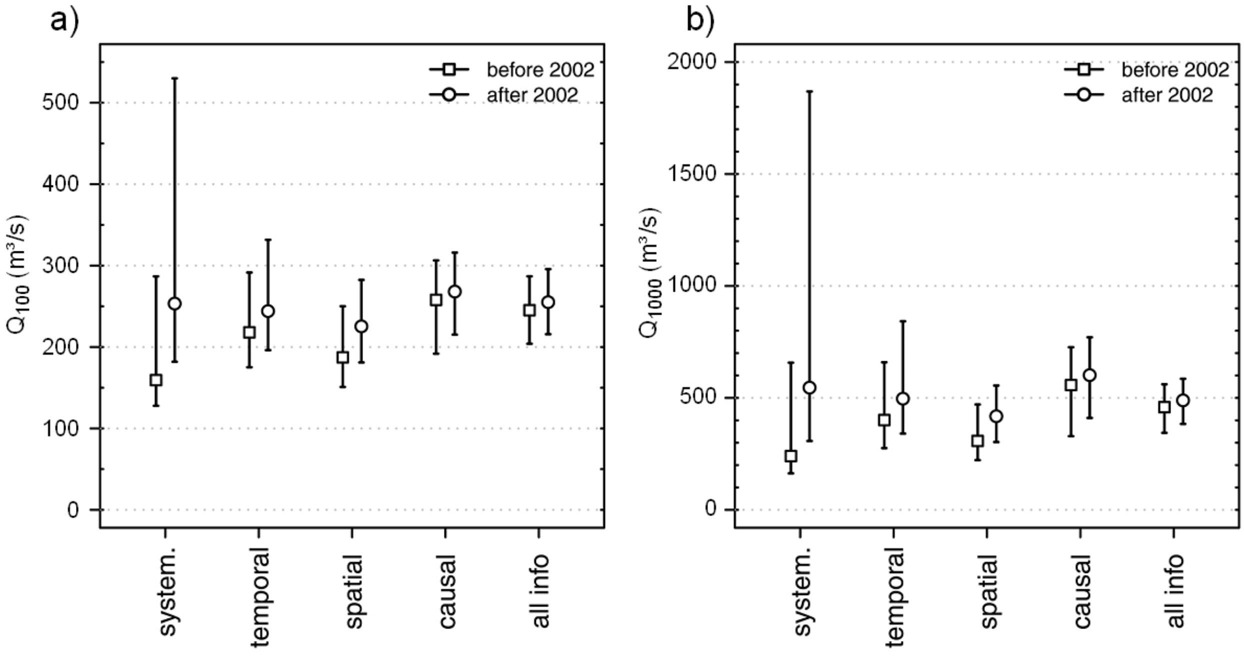

Figure 3: *Estimates of Q_{100} (a) and Q_{1000} (b) with 90% credible bounds for Zwettl at the Kamp, Austria, before and after the big 2002 event. In the first case (system.) just the systematic flood data are used. The following cases show the estimates using additional pieces of information (temporal, spatial, causal). Additional information reduces the uncertainty significantly. From Viglione et al. (2013).*

Slika 3: *Ocene stoletne Q_{100} (a) ter tisočletne Q_{1000} (b) povratne dobe z 90 % intervali zaupanja za Zwettl at the Kamp v Avstriji pred in po veliki poplavi, ki se je zgodila leta 2002. V prvem primeru (ang. system.) so uporabljeni samo sistematično pridobljeni podatki. Naslednji primeri pa prikazujejo ocene dodatnih informacij (časovne, prostorske, vzročne). Dodatne informacije izrazito zmanjšujejo stopnjo negotovosti. Povzeto po Viglione et al. (2013).*

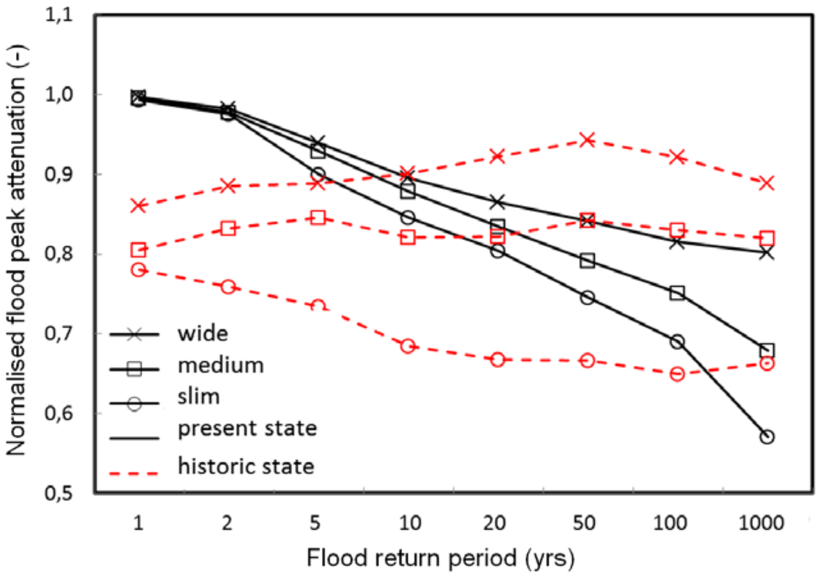

***Figure 4:** Flood retention for a reach of the Bavarian Danube between Neu-Ulm and Donauwörth. Flood peak retention is defined as the ratio of flood peak discharges with and without retention. For the current situation (solid lines) the retention effect decreases sharply with the flood magnitude, while for the historic situation (dashed lines) this is not the case. From Skublics et al. (2016).*

***Slika 4:** Zadrževanje poplavne vode na odseku bavarske Donave med Neu-Ulm in Donauwörth. Zadrževanje konice pretoka je definirano kot razmerje med konico pretoka z in brez zadrževanja. Za sedanje stanje (polne črte) se vpliv zadrževanja izrazito zmanjšuje z večanjem povratne dobe, medtem ko to za zgodovinske dogodke (črtkane črte) ne velja. Povzeto po Skublics et al. (2016).*

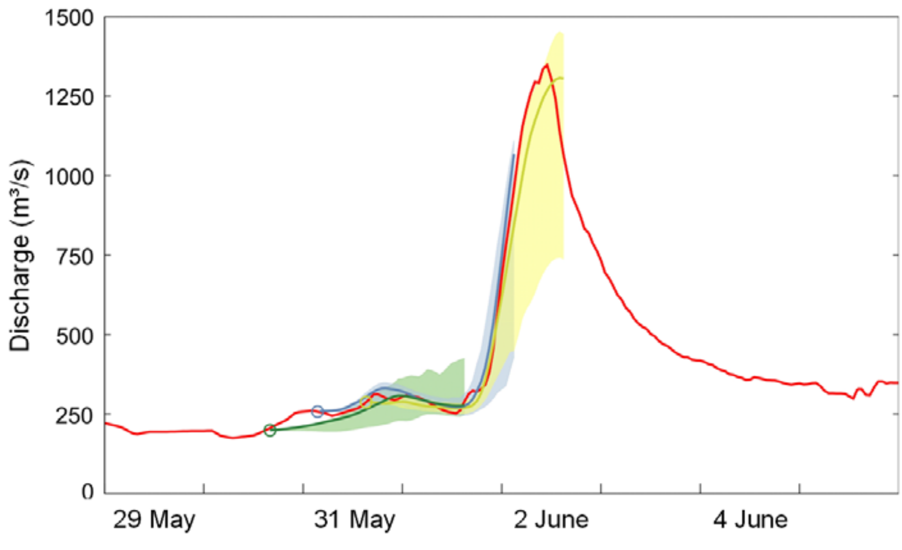

***Figure 5:** Flood forecasts for the Salzach at Golling during the 2013 flood. Forecast times: 30 May, 3 pm; 31 May, 3 am; 31 May, 3 pm. Timing of the flood peak: 2 June, 1 pm. Shaded areas indicate confidence intervals of the forecasts. Red line indicates observed hydrograph. Based on Nester et al. (2012).*

***Slika 5:** Poplavna napoved za Salzach pri Gollingu med poplavo leta 2013. Napovedani časi: 30. 5. ob 15:00; 31. 5. ob 3:00; 31. 5. ob 15:00. Čas nastopa konice pretoka: 2. 6. ob 13:00. Osenčena območja označujejo intervale zaupanja za napovedi. Rdeča črta označuje merjeni hidrogram. Prilagojeno po Nester et al. (2012).*

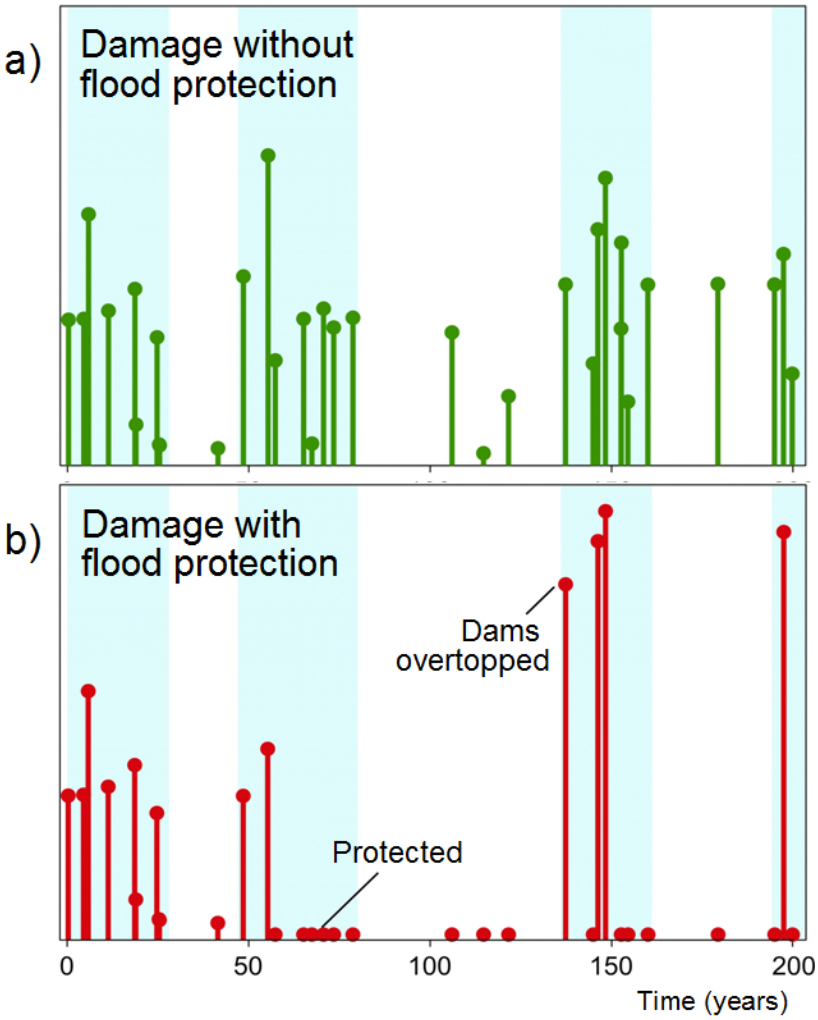

Figure 6: *Two scenarios of flood damage for a hypothetical city. (a) Flood management options involve the choice of settling close or far away of flood prone river but no levees. (b) Flood management options also involve the construction of levees. Light blue areas indicate flood rich periods, white areas flood poor periods. This approach is well suited for assisting outreach and education activities. From Blöschl et al. (2015); based on Di Baldassarre et al. (2013) and Viglione et al. (2013).*

Slika 6: *Dva scenarija poplavne škode za hipotetični primer mesta. (a) Upravljanje z vodami vključuje izbiro naselij blizu ali zelo daleč od reke, ki lahko poplavlja, vendar nasipi niso predvideni. (b) Upravljanje z vodami vključuje tudi izgradnjo nasipov. Obdobja označena s svetlo modro barvo so obdobja s pogostimi poplavami, bela območja pa prikazujejo obdobja, ko poplave niso pogoste. Ta postopek je zelo primeren za podporo dejavnostim ozaveščanja in izobraževanja. Povzeto po Blöschl et al. (2015); prilagojeno po Di Baldassarre et al. (2013) ter Viglione et al. (2013).*

On a longer time scale, it is important to assess and manage the awareness of the general public to flood risks. Brilly and Polic (2005) analysed the social aspects and public response to flood mitigation measures and information management for the Slovenian town of Celje. They conducted surveys that suggest that floods are indeed perceived to represent a serious threat, and that the perception of threat depends on the location of residence. The surveys also highlighted, among other measures, solidarity and the importance of insurance against floods. More generally speaking, an understanding of flood occurrence and the associated mechanisms may contribute to flood awareness. This is particularly relevant with respect to the effect flood protection measures may have on floods in the long term. These effects have traditionally been assessed by scenarios that account for individual factors (retention areas, levees, dams), while the new discipline of socio-hydrology adopts a more holistic perspective of analysing the two-way interactions between the socio-economic and hydrological system components (Sivapalan et al., 2012; Sivapalan and Blöschl, 2015). As an example, Fig. 6 shows simulated flood damage over a period of 200 years. The coupled model simulates the development of a hypothetical city in this period, specifically whether citizens decide to settle near the river (which entails economic benefits) or far away from the river (which avoids flood damage), and they can decide to construct flood control levees (which, however, can be overtopped). In Fig. 6a there is only the option of settling away from the river (but no levees are allowed) which results in a sequence of flood damages. If levee construction is allowed (Fig. 6b), flood damage can be initially reduced, but during a flood poor period people tend to build next to the levees which increases the damage once the flood rich period starts (at time 140 in the figure). These are clearly very complex dynamics. Models of this kind may help to increase flood awareness in complex human-water systems.

5. Concluding remarks

Floods will continue to occur in the future both in Austria and Slovenia, but suitable flood management tools have been developed, supported by advanced hydrological estimation methods and predictions. Professor Mitja Brilly has contributed tremendously to hydrological research and practice, and this publication is dedicated to him on the occasion of his 70th birthday. It is hoped that a new generation of hydrologists will continue to shape the discipline in a similarly energetic way he has over the years. Ad multos annos.

This line of research is deeply indebted to the work of Prof. Mitja Brilly and his group of researchers. This paper is dedicated to him on the occasion of his 70th birthday.

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