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Floodplain losses and increasing flood risk in the context of recent historic land use changes and settlement developments: Austrian case studies

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Abstract

Floodplains play a central role in flood risk management since they function as retention areas which attenuate and decelerate flood waves. However, during the last decades land use has changed distinctly on floodplains which has led to a change in topography due to the construction of levees and dykes. Using geographic information system analysis we assessed floodplain developments over 60 years for five Austrian rivers. We used these findings as input for hydrodynamic-numerical modelling. A comparison of computations of current and historic floodplain topographies demonstrated the complex impacts that changes on floodplains have on catchment level flood risk. Results showed that the losses of floodplains were in general linked to a deterioration in hydrological (flood peaks and travel times) and hydraulic (water level) parameters. In rare cases the unintentional overtopping of dykes resulted in an improved reduction of the peak of the flood wave, but included a worsening of local hydraulic conditions. Hence, this study demonstrates that general conclusions about an alteration of flood risk cannot be easily reached, with a demand for further site-specific assessment. This novel way of investigating the trends of flooding characteristics by including the historic development within a catchment offers valuable information to planners for a future flood risk management.

KEYWORDS

floodplain evaluation matrix, floodplains, historic changes, integrated flood risk management

1 | INTRODUCTION

Among all natural disasters, floods have the greatest damage potential worldwide (UNISDR, 2015). In 2016 a number of 164 large flood events all over the world was reported which affected more than 78 million people and implicated more than 4,700 deaths (CRED, 2016). International studies revealed exemplarily that the number of floods in Europe has dramatically increased recently (Barredo, 2007). Statements that are equally valid for Austria which has been hit by severe flooding events in the last years.

There are several reasons for the rise in flood events and the associated number of damages: Climate change certainly plays a significant role in this context (Vörösmarty et al., 2010), but also altered flow regimes for example, land use changes in the total catchment or constrained river morphologies and the associated loss of retention capacity in those reduced floodplains lead to a worsening of flood conditions (Bogardi, Leentvaar, & Nachtnebel, 2012; Milliman, Farnsworth, Jones, Xu, & Smith, 2008).

In developed countries, floods have especially been unintentionally intensified by hydraulic structures that were thought to protect people from flooding. Such conventional (structural) flood protection measures like dykes cut off floodplains from the active channel so that they are no longer capable of functioning as retention areas and lead to higher flood peaks and accelerated travel times downstream (Kundzewicz & Menzel, 2005; Messner & Meyer, 2006).

Nowadays, it is widely accepted that flood risk management needs an interdisciplinary approach (Bornschein & Pohl, 2018). More than ever, there is the need for decision-makers to adopt holistic approaches which do also comprise non-structural measures like the preservation and/or restoration of floodplains as it is demanded by the EU Floods Directive (EU, 2007). However, river floodplains have always attracted urban development. This is why nowadays, many floodplains have been cut off from the river, and worldwide more than 50% of the wetland surface is estimated to be lost, while in much of Europe, this percentage is even higher (Davidson, 2014; Kundzewicz & Menzel, 2005).

Land use changes in the catchment areas with potential impact on flood characteristics have been in the centre of attention of various studies (O'Connell, Ewen, O'Donnel, & Quinn, 2007). All of these studies with their highly diverging results demonstrate the complexity of this thematic area including various uncertainties. But a major effect accompanying land use changes has been neglected in most of these studies. This is the loss of floodplains when agricultural land is converted to higher value uses like urban areas which are then protected by dykes and therefore cut off from the river.

While there exists broad knowledge on inundation mapping and modelling techniques (e.g., Balica, Popescu, Beevers, & Wright, 2013; Hunter, Bates, Horrit, & Wilson, 2007; Merwade, Cook, & Coonrod, 2008; Teng et al., 2017; Yan, Baldassarre, Solomatine, & Schumann, 2015), only very few studies investigate these developments on a larger scale and in a historic context (e.g., Fliervoet, Van den Born, Smits, & Knippenberg, 2013; Herget & Meurs, 2010; Luo et al., 2015). And even less studies focus on rivers in mountainous regions like the alpine catchments where space is principally scarce and development on floodplains led to significant changes in the valleys. A study by Skublics and Rutschmann (2015) at the Upper Danube in Bavaria compared the flood situation between the actual state and historic conditions of 1800. It demonstrated the complex interaction of floodplain losses on the one hand and compensating flood protection measures on the other resulting in distinctly shortened flood wave travel times. Another study at the Tagliamento River in Italy (Spaliviero, 2003) outlined the loss of floodplains due to the construction of dykes and – associated with this – a consistent rise in flood risk.

Besides these few specific studies, there is still a strong need for integrating dynamics in land use development to state-of-the-art flood risk analysis. Therefore, due to the lack of detailed knowledge about the impacts of land use changes on flood processes this paper aims to present an integrative analysis of land use changes and consequences on flood hazard. The results of five Austrian rivers show the complexity of the evaluation of historic changes and their impact on flooding characteristics. These results shall serve as a basis for decision makers in order to evaluate different flood mitigation strategies. In the companion paper (Habersack & Schober, 2020) a method is presented for evaluating the current state of floodplains in regard to various parameters which are important for flood hazard analysis. This paper now complements this first paper by extending the view from the current status to a historic analysis of floodplain losses during the last decades and their effects on flood hazard.

2 | CASE STUDY SITES

Five Austrian rivers have been chosen to test the method on various geomorphological (slope, floodplain widths, etc.) and hydrological (flood wave shape and magnitude) settings in order to allow for comparisons between different river types (Figure 1). In the following, information about the rivers (especially their HQ_{100}-values) is given. The HQ_{100}-value refers to an extreme hydrologic flood event having a 100-year recurrence interval. These values have been obtained through long term gauge observations by the hydrographical services in Austria using the definitions and methodology of USGS (2019).

Inn: The Inn is the largest river in Tyrol and one of the major tributaries of the Upper Danube. It drains nearly all of North Tyrol and features in its middle and lower reach wide valleys which are home to several big cities like Innsbruck. The study area comprises the 190 km long course in Austrian territory from river-km 410 at Kajetan to river-km 220 at Kufstein at the Austrian-

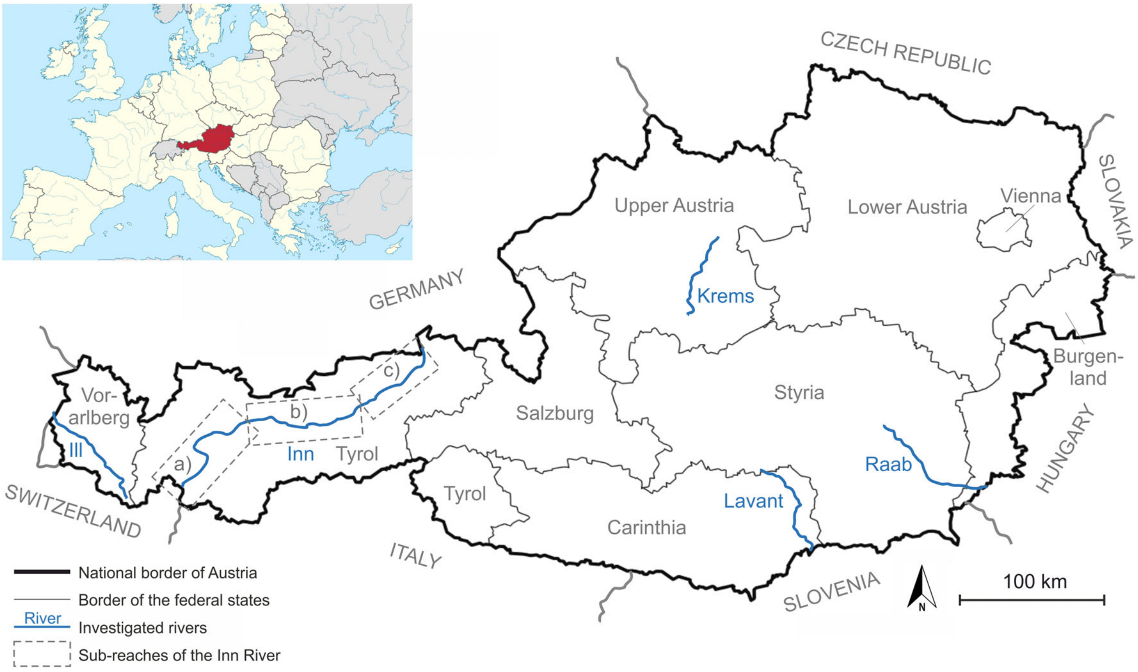


FIGURE 1 Map of Austria showing the five study reaches

German border (46°57′07.20″N; 10°30′45.21″E to 47°36′04.03″N; 12°10′41.27″E). The catchment area is about 9.310 km^2. The HQ_{100} at the outflow is about 2.388 m^3/s.

Ill: The Ill is a major river in Vorarlberg and discharges into the Rhine. The study area extends from river-km 60 to 0 (40°57′58.95″N; 10°04′01.27″E to 47°17′58.98″N; 9°33′30.87″E). The HQ_{100} at the outflow is about 360 m^3/s.

Krems: The Krems in Upper Austria has been exposed to serious flooding in 2002. Due to numerous settlements and industrial/commercial facilities along its 35 km long course, heavy damages occurred. The study area comprises the total river (47°51′24.42″N; 14°08′59.95″E to 48°12′20.03″N; 14°15′56.05″E). The HQ_{100} at the outflow is about 330 m^3/s.

Lavant: The Lavant is a big river in Carinthia featuring alpine characteristics in its upper reach and big settlements in its lower reach. It was investigated from river-km 35 to 0 (47°01′26.42″N; 14°43′45.91″E to 46°12′20.03″N; 14°56′38.09″E). The HQ_{100} at the outflow is about 300 m^3/s.

Raab: The Raab is a meandering lowland river in Styria. This river has been investigated from river-km 78 to 19 (47°15′49.27″N; 15°34′56.93″E to 46°56′02.39″N; 16°04′40.72″E). The HQ_{100} at the outflow is about 300 m^3/s.

In order to demonstrate the complexity of the investigated parameters, this paper will exemplarily present the results of the Inn River in detail, which is the largest of the examined rivers and covers by its different river reaches the main findings, which are also applicable to the other rivers. These three subreaches are depicted in Figure 1 and comprise the Upper Inn (Kajetan to Telfs, 82 km length), the Middle Inn (Telfs to Jenbach, 73 km length), and the Lower Inn (Jenbach to Kufstein, 35 km length). However, the general findings of all five rivers will be presented and discussed at the end of the paper.

3 | SOURCES AND METHODS

The methodology for the presented study can be divided into two major steps: (a) the assessment of land use changes over the past decades and (b) the analysis of these changes in regard to alterations of the flooding situation.

3.1 | GIS analysis of land use changes

For GIS analysis, geospatial referenced actual and historic aerial photos and area zoning plans have been imported and digitalized within the programme ArcGIS® (version 10.5). Data was collected for the last 60 years covering the time period of 1950–2010, with discrete evaluation dates of 1950, 1970, 1990, and 2010 (Table 1). Label datasets were compared and land use changes were assessed for both (a) absolute changes in m^2 and

TABLE 1 Input data for the GIS analysis of land use changes

	Inn (upper reach)	Inn (middle reach)	Inn (lower reach)	Ill	Krems	Lavant	Raab
Source of digital area zoning plan	TIRIS			VOGIS	DORIS	KAGIS	GIS-Stmk
Source of orthophotos 2010	TIRIS			VOGIS	DORIS	KAGIS	GIS-Stmk
Source of orthophotos 1950, 1970, and 1990	TIRIS, BEV			VOGIS	DORIS, BEV	BEV	BEV
Investigated area (km^2)	106.53			9.10	19.70	2.94	15.93

Note: TIRIS, GIS portal of Tyrolean Government; VOGIS, GIS portal of Government of Vorarlberg; DORIS, GIS portal of Upper Austria; KAGIS, GIS portal of Carinthia; GIS-Stmk, GIS portal of Styria; BEV, Federal Office of Metrology and Surveying of Austria.

(b) percental changes (%) related to the respective spatial extents of the five investigated rivers. Therefore, two spatial extents have been analysed in the presented study: (a) the current HQ_{100}-inundation area (flooded area that corresponds to a flood with a 100-year recurrence interval) according the Austrian flood risk zoning (HORA), and (b) the whole potential floodplain area which could be flooded by extreme events ($>HQ_{100}$) under negligence of anthropogenic hydraulic structures. For calculating and displaying land use along the river axis, these two spatial extents have been further segmented according to the official river kilometerage. Intersections have been placed between the positions of the official river kilometres perpendicular to the river axis. Hence, segments of 1 km length at the river axis with their respective areas according to the two spatial extents have been delineated.

Further, land use was categorised in seven classes: (i) settlements, (ii) industry and commerce, (iii) traffic areas, (iv) special areas (like landfills, wastewater treatment plants, or other communal infrastructure), (v) grassland and field, (vi) forest, and (vii) waterbodies. This classification was performed in accordance and under supervision of the federal countries, the Ministry for Environment and the scientific Start-Clim-Panel (Habersack et al., 2014). These seven classes represent different degrees of need for protection from flooding (classes i–iv feature high-value uses with higher vulnerability and therefore have high tendency of obtaining structural flood protection measures like dykes) and also different hydraulic roughness values which are important for hydrodynamic-numerical modelling.

3.2 | Hydrodynamic-numerical modelling of land use change impacts

The assessment of land use changes on floodplain areas indicates what kind of alterations took place within the examined time span but it does not provide any information about their influence on flood characteristics. Therefore, in a second step, hydrodynamic-numerical modelling has been employed to model different historical dates and to assess differences in flood characteristics with special focus on changes in peak flow, flood wave translation, and water levels.

The reference for this comparison was the actual state including current land uses and current hydraulic structures like dykes, retention basins, and so forth. Calculations have been performed by using unsteady hydrodynamic-numerical 2D-models which are capable of representing retention effects in combination with complex inundation pathways in the floodplains. The applied software is Hydro_As-2d (Nujic, 1999) which is in wide use in Austria, Germany, and Switzerland. These models have been set up civil engineer companies according to the official guidelines of the Ministry of the Environment for the creation of 2D-models for river flood studies in Austria (BMLFUW, 2010; BMLFUW, 2011; BMLFUW & ÖWAV, 2007). Detailed information about the models as well as relevant input parameters (inflow and outflow boundary conditions, roughness values, major tributaries, etc.) is given in Table 2. Calibration has been performed using recorded flood waves as well as rating curves from various gauging stations. The results of the calibration are documented in the respective technical reports of these civil engineer companies (Büro Pieler ZT GmbH, 2008; DI Humer, 2006, 2010; Hydroconsult & Plan.T, 2004; Hydroconsult, 2011; Hydrosim, 2009; Werner Consult, 2009a, 2009b; ZT Depisch, 2009) and have been validated by the hydrographical services of the respective countries. Hydrological input data consisted of synthetically generated HQ_{100} flood waves (Sackl, 1994) at the inflow of the model and steady state discharge data of the tributaries along the course of the river. The data is in accordance with the official longitudinal hydrological profiles of these rivers and has been approved by the hydrographical services of the countries.

TABLE 2 Model information and input data for the hydrodynamic-numerical modelling

	Inn (upper reach)	Inn (middle reach)	Inn (lower reach)	III	Krems	Lavant	Raab
Information about the hydrodynamic-numerical 2D models							
Creator of 2D-model	Werner Consult	Geoconsult	Hydroconsult	werner consult	Humer	Hydrosim/depisch	Pieler/hydro-consult
Year of creation	2011	2012	2011	2009	2006-2010	2010-2011	2004–2008
Contracting authority (Country of...)	Tyrol			Vorarlberg	Upper Austria	Carinthia	Styria
Topographic data	Basic topographic layer: digital elevation model DHM75_cc (cell size: 75 m × 75m) Refined topographic layer for floodplain areas: 3D airborne laser scan data (several points per m^2 in structures zones; max 20 m × 20 m in flat floodplain areas); thinning of point information and setting of break lines in a manner that differences to terrestrial survey are never greater than 10 cm in elevation Refined topographic layer for river bed: terrestrial and/or multibeam survey (1–5 points per meter) Topographic data was checked by the governments of the respective countries						
Number of elements	3,407,098	2,108,605	1,413,955	1,914,249	1,458,168	2,291,595	1,172,452
Model boundaries (river-km)	410–328	328–255	255–220	60–0	58–0	35–0	78–19
River length (km)	82	73	35	60	58	35	59
River bed elevation at inflow (m a.s.l.)	989.60	624.41	510.40	1,101.00	447.85	515.00	412.28
River bed elevation at outflow (m a.s.l.)	622.50	510.40	482.30	420.00	264.75	339.00	242.33
Mean slope of river bed (‰)	4.48	1.55	0.80	11.35	3.16	5.03	2.88
Calibration	Flood of August 2005; gauging curves at various gauging stations			Flood of August 2005; gauging curves at various gauging stations	Flood of August 2002; gauging curves at gauging station Kirchdorf	Floods of June 2004 and September 2009; gauging curves at various gauging stations	Floods of July 2005 and August 2005; gauging curves at gauging station Feldbach
HQ_{100} inflow (m^3/s) acc. to official hydrological longitudinal profile	620	1,436	1,836	34	91	180	180
HQ_{100} outflow (m^3/s) acc. to official hydrological longitudinal profile	1,436	1,836	2,388	360	330	300	300

(Continues)

TABLE 2 (Continued)

	Inn (upper reach)	Inn (middle reach)	Inn (lower reach)	Ill	Krems	Lavant	Raab
Relevant tributaries	Ötztaler Ache, Pitze, Sanna	Melach, Sill, Ziller	Brandenberger Ache, Brixentaler Ache, Kundler Ache	Alfenz, Galina, Lutz, Meng, Samina	Dambach, Nussbach, Piberbach, Reiflbach, Sulzbach	Granitzbach, Hahntrattenbach, Judenbach, Ragglbach, Rainzerbach	Rabnitzbach, Weizbach
Boundary condition inflow	Synthetically created HQ_{100}-floodwave (the synthetic HQ_{100} flood waves have been created using a bivariate flood statistic developed by Sackl (1994) based on recorded historical flood waves at the gauging stations and approved by the Hydrological Services of the respective countries)						
Boundary condition outflow = energy slope I_E (‰)	2.5	10.0	1.0	9.0	2.0	2.0	1.6 (main channel); 2.3 (floodplain)
Strickler-values k_{st} ($m^{1/3}/s$)							
(i) Settlement	7			12	2–10	10	8
(ii) Industry and commerce	7			10	10	10	8
(iii) Traffic areas	40			60	40	40	30
(iv) Special areas	7			10	10	10	8
(v) Grassland and field	20			17	12	14	15
(vi) Forest	10			10	10	10	8
(vii) Water bodies	32			25	24	30	30
Hydraulic structures on floodplains that have been removed for the topography of 1950							
Motorways	A12			A14	A9		B52/66/68
State roads	B171/174/186			B188/190	B138/139	B78	
Linear flood protection measures (dykes and walls) in riparian municipalities	Pfunds, Serfaus, Imst, Telfs, Kematen, Innsbruck, Wattens, Jenbach, Wörgl, Kufstein			Partenen, Gaschurn, Vandans, St. Anton, Bludenz, Nenzig, Feldkirch	Micheldorf, Kirchdorf, Inzersdorf, Schlierbach, Wartberg, Kremsmünster, Kematen, Neuhofen, Nöschbach, Ansfelden	St. Leonhard, Frantschach, Wolfsberg, St. Andrä, St. Paul, Ettendorf, Pfarrdorf	Weiz, Krottendorf, Gleisdorf, Studenzen, Kirchberg, Feldbach, Fehring
Others	Airport Innsbruck-Kranebitten			Channelisation measures at the inflow in the Rhine	Channelisation measures at the inflow in the Traun	Flood retention basin Wolfsberg	Rail road dyke in Raab valley

Based on these calibrated models, the floodplain topographies have been modified in order to calculate historic floodplain conditions by altering land uses and removing of hydraulic structures. Since this study aimed in determining changes on floodplains and their influence on flooding characteristics only, solely changes on floodplains within the last 60 years have been considered in the modelling scenarios. For that, flood protection dykes in the riparian municipalities, hydraulic relevant infrastructure (like motorways, state roads, or railway lines) as well as flood retention basins have been removed in the model with the floodplain topography of 1950 (Table 2). Potential changes within the river bed itself (like different river bed elevation, embankments, bridges, etc.) have been intentionally not considered in the analysis. Furthermore, hydrological conditions have been assumed to be the same for both scenarios – 1950 and 2010. Being well aware that these hydrological conditions changed over time (Formayer, Kromp-Kolb, & Schwarzl, 2009), we intentionally used the same discharge data in both scenarios. Therefore, the investigated scenarios do not represent exact replications of the historic time step, but do serve to quantify the impact of floodplain changes.

This impact of floodplain changes has been calculated for both, current and historic floodplain topographies, by using the FEM-parameters flood peak reduction (ΔQ) and flood wave translation (Δt) as well as water surface levels (WSL) (Habersack, Schober, & Hauer, 2015). Hydrological values are presented in this work in two ways: (a) as absolute values, and (b) as relative values referring to the length of one river kilometre in order to allow for comparisons between various rivers with different lengths.

4 | RESULTS

4.1 | GIS analysis of land use changes

The GIS analysis revealed the changes in land use on river floodplains within the last 60 years. Figure 2 presents the results for the urban area of Innsbruck, largest city and capital of Tyrol. On the left (a), land use for the year 1950 within the HQ_{100}-area is depicted, whereas on the right (b) the situation of 2010 is presented. It is clearly visible that major parts of the HQ_{100}-area have been extensively used as grasslands and fields in 1950 (green areas). On the contrary, the current situation of 2010 shows a strong shift to highly developed land uses – nearly all of the grassland areas have been replaced by settlement (red), commerce and industry (yellow), or traffic areas (grey).

Innsbruck, representing an urban area, shows the greatest changes in land use along the Austrian Inn River. However, this trend does also account for other municipalities and even rural areas. Figure 3 displays on the left side the distribution of land uses along the course of the Inn River for 1950 (a) and 2010 (b). The land use classes are presented as percentile portion of the HQ_{100}-

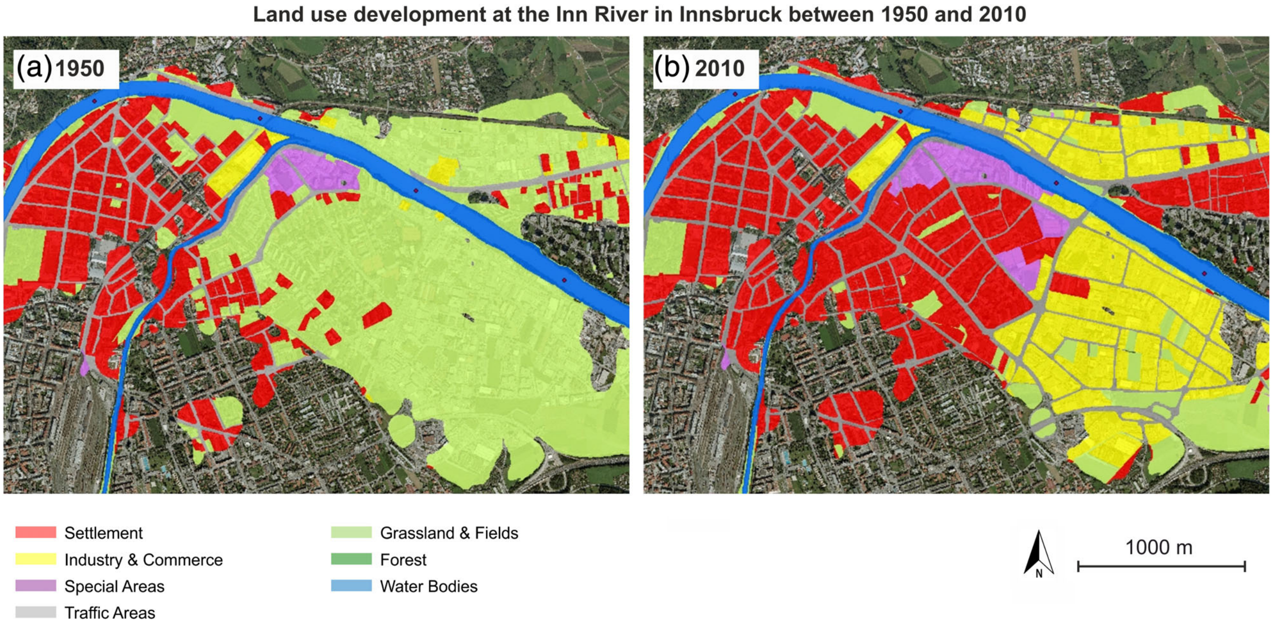


FIGURE 2 Land use development at the Inn River in Innsbruck between 1950 (a) and 2010 (b) (backdrop: aerial photo of 2010, source: TIRIS)

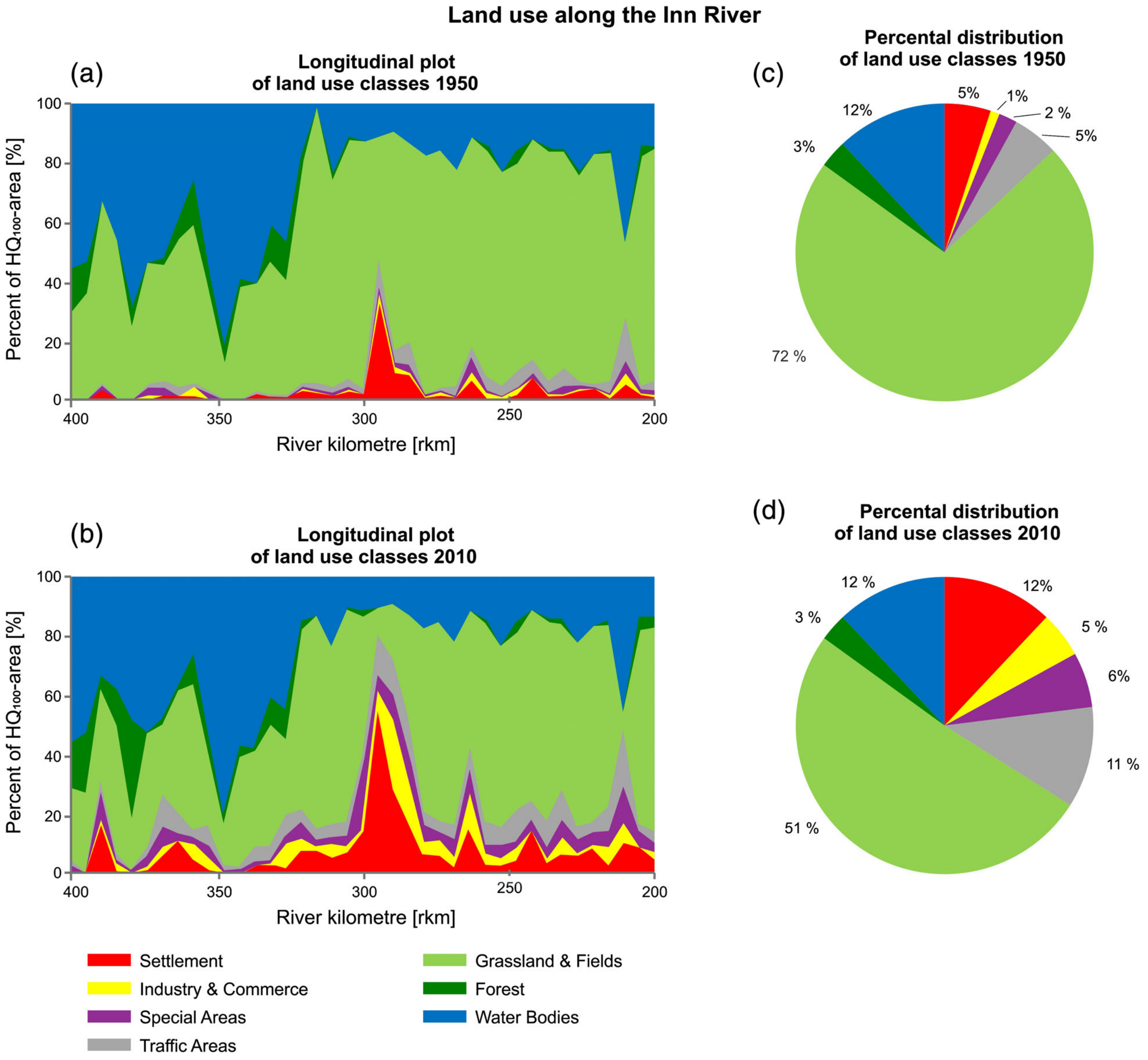


FIGURE 3 Land use changes along the Austrian Inn River between 1950 and 2010. Left side (a,b): land use distribution along the river course for the HQ_{100}-area. Right side (c,d): percentile distribution of land use classes within the whole potential river floodplain

area of each river kilometre. The capital of Innsbruck (river-km 300) is clearly visible in both time steps as ‘peak’, since high-value land uses like settlement, industry and commerce, and traffic areas did all the time represent a high portion within the floodplain areas. However, in 1950 these high-value land uses did only account for 50% of the HQ_{100}-area in Innsbruck. In 2010 this portion increased to 80%. The comparison between 1950 and 2010 (Figure 3a,b) exhibits that these high-value land uses increased within the last 60 years along the whole Inn River, almost entirely at the expense of grassland and fields.

Investigating the whole potential floodplain area along the Inn River (173.38 km^2), in 1950 13% were covered by settlement, industry and commerce, and traffic areas (23.05 km^2) and 72% were covered by grassland and fields (124.66 km^2). In 2010 34% (59.42 km^2) are covered by high-value land uses and grassland and fields have been reduced to 51% (88.93 km^2). The right-hand side of Figure 3 displays the percentile distribution of land uses for the whole potential floodplain along the Austrian Inn River for 1950 (c) and 2010 (d).

Figure 4 displays the development of the seven land use classes for each investigated historical date. Settlement, industry and commerce, special areas, and traffic areas show increases for each time step. However, there is a noticeable decline in the land consumption rate of these land uses within the last 20 years (1990–2010), but still land use consumption is going on (UBA, 2019). The reason for this might be the aggravated scarcity of

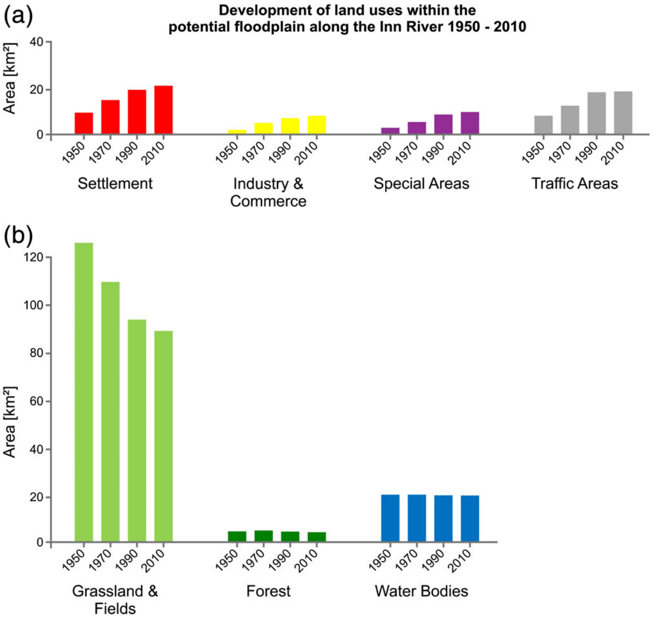


FIGURE 4 Development of land uses within the potential floodplain along the Austrian Inn River for 1950, 1970, 1990, and 2010

suitable land and the revised spatial planning laws. Land use classes of forest and water bodies did not change significantly within the investigated time period, but great changes are detectable for grassland and fields. These areas have been reduced in the same amount as the high-value land uses like settlement, and so forth increased. Values for these changes are given in Table 3.

4.2 | Hydrodynamic-numerical modelling of land use change impacts

GIS analysis of land use changes has revealed floodplain modifications along Austrian rivers during the last decades. These modifications comprise changes on floodplains (e.g., changes of roughness due to alterations in land use) and losses of floodplains (e.g., due to the protection of newly developed areas by dykes on former floodplain areas which are now perceived as flood-free – at least up to certain discharges as long as these protection measures are effective). The next step of this analysis was to determine the impact of these changes on flood characteristics by means of the FEM-parameters flood peak reduction (ΔQ), flood wave translation (Δt) and WSL.

Hydrodynamic-numerical models with the current floodplain topography of 2010 have been compared to a future scenario assuming the total loss of floodplains along the river. The results for a HQ_{100} flood wave for the three reaches of the Inn River are depicted in Figure 5. The red line represents the input flood wave in the respective river reach (consisting of the synthetic flood wave at the inflow and the steady state discharges of the tributaries along the river course). The blue line shows the output flood wave for the floodplain topography of 2010. The values for flood peak reduction and flood wave translation are given in the table below the figure. Flood peak reduction (ΔQ/km) is between 0.13 m^3/s (upper reach) and 6.80 m^3/s (lower reach); flood wave translation (Δt/km) ranges between 0.13 hr (upper reach) and 0.32 hr (lower reach). These differences can be attributed to a number of reasons: first, the upper reach is characterised by a rather steep slope (4.48‰) compared to the lower reach (0.80‰) and therefore retention effects generally turn out to be inferior there. Second, the river valley is relatively narrow in the upper section (ratio active channel to floodplain of 1:2 in the upper reach and 1:8 in the lower reach).

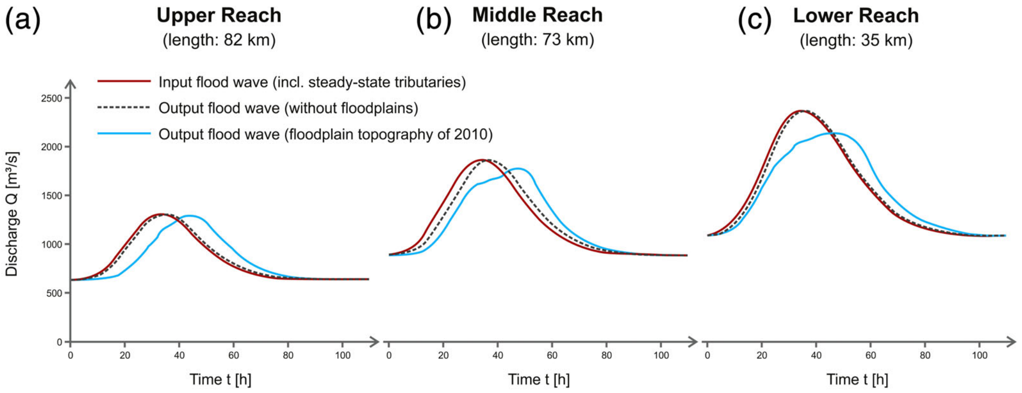
Despite the differences in retention capacity between these three reaches, all of them feature significant impact on the flood wave. Comparing these results with the model without floodplains (grey dashed line), the effects of floodplains become obvious. Without any floodplains both, flood peak reduction and flood wave translation, decreases drastically. Flood peak reduction per kilometre features values between 0.02 and 0.09 m^3/s and flood wave translation per kilometre is characterised by values between 0.03 and 0.07 hr. These small values result from the very minor effects from flood retention and delay within the active channel. The differences in the output waves between the topography of 2010 and the topography without floodplains represent therefore the effects of functioning river floodplains.

The total loss of river floodplains is an extreme scenario of the future, but losses of floodplains have already occurred within the last few decades, as the GIS analysis confirmed. Therefore, computations were performed for the 2010 and 1950 topography calculating the recently recorded flood event of 2005 which equals the recurrence interval of HQ_{80} (BMLFUW, 2006).

Figure 6 depicts the differences between those two topographies. On the left side (a) the inundated areas for these two topographies are presented for a selected site at the lower reach. While in 1950 large floodplain areas have been flooded by a wave of this recurrence probability (dark blue), in 2010 only the active channel contains the flood wave since the former floodplains have been cut off by railroad and motorway dykes. This kind of situation occurred on several sites along the lower reach. The impact of these changes is clearly visible in the flood hydrographs for the whole lower reach on the right side (b): the topography of 1950 (dark blue line) decreases and delays the flood wave much stronger than the recent topography of 2010. Flood peak reduction per kilometre

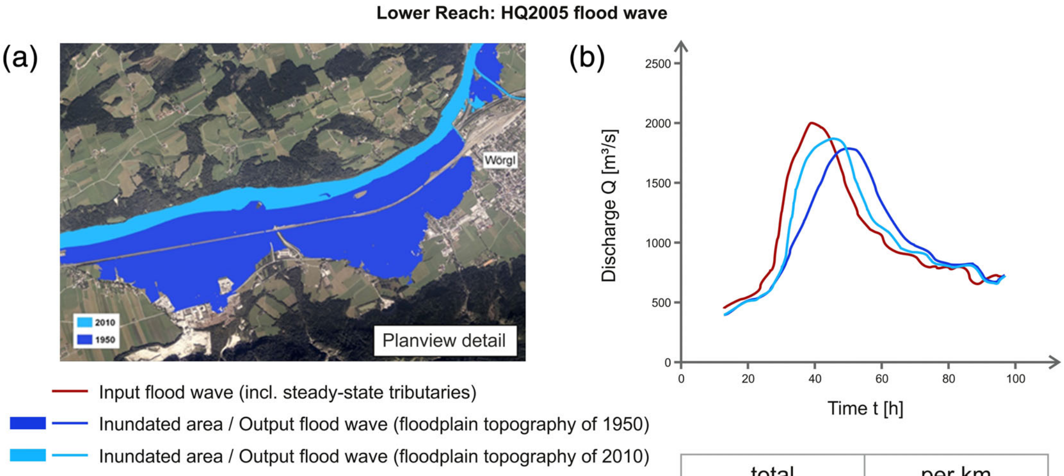
TABLE 3 Land use distribution within the potential floodplain along the five investigated Austrian rivers for different historic dates

Historical date	Total area		Settlement		Industry and commerce		Special areas		Traffic areas		Grassland and fields		Forest		Water bodies	
	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)	(km²)	(%)
Inn River																
1950	173.38	100.00	9.78	5.64	1.95	1.12	2.85	1.64	8.47	4.89	124.66	71.90	4.69	2.71	20.98	12.10
1970			15.39	8.88	4.09	2.36	5.52	3.18	13.21	7.62	109.09	62.92	5.12	2.95	20.96	12.09
1990			20.04	11.56	7.23	4.17	8.78	5.06	18.96	10.94	93.07	53.68	4.73	2.73	20.57	11.86
2010			21.80	12.57	8.36	4.82	9.95	5.74	19.32	11.14	88.93	51.29	4.46	2.57	20.56	11.86
Ill River																
1950	54.01	100.00	2.86	5.30	0.69	1.28	0.36	0.67	2.51	4.65	27.35	50.64	16.73	30.98	2.25	4.17
2010			7.43	13.76	2.65	4.91	0.05	0.09	4.98	9.22	20.96	38.81	13.84	25.62	4.53	8.39
Krems River																
1950	66.62	100.00	4.46	6.68	1.06	1.58	0.10	0.15	3.27	4.90	49.57	74.24	5.37	8.04	2.94	4.40
1970			5.89	8.75	1.74	2.59	0.38	0.57	4.16	6.19	46.43	69.05	5.64	8.39	2.99	4.45
1990			7.91	11.87	3.59	5.38	0.87	1.31	4.95	7.43	40.40	60.63	5.74	8.62	3.17	4.76
2010			9.15	13.74	4.50	6.76	1.13	1.69	5.31	7.97	37.14	55.74	6.20	9.31	3.19	4.79
Lavant River																
1950	22.52	100.00	1.77	7.87	0.60	2.67	0.14	0.62	0.95	4.20	14.66	65.09	3.53	15.67	0.87	3.88
2010			4.93	21.88	2.36	10.47	0.11	0.49	1.61	7.15	11.18	49.65	1.35	5.98	0.99	4.38
Raab River																
1950	50.31	100.00	3.14	6.25	0.60	1.19	0.12	0.23	2.42	4.81	40.27	80.07	1.12	2.22	2.63	5.22
1970			4.04	8.03	1.30	2.59	0.24	0.47	2.89	5.74	37.94	75.44	1.31	2.61	2.58	5.13
1990			4.76	9.46	2.91	5.78	0.62	1.22	3.64	7.24	34.35	68.29	1.40	2.78	2.63	5.23
2010			5.02	9.97	3.23	6.42	0.72	1.44	3.69	7.33	33.35	66.30	1.55	3.07	2.75	5.47



		total	per km	total	per km	total	per km
ΔQ [m^3/s]	current state (2010)	11.0	0.13	95.0	1.30	238.0	6.80
	without floodplains	1.4	0.02	2.0	0.03	3.0	0.09
Δt [h]	current state (2010)	10.25	0.13	12.75	0.17	11.25	0.32
	without floodplains	2.75	0.03	4.00	0.05	2.50	0.07

FIGURE 5 HQ_{100} flood wave transformation within the investigated reaches of the Inn River. (a) Upper, (b) middle, (c) lower reach—comparison of the floodplain topography of 2010 and the topography without floodplains



		total	per km
ΔQ [m^3/s]	current state (2010)	135.0	3.86
	historic state (1950)	214.0	6.11
Δt [h]	current state (2010)	5.75	0.16
	historic state (1950)	10.75	0.31

FIGURE 6 Comparison of flooding characteristics of the observed flood wave from 2005 (approx. HQ_{80}) at the lower reach of the Inn River for the topography of 2010 and 1950. Left (a): plan view of the inundated areas near the city of Wörgl. Right (b): flood wave transformations within the whole lower reach

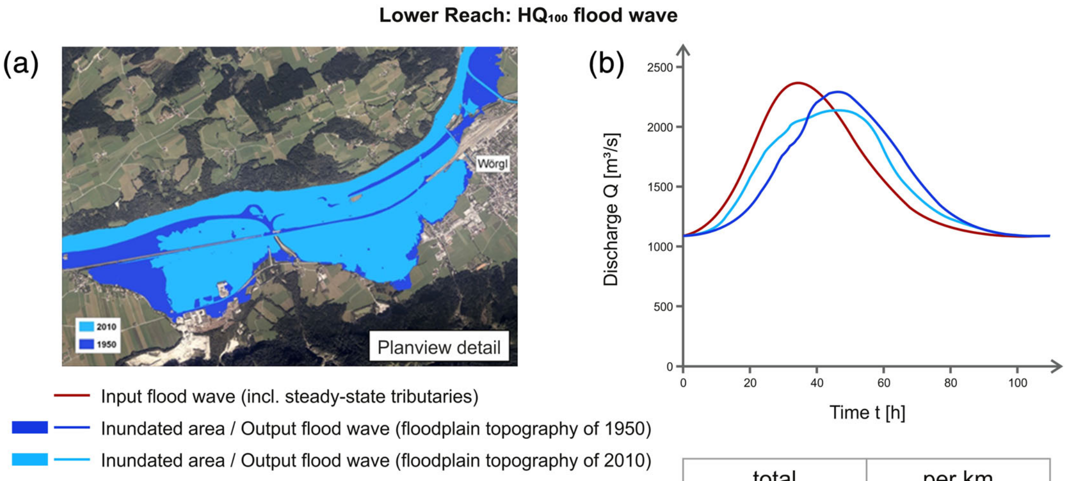
accounts for 6.11 m^3/s in 1950 whereas this value is reduced to 3.86 m^3/s in 2010. Flood wave translation per kilometre is also reduced from 0.31 hr in 1950 to 0.16 hr in 2010.

The loss of floodplains in these areas has led to a significant worsening of flood characteristics downstream: higher flood peaks and accelerated travel times deteriorate flood conditions throughout the whole reach.

However, as it was outlined in the introduction, no absolute flood protection can be achieved and structural measures like dykes clearly have their limitations – either by overtopping in cases of discharges higher than the design discharge or by failure, such as breach of a dyke. Therefore, scenarios with overtopping of the railroad and motorway dykes (which were not designed for flood protection initially) were computed. Overtopping of these dykes occur on certain sites already for recurrence intervals of HQ_{100}. On the left side of Figure 7a, the inundated area for a characteristic site of the lower reach is depicted. In both cases – 1950 and 2010 – the floodplain is inundated. In the topography of 1950, without railroad and highway dykes, flooding began already with relatively low discharges and filled the whole floodplain completely in the course of the rising limb of the flood wave. In contrast, the topography of 2010 is characterised by dykes which have been overtopped relatively late in the course of the flood wave (in the range between HQ_{80} and the HQ_{100}-peak). This led to a 'cropping' of the flood wave's peak similar to the functioning of a polder. The effects of these modified floodplain topographies can be seen on the right side of Figure 7b where the flood waves for the topography of 1950 (dark blue) and 2010 (light blue) are presented. In this case – due to the overtopping of dykes and the functioning of former floodplains as polders – the flood wave for 2010 is stronger attenuated than the flood wave for 1950. Flood peak reduction per kilometre for 1950 is 2.37 m^3/s while it is 6.80 m^3/s for 2010. The values for flood wave translation are pretty much the same for both topographies (0.31 hr for 1950 and 0.32 hr for 2010).

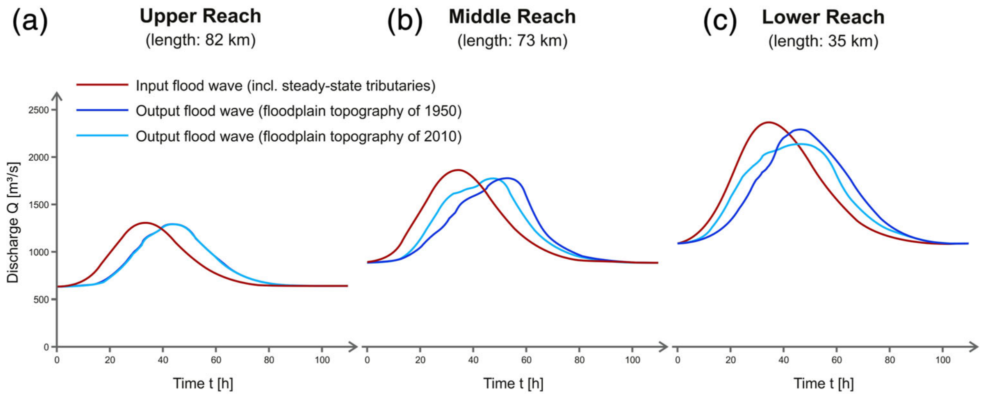
A very important aspect is that these effects of polder-like hinterland areas on flood peak reduction are only given for a certain kind of flood events (especially extreme events exceeding the design discharge of the dykes). However, these allegedly 'positive' effects are counteracted by the negative consequences of unintentional overtopping of railroad dykes and elevated roadways. Furthermore, settlements which have been built up during the last decades in these flood-free perceived areas feature considerably higher damage potential than the former natural floodplains.

Moreover, such effects do only occur in certain reaches. Figure 8 presents the computation results of all three reaches of the Inn River for a HQ_{100} flood wave for the topographies of 2010 (light blue line) and 1950 (dark blue line). As referred to previously, the cutting off floodplains and unintentional creation of polder-like structures effectuated in the lower reach (c) a stronger reduction of the flood peak for the 2010 topography than for 1950. However, flood wave translation remained nearly the same. In the middle (b) and upper (a) reaches the flood wave was transformed differently. In the middle reach – where also many floodplains have been cut off from the active channel – the flood peaks for the 2010 and the 1950 topography are very identical (flood peak reduction per kilometre between 1.30 m^3/s for 2010 and 1.19 m^3/s for 1950). But the flood wave translation shows significant differences. The construction of dykes led to



		total	per km
ΔQ [m³/s]	current state (2010)	238.0	6.80
	historic state (1950)	83.0	2.37
Δt [h]	current state (2010)	11.25	0.32
	historic state (1950)	10.75	0.31

FIGURE 7 Comparison of flooding characteristics of a synthetic HQ_{100} flood wave at the lower reach of the Inn River for the topography of 2010 and the topography of 1950. Left (a): plan view detail of the inundated areas near the city of Wörgl. Right (b): flood wave transformations within the whole lower reach



		Upper total	Upper per km	Middle total	Middle per km	Lower total	Lower per km
ΔQ [m³/s]	current state (2010)	11.0	0.13	95.0	1.30	238.0	6.80
	historic state (1950)	14.0	0.17	87.0	1.19	83.0	2.37
Δh [h]	current state (2010)	10.25	0.13	12.75	0.17	11.25	0.32
	historic state (1950)	10.50	0.13	18.50	0.25	10.75	0.31

FIGURE 8 HQ_{100} flood wave transformation within the three investigated reaches of the Inn River (a) upper, b) middle, (c) lower reach—comparison of the topographies of 2010 and of 1950

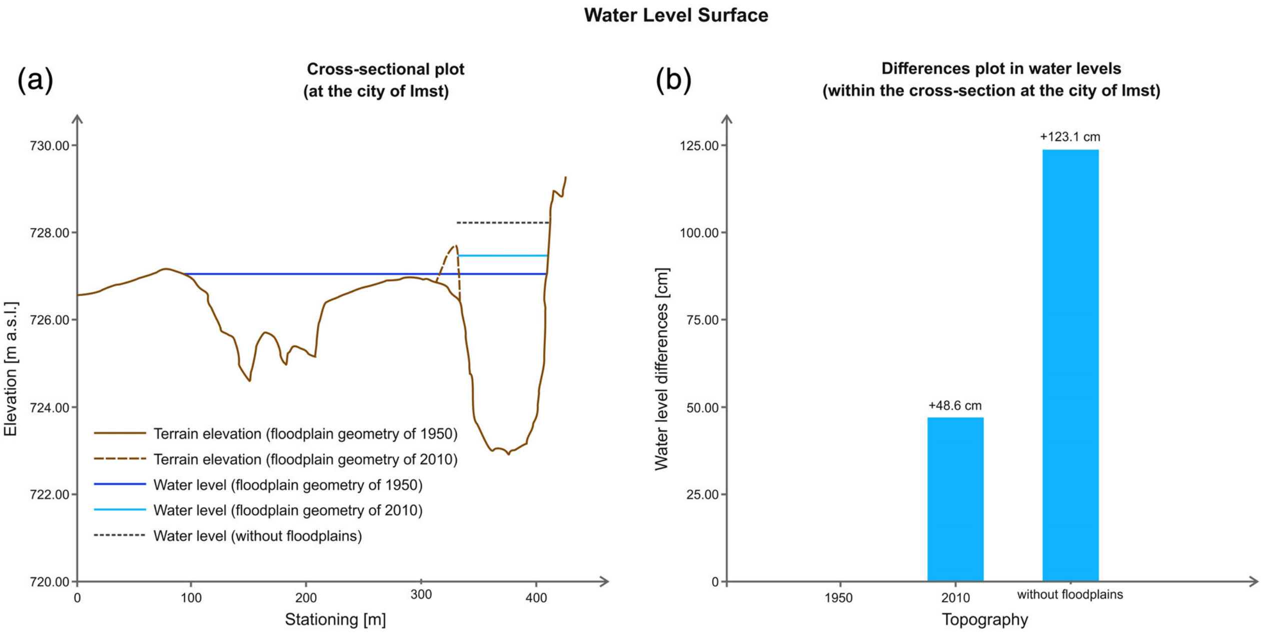


FIGURE 9 Change of HQ_{100} water levels due to floodplain losses – example city of Imst (upper reach): comparison of differences between the floodplain topographies of 1950 and 2010 as well as the model without floodplains. Left (a) cross-sectional plot; right (b) differences plot in water levels

an acceleration: the flood wave translation per kilometre in 1950 of 0.25 hr has been reduced to only 0.17 hr in 2010. For the upper reach the differences between 2010 and 1950 regarding the output flood waves are minor. However, the loss of floodplains did affect local hydraulic conditions in such regions as well.

Regarding local hydraulic conditions it can be generally stated that the reduction of floodplain width leads to higher water levels within the main active channel since the flow section is narrowed. These hydraulic effects are depicted in Figure 9 for a former floodplain close to the city of Imst (upper reach), which can be seen as representative for many sites along the Inn River. On the left side of Figure 9a, a cross-sectional plot presents the HQ_{100} water levels for the topography of 1950 (dark blue line), of 2010 (light blue line) and for the topography without

TABLE 4 Summarised results for all five case study sites

	(a) Land use changes					**(b) Changes in flood wave deformation**							
	HQ_{100} area	**1950 grasslands and fields**		**2010 grasslands and fields**			**HQ_{100}**	**1950**		**2010**		**Without floodplains**	
River	**(km^2)**	**(km^2)**	**(%)**	**(km^2)**	**(%)**	**Reach**	**(m^3/s)**	**ΔQ (m^3/s)**	**ΔT (hr)**	**ΔQ (m^3/s)**	**ΔT (hr)**	**ΔQ (m^3/s)**	**ΔT (hr)**
Inn	106.53	74.55	70	55.73	52	Upper R.	1,436	14	10.50	11	10.25	1	2.75
						Middle R.	1,836	87	18.50	95	12.75	2	4.00
						Lower R.	2,388	83	10.75	238	11.25	3	2.50
III	9.10	2.38	26	1.86	20	Upper R.	360	1	3.70	1	3.10	1	2.50
						Middle R.	810	40	5.50	19	6.90	1	4.00
						Lower R.	815	272	7.40	56	3.00	5	2.00
Krems	19.70	12.57	64	10.22	52	Upper R.	189	20	4.25	22	4.50	15	2.25
						Middle R.	328	31	5.75	35	5.75	22	3.00
						Lower R.	306	74	5.00	79	4.75	19	2.25
Lavant	2.94	1.66	56	1.47	50	Lower R.	268	37	4.80	33	3.60	5	1.00
Raab	15.93	12.86	81	11.12	70	Lower R.	300	16	15.50	18	16.00	2	6.00

Note: (a) Changes in land use for 1950 and 2010 (decrease of grasslands and fields); (b) changes in flood wave deformation for the topography of 1950, 2010, and without floodplains.

floodplains (grey dashed line). In the 1950 topography the adjacent floodplain was inundated while this was not possible anymore in the 2010 topography because of the construction of a highway dyke. Since the cross-section was narrowed, the 2010 water level was increased by +48.6 cm (left side of Figure 9b). Regarding the topography without any floodplains, the effects of floodplains losses further upstream throughout the whole reach become obvious: the water level is increased by +123.1 cm compared to the 1950 topography.

4.3 | Integrated view on land use changes and changes in flood characteristics

Table 4 presents the results for the case study sites for HQ_{100}. All five rivers show strong changes in floodplain land use, identifiable by the distinct decrease of grassland & fields (left side of the table, [a]). However, these changes did divergently affect flooding characteristics (right side of the table, [b]). For some rivers, flood conditions deteriorated in terms of reduced peak reductions and shortened translation times (e.g., Ill and Lavant). For other rivers, these losses of floodplain areas have been compensated, intentionally or not, by polder-like structures due to road embankments and dykes (e.g., Krems and Raab). However, all rivers have in common that the total loss of floodplains would lead to a drastic deterioration of hydrological parameters. Moreover, hydraulic parameters like water levels deteriorated with ongoing loss of floodplains throughout all investigated catchments.

5 | DISCUSSION

In Austria, land consumption was determined with 12.9 ha/day in the period 2015–2017 (UBA, 2018). This extraordinary high rate in land consumption causes high pressure on existing floodplains especially in the alpine part of Austria (e.g., where the presented Inn River is situated). The Inn is a good example for the rapid development of floodplains along Alpine rivers within the last 60 years. Due to the mountainous topography of this region which is characterised by numerous gravitational natural hazards like avalanches or landslides, areas for permanent settlement purposes are mostly limited to the narrow valley bottoms along the river courses.

It is consequential that changes on floodplains (e.g., changes of roughness due to land use changes) and losses of floodplains (e.g., due to the protection of newly developed areas by dykes on former flood-prone areas) have impact on flooding characteristics for higher floods that exceed bankfull discharge. However, due to complex flow situations it is difficult to predict precisely how these changes will manifest in the highly distinct topographical settings of each river (Schober, Hauer, & Habersack, 2015). In order to gain better insight of potential impacts of such changes, hydrodynamic-numerical modelling can serve as appropriate tool to investigate the effects of different scenarios of floodplain topography on flooding characteristics.

Here, the presented example of the Inn River demonstrates the complexity of flow processes on floodplain areas. The Inn, as one of the largest Alpine rivers with a high pressure on floodplain areas due to population growth and development purposes, illustrates the trends that many Alpine rivers undergo these days. Changes of floodplain land use over the last 60 years led to different impacts on flood waves depending on floodplain topography and hydrologic characteristics of the flood wave.

The findings of this study support the general statements of O'Connell et al. (2007) that changes in the catchment and on floodplains can vary greatly from river to river. Each river shows its own characteristic, therefore, general conclusions can hardly been drawn without specific analysis of the situation especially when considering overtopping of structural flood protection measures. Milliman et al. (2008) mention in their study the strong influence that land use changes may have on flow regimes. Some of the presented findings are similar to a study conducted at the Bavarian Danube (Skublics & Rutschmann, 2015) where historic and recent river topographies were investigated regarding their impact on flood characteristics. As in these cases, polder-like structures had, depending on the recurrence interval, in some cases positive effects on flood peak reduction but at the same time the flood wave was accelerated and water levels have been raised at least locally. Both studies demonstrate the complexity of these systems and show that changes on floodplains have impact on many parameters.

The present study revealed that in most cases of floodplain losses flood wave translation has been distinctly reduced implicating problems for local emergency forces which are now under compulsion to react to the approaching flood much faster. On the other hand, flood peak reduction depends on whether dykes are, intentionally or not, overtopped or not (Schober et al., 2015). In many cases dykes and elevated roadways (e.g., the Inntal motorway) have decoupled the original floodplains from the active channel. However, in case of higher recurrence intervals these dykes are overtopped in certain sections and the hinterland areas now function as polders (like bypass detention basins). Since this effect does only occur for higher flows, the peak of the flood wave can be dropped more efficiently than by means of natural retention areas where flooding begins even for minor flood events above bankfull discharge (>HQ_{1-2}). Of course, this effect cannot be considered positively alone. The deterioration of hydraulic parameters like water levels is associated with every loss of floodplains. Besides the unintended overflow of dykes and important infrastructure lines (like motorways), hinterland areas are nowadays often taken for high valuable land uses like settlement or industry and commerce since people tend to feel safe behind those dykes. In case of flooding of these areas, damages are much higher nowadays than decades back when these regions have been used as agricultural areas that could be flooded from time to time.

However, in general the ongoing loss of floodplain areas especially in mountainous regions where space is a scarce resource will impose great challenges on flood risk management within the next years. Therefore, methodological approaches for assessing the effectiveness of floodplains like the applied FEM-parameters (see companion paper, Habersack & Schober, 2020) represent a valuable tool for decision makers in the field of flood risk management when it comes to the preservation and, where possible, the restoration of floodplains as is demanded by the EU Floods Directive (EU, 2007).

6 | CONCLUSIONS

As demanded by the EU Floods Directive (EU, 2007), floodplain preservation and restoration is considered as a sustainable non-technical measure to ensure multiple benefits of flood protection within an integrated river basin management. However, the historic analysis for five case study rivers in Austria presented in this paper demonstrated, that changes of floodplains took place slowly but constantly over the last decades. These changes manifested in two ways: (a) land use shifted from less vulnerable land use classes like grasslands and fields to high value land use classes like settlement, industry and commerce, and traffic areas. This change was clearly detectable for all five investigated rivers within the last 60 years and has been presented in detail for the Inn River. These changes in land use led to alterations of surface roughness which directly influences hydraulic parameters during flooding. Furthermore, (b) these land use changes led to structural changes of the floodplain topographies, for example, the erection of levees for elevated railroads and highways or the construction of dykes in order to protect settlements, commercial areas, or valuable infrastructure.

Structural changes of floodplain topographies especially, provided a summation of great total floodplain losses which in turn changed flooding characteristics significantly. In general, the loss of floodplains due to the construction of dykes has a negative impact in regard to

(a) hydrological parameters (such as flood peak reduction and flood wave translation) which affect flood hazard further downstream throughout the whole basin and (b) hydraulic parameters (such as water levels) on a local scale. This worsening of conditions could be detected for most of the investigated river reaches. However, the presented case studies demonstrated that in few cases dykes functioned, intentionally or unintentionally, as polders when they were overtopped by higher discharges. This may result in better values for flood peak reduction but when considering the big picture, simultaneously deteriorates other parameters like flood wave translation or water levels (especially when the unintentionally flooded areas are already developed with high-value uses like settlements).

In summary, this study revealed that each river's flooding characteristic, despite the fact that land use changes for all rivers showed the same tendencies, was highly dependent on specific topographic floodplain features. Hence, general conclusions about alterations in flooding characteristics cannot be drawn from land use analysis alone. For this sort of analysis it is crucial to complement the land use analysis with hydrodynamic-numerical modelling, which enables investigation of the effects of hydraulic relevant structures. Doing so, river specific conditions can be taken into account which is essential as it is underpinned by the heterogeneity of results between the presented rivers.

This study highlights that

1. Floodplain management is not only a matter of scales in space but also of scales in time. Knowledge of previous conditions is crucial for estimating potential future trends which are the basis for adaptive and dynamic flood risk planning.
2. Flood protection measures may not be evaluated just on a local scale. Effects of interaction and summation must be assessed on reach or river scale in order to obtain a bigger picture of positive and negative impacts.
3. Having information on reach or river scale, more detailed assessments about the contribution of single floodplains throughout time can be carried out. For this purpose, the method presented in the companion paper (Habersack & Schober, 2020) offers the appropriate tools.

Moreover, for future investigations in the context of changed river topographies and flooding characteristics, the analysis of sediment transport issues and changes in morphodynamics deserve consideration. Sediment transport during floods may change flooding characteristics significantly depending on where sediment is eroded or deposited (Hooke, 2015; Krapesch, Hauer, & Habersack, 2011; Lane, Tyefi, Reid, Yu, & Hardy, 2006; Neuhold, Stanzel, & Nachtnebel, 2009; Totschnig, Sedlacek, & Fuchs, 2011). The negligence of sediment transport in hydrodynamic-numerical models therefore imposes great uncertainties upon the results. Although not the focus of this study, we recommend that suitable sediment transport calculations or estimations should therefore be incorporated in the models more commonly with special regard to model calibration and sensitivity analysis.

In summary, ongoing land consumption of floodplains will lead to an even higher flood risk in the future. Hence it is important to understand the impact of these historic changes in order to prevent undesirable developments in the near future. To support this there is a need to establish a stronger connection between scientific research, flood risk management and spatial planning.

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REFERENCES

Balica, S., Popescu, I., Beevers, I., & Wright, N. (2013). Parametric and physically based modelling techniques for flood risk and vulnerability assessment: A comparison. *Environmental Modelling & Software*, *41*, 84–92.

Barredo, J. (2007). Major flood disasters in Europe: 1950–2005. *Journal of Natural Hazards*, *42*, 125–148.

BMLFUW. (2006). *Flood 2005 – Documentation (Hochwasser 2005 – Ereignisdokumentation)*. Federal Ministry of Agriculture, Forestry, Environment and Water Management.

BMLFUW. (2010). *Guidance document for the definition and harmonization of design events (Leitfaden zur Festlegung und Harmonisierung von Bemessungsereignissen)*. Federal Ministry of Agriculture, Forestry, Environment and Water Management.

BMLFUW. (2011). *Guidance document: Methods for the estimation of flood water data (Leitfaden: Verfahren zur Abschätzung von Hochwasserkennwerten)*. Federal Ministry of Agriculture, Forestry, Environment and Water Management.

BMLFUW & ÖWAV. (2007). *River modelling – Guidance document for hydrodynamic-numerical modelling (Fließgewässermodellierung – Arbeitsbehelf Hydrodynamik)*. Federal Ministry of Agriculture, Forestry, Environment and Water Management & Austrian Association for Water and Waste Water.

Bogardi, J., Leentvaar, J., & Nachtnebel, H. (2012). *GWSP river basins and change*. UNESCO.

Bornschein, A., & Pohl, R. (2018). Land use influence on flood routing and retention from the viewpoint of hydromechanics. *Journal of Flood Risk Management*, *11*(2018), 6–14.

Büro Pieler ZT GmbH. (2008). River flood study Raab – district Weiz (Abflussuntersuchung Raab – Bezirk Weiz) (Tech. Rep.).

CRED (2016). In D. Guha-Sapir, P. Hoyois, & P. Wallemacq (Eds.), *Annual disaster statistical review 2016*.

Davidson, N. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, *65*(10), 934–941.

DI Humer. (2006). Hazard zone plan Krems (Gefahrenzonenplan Krems) (Tech. Rep.).

DI Humer (2010). Hazard zone plan for the Upper Krems River (river km 45,500 to 57,624) (Schutzwasserwirtschaftlicher Gefahrenzonenplan Obere Krems (Fkm 45,500 bis 57,624)) (Tech. Rep.).

EU. (2007). Directive on the assessment and management of flood risks (2007/60/EC). European Parliament and Council.

Fliervoet, J., Van den Born, R., Smits, A., & Knippenberg, L. (2013). Combining safety and nature: A multi-stakeholder perspective on integrated floodplain management. *Journal of Environmental Management*, *128*, 1033–1042.

Formayer, H., Kromp-Kolb, H., & Schwarzl, I. (2009), Impact of climate change on flood events in Upper Austria (Auswirkungen des Klimawandels auf Hochwasserereignisse in Oberösterreich). Final Report. Institute of Meteorology, BOKU, Vienna.

Habersack, H., & Schober, B. (2020). Floodplain evaluation matrix FEM – A multiparameter assessment methodology. *Journal of Flood Risk Management*.

Habersack, H., Schober, B., & Haspel, D. (2014). Loss of floodplains and flood risk under consideration of climate change (Überflutungsflächenverlust und Hochwasserrisiko unter Berücksichtigung des Klimawandels). Final Report of StartClim2013.B. BMLFUW, BMWFW, ÖBF and Country of Upper Austria.

Habersack, H., Schober, B., & Hauer, C. (2015). Floodplain evaluation matrix (FEM): An interdisciplinary method for evaluating river floodplains in the context of integrated flood risk management. *Natural Hazards*, *75*(1), 5–32.

Herget, J., & Meurs, H. (2010). Reconstructing peak discharges for historic flood levels in the city of Cologne, Germany. *Global and Planetary Change*, *70*(1–4), 108–116.

Hooke, J. (2015). Variations in flood magnitude – Effect relations and the implications for flood risk assessment and river management. *Geomorphology*, *251*, 91–107.

Hunter, N., Bates, P., Horrit, M., & Wilson, M. (2007). Simple spatially-distributed models for predicting flood inundation: A review. *Geomorphology*, *90*, 208–225.

Hydroconsult. (2011). River flood study Tyrol 2 – Inn River km 220,20 to 255,35 (Abflussuntersuchung Tirol 1 – Inn km 220,20 bis km 255,35) (Tech. Rep.).

Hydroconsult & Plan.T. (2004). River flood study Raab 2004 (Abflussuntersuchung Raab 2004) (Tech. Rep.).

Hydrosim. (2009). Assessment of retention areas at the Lavant River – river km 17 to 35 (Retentionsraumuntersuchung Lavant – km 17 bis km 35) (Tech. Rep.).

Krapesch, G., Hauer, C., & Habersack, H. (2011). Scale oriented analysis of river width changes due to extreme flood hazards. *Natural Hazards and Earth System Sciences*, *11*(8), 2137–2147.

Kundzewicz, Z. W., & Menzel, L. (2005). Natural flood reduction strategies – A challenge. *International Journal of River Basin Management*, *3*(2), 125–131.

Lane, S., Tyefi, V., Reid, S., Yu, D., & Hardy, R. (2006). Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms*, *32*(3), 429–446.

Luo, P., Apip, He, B., Duan, W., Takara, K., & Nover, D. (2015). Impact assessment of rainfall scenarios and land-use change on hydrologic response using synthetic area IDF curves. *Journal of Flood Risk Management*, *11*(Suppl. 1).

Merwade, V., Cook, A., & Coonrod, J. (2008). GIS techniques for creating river terrain models for hydrodynamic modelling and flood inundation mapping. *Environmental Modelling & Software*, *23*, 1300–1311.

Messner, F., & Meyer, V. (2006). Flood damage, vulnerability and risk perception – Challenges for flood damage research. In J. Schanze, E. Zeman, & J. Marsalek (Eds.), *Flood risk management: Hazards, vulnerability and mitigation measures* (Vol. 67, pp. 149–167).

Milliman, J. D., Farnsworth, K. L., Jones, P. D., Xu, K. H., & Smith, L. C. (2008). Climatic and anthropogenic factors affecting river discharge to the global ocean, 1951–2000. *Global and Planetary Change*, *62*(3–4), 187–194.

Neuhold, C., Stanzel, P., & Nachtnebel, H. (2009). Incorporating river morphological changes to flood risk assessment: Uncertainties, methodology and application. *Natural Hazards and Earth System Sciences*, *9*(3), 789–799.

Nujic, M. (1999). *Hydro_as-2D – A two-dimensional hydrodynamic numerical model for hydraulic engineering*.

O'Connell, E., Ewen, J., O'Donnel, G., & Quinn, P. (2007). Is there a link between agricultural land-use management and flooding? *Hydrology & Earth System Sciences*, *11*(1), 96–107.

Sackl, B. (1994). *Determination of design flood waves for observed and non-observed catchments* (Ermittlung von Hochwasser-Bemessungsganglinien in beobachteten und unbeobachteten Einzugsgebieten).

Schober, B., Hauer, C., & Habersack, H. (2015). A novel assessment of the role of Danube floodplains in flood hazard reduction (FEM method). *Natural Hazards*, *75*(1), 33–50.

Skublics, D., & Rutschmann, P. (2015). Progress in natural flood retention at the Bavarian Danube. *Natural Hazards*, *75*(1), 33–50.

Spaliviero, M. (2003). Historic fluvial development of the Alpine-foreland Tagliamento River, Italy, and consequences for floodplain management. *Geomorphology*, *52*(3–4), 317–333.

Teng, J., Jakerman, A., Vaze, J., Croke, B., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201–216.

Totschnig, R., Sedlacek, W., & Fuchs, S. (2011). A quantitative vulnerability function for fluvial sediment transport. *Natural Hazards*, *58*(2), 681–703.

UBA. (2018). *Eleventh environment assessment report [Austria]*. Vienna: Umweltbundesamt.

UBA. (2019). *Land consumption in Austria* (Flächenverbrauch in Österreich). Data provided by Umweltbundesamt (UBA). Available from https://www.umweltbundesamt.at/umweltsituation/raumordnung/rp_flaecheninanspruchnahme/

UNISDR. (2015). *Global assessment report on disaster risk reduction*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction.

USGS. (2019). *The 100-year flood*. Water Science School. Available from https://www.usgs.gov/special-topic/water-science-school/science/100-year-flood?qt-science_center_objects=0#qt-science_center_objects

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., … Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*, 555–461.

Werner Consult. (2009a). River flood study Tyrol 1 – Upper Inn River (Abflussuntersuchung Tirol 1 – Oberer Inn) (Tech. Rep.).

Werner Consult. (2009b). *Ill River – Assessment of flood protection status from the river mouth at the Rhine to Partenen (km 0–60)* (Ill – Schutzwasserwirtschaftliche Bestandserhebung von der Mündung in den Rhein bis Partenen (km 0–60)) (Tech. Rep.).

Yan, K., Baldassarre, G., Solomatine, D., & Schumann, G. (2015). A review of low-cost space-borne data for flood modelling: Topography, flood extent and water level. *Hydrological Processes*, *29*, 3368–3387.

ZT Depisch. (2009). *Lavant – Assessment of retention areas (river km 0,000-17,000)* (Lavant – Retentionsraumuntersuchung (Flkm 0,000–17,000)) (Tech. Rep.).

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