Changes in land cover and land use in the upper Salzach catchment (Salzburg/Tyrol) between 1830 and 2016

Masterarbeit

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EIDESSTATTLICHE ERKLÄRUNG

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Diplomarbeit selbständig angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher weder in gleicher noch in ähnlicher Form einer anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht.

Yvonne Constanze Sterle, B.Sc. Wien, …………………………………….

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ABSTRACT

Land cover/use (LC/LU) change is one of the major drivers for changes in local to regional flood risk. In order to provide data for a subsequent spatially distributed rainfall-runoff model assessing these changes in more detail, a comparative analysis of land transformations between 1830 and 2016 in the upper Salzach catchment (Austria) was conducted. Based on the Franziscean Cadastre, the historic distribution of LC/LUs was reconstructed to almost the level of exact plots of land. The catchment-wide analysis revealed considerable increases of LC/LUs often associated with higher flood risk. Thus, settlement areas experienced a 6.5-fold increase, rivers and streams got truncated by 22.4% and glaciers declined by 70.2%. In contrast, many LC/LUs which were historically reported to reinforce floods have been converted. Formerly extensive, waterlogged wetlands as well as croplands have virtually vanished and lost 99.3% and 98.8% of their former area, respectively. 31% of former alpine pastures became wooded. Forests and standing water bodies increased by 13.6% and 80.5%, respectively. Along fluvial corridors, i.e. in areas being flood-prone to ca. 300-year floods (HQ_{300} zones), patterns of LC/LU change found in the total catchment, in general, were confirmed. However, some LC/LUs showed even more distinct shifts. Here, sparsely wooded lands lost 60.3% of their former area, whereas grasslands increased by 95.3% and settlement areas showed an 8.2-fold increase. Overall, these land transformations involved river regulation and flood protection measures, which shortened the area of HQ_{300} zones by 16km² (or -9%). Although this truncation and some of the present-day LC/LU changes are generally attributed to increased flood risk, historic long-term land management is estimated to have been even more detrimental in terms of the flooding situation. Until the early 19th century, extensive deforestation in the tributary catchments and transformation of clearcut areas to Alpine pastures and cropland was reported to have led to reduced water retention capacities and high erosion rates, eventually causing the aggradation of the Salzach river bed, locally superelevated river banks, laterally large saturated swamp areas and, thus, frequent severe flooding. Taking into account the historic flooding conditions in 1830 and comparing it with the present situation, it is assumed that, overall, the flood risk has decreased on the regional scale due to the cessation of detrimental, historic land management.

Keywords: historic, present, land cover, land use, transformation, runoff formation, floods

CONTENT

1 INTRODUCTION

In recent years, an increasing number of scientific work in Europe and Austria focused on a possible rise in the frequency and magnitude of river floods induced by climate change (HALL et al. 2014, BLÖSCHL et al. 2015, BLÖSCHL et al. 2020). But although climate change has and had an important impact on runoff extremes (APCC 2014), many other factors of our modern society interfere with a catchment's hydrology (MERZ et al. 2012). Land cover and land use (LC/LU), for example, may have a significant local effect on river runoff formation by altering surface roughness, infiltration and water storage capacities of soils (NISBET AND THOMAS 2006, JAMES AND LECCE 2013). Together with precipitation characteristics and resulting antecedent soil moisture conditions, these factors may strongly impact on flood magnitude (cf. BRONSTERT et al. 2001, BLÖSCHL et al. 2013). Of course, historic LC/LU are not exempt from this effect. Over centuries, humans have strongly impacted on the hydrology of natural systems by altering the land surface and the way it is managed. In more recent years, i.e. over the last 200 years, humans have, additionally, begun to systematically train rivers and streams as well as their fluvial corridors to satisfy human needs for more intense land use and flood protection (BRIERLEY AND FRYIRS 2005, JAMES AND LECCE 2013). In order to reduce flood damage, former hydraulic engeneering measures focused on rapid flood conveyance by straightening and narrowing rivers and streams, thereby confining fluvial corridors. Today, however, awareness of increased flood risks in downstream regions associated with these river regulation measures has led to a rethink (PATT et al. 2011). A more holistic approach of flood protection claiming more room for running waters and integrating flood retention areas adjacent to rivers and streams is now to be implemented. In this context, it is important to investigate the framework conditions under which such an integrated flood risk management (IFRM) is viable. This is the aim of the transdisciplinary research project PoCo-FLOOD (Policy Coordination in flood risk management), under which auspices this master thesis is written. Starting in spring 2019 and funded by the Austrian Academy of Sciences (Research Programme: Earth System Sciences, project leader: Walter Seher, IRUB/BOKU) this research project aims at supporting the shift from traditional flood defence management to an IFRM in Austria by exploring "*interdependencies, conflicts and options for policy coordination between the sectors flood protection, hydropower (energy), agriculture and spatial planning*". This way, challenges and opportunities of policy coordination shall be identified to improve flood hazard prevention and flood mitigation by a multi-sectoral approach. The following three objectives are to be achieved (LÖSCHNER et al. 2019a):

1. to improve the understanding of the sectoral interrelations, which arise from the shift towards an IFRM
2. to broaden the knowledge and evidence base concerning the limitations and conflicts of interest of enhancing policy coherence in IFRM
3. to co-develop options for coordinated flood policies together with stakeholders and policy representatives

Fields of interaction at catchment scale analysed in this project will be (LÖSCHNER et al. 2019b):

1. Flood retention in the headwaters (retention potential by hydropower dams)
2. Water storage on agricultural land (retention potential on agricultural land)
3. Flood protection and land development (mitigation of future increases in flood damage and development of flood-adapted land uses)

To provide the necessary data basis, several working packages were conducted, some of which are presented in this master thesis. These involve the

1. Reconstruction of the historical LC/LU in the Upper Salzach catchment based on historical maps, in particular the Franziscean Cadastre of Salzburg from 1830
2. GIS-based analysis techniques linking geo-referenced data sets of historical and current land uses with data sets of flood risk zones in order to quantitatively evaluate changes in LC/LU and
3. To qualitatively analyse and estimate resulting potential changes in natural water retention and flood characteristics.

1.1 OBJECTIVES

Thus, the overall objective of this master thesis is the reconstruction of altered framework conditions for flood waters in the Upper Salzach catchment by analysing changes between the historic (around 1830) and present (2016) LC/LU. Additionally to the global LC/LU differences in the total study area between the two periods, special consideration is also set on LC/LU changes along river corridors touched by 300-year floods (HQ_{300}). The potential hydrological effect of individual LC/LU types and associated management practices will be assessed with scientific literature. Eventually, these analyses shall allow estimates about changes in flood risk since 1830, which will be discussed with regard to the interplay between climate (change), LC/LU and river regulations.

1.2 RESEARCH QUESTIONS AND HYPOTHESES

According to the objectives illustrated above, the following research questions and associated hypotheses are to be answered.

1. *Which changes in land cover/land use occurred between 1830 and 2016 in the upper Salzach catchment?*

In the Alps, a distinct shift from agrarian societies to industrial societies in the course of the Industrial Revolution brought forth remarkable changes in the distribution and extent of LC/LUs over the last 200 years (BÄTZING 2015). Along economically favourable yet often wet valley floors, extensive drainage projects were conducted in the 19th century in order to intensify their exploitation (e.g. MATHIEU 1998). Former cropland cultivation got replaced by more lucrative livestock farming (BÄTZING 2015). With ongoing economic growth and urbanisation, towns, cities and infrastructure continuously expanded further into fluvial corridors (MATHIEU 1998, BÄTZING 2015). In higher altitude regions, however, many agricultural lands (i.e. cropland, Alpine meadows and pastures), which - under todays economic constraints - had become unproductive were either extensified or abandoned (BÄTZING 2015). As a result of these developments, between the 19th and 21st century, agricultural areas throughout the Alpine region shrinked by between 6% and 67% (TAPPEINER et al. 2006) and many abandoned Alpine grasslands got encroached by scrubs and trees (BÄTZING 2015).
Similar developments were also stated for the study region. In the period 1817-2011, the number of buildings in Pinzgau showed a sixfold increase. Alongside these increases in settlement areas, sealed surfaces were further increased by the construction of roads and other infrastructure (PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Swamps, which formerly occupied large areas along the Salzach valley (25km² according to WIESBAUER AND DOPSCH 2019), were extensively drained in order to reclaim lands for agricultural production (DÜRLINGER 1866, MADER 2000, WIESBAUER AND DOPSCH 2019). Like in other Alpine valleys with unfavourable soils, this agricultural production shifted from cropland cultivation to grassland management (cf. TAPPEINER et al. 2006, BÄTZING 2015, PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Both the transition in agricultural management and the abandonment of unproductive soils, e.g. at higher elevations resulted in a decline of croplands of approximately 90% between 1881 and 2013 (PROVINCIAL GOVERNMENT OF SALZBURG 2016a).

Similarly, large areas of Alpine grasslands have been abandoned or extensified. Until 2013, they lost more than 65% of their former extent in 1881 (PROVINCIAL GOVERNMENT OF SALZBURG 2016a, cf. LFI 2019). Many abandoned Alpine meadows and pastures, today, got recolonized by woody vegetation, thereby significantly contributing to the rate of forest growth in Austria (BFW 2011, LFI 2019). Thus, until 2013, the area of forests in Salzburg increased by more than 20%, compared to their former extent in 1881 (PROVINCIAL GOVERNMENT OF SALZBURG 2016a, cf. BFW 2011). At highest elevations, considerable changes in land cover emerged from climate induced glacier melt (FISCHER et al. 2015, FISCHER et al. 2019). Between the last glacier maximum around 1850 (end of the Little Ice Age, LIA) and 2015, the total glacier area in the study region was shown to have declined by 94km² from formerly 143km² to only 49km² today. This is equivalent to a loss of more than 65% of their former area (data from GROß AND PATZELT 2015 and BUCKEL AND OTTO 2018). Glacier recession progressively uncovers wastelands, whose recolonization by plants providing significant ground cover may take multiple decennies (FISCHER et al. 2019), thereby potentially increasing the area of wastelands in the mid-term. In addition, naturally impounded melt waters frequently built up glacial lakes, which are rapidly growing in response to climate change (SHUGAR et al. 2020). Together with artificial high Alpine reservoir lakes for hydropower generation built in the 20th century (VERBUND HYDRO POWER AG 2013, ÖBB-INFRASTRUKTUR AG 2019) this most probably has led to an increase in the area of standing water bodies. Thus, the following hypotheses are to be tested:

HYPOTHESES 1:

- Increase of sealed surfaces (infrastructure and settlement areas)
- Decrease of wetland areas
- Decrease of cropland
- Decrease of mountain pastures
- Forest expansion
- Decrease of glaciers
- Increase of wasteland
- Increase of standing water bodies

The second research question refers to differences in LC/LU change when comparing general developments in the total catchment with changes in the fluvial corridors only (HQ_{300} zones, i.e. flood prone areas at approximately 300-year floods).

2. *Which changes in LC/LU can be detected in the HQ_{300} areas between 1830 and 2016 and in which way do they differ from changes in the total catchment?*

Due to their good accessibility and high productivity, floodplains in the Alps have been subject to substantial human transformations. While being majorily used as extensive pasture lands in the early Modern Age, most fluvial corridors have been regulated since the 18th and 19th century in order to intensify (agricultural) land uses (MATHIEU 1998, BÄTZING 2015, HAIDVOGL AND TASSER 2019) or to enable any usage of wetland covered valley floors in the first place. The latter objective had been a great concern, as many Alpine valley floors got progressively marshy in direct response to increased precipitation amounts and intensities along severely deforestated hillslopes in the late 18th and 19th century (HAIDVOGL et al. 2019, HAUER et al. 2019). This particularly was the case along the upper Salzach valley. Here, large-scale deforestation over centuries had amplified erosional processes in the tributaries to such an extent that the Salzach Rivers' transport capacity had become insufficient to convey the high amounts of bedload into downstream regions. Failing to erode the material, which gradually built up, the river bed of the Salzach River was progressively lifted, locally causing superelevated river banks of about 1.5m height difference with regard to the river surroundings. Correspondingly, groundwater levels were lifted, too, and valley floors began to transform into swamps. High amounts of precipitation and low water retention capacity in deforested, mountainous sub-catchments in combination with superelevated river banks and high groundwater tables also led to

frequent severe floodings of the valley floors, extensively inundating them and, thus, intensifying paludification between Neukirchen and Bruck (cf. PILLWEIN 1843, STREFFLEUR 1852, LORENZ 1857, MADER 2000, WINDING AND VOGEL 2003, WIESBAUER AND DOPSCH 2019). Throughout the Alpine region, a package of measures had been conducted during the late 19th and early 20th century, including wetland drainage, river straightening and decoupling from side arms along with dredgings, bank protection measures and levee construction. These measures aimed at lowering the river bed and, thus, the water table to facilitate soil drainage and at increasing the flood conveyance by shortening the river length and increasing the rivers' gradients (PATT et al. 2011, HAIDVOGL AND TASSER 2019). As a consequence of these regulations, Alpine running waters lost 4.3% of their historical extent (HOHENSINNER et al. 2021b) and floodplain areas got considerably truncated (e.g. SCHOBER et al. 2020). Remaining floodplain forests were cleared and/or severely impaired due to hydrological alterations associated with hydro-engeneering structures (BLOESCH AND FRAUENLOB 1997, LAZOWSKI 1997, KLIMO AND HAGER 2001, HAIDVOGL AND TASSER 2019). This was not only a development of Alpine floodplains, but applies to floodplains around the world (TOCKNER AND STANFORD 2002, DAVIDSON 2014). As was shown by TOCKNER AND STANFORD 2002 (using worldwide catchment data from REVENGA et al. 1998), riparian areas are significantely more severely impacted by land use changes than the total catchment. The authors stated that the most impacted riparian corridors in terms of LC/LU changes were found in Europe. Here, between about 60% and 99% of the riparian corridors have been transformed to cropland and/or to urban areas.
Thus, the following hypotheses are to be tested:

HYPOTHESES 2:

- More distinct increase of sealed surfaces compared to the entire upper Salzach catchment
- More distinct decrease of wetlands compared to the entire upper Salzach catchment
- Decrease of (floodplain) forests
- Decrease of the total area of running waters
- Decrease of the HQ_{300} area

Altogether, these land transformations may have affected erosional and hydrological processes in the upper Salzach catchment, which – eventually – may have impacted on runoff behaviour and flood regime. Thus, the third research question assesses the hydrological implications associated with regional LC/LU change.

3. *What are the potential effects of present changes in LC/LU on the runoff behaviour and the flood regime?*

Following previously stated information given by MATHIEU 1998, TAPPEINER et al. 2006 and BÄTZING 2015, this question will be assessed by distinguishing between potential effects of LC/LU change in mountain regions and those along valley floors.
Large areas of highest altitude regions in the study area are covered by glaciers. Under cold climatic conditions, they act as precipitation buffers by retaining precipitation amounts over long periods of time of up to hundreds of years (FISCHER et al. 2018). One reason is their thick snow cover, allowing to accumulate not only solid precipitation, but also to absorb rainfall amounts of up to 50% of the snow covers water equivalent (DYCK AND PESCHKE 1995). However, with progressively accelerated rates of glacier melt due to climate change (FISCHER et al. 2015), an increasing number of glaciers is either degraded or lost (FISCHER et al. 2018). Degraded glaciers often no longer provide the buffering capacities they had previously. In fact, they may accelerate runoff reactions and severely reinforce floodings in the course of precipitation events (BRAUN AND WEBER 2006). On areas formerly covered by glaciers, it takes time for soils to develop and for plants to colonize them, so that for the following decades most of these spots are subsequently covered only by sparsely vegetated rocks (predominantely mosses and herbaceous taxa, FISCHER et al. 2019). Those bare rocks and shallow, sparsely vegetated or unvegetated soils in steep terrain limit the water retention capacity in high Alpine regions. Thus,

although dependent on the catchment's geology and topography, water retention capacities are generally low and precipitation amounts most often are rapidly transmitted to subjacent areas (cf. LORENZ 1857, BRONSTERT et al. 2002, VERBUNT et al. 2005, KIRNBAUER et al. 2008). On the other hand, new land uses in high Alpine regions, i.e. reservoirs for hydropower generation, were found to locally and regionally reduce flood runoff of small to medium floods by retaining large volumes of water (e.g. VERBUNT et al. 2005 for Switzerland, LEBIEDZINSKI et al. 2020 for Salzburg). Similarly, aforementioned LC/LU changes at subjacent mountain sites (i.e. abandonment of Alpine meadows and pastures, recolonization of those areas by forests, abandonment of elevated croplands) are generally associated with increased water retention capacities, thus, reduced surface runoff and lower stream discharges. For instance, WAGNER et al. 2009 stated that runoff coefficients in agricultural landscapes are highest for several types of cropland and lowest on grasslands (those of pastures being higher than those of meadows). Runoff coefficients of grassland areas could only be further reduced by set-aside or conversion into forests. This was confirmed by evidence of LEITINGER et al. 2010 and MAYERHOFER et al. 2017, assessing surface runoff formation on different types of Alpine grasslands. Thus, LEITINGER et al. 2010 showed that maxmimum runoff coefficients were up to 8 times higher on Alpine pastures at the end of the grazing season as compared to those on abandoned areas dominated by graminoids, herbs and dwarf shrubs. The main reason for these differences was cattle trampling, leading to soil compaction and thus, reduced infiltration capacities. Hydrological effects associated with changes in forest cover were reviewed e.g. by BROWN et al. (2005), supporting that increases in forest cover lead to reductions in water yield. VERBUNT et al. (2005) simulated hydrological effects when converting a fully grass covered catchment into a completely forested one and found that afforestation decreases runoff as a result of increased evapotranspiration. Likewise, other authors (e.g. BESCHTA et al. 2000, SALAZAR et al. 2012 or BLÖSCHL et al. 2018) confirmed that forests attenuated runoff formation. Yet, this effect was found to be limited to small catchments and small flood-inducing events.

Along the valley floors, increases of sealed surfaces by urbanisation are generally associated with faster runoff reactions as well as increased flood peaks and volumes. This is due to highly reduced surface roughness and infiltration capacities as well as rapid and efficient conduction of surface runoff to the sewage system or receiving waters (WEILER 2016). When comparing flood discharges in the course of a convective storm event under historic and present-day settlement areas (0.8% of the total catchment in 1844, 7.4% in 2001) in the German Lein catchment, BRONSTERT et al. 2001 simulated an approximately doubling of flood maxima occurring more than two hours earlier than under historic conditions. Similarly, river regulations, i.e. the constriction and loss of runoff areas as well as of retention areas, were shown to accelerate floodwaters and to increase flood peaks in downstream regions (cf. BRIERLEY AND FRYIRS 2005, PATT et al. 2011, HOHENSINNER et al. 2018, SCHOBER et al. 2020). In contrast, other land use changes along the valley floor are generally associated with reduced flood risks – first and foremost the drainage of extensive swamps along the Salzach valley (cf. KOCH-STERNFELD 1811, WIESBAUER AND DOPSCH 2019) and their conversion to grasslands. Other than the widespread notion that wetlands generally reduce flood risk by providing water retention capacities similar to a sponge, BULLOCK AND ACREMAN 2003, KIRNBAUER et al. 2008 as well as ACREMAN AND HOLDEN 2013 have shown that this may not necessarily apply. In fact, headwater wetlands frequently reinforced floods rather than attenuating them (BULLOCK AND ACREMAN 2003). Thus, KIRNBAUER et al. 2008 found that – in the course of advective precipitation events - some headwater wetlands in the Saalach catchment did not only show immediate surface runoff reactions but also produced a second, delayed runoff peak of considerable duration and volume after the precipitation event had ceased. For wetlands to fulfil any flood attenuating function, they need to be unsaturated, i.e. the groundwater table needs to be below the surface (cf. HOLDEN AND BURT 2002, BULLOCK AND ACREMAN 2003, ACREMAN AND HOLDEN 2013). However, more than one third of the 25km² of swamps covering the Salzach valley were historically described as being waterlogged (cf. KOCH-STERNFELD 1811, WIESBAUER AND DOPSCH 2019). The net effect of drainage often is difficult to determine and may vary depending on several factors, e.g. soil and drainage types (WEILER 2016). However, in regions, whose water table had been near to the surface prior to the drainage, this measure will most likely result in its lowering, providing new water storage capacities during flood events and thereby reducing floods (cf. ROBINSON

1990). Aside from these hydrologically favourable transformations, extensive croplands, which formerly covered large areas in the valleys were converted to grasslands. As was set out earlier, such transformations are generally associated with higher water retention capacities and a reduction in runoff coefficients (WAGNER et al. 2009).

HYPOTHESES 3:

In mountain regions:

- Increased surface runoff due to glacier melt and the continuous uncovering of wasteland (talus fans, moraines, rocks) providing only little water retention capacities
- Faster and more pronounced runoff reactions due to the loss and degradation of glaciers buffering precipitation
- Generally higher water retention, reduced surface runoff and lower discharges of tributaries due to forest growth and abandonment of alpine pastures
- Locally/Regionally reduced flood runoff due to large reservoirs of storage power plants

Along the valleys:

- Increased surface runoff and contribution to floodwaters due to considerable increases of sealed surfaces along river corridors
- Acceleration of floodwaters and increases in flood peaks in downstream regions due to the constriction and loss of runoff areas as well as of flood retention areas
- Reduced surface runoff and flood runoff due to the drainage of waterlogged swamps adjacent to the Salzach River
- Higher water retention capacity due to the drainage of waterlogged swamps and the conversion of croplands in grasslands
- Regional decreases in flood magnitude due to the cessation of historic land management favouring detrimental erosional processes and increased runoff formation

1.3 TERMS AND DEFINITIONS

Due to the complexity of this topic, a brief overview of terms and definitions is given in the following sub-chapters.

1.3.1 LAND COVER (LC)

Land cover is defined as "*the observed (bio)physical cover on the earth's surface*", including bare rock and bare soils, water surfaces (FAO 2000), forests, (near)natural areas and wetlands as well as man-made structures such as settlements or agricultural areas (DIRECTIVE 2007/2/EC ANNEX II). In short terms, land cover refers to the surface cover without addressing its use (e.g. grassland, forest, urban infrastructure etc.) (COFFEY 2013).

1.3.2 LAND USE (LU)

Land use, on the other hand, is defined as "*the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it*" (FAO 2000). The term "land use" refers to current and future functions or the socio-economic purpose of areas (e.g. residential areas, industrial areas, recreational areas, agricultural and forested land etc.) (DIRECTIVE 2007/2/EC ANNEX III). Thus, it describes how land cover is used, rather than to describe surface cover alone (e.g. pastures on grassland). Of course, the same land cover type can be assigned to a variety of different land uses (e.g. grassland as pastures, parks, sports ground, wildlife sanctuary etc.) (COFFEY 2013).

1.3.3 MEAN DISCHARGE AND FLOODS

In general, flood water is defined as a water level or discharge, which surpasses a given critical value, i.e. the bankfull stage, thus, overtopping the river banks and inundating land, which normally is not (cf. DIRECTIVE 2007/60/EC, HOLMES AND DINICOLA 2010). A flood is, thereby, shaped by the interplay of climatic, topographic, geologic and pedologic characteristics, which determine the amount of surface and subsurface runoff in the course of precipitation events. Due to immutability of these factors, any reductions in surface runoff as well as any increases in water retention, which may reduce flooding, can only be achieved when changing the type and/or management of LC/LU (WAGNER et al. 2009). The most important attributes of floods are their peak flow, their volume and duration as well as the lag time, i.e. the time gap between the precipitation maximum and the flood peak (ACREMAN AND HOLDEN 2013, see Figure 1).

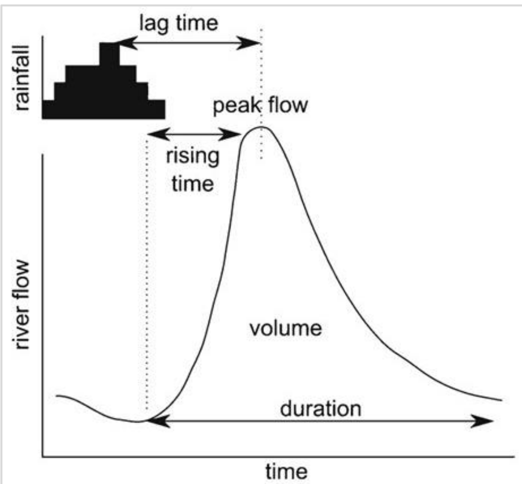

***Figure 1**: Hypothetical river flood hydrograph (ACREMAN AND HOLDEN 2013).*

The magnitude of floods is referred to by using the statistical annual exceedance probability (AEP) of discharges at a given gauge. For many scientific and societal issues, the 1-percent AEP flood is an important measure. Its chance of being equalled or exceeded in any single year is 1 in 100. Thus, it has an average recurrence interval of 100 years, which is often referred to as the "100-year flood" (HOLMES AND DINICOLA 2010, cf. ÖNORM B 2400).). The same applies of course to a 300-year flood (HQ_{300}). Other runoff parameters are shortly described in the table below.

***Table 1**: Description of several runoff parameters used in this paper.*

Parameter	**MQ**	**MJHQ**	**HQ_{10}**	**HQ_{100}**	**HQ_{300}**	**HHQ**
Signification	Mean discharge over a given period of years at a given gauge station	Mean yearly flood discharge over a given period of years at a given gauge station	Flood discharge, that is statistically equalled or exceeded every 10 years at a given gauge station	Flood discharge, that is statistically equalled or exceeded every 100 years at a given gauge station	Flood discharge, that is statistically equalled or exceeded every 300 years at a given gauge station	Highest flood ever measured since the commissioning of a given gauge station

1.3.4 RUNOFF FORMATION

Flood discharge is formed by various runoff processes. In short, storm runoff is generated either when the storage capacity of soils is exhausted (saturation excess overland flow), e.g. after longlasting precipitation events or when infiltration capacities are lower than precipitation intensities (infiltration excess overland flow or Hortonian overland flow). In the latter case, precipitation amounts arriving at the soil surface at a given time exceed the readiness of soils to percolate them, hence, leading to rapid surface runoff (BRONSTERT et al. 2002, DISSE 2020). In addition, subsurface stormflow and deep percolation are further runoff processes to be considered. Subsurface stormflow is often found on steep, shallow soils with good infiltration capacities underlain by an impermeable horizon of higher bulk density or less permeable bedrock, and – regarding the boundary conditions – high antecedent soil moisture and high groundwater levels (BRONSTERT et al. 2002, NAEF et al. 2002). The relative importance of different runoff processes within a catchment varies with climatic, topographic, geologic and pedologic conditions as well as with vegetation cover and, thus, seasonally. These parameters are, generally, of paramount importance, as they set the preconditions for runoff formation (see Figure 2). However, with progressively higher antecedent soil moisture conditions or higher magnitudes of precipitation events, even the role of physiographic factors (i.e. topography, geology, soils, vegetation and land use) becomes less pivotal. Similarly, with increasing catchment area concerned by a flood inducing event, the characteristics of the stream network come to the fore, while physiographic factors become less important (BRONSTERT et al. 2001).

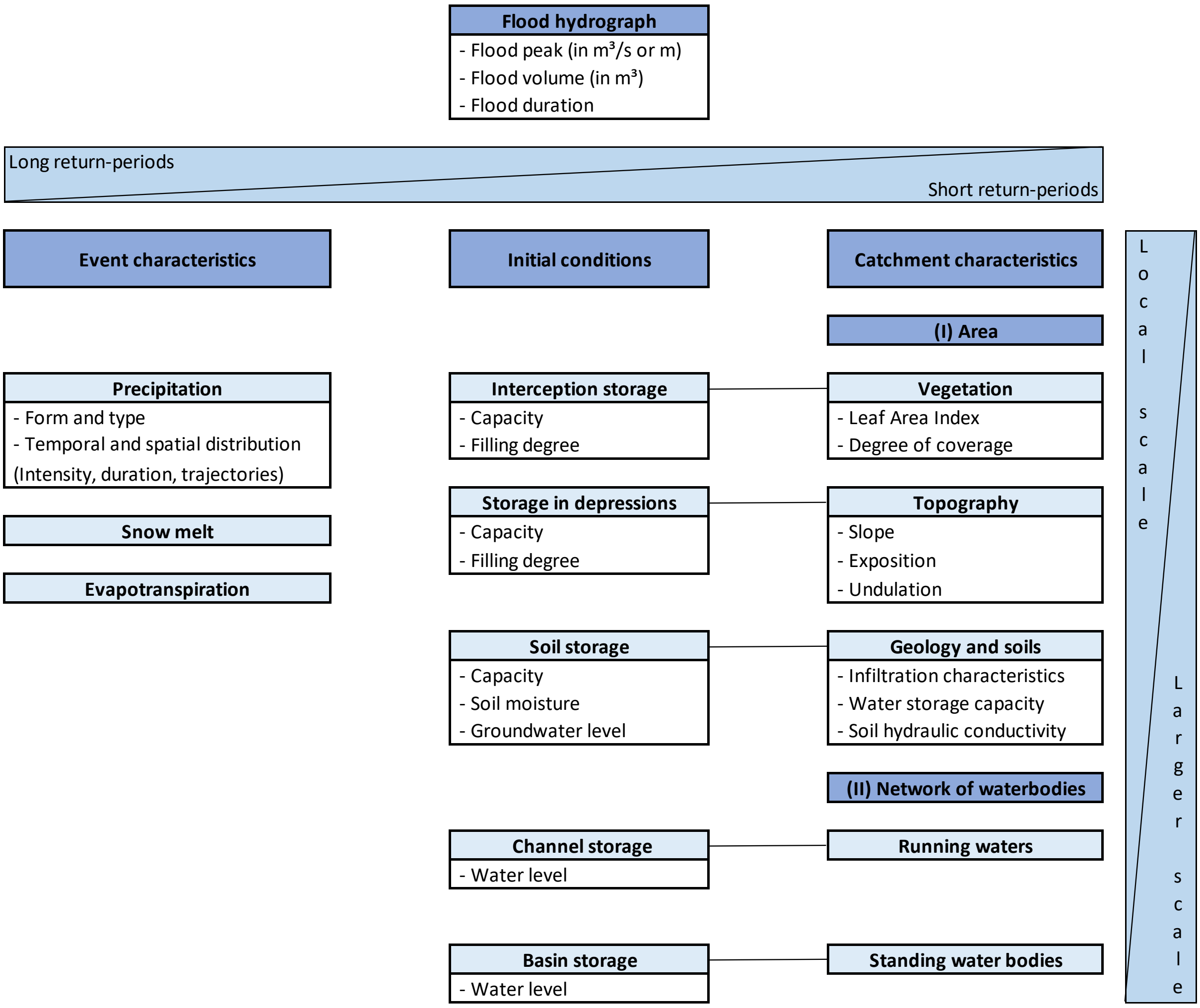

***Figure 2**: Schematic overview of hydroclimatic and physiographic factors shaping river floods, shown as a function of the event's return period and the catchment area affected (modified after BRONSTERT et al. 2001, using information from HERRMANN 1992, BLÖSCHL AND SIVAPALAN 1995, DYCK AND PESCHKE 1995). Note the importance of the different types of water storages, their general retention capacity and their actual filling ratio at the beginning of precipitation and snow melt events).*

Each of the aforementioned runoff process is associated with a given response time. For instance, soils prone to Hortonian overland flow react either immediately or with a short lag time, depending on the intensity of factors reducing the infiltration capacity (e.g. scarcity of macropores, clay content, degree of soil compaction and surface sealing, hydrophobicity of soils, impermeability of bedrock). Likewise, runoff reactions of soils usually governed by saturation processes can be rapid and strong in case antecedent soil moisture conditions are high. If so, short bursts of rainfall may lead to immediate saturation overland flow. In contrast, on dry, thick and permeable soils, which are rich in macropores, saturation overland flow will be much delayed. The actual catchment response to intense precipitation depends on the spatial distribution of the dominant runoff processes. Small catchments where large areas produce Hortonian overland flow will react strongest to convective precipitation events, irrespective of antecedent soil moisture conditions, whereas catchments dominated by subsurface flow processes will react slower to any type of precipitation and will produce smaller peak flows than catchments with large Hortonian or saturation overland flow. In order to reduce storm runoff and flood flows by land use changes, rapid runoff processes have to be transformed into slower ones (e.g. saturation overland flow, subsurface flow and deep percolation) in sizeable parts of the catchment (NAEF et al. 2002). However, as saturation overland flow, subsurface storm flow and deep percolation are determined primarily by geology and topography, LC/LU change exerts only minor influence on these types of runoff formation.

Still, in terms of infiltration capacities, overground water storage capacities (interception storage or litter storage) and water retention in the landscape (e.g. reservoirs, ponds and lakes), LC/LU may play an important role (see Table 2) (BRONSTERT et al. 2002, WAGNER et al. 2009). For instance, changes in the extent and type of vegetation may considerably alter runoff formation by modifications in evapotranspiration, root penetration and interception storage (BROWN et al. 2005). It should be considered, however, that any potential reduction in storm runoff by changes in land use or management practices is restricted to sites, where infiltration and matrix wetting can be enhanced (NAEF et al. 2002, cf. VERBUNT et al. 2005). With timescales ranging up to hundreds of years, resulting hydrological responses, generally, are difficult to detect in the short term. In addition, the short-term response may significantly differ from long-term responses of land use change, thus, adding complexity to the catchment system (ROGGER et al. 2017).

***Table 2**: Potential impact of land-use changes on surface and near-surface hydrological processes (fluxes and storages) and relevance for components of the hydrological cycle (BRONSTERT et al. 2002).*

Process	Potential impact of land-use changes and relevance for components of the hydrological cycle
Interception storage	Greatly affected by vegetation changes (e.g. crop harvest, forest cutting); relevant for evapotranspiration/energy balance
Litter storage	Affected by vegetation changes, in particular forest cutting; relevant for evapotranspiration/energy balance
Root zone storage	Affected by management practices like tilling method etc.; relevant for evapotranspiration and storm runoff generation
Infiltration-excess overland flow	Affected by crop cultivation and management practices; relevant for storm runoff generation in the case of high rainfall intensities and low soil conductivity; may be enhanced by soil siltation and crusting
Saturation-excess overland flow	Only slightly affected by land-use changes (process is controlled by topography and subsurface conditions)
Subsurface stormflow	Only slightly affected by land-use changes (process is controlled by topography and subsurface conditions)
Runoff from urbanised areas	Highly affected by sewer system and sewage retention measures; relevant for storm runoff *from urban areas*
Dezentralised retention in the landscape	Affected by landscape structuring and agricultural rationalisation of arable land; relevant for storm runoff concentration *from arable land*

2 STUDY AREA

The following sub-chapters provide an overview of the main determinants for runoff formation in the upper Salzach catchment, describing its topography and geology as well as historic and present climate and the major factors determining historic and present hydrologic conditions of rivers and streams.

2.1 CATCHMENT AREA AND TOPOGRAPHY

The study area is located in the eastern part of the Federal State of Salzburg in Austria, and comprises the political district of Zell am See (district of Pinzgau) and some minor parts of Sankt Johann im Pongau (district of Pongau) at its western borders. At its north eastern borders, it includes parts of the Salzach catchment situated in Tyrol (district of Kitzbühel) and at its southern borders small areas of Carinthia (see Figure 3).

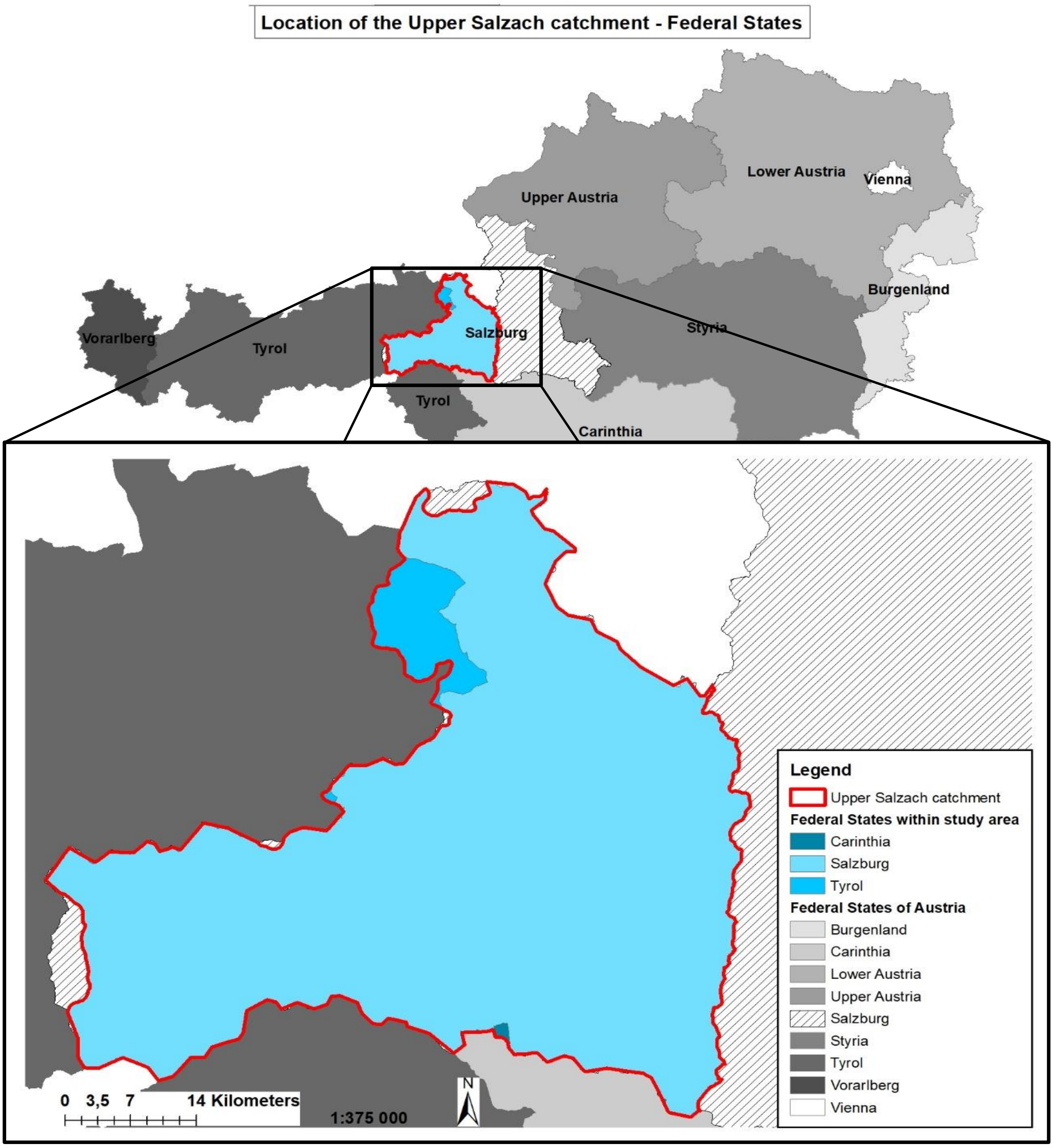

***Figure 3**: Location of the study area within the Federal States of Austria. In red: limits of the study area; coloured: Federal States within the study area; grey: all other Federal States.*

The study region is divided into the Saalach catchment in the northern part of Pinzgau and the Salzach catchment in the southern part (see Figures 4 and 5), amounting to a total catchment area of 2704km². In direct proximity to the Alpine divide, the topography in both catchments is characterized by a mountainous relief with steep slopes controlling (surface) runoff characteristics and flow velocities (cf. MADER et al. 1996, BRIERLEY AND FRYIRS 2005). Thus, more than 70 mountain peaks >3000m a.s.l. can be found along the southern High Tauern massif draining into the Salzach valley. One of these peaks is the Großes Wiesbachhorn, which is the highest summit in the study area with 3563m a.s.l. However, the Großvenediger, which is the highest peak of Salzburg (3658m a.s.l.) and located in the same region is not part of the study area. Due to these altitudes, a considerable share of the High Tauern massif is covered by glaciers, several of them with an extent of more than 4 km², such as the Obersulzbach Kees (9.7km² in 2007) or the Krimmler Kees (4.2km² in 2007) of the Venediger group (STOCKER-WALDHUBER et al. 2012). Along the Salzach valley, altitudes fall to a minimum of 624m a.s.l. In contrast, elevations in the northern Saalach catchment are much lower. Governed by the Kitzbühel Alps, Loferer and Leoganger Steinberge in the east and the Steinernes Meer massif in the west, altitudes range between 512m a.s.l. in the valleys up to a maximum altitude of about 2800m a.s.l. at Steinernes Meer. The relief as well as slope gradients and slope lengths have important implications on surface and subsurface runoff formation. In steep mountain regions, infiltration processes are generally impeded and runoff velocities are high (WAGNER et al. 2009). Thus, catchments in the High Tauern region show fast hydrological responses to precipitation events and snow melt. Apart from highly inclined slopes, this is also due to the high amount of bare surfaces (bare rocks) (GAÁL et al. 2012), leading to rapid surface runoff. Infiltration processes on debris, in contrast, may delay runoff formation to a certain degree (KIRNBAUER et al. 2008, GAÁL et al. 2012). In karst regions like the Saalach catchment, where subsurface and near-surface stormflow constitute important components for flood formation, flood hydrographs are comparatively smooth and catchment response times are slower than in the High Tauern region (GAÁL et al. 2012).
In addition to amplified surface runoff formation, slope lengths and, hence, flow lengths also determine the transport capacities of surface runoff and, hence, erosion. Thus, the longer the slope length and flow length, the higher the transport capacity of surface runoff (WAGNER et al. 2009).

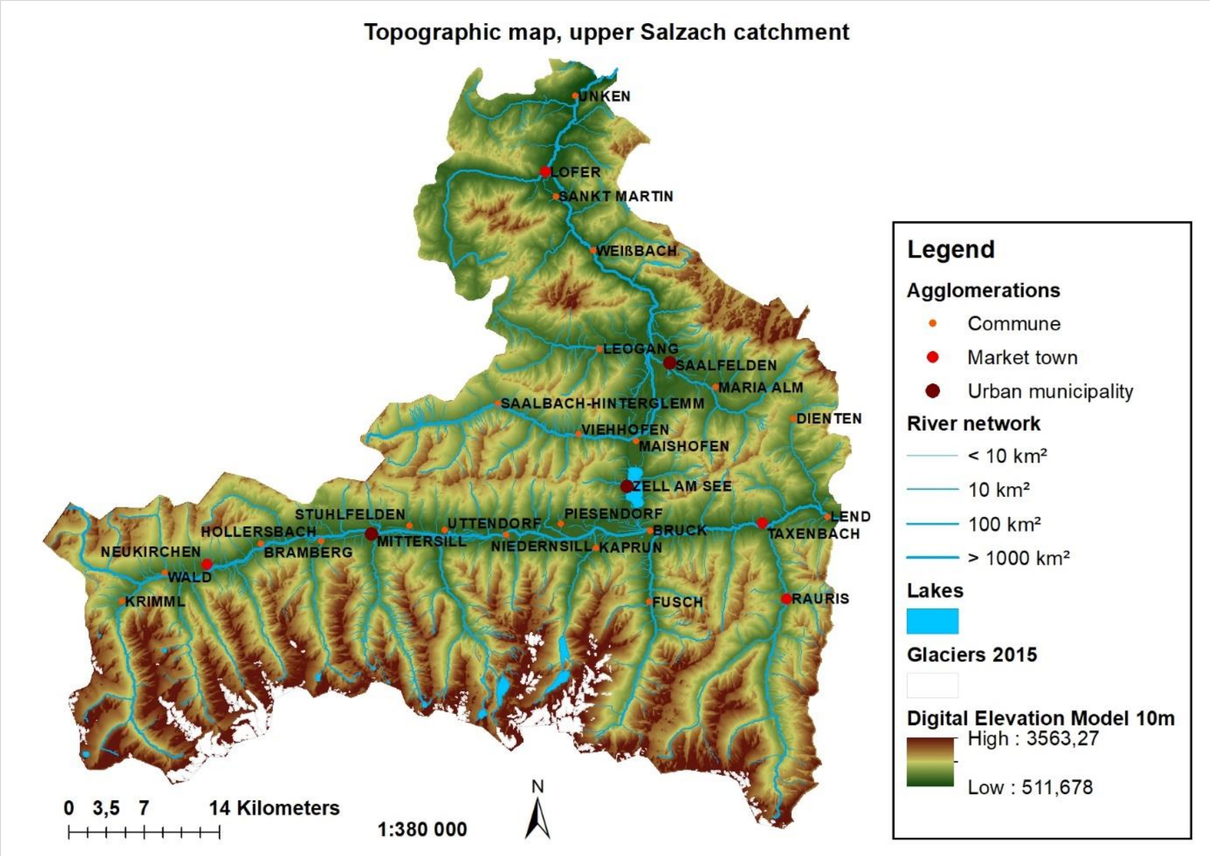

***Figure 4**: Topography of the upper Salzach catchment. Data from* OPEN DATA AUSTRIA*, www.data.gv.at.*

The Tyrolian Kitzbühel Alps are the source area of the Saalach River, which originates at approximately 2000m a.s.l. (KAINZ AND GOLLMANN 2009). In its uppermost sections along the first few kilometers, it passes through a V-shaped valley with high slopes of 68.6‰, rapidly falling to 17.2‰ in the wider valleys further downstream up to Maishofen. In this section, it flows from west to east, while turning north in proximity to Maishofen. The primary natural environment of the Saalach River over the first kilometres is dominated by forest, meadows and pastures. However, after a comparatively short flow stretch with natural surroundings, the share of settlement areas along the Saalach River increases shortly before the city of Saalbach-Hinterglemm. Further downstream, in the wide valley plain between Maishofen and Saalfelden am Steinernen Meer, urbanisation is even more intense. The remaining areas of the valley floor are covered by grassland, while more elevated areas are wooded. Similar characteristics can also be found along its two major tributaries in this section, Leoganger Ache and Urschlaubach. Just like the Saalach, both river corridors are accompanied by forest only over a few kilometres in their headwater sections as well as in higher elevations and are subsequently dominated by meadows, pastures and settlement areas. Between Maishofen and Saalfelden, the Saalach River flows in northerly direction with a moderate slope of 5.1‰. Afterwards, despite being confined by the Loferer and Leoganger Steinberge in the east and by the Berchtesgaden Alps in the west ("Sohlenkerbtal"), the Saalach River follows an even lower slope of 3.3‰ to 4.3‰ in north-easterly direction until Lofer, where it turns northwest and passes a V-shaped valley (7.8‰). The relative share of forests significantly inreases in this part of the catchment, resulting in large areas being wooded. In addition, wastelands occupy important areas, too. Still, the direct river surrounding environment of the Saalach River in this section are grasslands and settlements. From Lofer onwards until the northern catchment outlet, the Saalach then again flows through forested land as well as alongside meadows and pastures (with the exception of passing the town of Unken). The Unkenbach catchment, a tributary of the Saalach in this section, is particularly wooded. Likewise, the catchment of the Loferbach features important shares of forests, but its river corridors are also characterized by meadows, pastures and settlements. Shortly after the town of Unken, the Saalach River leaves the Austrian territory, in parts constituting the Austrian-

German border. These borders represent the limits of the study area. After its passage through Bavaria, the Saalach River becomes a tributary of the Salzach River north of the city of Salzburg. Altogether, it drains a catchment area of 1150km² (MUHAR et al. 1996) with a river length of 106km (PROVINCIAL GOVERNMENT OF SALZBURG 2020) and an elevation difference of more than 1362m (see Table 3). As the study area is limited to the Austrian part of the Saalach River, its catchment area is reduced to 889km² being analysed.

***Table 3**: General characteristics of the Salzach and Saalach rivers. Data from MUHAR et al. 1996, KAINZ AND GOLLMANN 2009, HYDROCONSULT GMBH 2011, PROVINCIAL GOVERNMENT OF SALZBURG 2020.*

General characteristics		
River	Salzach	Saalach
Stream source	Salzburg, Kitzbühel Alps (c. 2300m a.s.l.)	Tyrol, Kitzbühel Alps (c. 2000m a.s.l.)
River mouth	Bavaria, Haiming (c. 343m a.s.l.)	Salzburg, near Salzburg city (c. 408m a.s.l)
Elevation difference [m]	≈ 1957	≈ 1362
River length [km]	227	106
Total catchment area [km²]	6734	1150
Bedload transport	High	High
Characteristics within the study region		
Catchment area [km²]	1815	889
Slope [‰]	Source → Krimmler Ache 90.5 Krimmler Ache → Bruck 3.0 Bruck → Schwarzach 6.1	Source → Labeckalm 68.6 Labeckalm → Atzing 17.2 Atzing → Buchweißbach 5.1 St. Martin → Lofer 3.3 Lofer → Austrian border 7.8

Like the Saalach River, the Salzach River has its source in the Kitzbühel Alps at approximately 2300m a.s.l. At its uppermost section up to its confluence with the Krimmler Ache, the Salzach River features very high slopes of up to 90.5‰ and flows through a narrow valley in southern and southeastern direction. Vast areas of its upper catchment are covered by grassy and woody vegetation. The river itself is predominantly surrounded by forests and – in parts – by meadows and pastures. After passing this steep mountainous region, the Salzach valley gradually widens to a west-east oriented floodplain valley ("Sohlental") between the confluence with the Krimmler Ache and the city of Bruck. The slope drops to 3‰, thus, allowing for soil cultivation and housing in former times. Hence, the share of settlements sharply increases in this section, while meadows and pastures constitute the dominant LC/LU on the valley floor. At more elevated sites, forests prevail, which are progressively superseded by grassy vegetation with ancreasing altitudes. The highest elevations are covered by large areas of wasteland and glaciers. Shortly after Bruck and up to the study area's outlet at Lend, the valley narrows again and turns into a ravine, with slopes of 6.1‰ (MUHAR et al. 1996). It is only after the city of Taxenbach that the Salzach River again flows through more forested land, which continues to be accompanied by meadows, pastures and settlements. After the outlet of the study area, the Salzach River turns north shortly after St. Johann im Pongau and follows this direction up to the city of Salzburg, where it conjoins with the Saalach River. Just like the Saalach River, the Salzach River is a border delimiting water body starting north of the city of Salzburg up to its confluence with the Inn River northeast of the Bavarian city of Burghausen. Altogether, the Salzach River drains a total catchment area of 6734km², which is approximately 74% of the federal state's territory, making it the biggest river of Salzburg (WIESBAUER AND BRANDECKER 1994). The upper catchment area analysed in this paper amounts to 1815km². A general overview of basic characteristics of both rivers is given in Table 3, a map of the main sub-catchments is depicted in Figure 5.

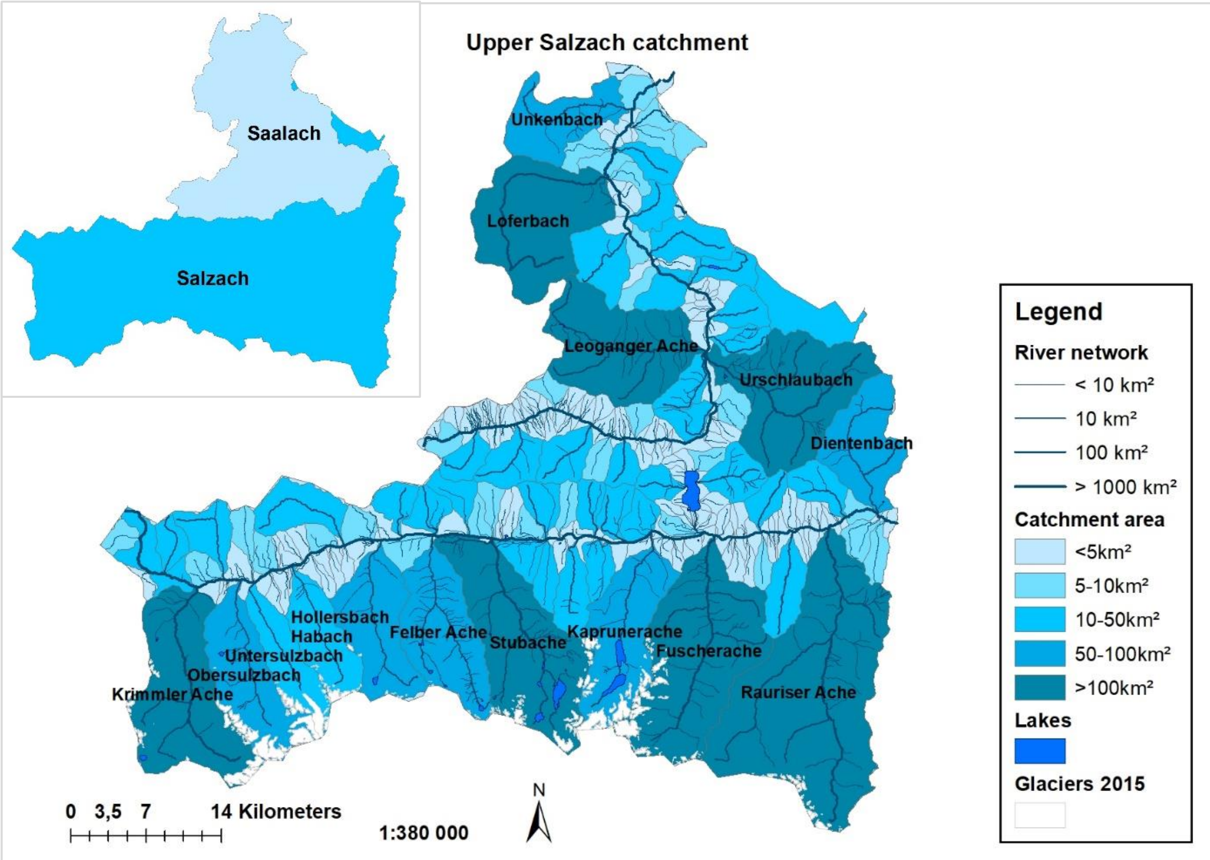

Figure 5*: Main sub-catchments within the upper Salzach catchment. The 15 biggest sub-catchments are labelled. Data from* O*PEN* D*ATA* A*USTRIA, www.data.gv.at.*

Owing to the narrow valleys and steep slopes in their headwater section, both rivers show straight courses (MUHAR et al. 1996) with high flow velocities, strong currents and high bed load transport rates. Likewise, many of the upper Salzach tributaries' are to be classified as torrents. The most important Salzach tributaries in terms of catchment size and total runoff predominantly have their source in the southern High Tauern massif at elevations above 2000m a.s.l., some of them originating in glaciated regions. Just like their receiving waters, these tributaries feature straight courses in narrow valleys with high slopes, resulting in strong currents and high bed load transport (KAINZ AND GOLLMANN 2009, cf. BRIERLEY AND FRYIRS 2005) as well as fast runoff responses (BRAUN AND WEBER 2006, GAÁL et al. 2012). In particular, the major Salzach tributaries coming from the High Tauern are the Krimmler Ache, the Stubache, the Fuscher Ache and the Rauriser Ache. Solely, the Dientenbach is the only major tributary not originating in the southern High Tauern region, but in the Steinernes Meer plateau north of the Salzach valley. Their catchments are characterised by large areas of wasteland, grasslands, forest and - in some cases - by glaciers. Only two catchments, the ones of the Kapruner Ache and the Rauriser Ache, feature relevant settlements along their river corridors. The main tributaries of the Saalach River are the Urschlaubach, the Loferbach, the Leoganger Ache and the Unkenbach, all originating either in the Greywacke zone or the Limestone Alps.

After the first kilometres, most river sections of the Saalach and the Salzach River are running along wider valley floors with lower slopes, resulting in comparatively lower flow velocities. Still, stream power and sediment transport capacities are generally high due to progressively increasing discharges (cf. BRIERLEY AND FRYIRS 2005). In the valley section between Krimml and Bruck, however, the Salzach River features a very low slope, which was even lower in 1830. Thus, in this section, bedload transport capacities were insufficient, leading to detrimental hydrological developments associated with LC/LU change (cf. chapter 2.4).

2.2 GEOLOGY AND SOILS

Geology and soils are major determinants for catchment characteristics, strongly impacting on river discharges (GAÁL et al. 2012). For instance, though river runoff generally increases with increasing catchment area, this might not be the case in kart areas, where considerable water volumes might percolate into subsurface cavities and might be transferred to neighbouring catchments (MADER et al. 1996). But geology and soils also affect surface runoff and flood magnitude. By temporarily storing precipitation and delaying runoff, they might attenuate peak flows (BMLFUW 2013). In this regard, depending on the soil type and its substrate composition, mean storage capacities of dry soils range between 100-300mm of precipitation (LÄNDERARBEITSGEMEINSCHAFT WASSER 2000). One major determinant for the characteristics of soil water storage is the geologic parent material. In setting the preconditions for soil evolution, it strongly impacts on soil texture, porosity, compaction, lime and humus content as well as on chemical processes (BFW s.a. a). Together with soil depth, depth to groundwater table and relief, these factors define not only surface and subsurface flow velocities, but also infiltration capacities as well as saturation levels and, hence, soil water storage capacities (BMLFUW 2013, see also MADER et al. 1996, NIEHOFF 2001).

Being major parameters in attenuating floods, the importance of soil texture and antecedent soil moisture are briefly described in the following. In general, soils consist of varying fractions of sand, silt and clay. Their mixture within the soil matrix determines the water retention capacity and hydraulic conductivity as well as the ability of roots to penetrate the soils, thereby creating additional flow paths (BFW s.a. a). In this regard, gravelly and sandy soils are generally associated with high permeabilities and low water holding capacities resulting in rapid deep percolation into regional aquifers, so that flood peaks are delayed and/or reduced (GAÁL et al. 2012). Due to high rates of infiltration, LC/LU changes in regions with sandy soils may notably impact on the local flood response, especially in case the subsequent LC/LU type reduces the permeability of soils. The same is the case for LC/LU change and management practices on more vulnerable, silty soils, which tend to siltation and compaction (NIEHOFF 2001). However, in catchments with relatively shallow soils, the actual soil composition may be negligible, because low soil depths result in fast flood responses (GAÁL et al. 2012). As was indicated before, the capacity of soils to store high volumes of water depends not only on physical characteristics, but also on water saturation prior to precipitation or snowmelt events (LÄNDERARBEITSGEMEINSCHAFT WASSER 2000). Their buffering effect is highest for permeable, deep and dry soils on plain or undulated grounds. Saturated soils, in contrast, rapidly generate translatory flow and saturation excess surface runoff (cf. BRONSTERT et al. 2001). Thus, the most severe historic flooding along the Upper Danube were reinforced by the mechanism of high antecedent soil moisture or (locally) reduced by either high soil permeability or dry soils and low ground water levels (BLÖSCHL et al. 2013). However, the ability of soils to store large amounts of water or to divert them into regional groundwater aquifers is also shaped by other factors. Thus, it is the interplay of climatic inputs, topography, geologic parent material, vegetation and human alterations of the landscape, which altogether shape the hydrological response of soils (BFW s.a. a).

In the following, an overview of the geological characteristics in Pinzgau is given. In addition, pedological conditions affecting the water retention of soils are described. However, as water retention in high altitude mountainous region is limited due to high slopes and generally rather shallow, raw soils the following pedologic descriptions are limited to agriculturally used valley bottoms.

In general, Pinzgau is divided into three different geological regions: The limestone Alps in the North, the central Greywacke zone and the Tauernkristallin region in the South (see Figure 6).

As the name implies, lithology of the Pinzgau Limestone Alps and Limestone foothills is predominantly characterized by limestone, dolomite and – to a smaller extent – by marl and sandstone (GEOLOGICAL SURVEY OF AUSTRIA s.a., see Figure 7). This area is strongly karstified and disposes of extensive cave systems (WIESBAUER AND BRANDECKER 1994), constituting medium-sized to extensive groundwater resources of medium to high water yield (GEOLOGICAL SURVEY OF AUSTRIA s.a.). Thus, valley soils in this region are generally moderately to highly permeable, except for soils northwards of Lofer and in the region southeast of Saalfelden, where permeability is medium to very low. These are soils of rather high bulk density with higher shares of loam in contrast to the rest of the region in which more sandy soils dominate. The sandiest, shallowest and driest soils (rendsina and ranker) in this part of the Saalach catchment are found along the Leoganger Ache and Loferbach. In contrast, the vast majority of soils in this region are considerably deeper (medium to deep soil depths) and moister, being at least well provided or even wetter. The moistest or wettest soils in the Limestone Alps region are found southeast of Saalfelden along the Urschlaubach (BFW s.a. b).

The central Greywacke zone between the limestone Alps in the North and the High Tauern region in the South is built of metamorphic volcanic rock, (quartz) phyllites and argillaceous schist (WINDING AND VOGEL 2003, GEOLOGICAL SURVEY OF AUSTRIA s.a.). This type of bedrock is easily weathered and of low stability, resulting in frequent mass movements (KIRNBAUER et al. 2008). Historically, this high weatherability of soils was, to some extent, also made responsible for the progressive paludification of Pinzgau over the last centuries, causing an accumulation of debris in the valley plains (cf. STREFFLEUR 1852, LORENZ 1857 cf. chapter 2.4).

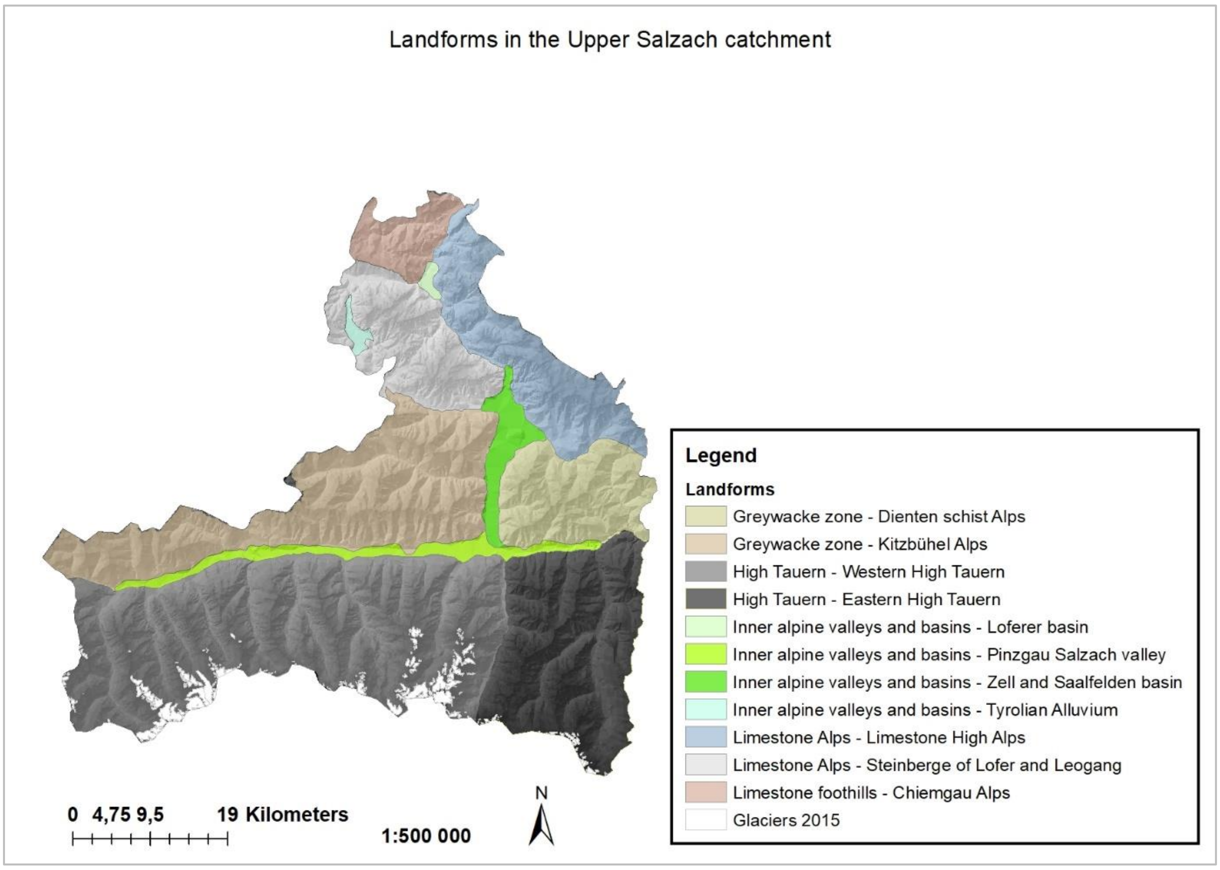

***Figure 6**: Landforms in the Upper Salzach catchment (PROVINCIAL GOVERNMENT OF SALZBURG 2019a). Glacier data from BUCKEL AND OTTO (2018).*

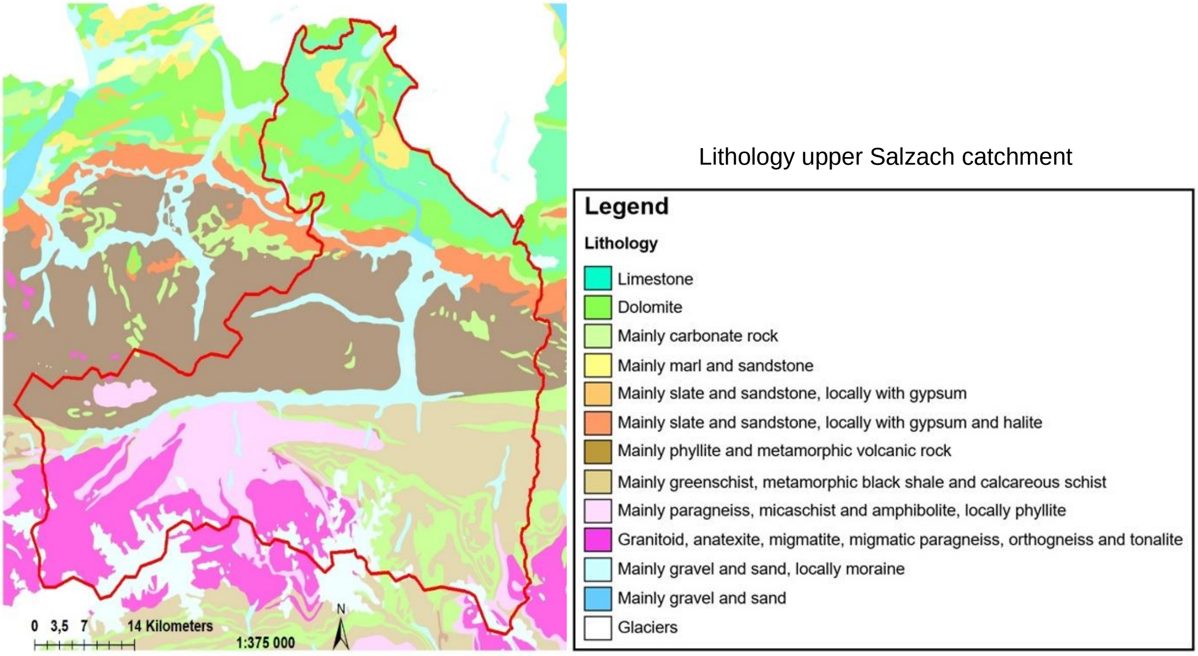

***Figure 7**: Lithology in the Upper Salzach catchment (Geological Survey of Austria s.a.).*

In the Greywacke zone, soils of generally moderate to deep soil depth are characterised by important areas of silty and loamy soil texture interspersed with sandy substrate. In this regard, river corridors tend to provide deeper soils with higher shares of sandy soil texture, whereas hillslopes are predominantly characterised by soils of moderate soil depth and higher shares of silty and loamy soils. Despite this tendency towards finer substrate, soil permeabilities throughout this geological region are generally medium to high along both, the valley bottoms and the hillslopes, even though soils might be wet. An exception is the valley floor close to Piesendorf, where silty, wet soils are rather impermeable. Similarly, some soils along the hillslopes are either well provided with water or wet and, regionally, tend to be less permeable. This is the case e.g. for hillslope soils along the northern Salzach valley close to Hollersbach and between Uttendorf and Niedernsill.

A major exception from this general pattern of soils can be found along the northern hillslopes of the Salzach valley between Gries and Lend. Here, the sandiest and shallowest soils can be found. Some of these soils are rather dry and highly permeable, but there is also a considerable number of soils being oversupplied by water with moderate to low permeability (BFW s.a. b).

The southern Tauernkristallin of the High Tauern region is characterised by Tauern granite, calcareous phyllite as well as greenschist and chlorite schist. The main mineral of this region – the Tauern granite is of high stability and bedrock permeability is restricted to fissured areas (Wiesbauer and Brandecker 1994). Thus, groundwater in both regions, the High Tauern (Tauernkristallin) and the Greywacke zone, is restricted to local reservoirs of limited water yield (Geological Survey of Austria s.a.). In comparison to the aforementioned geological regions, valley soils in the Tauernkristallin consist of much coarser material. Characterized primarily by sandy substrate with only minor shares of sandy loam (loose sediment braunerde, pararendsina), soil permeabilities are generally moderate to very high. However, shallow to moderately deep soil depths limit the water retention capacity in this region. Throughout the Tauernkristallin, soil moisture is very heterogeneous and soil moisture conditions of individual parcels may significantly vary throughout the year. In general, high soil moisture conditions tend to accumulate along stream corridors, while adjacent hillsides are dry.

Due to these regional differences in soil texture, permeability, moisture content and soil depth, soils along the river corridors quite differently contribute to surface runoff attenuation. Figure 8 depicts the spatial distribution and capacity of soils to store precipitation, thereby delaying and reducing surface runoff. Factors such as water conditions, soil type, hillslopes and – if present – aquifers were considered for determination. However, it should be noted that possible alterations by e.g. agricultural uses or impaired soil structures were not taken into account (PROVINCIAL GOVERNMENT OF SALZBURG 2014). As can be seen, soil contribution to runoff regulation is quite unevenly distributed. Along the the Rauriser Ache, shallow soils along hillsides of considerable slope rapidly transfer considerable amounts of water into the valley, locally increasing soil moisture and causing saturated, wet soils, which further decreases water storage capacities. In contrast, most soils on the hillsides of the upper Saalach valley are at least well provided with water or wet, but only of moderate soil depth and – at some locations – of only moderate or low soil permeability. Hence, they might rapidly be saturated, transferring considerable amounts of water directly onto the narrow fluvial corridor. Likewise, shallow soils along the Fuscher Ache valley are constantly or at least temporarily saturated with water, reducing their contribution to runoff regulation. Between Bruck and Lend, some areas are quite wet, soils are rather shallow and permeability often is only moderate, reducing the ability of soils to contribute to surface runoff reduction. In the region southeast of Saalfelden as well as in the region north of Lofer low contributions to runoff regulation might be explained by already wet soils of low permeability. In contrast, surface runoff attenuation is highest on deep, sandy and silty soils of moderate to high permeability in the remaining surroundings of Saalfelden (cf. BFW s.a. b).

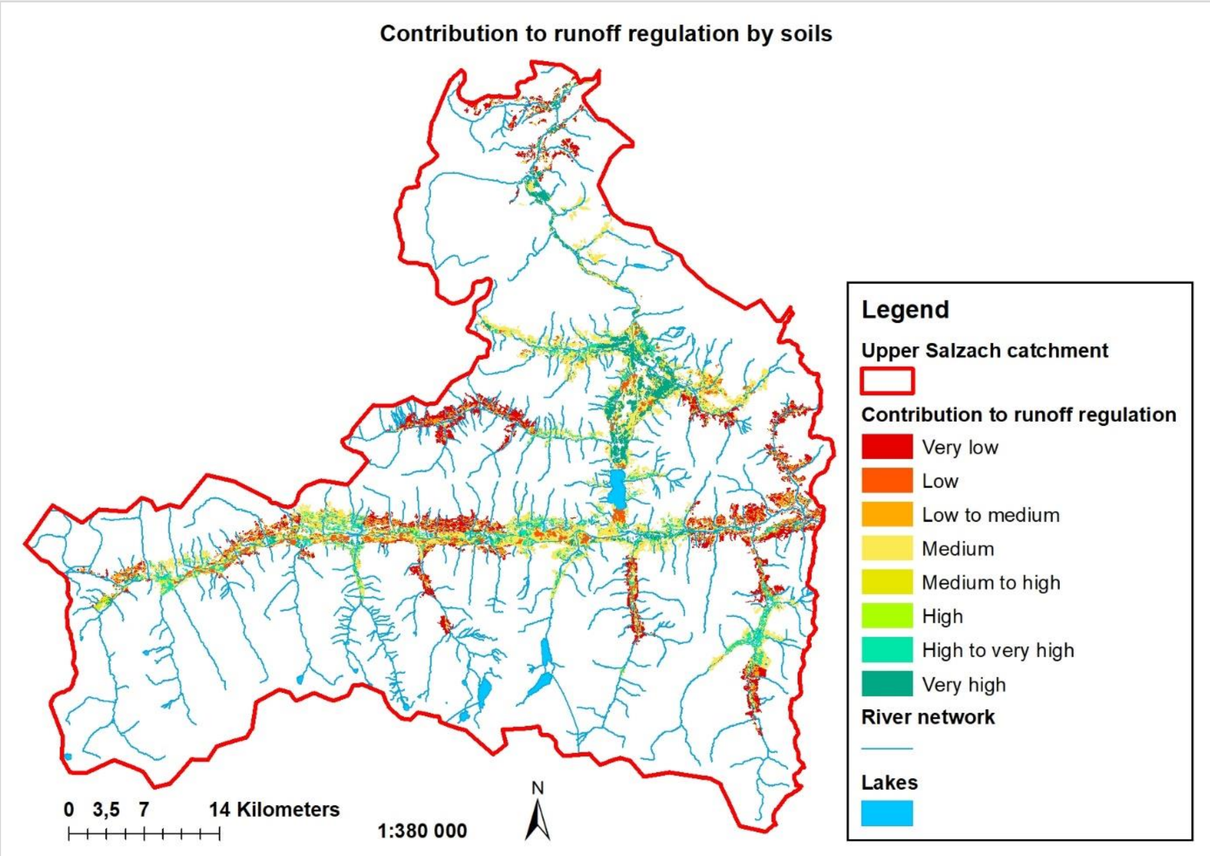

Figure 8: *Capacity of soils in the upper Salzach catchment to reduce surface runoff. Analysis is restricted to agricultural areas and is based on water conditions in soils, soil types, slopes and aquifers. Data from PROVINCIAL GOVERNMENT OF SALZBURG (2015).*

2.3 PAST AND PRESENT CLIMATIC CONDITIONS

The study area is located in the warm temperate west wind zone of temperate latitudes, in which climate is primarily driven by the Atlantic Ocean. Additionally, Mediterranean and continental air masses from Eastern Europe affect the local climate (AUER et al. s.a.). But the most important climate driver in the Alpine region is altitude, causing small differences in elevation to result in great differences of temperature (e.g. exposition, shading), precipitation patterns (blockage effect) and wind (AUER ET AL.

s.a.; RUBEL et al. 2017). As a consequence, local climates are very heterogeneous and diverse (AUER et al s.a.).

Due to its high proportion of mountainous regions, mean annual temperatures in Salzburg are rather low, but increasing with 4.1°C (1961-1990, HÖFLER et al. 2020), 4.6°C (1971-2000, CHIMANI et al. 2016a) and 4.96°C (1981-2010, WALTL 2018) mean annual temperatures over the last observation periods. In the mid-19th century, which marks the end of the Little Ice Age, yet mean annual temperatures were around 2°C colder than in the period 1971-2000 (APCC 2014, HOHENWALLNER-RIES et al. 2018). This led to great glacier advances into the nival region (AUER et al. s.a.), which were amplified by a very wet climate in the beginning of the 19th century. However, considering the 19th century as a whole, climate was more continentally influenced than climate of the 20th century (AUER et al. 2014).

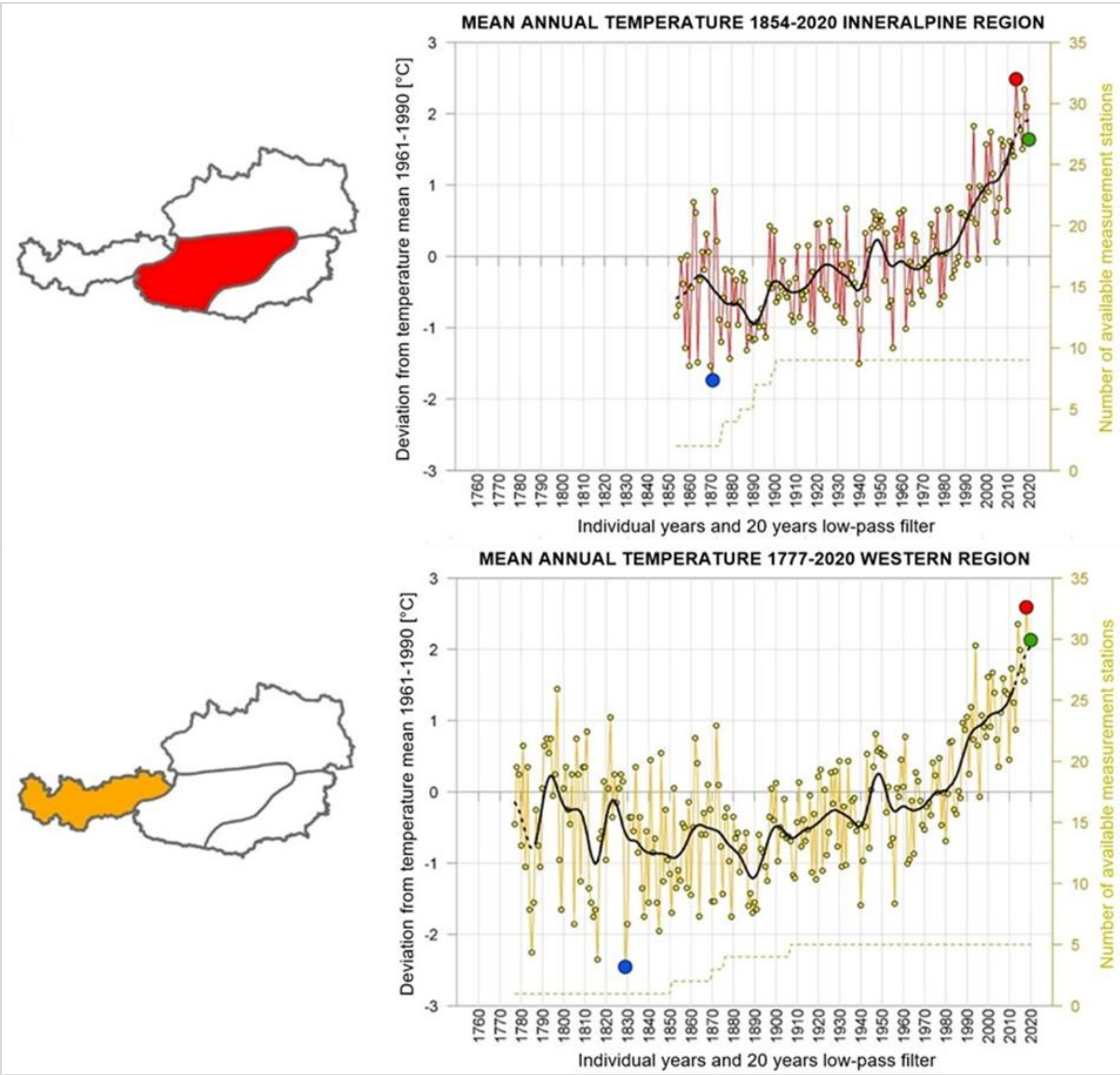

***Figure 9**: Long-time temperature records in the study region based on the HISTALP dataset, for individual years (coloured line) and smoothed by 20-year low pass filter (black line). Blue dots: lowest value of the records; Red dots: highest value of the records; green dots: values in 2020; modified after ZAMG 2021.*

Increasing temperature trends over the last 200 years were not only identified for the annual mean, but in all seasons since the mid-19th century (AUER et al. 2014), resulting in a significant increase of hot temperature extremes and a corresponding decrease of cold temperature extremes throughout Austria (AUER et al. 2010, NEMEC et al. 2012). Thus, the four warmest years (2014, 2015, 2018 and 2019) in Salzburg since beginning of observations have all been measured within the last decade (HÖFLER et al.

2020). As mentioned before, elevation is an important driver for temperature. In this regard, mean annual temperatures (period 1981-2010) in the mountain regions (>1500m a.s.l.) of Pinzgau range between -5 to 4°C, as opposed to inner alpine valleys (up to 1000m a.s.l.), where temperatures range between 5,7°C and 7°C (ZAMG 2012). For illustration of disparities, monthly means of air temperature and precipitation for the period 1981-2010 and the year 2018 are shown in Figure 10. As can be seen, in summer (June-August), mean monthly temperatures attain between 13-17°C at lower elevations and not more than +3°C at the highest elevations (e.g. Sonnblick). Accordingly, summer days (temperature maxima ≥ 25°C) rarely occur in more mountainous regions >1500m a. s. l. During winter (December-February), inneralpine valleys showed temperature means between -2 and -5°C and a yearly mean of 121-155 days of frost, whereas -10 to -12°C and >300 days of frost are measured in highest altitudes (ZAMG 2012).

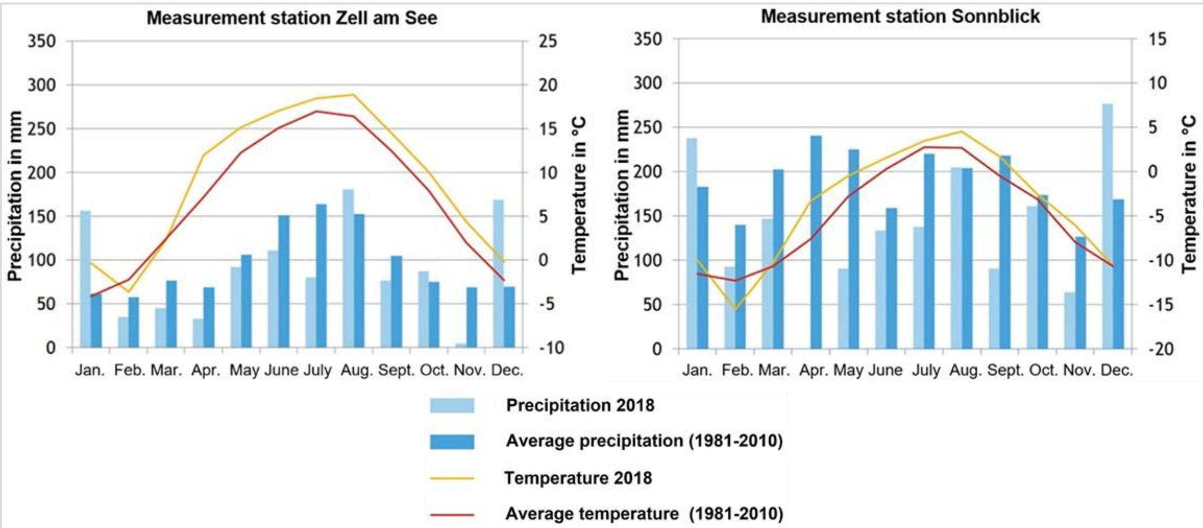

Figure 10*: Temperature and precipitation of an inner alpine valley (Zell am See) and a summit (Sonnblick) in the study area for the year 2018 in comparison to the observation period 1981-2010 (modified after* PROVINCIAL GOVERNMENT OF SALZBURG *2019b).*

Precipitation is distributed unevenly over the territory. Highest amounts of precipitation occur in the northern foothills and limestone Alps as well as over the southern Alpine divide. Being exposed towards western and northwestern winds transporting moist air masses from the Atlantic, which are blocked by local mountain massifs, these regions are subject to frequent orographic rain. In contrast, located in their rain shadow, sheltered inner alpine valleys receive much less precipitation (AUER et al. s.a.). This is reflected by the mean annual precipitation in the study area for the observation period 1981-2010, ranging between 1019mm at Uttendorf (Salzach valley) and 2403mm at Rudolfshütte (High Tauern). Throughout the study area, precipitation maxima occur during the summer months (June-August, see also Figure 10), which contribute up to 45% of the yearly precipitation sum (Moserboden, ZAMG 2012). Summer precipitation maxima are primarily caused by convective rainfall in the course of storm events (AUER et al. s.a.). These short and heavy rainfall events are of particular importance for the runoff formation of small river catchments, such as those in the study area, as opposed to advective precipitation events, which play a major flood-generating role in larger catchments (BRONSTERT et al. 2002). In the period 1850-2000, summer precipitation amounts have not changed much (AUER et al., s.a.). Yet, HASLINGER et al. (2011) detected negative trends of summer precipitation (June-August) in the period 1800-2003 between -2 to -5% in the Western Danube catchment, in which the study area is situated. In regions close to Pinzgau, these trends also showed to be significant. In contrast, winter precipitation amounts as well as yearly precipitation sums have changed more considerably. Since the beginning of measurements in the city of Salzburg (1850) up to the year 2000, winter precipitation increased by 11%, while yearly precipitation amounts increased by 9% (AUER et al. s.a.). Similar progressions could also be demonstrated for the Western part of Austria, in which yearly precipitation amounts increased by about 10% to 15% since 1860, whereas trends are not clear in the inner alpine section (Figure 11). Still, today's precipitation amounts in the inner alpine region are the highest since the beginning of measurements in 1858. It should be noted that these trends and the following figure do not include the very wet beginning of the 19th century, which led to great glacier advances and contributed to the glacier maximum extent in the 1850s to 1860s (AUER et al. 2014, FISCHER et al. 2019).

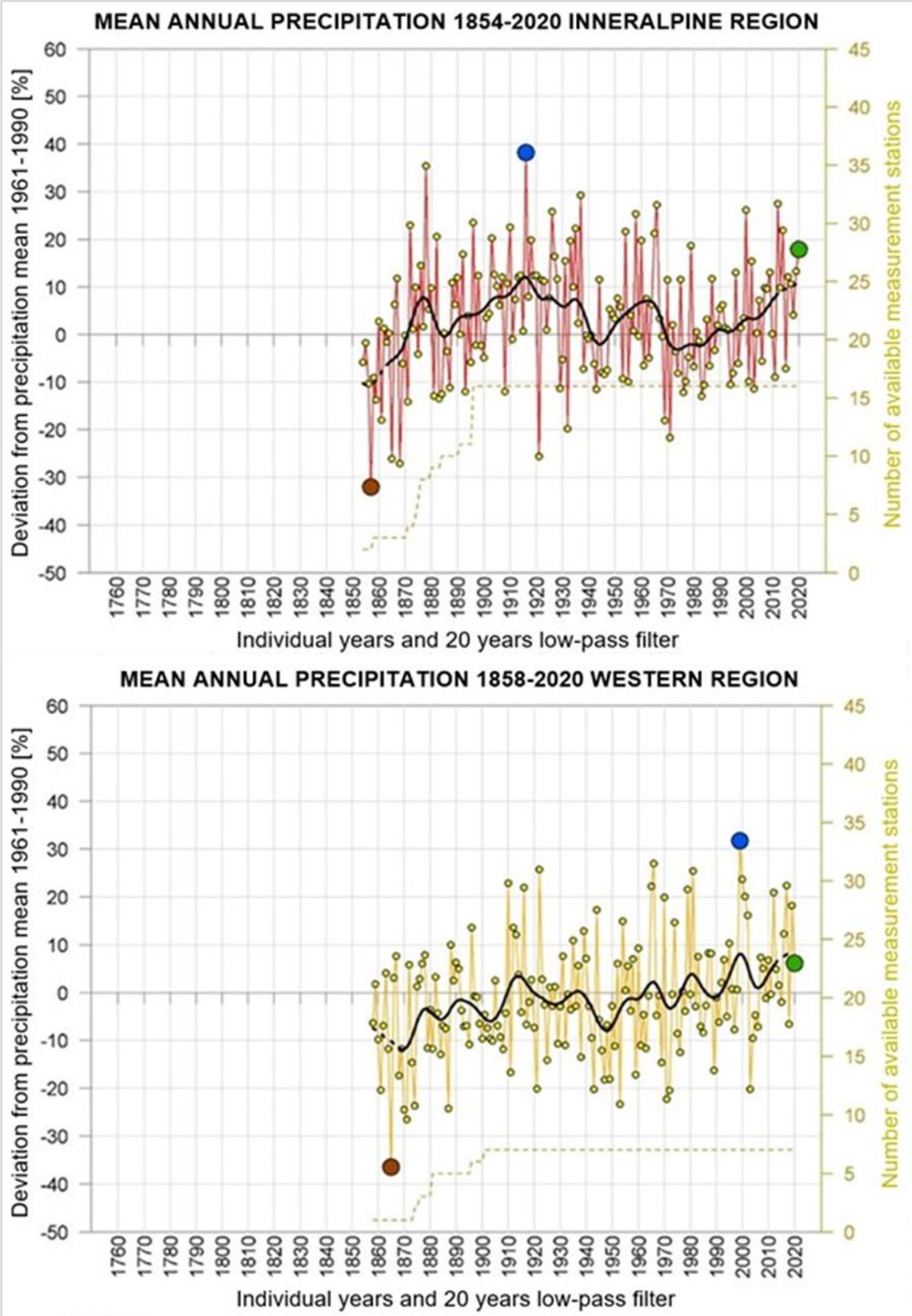

***Figure 11**: Long-time precipitation records in the study region based on the HISTALP dataset, for individual years (coloured line) and smoothed by 20-year low pass filter (black line). Brown dots: lowest value of the records; Blue dots: highest value of the records; green dots: values in 2020 (modified after ZAMG 2021).*

In the study area, during the most recent observation period 1981-2010, a mean of 35-45 days of precipitation ≥ 10mm was observed in the inner alpine valleys, while 50-84 days were count in the mountain regions (ZAMG 2012). In the recent past (1971-2000), trends of extreme precipitation indices were shown to be insignificant and randomly distributed over the territory of Austria. Nevertheless, it could be shown, that the vast majority of stations showed increasing trends in heavy precipitation days, both for 20mm and 30mm events (AUER et al. 2010).

Due to its high elevations and geographical exposition, snow is an important climate component not only for plant communities and local climate, but also for the study region's hydrology. Snow might act as a temporal water storage in the landscape, deferring runoff formation to late spring, when snow melts, but also has a local cooling effect due to its high albedo (NACHTNEBEL et al. 2014). The share of snow on precipitation increases linearly with higher elevations. At lowest elevations of the study area, on average 15% of the precipitation is snow. This value increases to 40% at 1500m a.s.l. and 55% at 2000m a.s.l. However, at lower elevations (<500m a. A.) snow precipitation is restricted to several months (October to May), whereas regions above 1000m a. A. might experience snow fall at any time of the year (AUER et al., s.a.). The importance of snow as water storage can be inferred by the duration of snow cover in the study area. For instance, over the period 1981-2010, valley floors sustained a 1cm- snow-cover on average for 3-4 months (97 to 137 days) of the year, mainly between December and March. At higher elevations (≥ 1500m a. A.), mean snow cover duration is prolonged to 6-12 months (174-359 days) per year, either between November and May or throughout the year at highest elevations close to 3000m a.s.l (ZAMG 2012). Snow depth maxima occur at different times of the year, depending on the region's altitude. In the valleys, highest snow depths (referred to the period 1961-1990) were measured in winter, in January or February. During this time of the year, mean snow depths ranged from 20 to 60cm. With increasing altitude, maximum snow depths increased and highest values were measured later in the year, e.g. approx. 500cm snow depth in April or May at Sonnblick. In the long-term, neither unhomogenized observational data from 1901-2000 for the city of Salzburg, nor homogenized data for the period 1961-2012 for the entire region could describe significant trends of yearly amounts of new snow, snow depths or snow cover duration in the study region, but high year-to-year fluctuations and inter-annual as well as decadal variability (AUER et al., s.a., SCHÖNER et al. 2018). However, these non-significant trends stand in contrast to most other Austrian regions (12 stations out of 15), showing significantly negative trends, irrespective of their altitude, for mean and maximum snow depth as well as for snow cover duration over the period 1950-2017. It is obvious, that temperature increases over the last 130 years (AUER et al. 2014) must have led to considerably higher declines of snow-related parameters than identified for the shorter period of 1950-2017 (cf. SCHÖNER et al. 2014). Relating to increasing temperatures, HANTEL et al. 2012 calculated a rise of the median snow line (50% probability to encounter 5cm snow depth over the year) of 166m/°C in winter and 123m/°C in summer in the Swiss-Austrian Alps over the period 1961-2010. Furthermore, areas being at least 50% snow covered in winter were calculated to shrink by about -7% per decade due to global warming (ibidem, 2012). In Austria, regions at elevations between 500 and 1000m a.s.l. experienced strongest decreases of snow depth and snow cover duration, as these regions are most sensitive to temperature increases. Here, a snow cover duration reduction of -1 day per year over the period 1961-2012 has been found. This corresponds to a reduction of approximately 1.5 months. With increasing altitudes (>1000m a.s.l.), the temperature sensitivity of snow is superseded by sensitivity towards precipitation (SCHÖNER et al. 2018). However, this does not necessarily mean, that high alpine regions are insignificantly affected by temperature increase. In Switzerland, KLEIN et al. (2016) found high alpine regions to be as sensitive to temperature as low-elevation stations, causing significant reductions of snow cover duration (later snow onset, earlier snowmelt), days with snowpack and annual maximum snow depth for the period 1970-2015, irrespective of altitude or geographical position. Major reasons are long-term increases in sunshine duration and temperatures (especially in spring), declining summer snow fall and an increased ratio of rain/snow in all seasons, reducing surface albedos, which further enhances melting processes (ibidem, 2016, SCHÖNER et al. 2014).

These temperature increases and the transition from solid to wet precipitation are also unfavourable for the region's glaciers and contribute to the distinct recession in area and volume over the last decades (NACHTNEBEL 2014). Thus, total glacier area in the region declined by 94km² between the last glacier maximum in 1850 (end of the Little Ice Age, LIA) and 2015, from formerly 143km² to only 49km² today. This corresponds to an area reduction of more than 65% (data from GROß AND PATZELT 2015 and BUCKEL AND OTTO 2018). Since 1930, mass balances of all Austrian glaciers are highly negative, suspended only by a short period of glacier advance between 1965 and 1985 (FISCHER et al. 2018).

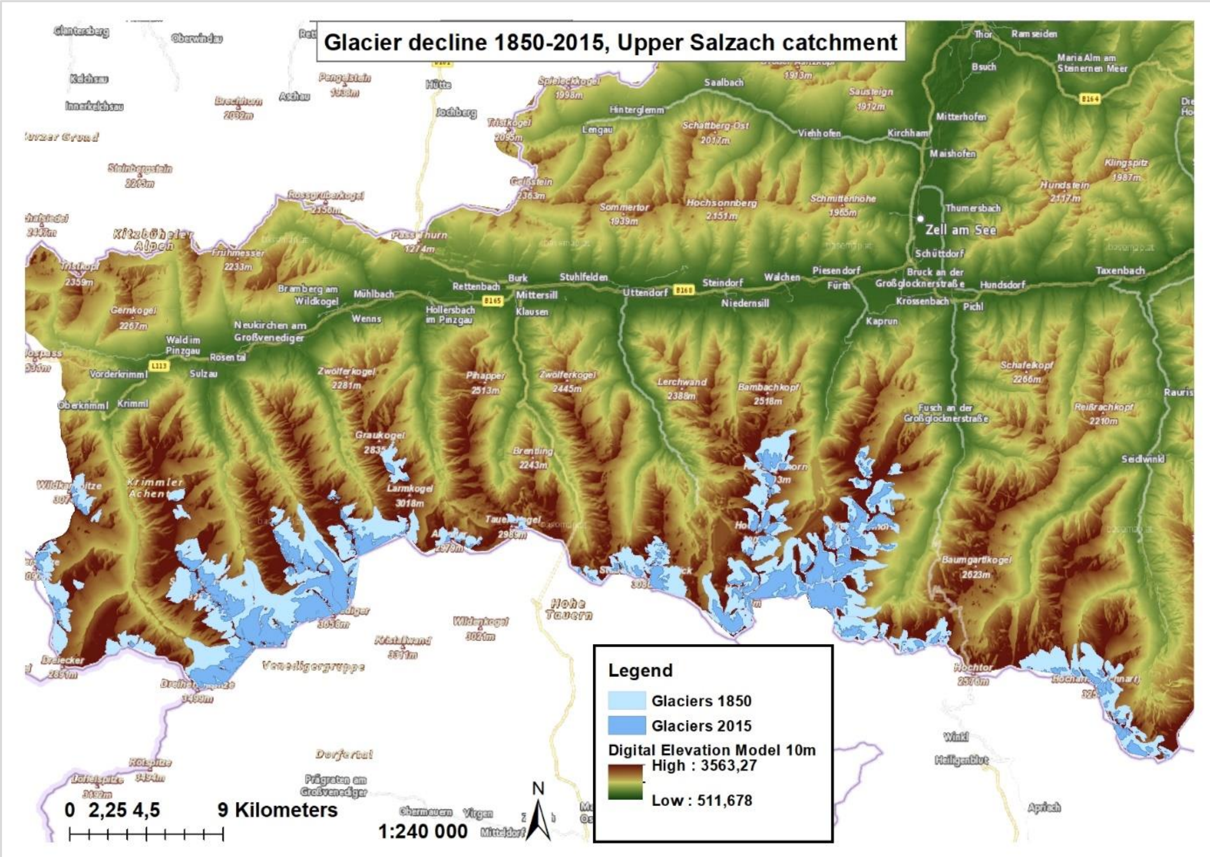

Figure 12: Glacier extent in Pinzgau in 1850 (LIA maximum, GROß AND PATZELT 2015) compared to 2015 (BUCKEL AND OTTO 2018), with additional topographic information from DEM 10m (OPEN DATA AUSTRIA, www.data.gv.at) and basemap overlay (GEOLAND, www.geoland.at).

Glacier melt is found to occur at increasing speed, with 0.3% glacier area loss per year between 1850 and 1969 (119 years), 0.6.% per year between 1969 and 1998 (29 years) and 1.2% between 1998 and 2008 (10 years) (FISCHER et al. 2015). Trends of glacier melt will persist up to a maximum melting rate and will then be followed by lower melt water contributions (e.g. WEBER et al. 2009). Most likely, many of the Austrian glaciers may already have reached their maximum glacier melt contributions (NACHTNEBEL et al. 2014). This has important implications on rivers and streams in the glaciated high Alpine regions of the Upper Salzach catchment, which are considerably influenced by these ice masses determining runoff at the local scale, contributing to yearly discharges, accounting for runoff regimes and counterbalancing low flow events (WEBER et al. 2009). For instance, in the period 1991-2000, glaciated headwaters (e.g. Krimmler Ache, Obersulzbach and Untersulzbach, Kapruner Ache and Fuscher Ache) in the region received more than 30% of their runoff from surrounding glaciers. This share of glacier waters on total runoff decreases rapidly further downstream (e.g. only between 4-8% at Taxenbach), accentuating the locally limited role of glaciers (WEBER AND PRASCH 2009a). In extremely hot and dry summers, however, these glacier melt contributions are not limited to the headwater sections, but largely augment runoff further downstream (KOBOLTSCHNIG AND SCHÖNER 2011). For instance, the summer of 2003 was one of the hottest summers in Pinzgau since the beginning of measurements, featuring temperatures that were 4°C to 6°C higher than over the long-term reference period 1961-1990 (SLUPETZKY AND WIESENEGGER 2005). Taking into account climate projections (cf. APCC 2014), it can be deduced that the temperatures in 2003 might quite well reflect mean summer temperatures at the end of the 21st century. In comparably hot and dry years in the future, glacier melt might significantly augment local river runoff in a short-term and annual perspective, which would otherwise be reduced to a minimum low flow. For instance, in 2003, glacier melt in August at Mittersill was found to account for 58% of total runoff (KOBOLTSCHNIG AND SCHÖNER 2009), while glacier contribution to yearly runoff was 15% (KOBOLTSCHNIG et al. 2008). Likewise, SLUPETZKY AND WIESENEGGER (2005) demonstrated the important drought compensating role of glacier melt to river runoff in 2003, not only on the local scale, but for the Salzach River up to the city of Salzburg. Accordingly, during some days in August 2003, glacier melt in the headwater sections contributed approximately 25-30% of total runoff in the city of Salzburg. In the future, this runoff compensating effect of glaciers diminishes with decreasing glacier areas in the catchment, further altering runoff characteristics of the upper Salzach catchment (cf. HANZER et al. 2018).

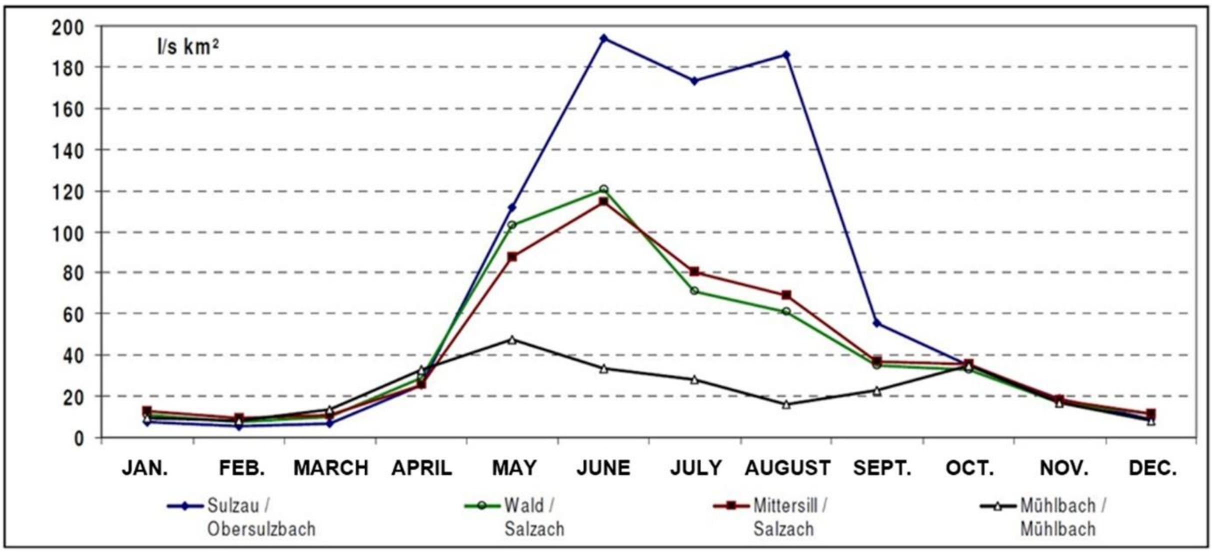

***Figure 13**: Comparison of the specific discharge [l/skm²] in 2003 for two Salzach gauges with glaciated sub-catchments (Wald and Mittersill), one tributary from the glaciated High Tauern (Obersulzbach) and one triburaty from the unglaciated northern Kitzbühel Alps (Mühlbach). Modified after SLUPETZKY AND WIESENEGGER 2005.*

Finally, glacial melt waters might, in some cases, also critically increase runoff resulting from summerly precipitation amounts, thereby reinforcing floods in headwater sections. On a historic perspective, such processes were reported to have exacerbated local flooding in Pinzgau quite regularly (LORENZ 1857, cf. chapter 2.4). But as quantitative data of glacier contribution to past floods in Austria is lacking, the following statements are based on qualitative descriptions. Necessary preconditions for such a flood augmenting mechanism are not only large ablation areas, but also a highly elevated snowfall line, allowing heavy precipitation to fall as rain. In case the glacier is covered by a thin snow cover, such rain fall events are able to melt these snow volumes, which then further add to runoff. Otherwise, if the glacier is already free of snow or with only little remaining firn (lower albedo, higher melt rates) e.g. in late summer, rainfall amounts directly flow off and rapidly increase runoff. Finally, runoff reactions are accelerated in case the glaciers already have substantially melted and have thereby developed highly efficient canal systems, which rapidly transfer runoff (BRAUN AND WEBER 2006). As preconditions for glaciers to fulfil such effects are bound to warm conditions, one could deduce that such mechanisms might be of importance in a future warmer climate.

2.4 HYDROLOGY

Situated in a humid, alpine region, snow and ice are the predominant factors determining the runoff regimes in the catchment (cf. Table 4). During winter, precipitation is temporarily stored in snow and glacier ice. Only a very small portion of precipitation contributes to river runoff, generally leading to low flow conditions in this season. During early and midsummer, however, snow and ice are gradually being melted and contribute largely to river runoff (MADER et al. 1996). In combination with highest precipitation sums in this season throughout the entire study region, this leads to a pronounced flood seasonality with average annual flood maxima occurring between June to July (PARAJKA et al. 2010) and maximum annual floods taking place between July and August, coinciding with annual maximum daily precipitation rates (MERZ AND BLÖSCHL 2003). Solely disposing of glaciers, the runoff regime of the Upper Salzach is therefore to be described as nivo-glacial with runoff maxima in June and July. In contrast, due to the absence of glaciers in the Saalach catchment, runoff regimes are moderately nival with runoff maxima in May (MADER et al. 1996). In the past (1961-1990 compared to 1981-2010), runoff regimes in Pinzgau only changed at two gauges analysed by LEBIEDZINSKI AND FÜRST (2018), shifting from nival regimes with higher amplitudes and runoff peaks in May or June to nival regimes with lower amplitudes and earlier runoff peaks (April), due to declining nival controls. However, for most gauges located north of the main Alpine ridge, a general trend towards more balanced regimes with lower amplitudes in early summer (April to June), sometimes earlier peak discharges and higher runoff volumes in autumn and winter (low flow period) was found. Furthermore, many analysed gauges with nival regimes showed higher spring runoff, decreasing summer runoff and generally increasing pluvial controls. In contrast, despite retreating glaciers, no change could be detected for glacial runoff regimes. Similar results in terms of shifts in yearly runoff characteristics of Alpine rivers have also been found by BARD et al. (2015) and ZAMPIERI et al. (2014).

The most important flood inducing process type in the period 1971-1997 in the study region were long-lasting, low-intensity rainfall events, which most frequently led to flooding in northern Pinzgau and in the region of Steinernes Meer (MERZ AND BLÖSCHL 2003), but which also frequently caused floods in the High Tauern region. Thus, 58% of floods in the latter region resulted from long-lasting rainfall (GAÁL et al. 2012). This process is generally associated with sustained rainfall over several days or weeks, leading to high antecedent soil moisture or soil saturation and, thus, extensive flooding in larger catchments (1000km² to 300 000km²) (MERZ AND BLÖSCHL 2003, BRONSTERT et al. 2002). Another important flood inducing process, especially in the High Tauern region, are short rainfall events of high intensity (disparate to flash floods), causing 35% of all floods in this region (MERZ AND BLÖSCHL 2003, GAÁL et al. 2012). Flood runoff associated with this mechanism is a combination of saturation excess overland flow, infiltration excess overland flow and fast subsurface flow. Short rainfall floods are generally limited to the local or regional scale. Nevertheless, they frequently cause floods of higher recurrence intervals (>10-year floods) and, thus, this process type may lead to severe damage. Both, long-lasting and short rainfall events might occur throughout the year, but are most prevalent during the summer months. Finally, rain-on-snow events play an important role for flood generation in the study region, too. Here, snow lying on saturated soils is melted by rainfall, leading to an increased surface runoff deriving from both, rainfall and snowmelt. Such mechanisms are prevalent in alpine catchments and are restricted to the winter half-year.

Table 4: Main rivers, their (glaciated) catchment area and runoff regimes. Data from MADER et al. 1996, MUHAR et al. 1996, BMLFUW 2015; glacier data based on 2015 from BUCKEL AND OTTO 2018.

River system	River name	Gauge station	Natural Catchment Area [km²]	Effective Catchment Area [km²]	Glacier Area Within [km²]	Share of Glaciers [%]	Runoff regime 1990
Saalach	Saalach	Viehhofen	150.8	150.8	0	0	Moderate nival, maximum in May
Saalach	Urschlaubach	Saalfelden	119.5	119.5	0	0	Moderate nival, maximum in May
Saalach	Leogangbach	Uttenhofen	112.3	112.3	0	0	Moderate nival, maximum in May
Saalach	Saalach	Weißbach b. L.	567.5	567.5	0	0	Moderate nival, maximum in May
Saalach	Loferbach	Lofer	107.4	107.4	0	0	Moderate nival, maximum in May
Saalach	Saalach	Unken	857.2	857.2	0	0	Moderate nival, maximum in May
Salzach	Krimmler Ache	Krimml	110.7	110.7	5.9	5.4	No data
Salzach	Salzach	Wald i. P.	206.8	176.1	5.9	2.9	Nivo-glacial, maximum in July
Salzach	Obersulzbach	Sulzau	80.7	80.7	12.5	15.5	Glacial, maximum in July
Salzach	Untersulzbach	Neukirchen a. G.	40.5	40.5	4.5	11.0	Glacial, maximum in July
Salzach	Habach	Habach	45.3	45.3	1.8	3.9	Nivo-glacial, maximum in July
Salzach	Salzach	Mittersill	582.6	551.9	32.8	5.6	Nivo-glacial, maximum in June
Salzach	Felber Ache	Haidbach	74.5	72.2	0.2	0.2	Nival, maximum in June
Salzach	Stubache	Uttendorf	127.9	142.3	4.7	3.7	Winter-nival
Salzach	Kapruner Ache	Kaprun	88.6	169	8.8	9.9	Glacial, maximum in August
Salzach	Salzach	Bruck a. d. G.	1168.7	1230.5	46.3	4.0	Winter nival
Salzach	Fuscher Ache	Bruck a. d. G.	161	144.6	7.6	4.7	Nivo-glacial, maximum in July
Salzach	Hüttwinklache	Bucheben	96.1	75.1	2.3	2.4	Nivo-glacial, maximum in July
Salzach	Rauriser Ache	Rauris-Unterland	242.2	221.2	2.5	1.05	Nivo-glacial, maximum in June
Salzach	Dientenbach	Dienten a. H.	53.4	53.4	0	0	Nivo-pluvial, multiple maxima

Characteristic discharges of rivers and streams in the study region in terms of mean flow (MQ), mean yearly flood discharges (MJHQ) and flood discharges of higher recurrence intervals (HQ_{10}, HQ_{100} and HQ_{300}) are listed in Table 5. As can be seen, some of the highest flood discharges were measured within the last 20 years. This is mainly due to the comparatively short observation period for Austrian gauges starting in 1951 or later. Yet, recent studies showed that the current period from 1992 up to now indeed represents a flood-rich period in the study region when compared to flood events over the last 500 years (BLÖSCHL et al. 2020). This is confirmed by GODINA 2005 (cited after BMLFUW 2009), who found increasing flood trends for the Salzach River analysing a 120 year flood observation record. Other flood-rich periods relevant for the study region were found to be 1500-1516, 1564-1576, 1636-1660 and 1788-1792 (BLÖSCHL et al. 2020, see also Table 6). Recent studies analysing the cumulation of floods over the last decades in Austria (e.g. SCHÖNER et al. 2011, BLÖSCHL et al. 2017) found that floods increased both, in frequency and magnitude. Over the period 1955-2014, these increases were particularly pronounced in small catchments (<500km²) north of the main Alpine ridge and were equally strong both in winter and in summer. In the subregion including the Saalach catchment, yearly flood magnitudes measured over the period 1955-2014 significantly increased at 11.4% of all gauge stations (at 13.3% in catchments >500km² and 10% in catchments <500km²). This increment is even more distinct when analysing the shorter period 1976-2014 for which 37.3% of all gauge stations showed significantly increasing trends in yearly flood magnitudes (23.8% of catchments >500km² and 44.7% of catchments <500km²). Likewise, trends are also increasing in the subregion, which includes the Salzach valley and its tributaries in the High Tauern. Here, 36.4% of all gauge stations showed significantly increasing yearly flood discharges over the period 1955-2014 (22.2% in catchments >500km², 41.7% in catchments <500km²). But as opposed to trends in the Saalach catchment, trends in yearly flood discharges measured over the shorter period 1976-2014 are not as distinct in the Salzach catchment. Positive significant trends could only be observed at 10.9% of all gauge stations (11.1% in catchments >500km² and 10.8% in catchments <500km²). For both regions and both periods, the vast majority of insignificant trends features an increasing tendency. Overall, yearly flood discharges in catchments north of the main Alpine ridge increased by a rate of 2.7% per decade for the period 1955-2014 and 8% per decade for the period 1976-2014 (BLÖSCHL et al. 2017).

Table 5:Long-term mean yearly runoff, mean yearly flood runoff, flood discharges of 10 to 300-year recurrence intervals and highest flood measured for gauges of the study site and for the gauge station Burghausen. In bold: floods of the last 20 years. Data from Wiesbauer and Brandecker 1994, Hydroconsult GmbH 2011, flussbau iC GesmbH 2015, Bmlfuw 2017, Werner Consult Ziviltechniker GmbH 2019, Bmlrt 2020 and Bavarian State Office for Environment 2021.

River system	Gauge (water course)	MQ [m³/s]	MJHQ [m³/s]	HQ_{10} [m³/s]	HQ_{100} [m³/s]	HQ_{300} [m³/s]	HHQ [m³/s] (year)	Observation period
Saalach	Viehhofen (Saalach)	5.2	47	74	148	195	167 **(2013)**	1961-2017
Saalach	Saalfelden (Urschlaubach)	4.4	49				112 **(2013)**	1951-2017
Saalach	Uttenhofen (Leogangbach)	2.8	25.5				66.3 **(2013)**	1961-2017
Saalach	Weißbach (Saalach)	20	193	246	402	480	489 **(2013)**	1961-2014
Saalach	Lofer (Loferbach)	5.2	43				106 **(2013)**	1961-2017
Saalach	Unterjettenbach (Saalach)[a]	38	281	537	800	931	807 **(2013)**	1901-2013
Salzach	Wald (Salzach)	7.4	78	135-145[b]	233-252[b]		240 (1987)	1991-2017
Salzach	Kees (Obersulzbach)	1.6	16.5				22.7 **(2009)**	1989-2017
Salzach	Sulzau (Obersulzbach)	4.8	47				129 **(2014)**	1961-2017
Salzach	Neukirchen (Untersulzbach)	2.2	22				71.6 **(2014)**	1971-2017
Salzach	Habach (Habach)	2.3	25				102 **(2005)**	1980-2017
Salzach	Mühlbach (Mühlbach)	1.1	17				28.7 **(2010)**	1987-2017
Salzach	Mittersill (Salzach)	25	198	272-282[b]	370-394[b]		320 (1966)	1951-2017
Salzach	Haidbach (Felber Ache)	3.3	24	42	90	115	54 (1965)	1951-2016
Salzach	Stuhlfelden (Stuhlfeldnerbach)	0.4	4.5				16.9 **(2013)**	1994-2017
Salzach	Kaprun (Kapruner Ache)	9.5	42	50	62	67	63.6 (1980)	1961-2017
Salzach	Ferleiten (Fuscher Ache)	2.9	24				43.2 (1987)	1961-2017
Salzach	Bruck (Fuscher Ache)	6.2	40	52	100	125	107 **(2013)**	1961-2017
Salzach	Bruck (Salzach)	52	244	342	375	400	410 (1966)	1961-2017
Salzach	Bucheben (Hüttwinklache)	3.9	36				91 (1966)	1961-2017
Salzach	Rauris (Rauriser Ache)	9.4	60	127	156	166	160 (1966)	1961-2017
Salzach	Burghausen (Salzach)	251	1200	2150	3300		4000 **(2013)**	1901-2013

[a] Shortly after the German border
[b] Values referring to the period 1950-1990

2.4.1 CHANGES IN HYDROLOGY ASSOCIATED WITH HISTORIC LAND MANAGEMENT

Today, the hydrology of rivers and streams in the Upper Salzach catchment is highly affected by numerous river engineering measures. Only the first few kilometres of the Salzach River are free-flowing sections with only local bank protection measures. The remaining sections further downstream are either straightened, fixed, diverted, impounded for hydropower generation or influenced by weirs and local flood protection measures. The same applies to the Saalach River, which is slightly less regulated (MUHAR et al. 1996). These alterations add up to a long history of anthropogenic interferences over centuries, which strongly impacted on the hydrological and morphological characteristics of rivers and streams in the upper Salzach catchment (DÜRLINGER 1866, MADER 2000). As of the Middle Ages, forests in Pinzgau have been extensively cleared to meet industrial demands for energy and construction of the salines in Reichenhall and Hallein as well as of metallurgy in Rauris and Gastein. Besides, wood was indispensable for domestic uses, infrastructure and transportation (e.g. ships and wooden bank protections). The wood was drifted along rivers and streams in the catchment. As many of them had rather low discharge volumes, water had to be temporarily impounded by logging dams to allow for sufficient tractive forces when opening the dam. This led to frequent artificial flooding (KOLLER 1975) and heavy river bank erosion along drifting waters due to the momentum of trunks (WIESBAUER AND DOPSCH 2019). The intensification of these industries in the following centuries, led to a further increasing demand of wood, not only for production purposes, but also for the transportation of goods and river regulations, allowing to transfer progressively more products to the key markets and to drift an increasing amount of wood (KOLLER 1975). At the end of the 16th century, salt production in the saline of Hallein and, thus, fellings in the forests of Pinzgau reached a maximum. In the year 1590, for instance, its demand was about 210 000m³ of wood, which corresponds to a woodpile of approximately 1m width, 2m height and 105km length. Adding to this, gold and silver mining industries were at their production maximum simultaneously (although collapsing shortly afterwards), further raising deforestation (WINDING AND VOGEL 2003).

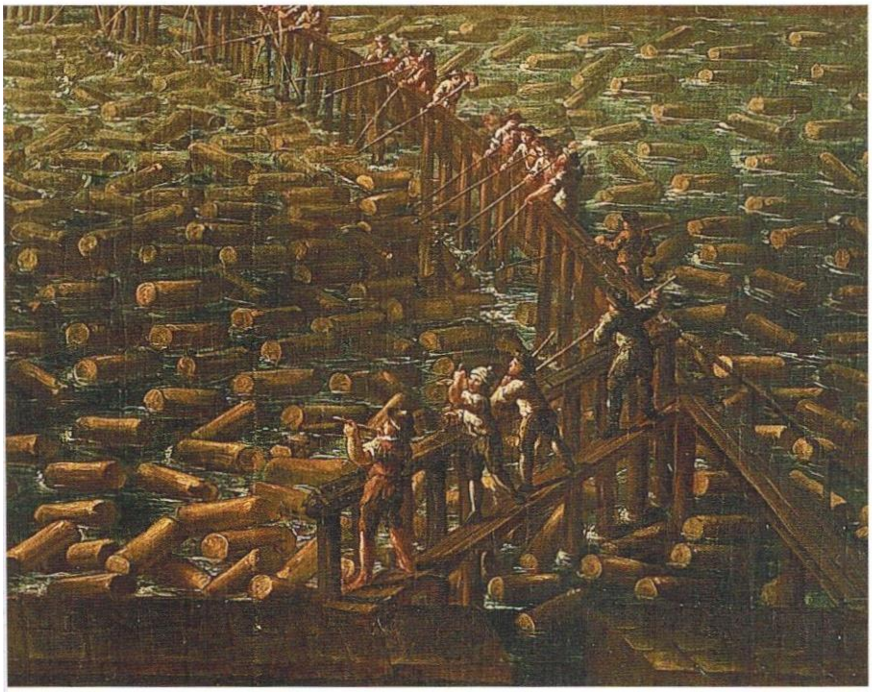

Figure 14*: Wood screening along the Salzach in Hallein. Museum of the Celts Hallein, painted by Benedikt Werkstötter 1757-1758.*

***Figure 15**: Wood drift along the Salzach River, Salzburg Museum Nr. 2223.*

Up to the year 1592, clear-cutting of large areas at a time in easily reachable forests was common practice. But after wood resources had almost been depleted in many catchments, e.g. at the end of the 16th century along the Rauris valley or at the beginning of the 17th century along the Saalach River, also remote forests had to be exploited (TREML et al. 1995, cited after WIESBAUER AND DOPSCH 2019, cf. KOLLER 1975). The degradation of forests was further promoted by common management practices, such as subsequent burning for crop cultivation over several years or the transformation of cleared areas into (high) alpine pastures, which both impeded natural regeneration (KOLLER 1975). The consequence of deforestation and detrimental management practices over centuries along the Salzach River and in its mountainous sub-catchments (e.g. Trattenbach, Mühlbach, Hollersbach, Obersulzbach, Untersulzbach) (KOLLER 1975) was a highly reduced soil and slope stability as well as a lowered water retention capacity of soils due to lacking root penetration and soil protection by tree canopies (STREFFLEUR 1852, LORENZ 1857, MADER 2000). Situated in a region with regionally easily wheathered bedrock and high yearly precipitation amounts, on the one hand, this led to frequent mass movements accumulating debris into Salzach tributaries, which already showed high erosion rates and, thus, bedloads due to wood drifting practices (cf. PILLWEIN 1843, STREFFLEUR 1852, LORENZ 1857, WIESBAUER AND DOPSCH 2019). On the other hand, precipitation events rapidly entailed drastically increased runoff, transforming mountain streams into fast-flowing torrents with high tractive power, which now eroded also coarser bed load fractions into downstream areas (PILLWEIN 1843, LORENZ 1857, MADER 2000).

Figure 16*: Mudflow of Schmittenbach on the 3rd of July 1737 destroying the town of Zell am See. Provincial archive of Salzburg, city archive of Zell am See, "Raitt-Buech", book-like: Number 6.*

The material got deposited in the confluence sections with the Salzach River, whose gradient between Krimml and Bruck was too low for providing sufficient bedload transport capacities to allow the relocation into downstream regions. Failing to erode the material which gradually built up, the river bed of the Salzach was progressively lifted, locally causing superelevated river banks of about 1.5m height difference with regard to the river surroundings. Correspondingly, groundwater levels were lifted, too, and valley floors of Pinzgau began to transform into swamps. The low water retention capacity in the mountainous sub-catchments in combination with the superelevated river banks and high groundwater tables also led to frequent severe floodings of the valley floors, extensively inundating them (see Figure 17 for historic HQ_{300} zones) and thus intensifying paludification between Neukirchen and Bruck (cf. PILLWEIN 1843, STREFFLEUR 1852, LORENZ 1857, MADER 2000). Table 6 gives an overview of historically transmitted flood events and natural disasters between the 16th and 19th century along the Salzach valley. It should be noted, however, that this list does not include every severe flooding of past centuries, but only a summary of such events stated in literature. Because of missing quantitative information about flood magnitudes in Pinzgau, the historic flood discharges at Burghausen in Bavaria are shown for exemplification and comparison with today's flood magnitudes in Table 5. This gauge station is the oldest along the Salzach River and allows for quantification of historic flood discharges thanks to historic flood marks, which are lacking in Pinzgau (WIESBAUER AND DOPSCH 2019). Of course, high flood magnitudes in Burghausen do not translate into high flood magnitudes in Pinzgau. But as historic descriptions agree on the intensity of flooding in both regions, this might be an interesting additional information. As can be seen, severe flooding was rather frequent.[1] Referring to this situation, LORENZ (1857) reports that already moderate autumn rainfall events caused extensive inundations of valley floors. Furthermore, if past and present flood discharges are compared, it becomes clear, that past flood magnitudes in Burghausen were higher than magnitudes of today's HQ_{100} (see Tables 5 and 6). In the year 1598, flood discharge in Burghausen was even as high as a today's HQ_{1200} (WIESBAUER AND DOPSCH 2019). Given the aggradation of the Salzach's river bed as well as the increased runoff in

[1] In addition to the flood reinforcing mechanisms stated above, the number of flood events is also shaped by atmospheric forcing inducing flood-rich periods at several episodes in the past (see BLÖSCHLet al. 2020).

tributary streams due to deforestation, it is plausible, that unquantified flood discharges in Pinzgau might also have been more severe than today's. This assumption is supported by PATT et al. 2011, reporting that high rates of historic deforestation and subsequent agricultural uses on formerly wooded land in Germany had resulted in significantly increased flood runoff in those days.

Table 6*: Historical records of floods and natural disasters along the Salzach River between 1500 and 1900. In black: information from floods in Pinzgau; in blue: Flood information from the gauge in Burghausen. Data from PILLWEIN 1843, LORENZ 1857, SCHILLER 1977, LAHNSTEINER 1980, MADER 2000, WINDING AND VOGEL 2003 and GODINA 2018 (cited after WIESBAUER AND DOPSCH 2019).*

Year	Event magnitude	Region	River section
1501	Extreme flood	Mittersill	Upper Salzach
1538	Regional flood devastations	Hollersbach	Upper Salzach
1564	Severe flood	Rauris	Upper Salzach
1570	Ca. 4400 m³/s	Burghausen	Lower Salzach
1572	Extreme flood Ca. 4200 m³/s	Neukirchen and Mittersill Burghausen	Upper Salzach Lower Salzach
1597	Severe flood	Pinzgau	Upper Salzach
1598	Salzach bursts into lake Zell Ca. 4600 m³/s	Zell am See Burghausen	Upper Salzach Lower Salzach
1599	Severe flood	Pinzgau	Upper Salzach
1647	Regional flood devastations	Hollersbach	Upper Salzach
1686	Extreme flood	Bramberg, Hollersbach and Zell am See	Upper Salzach
1702	Extreme flood	Mittersill	Upper Salzach
1736	Ca. 3500 m³/s	Burghausen	Lower Salzach
1757	Extreme flood	Mittersill	Upper Salzach
1762	Severe flood	Pinzgau	Upper Salzach
1786	Extreme flood Ca. 3800 m³/s	Mittersill Burghausen	Upper Salzach Lower Salzach
1787	Ca. 4000 m³/s	Burghausen	Lower Salzach
1789	Outbreak of Mühlbach at Niedernill (debris flow of 20 million m³)	Niedernsill	Upper Salzach
1794	Land slide of 30 million m³, impounding the Salzach to a 6km long dammed lake	Embach	Upper Salzach
1798	Severe flood	Niedernsill	Upper Salzach
1803	Regional flood devastations	Pinzgau	Upper Salzach
1807	Extreme flood	Stuhlfelden and Mittersill	Upper Salzach
1815	Extreme flood	From Krimml to Niedernsill	Upper Salzach
1816	Regional flood devastations	Hollersbach	Upper Salzach
1821	Severe flood	Zell am See and elsewhere in Salzburg	Salzach
1823	Severe flood	Rauris	Upper Salzach
1826	Regional flood devastations	Dürnbach	Upper Salzach
1827	Severe flood	Mittersill, Zell am See and St. Georgen near Taxenbach	Upper Salzach
1830	Regional flood devastations	Neukirchen and Rauris	Upper Salzach
1846	Extreme flood	Hollersbach and Mittersill	Upper Salzach
1849	Regional flood devastations	Hollersbach	Upper Salzach
1878	Extreme flood	Mittersill	Upper Salzach
1879	Regional flood devastations	Pinzgau	Upper Salzach
1899	Ca. 3350 m³/s	Burghausen	Lower Salzach

During the following centuries, paludification proceeded until swamps reached their maximum extent at the turn of the 18th and 19th century. At that time, swamps occupied an area of 15 000 morgen of land in Upper Pinzgau (KOCH-STERNFELD 1811) and 80 000 morgen of land in total alongside the Salzach valley (MADER 2000). Other sources refer to a total swamp area of 25km² along the upper Salzach valley (WIESBAUER AND DOPSCH 2019). Based on own calculations, the area of wetlands on the valley floors between Neukirchen and Bruck around 1830 amounted to approximately 21km². However, this value includes all types of wetlands, as the Franziscean Cadastre does not sufficiently distinguish between swamps and e.g. wet meadows. More than one third of these swamps were constantly waterlogged (KOCH-STERNFELD 1811). In order to prevent further paludification and floodings, but also to finally exploit the valley floors, first coordinated hydraulic engineering measures along the Salzach started at the beginning of the 19th century (LORENZ 1857, DÜRLINGER 1866, MADER 2000). As of 1886, both rivers the Salzach and the Saalach were almost continuously regulated (WINDING UND VOGEL 2003). Many different measures were implemented, comprising dredgings (Sohlräumung), bed load excavations, blastings of the river bed (e.g. near Bruck), river bend cut offs, river straightening, curtailments in river width, bank protection, levee constructions and drainage ditches. The main aim of these measures was to increase the slope (e.g. by blastings and river bend cut-offs) and flow velocities (e.g. by curtailments in river width), in order to increase the tractive and erosional forces, which were required for the intended deepening of the river bed. River bed incision was crucial to drain adjacent floodplains (i.e. swamps) and to reduce the frequency of overbank flow and flooding. And in fact, these systematic efforts finally yielded the aimed outcomes. Several years after implimentation, the upper Salzach river bed and the water table of adjacent terrains were found to gradually deepen, so that swamps (potential agricultural land) were gradually drained. In combination with the drainage channels and ditches mentioned above, valley floors were successfully dried up by the end of the 19th century. Furthermore, these modifications and the construction of lateral flood levees allowed flood waters to pass more rapidly, ultimately reducing local flood risk (DÜRLINGER 1866, MADER 2000, WINDING AND VOGEL 2003, WIESBAUER AND BRANDECKER 1994, PATT et al. 2011). In regions further downstream, however, the accelerated transmission of upstream floods required enhanced flood protection (cf. PATT et al. 2011, WIESBAUER AND DOPSCH 2019).

Owing to the torrential character of many Salzach tributaries, these streams have also been affected by regulations. Many of them were straightened in parts and most of them were provided with debris dams and weirs (MADER 2000, WIESBAUER AND BRANDECKER 1994). Along with excavations and weirs in the Salzach itself, this has led to bed load deficits and heavy river bed incision/degradation in downstream sections (WINDING AND VOGEL 2003, WIESBAUER AND BRANDECKER 1994, MUHAR et al. 1996). Hydrology is further affected by the energy sector. Diversions impact on the hydrology of many rivers and streams in both catchments (Salzach and Saalach), by artificially expanding or reducing their natural catchment area in order to augment the exploitable water volume for power generation. In addition, several storage power plants in the High Tauern region (Stubache and Kaprunerache) and numerous small and several large run-of-river power plants in Wald as well as near Bruck (cascade of run-of-river power plants up to Bischofshofen) alter natural flow regimes in the Salzach catchment (WIESBAUER AND BRANDECKER 1994). In contrast, the Saalach river is comparatively less impacted by only one storage power plant (Diessbach) and lesser and smaller run-of-river hydropower plants (data from SAGIS, see https://www.salzburg.gv.at/sagismobile/sagisonline/map/Wasser/Wasser). The operation of storage power plants is altering yearly runoff characteristics of rivers and streams in both catchments towards higher winter discharges and lower summer discharges (WIESBAUER AND BRANDECKER 1994). But the effect of power plants on runoff is not limited to alterations in seasonal runoff characteristics. Storage power plants in the study area can also contribute to reduce mean yearly floods in downstream sections between approximately 78% (gauge station Kaprun, Kapruner Ache) to 2% (Pegel Achleiten, Danube) by retaining water volumes (LEBIEDZINSKI et al. 2020). However, in less intensely regulated sub-catchments high amounts of precipitation falling on high slopes and mountain soils with low water retention capacity generally tend to lead to rapid runoff reactions and fast transmissions of flood waters to downstream sections (cf. BRAUN AND WEBER 2006). Owing to the generally narrow valley topographies, flood zones frequently overlay with densely populated and intensely used valley floors, which in the past has caused great damages.

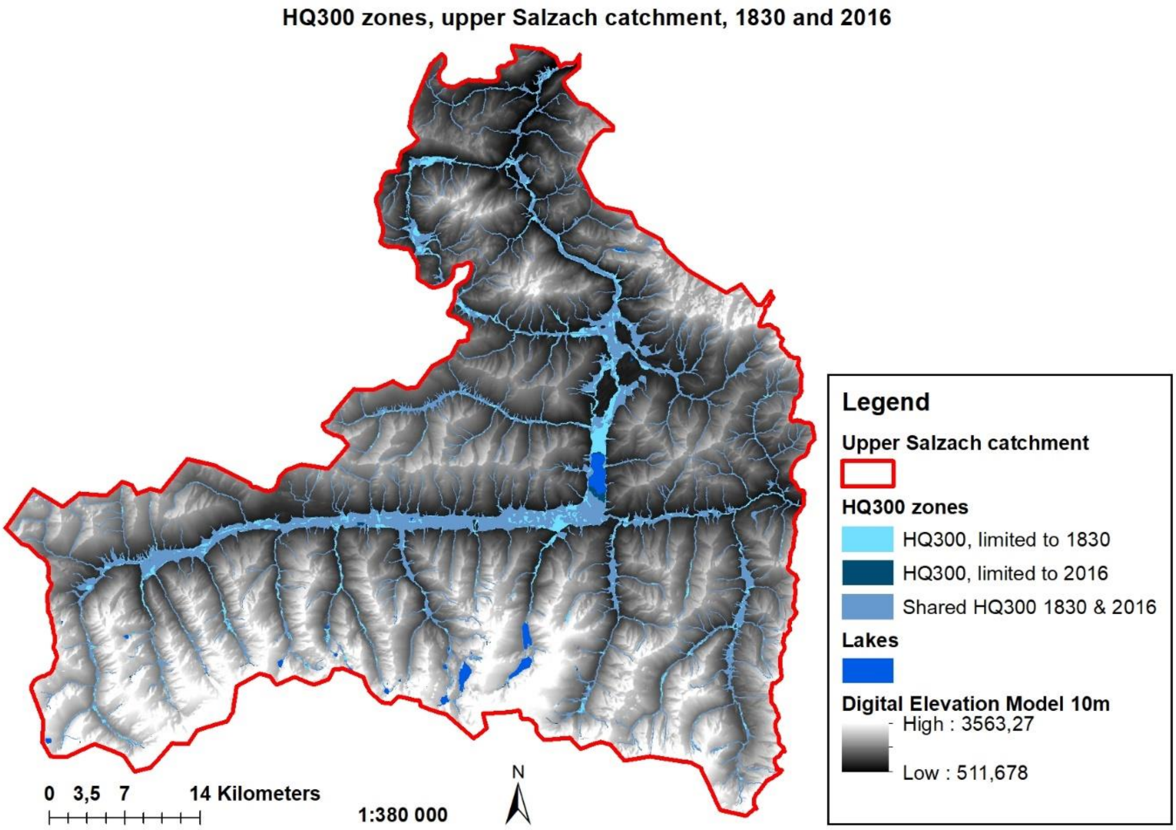

***Figure 17**: HQ_{300} zones in 1830 and 2016. Digital elevation model and lakes from OPEN DATA AUSTRIA, www. data.gv.at.*

3 BASIC DATA

The centrepiece of this work is a GIS digitisation of the historic LC/LU in the upper Salzach catchment, allowing for comparisons with today's LC/LU and the detection of changes. For this purpose, multiple different historic and up-to-date data sources had to be used for data preparation and analysis. This chapter describes, which data were used and how they were compiled.

3.1 DATA BASIS OF HISTORICAL LC/LUS

As primary data source for the reconstruction and digitisation of the historic LC/LU, the georeferenced Franziscean Cadastre (Urmappe) for Salzburg with a map scale of 1:2 880 (sporadically 1:5 760 in mountain regions and 1:1 440 in urban areas) dating back to 1830 (ULBRICH 1961, FUHRMANN 2007) was used. This historic map, which covers great parts of the Austrian empire, was compiled by numerous military surveyors on behalf of the Habsburg Monarchy. It served as information basis for calculation of land taxes associated with the land use on individual parcels (TIROLER LANDESARCHIV 2006, FUHRMANN 2007). Not disposing of the Franziscean Cadastre in the Tyrolian part of the upper Salzach catchment, historic LC/LU in this area had to be digitised with a different map, the "Kulturenskelettkarte" of Kitzbühel with a map scale of 1:36 000 dating back to 1855-1861. This map is a lower resolution copy of the Franziscean Cadastre (see TIROLER LANDESARCHIV 2006) and is therefore less detailed than the original, e.g. regarding the representation of small parcels, settlement areas or river courses. As both maps lacked detail in high altitudes, additional maps and data had to be drawed on. For the purpose of mapping historical glacier extents, present glacier data of 2015 from BUCKEL AND OTTO (2018) and orthophotos were combined with information from the Second Military

Survey (Franziscean Land Survey) with a map scale of 1:28.000 dating back to 1807-1808 as well as from the Third Military Survey (Franzisco-Josephinian Land Survey) with a map scale of 1:25.000 dating back to 1869-1887 (see www.mapire.eu). Being dedicated for military uses, the latter two historic maps primarily focused on a detailed representation of the terrain and its landscape structures and, thus, optimally complimented the aforementioned historic maps. For a more exact reproduction of former wasteland areas in high altitudes, wasteland data from the current land cover dataset were introduced under the assumption that today's wasteland areas already existed in the early 19th century.

3.2 DATA BASIS OF PRESENT LC/LUS

Today's LC/LU data was primarily based on the Sentinel-2 based LISA (Land Information System Austria) High Resolution Land Cover Map Level II data set. This map is a raster data set with a pixel resolution of 10m, a minimum mapping unit of 100m² and an overall thematic accuracy between 80-85% (GEOVILLE INFORMATION SYSTEMS GMBH 2017). However, some LC/LU types were not represented with sufficient accuracy and additional information had to be drawn from several other data sets. For instance, INVEKOS data (INtegriertes VErwaltungs- und KOntrollSystem, BMLFUW et al. 2017) depicting agricultural plots in Austria on a scale of individual parcels was used as supplementary data for agricultural land uses, which were not accurately represented by the LISA map. By this means, additional information about meadows and pastures, cropland, vineyards and fruit plantations were integrated to the data set. Likewise, if compared to orthophotos it could be seen that the representation of glacier areas in the LISA map was insufficient. Hence, glacier data based on the Austrian Glacier Inventory GI4 from 2015 (BUCKEL AND OTTO 2018) had been used as supplement. Being fragmentarily mapped, auxiliary data of ponds, rivers and streams was needed, too. Thus, information of ponds and big rivers was extracted from GIS shapefiles of OpenStreetMap from Geofabrik GmbH (see RAMM 2019). However, many bigger streams were still not represented and had to be mapped manually using orthophotos. For smaller running waters with catchment areas > 10km², a GIS data set of the "SPARE" project (Strategic Planning for Alpine River Ecosystems, MUHAR et al. 2018) was used. This data set depicts rivers and streams as polylines, which had to be classified in terms of their stream order and catchment area. Subsequently, a mean buffer width for each classification corresponding to the actual river width was defined, converting those polylines into polygones. The smallest streams (i.e. streams with catchment areas <10km², but historic river widths >5m) were integrated by using polyline data from OpenStreetMap, which were buffered according to the aforementioned procedure. Finally, standing water bodies had to be split from running waters, as the LISA data set does not differentiate between those land covers. The resulting data set approximates the LC/LU state in 2016.

3.3 DATA BASIS FOR HQ_{300} ZONES

The data basis for determination of current flood zones was a standardised GIS data set provided by the Federal Ministry of Agriculture, Regions and Tourism (Section I, Water Management), which comprised flood-prone areas at 300-year floods (HQ_{300} zones) and inundation areas of the years 2019-2020 for larger rivers (derived from Bundeswasserbauverwaltung (BWV), see BWV 2014), smaller torrents and gullies in valley sides (derived from Wildbach- und Lawinenverbauung (WLV), see BMLFUW 2011). However, this data set only contained information for regions, which formerly had been part of flood related projects. It was therefore necessary to integrate data from HORA (Natural Hazard Overview & Risk Assessment Austria; BMLFUW 2014, see also https://hora.gv.at/), depicting flood zones of HQ_{200} events. Technically speaking, the areas resulting from all three data sets represents flood zones for $HQ_{200-300}$. However, hereafter it is referred to as HQ_{300} zone. Artificial gaps (deriving from different data sets) and missing flood zones for smaller streams were manually filled or added by means of a Digital Elevation Model (DEM) with 10m resolution and orthophotos. Errors emerging from this estimation of flood zones via DEM and orthophotos are expected to be negligible, as many of those small streams flow along narrow valleys with small flood zones. Based on the resulting map of current

HQ_{300} zones, the Franziscean Cadastre, current orthophotos and a DEM of 10m resolution, the extent of historic HQ_{300} zones was derived according to the procedure decribed in chapter 4.3.
The resulting data set was used for analyses of LC/LU changes along fluvial corridors. All of these data preparation procedures of present LC/LU data as well as of present and historic HQ_{300} zones were done by Severin Hohensinner.

4 METHODS

In order to produce a methodologically sound comparative analysis, both the historic and current data set required preliminary data adjustments, which comprised the aggregation of a large number of depicted LC/LU types into a roundup of a processible number of hydrologically different LC/LUs. Furthermore, historic HQ_{300} zones had to be delimited. These data preparation steps as well as the mapping and evaluation procedure are shortly delineated in the following sub-chapters.

4.1 LC/LU CLASSIFICATION

Prior to digitisation, the numerous different LC/LU types in the Franziscean Cadastre were pooled into groups of hydrologically similar LC/LU classes. This was done to meet the requirements of a subsequent rainfall-runoff modelling study analysing the hydrological effect of LC/LU changes in more detail. The number of LC/LU types to be mapped was thereby reduced from originally more than thirty to eleven. Table 7 shows the classification system chosen for digitisation. As can be seen, in some cases one historic category could be assigned to two differing LC/LU types, depending on either their proximity to settlements (e.g. orchards or vegetable gardens) or on their actual use (e.g. military areas and parks). Thus, for instance, vegetable gardens located within settlement areas were to be mapped as settlements, whereas they have been digitised as cropland if situated elsewhere. Analogously, the other LC/LU types of multiple assignability had been classified. At times land lots represented in the Franziscean Cadastre were compounds of two LC/LU types, e.g. trees on wetlands. In such cases, these parcels were digitised according to the hydrologically more relevant LC/LU type, e.g. wetlands.

Table 7: *Classification system for digitisation (DG) of the Franziscean Cadastre (FC).*

LC / LU type in FC	Classification for DG
Farmland	Cropland
Vegetable fields	Cropland
Vegetable gardens	Settlement or cropland
Deciduous forest	Forest
Mixed forest	Forest
Coniferous forest	Forest
Ice	Glaciers
Floodplain meadows	Meadows & pastures
Pastures	Meadows & pastures
Dry grasslands	Meadows & pastures
Bushy meadows	Meadows & pastures
Rivers	Rivers & streams
Gravel bars along rivers	Rivers & streams
Rocks	Wasteland
Loam pits	Wasteland
Debris	Wasteland
Quarry	Wasteland
Clay pits	Wasteland
Moors	Wetland
Swamps	Wetland
Bulrush	Wetland
Peat exploitation	Wetland
Buildings	Settlement
Cemetery	Settlement
Ornamental gardens	Settlement
Parks	Settlement or meadows and pastures
Military	Settlement or meadows and pastures
Orchards	Settlement or sparsely wooded land
(Fruit) trees on meadows	Sparsely wooded land
Ponds	Standing water bodies
Lakes	Standing water bodies
Vineyards	Viniculture

In accordance to the classification system used for digitisation of the Franziscean Cadastre, LC/LU classes of the LISA data set had to be adapted correspondingly (see Table 8).

***Table 8**: Re-classification of current LC/LU types.*

Raster code	LISA L2 name	Classification
11	Built-up	Settlement
12	Flat sealed surfaces	
31	Permanent soil	Cropland
32	Bare rock and screes	Wasteland
60	Water	Rivers & streams
		Standing water bodies
70	Snow and ice	Glaciers
91	Broad-leaved trees	Forest
93	Coniferous trees	
100	Bushes and shrubs	Sparsely wooded land
122	Herbaceous periodic	Meadows & pastures
125	Herbaceous permanent low productivity	Meadows & pastures
126	Herbaceous permanent high productivity	Meadows & pastures
130	Reeds	Wetland

4.2 LC/LU DIGITISATION

The Franziscean Cadastre was manually vectorised using ESRI ArcGIS 10.6.1, digitising all parcels as shapefile polygons and adding the respective LC/LU class as attribute values. Due to time restrictions, some small scaled structures in the historic map could not be mapped. Hence, historic trails, streets, bridges, wells, ditches or ducts were not taken into account. Similarly, small LC/LU parcels of less than 10m areal extent, lying in between larger parcels of differing LC/LU types, were not to be separately delineated. However, emphasizing on highest accuracy, many smaller structures are included nonetheless. Settlements had to consist of at least two or more buildings in order to be considered for vectorisation and were digitised together with surrounding trails, streets or other adjacent infrastructure. The minimum width for streams to be mapped was predefined to 5m, including sediment bars. If stream width was continuously smaller than 5m, streams were excluded from vectorisation. In order to provide a methodologically sound comparative analysis, only those running waters, which had been mapped in the Franziscean Cadastre were included into the LC/LU dataset of 2016. Eventually both, the historic and the present dataset contained all running waters with catchment areas >10km² as well as numerous smaller streams in smaller catchments with historic stream widths of at least 5m.
The georeferenced Franziscean Cadastre featured gaps and distortions, which were particularly frequent at the transition of adjacent map sheets as well as along of rivers and municipal boundaries. These problems were solved by means of a second georeferenced online version of the Franziscean Cadastre on www.mapire.eu, allowing to estimate the distribution of LC/LU types within gaps as well as to measure river widths along distorted river sections. In case river courses got displaced along two adjacent map sheets, both ends were interlinked in a way to reduce artificial breaks to a minimum.
Due to coarser resolution and representation of LC/LUs in the Tyrolian Kulturenskelettkarte, mapping had to be adjusted in this area. Partially missing data about sparsely wooded land was compensated with online information of the Franziscean Cadastre on www.mapire.eu. Inaccurate or displaced stream and river courses had to be manually rectified by means of data from HQ_{300} zones and orthophotos to assure that running waters are located within flood zones. Likewise, the width of running waters had to be

verified in the Franziscean Cadastre via www.mapire.eu to subsequently buffer river segments according to their historical width. These buffered river segments were then clipped with HQ_{300} zones to eliminate overlapping areas and to make sure all river sections are located within HQ_{300} flood zones. Owing to these corrections, surrounding LC/LUs got slightly displaced.

After digitisation of the Franziscean Cadastre further data refinement procedures were done to improve accuracy of the historic map in mountainous regions, where inaccuracies were highest. Assuming, that all current wasteland areas must have been wasteland areas in 1830 when climate was colder, wastelands from the LISA 2016 map were clipped into the historic map. In a second step, historic rivers, standing waters, settlements, wetlands and cropland were reintegrated into the map in order to prevent other historical LC/LUs of being overwritten by wastelands. Additionally, former glacier areas had to be inserted, as those areas were not represented by the Franziscean Cadastre of Salzburg. This was done by means of data described in chapter 3.1.

4.3 Determination of historic HQ_{300} zones

The primary basis for approximating historic fluvial corridors were current HQ_{300} zones. In the following procedure, the Franziscean Cadastre, current orthophotos and a DEM (10m resolution) were used to detect any anthropogenic impairments of runoff (i.e. artificially raised terrain due to dams, embankments, streets, railway lines, or settlements) for every segment of rivers and streams. If interferences had been detected (i.e. if the terrain was artificially raised), the lateral extent of flood waters prior to such influences was estimated. This was done by an elevation measurement along the current flood water limit, which was then compared to elevations of the surrounding terrain. Historical flood zones were then laterally expanded until higher elevations were reached. As described above, most river sections along the upper Salzach River were intensely regulated and straightened, possibly leading to river bed incisions and a lowering of the water table. If both, the Franziscean Cadaster and orthophotos confirmed that former water tables within a river section must have been higher and floodplains wider, historical inundation areas were assumed to be larger than today. In such cases, laterally differing forms of land use in the Franziscean Cadastre (e.g. boundaries between pastures and cropland) that indicated small terrain steps were matched with the DEM and historic HQ_{300} zones were laterally expanded accordingly. In most cases, the historical floodplain zone was clearly identifiable in the Franziscean Cadastre. If so, these areas were directly classified as HQ_{300} zones. In a final step, standing water bodies situated within HQ_{300} flood zones were removed, as they are not inundation areas in a narrower sense. Thus, HQ_{300} zones were determined for every river and stream in the historical and present LC/LU maps with catchment areas >10km². Additionally, the dataset includes HQ_{300} zones for numerous smaller streams with historical stream widths of at least 5m and for many smaller areas along of valley flanks, being classified by WLV as being prone to flooding or mudslides. It should be noted that historic HQ_{300} zones derived by using present-day data do not necessarily translate into areas being inundated by a 300-year flood in 1830. Over time, both, climate change and LC/LU change have significantly altered flood recurrence intervals. It is therefore impossible to assign any former recurrence interval to areas being referred to as historic HQ_{300} zones, which might, in reality, have been flooded either by floods of higher or lower recurrence intervals than today's 300-year floods. Thus, HQ_{300} zones of 1830 analysed in this work are to be interpreted as historic flood zones, which would have been inundated at floods with similar water levels as today's HQ_{300} events.

4.4 Analysis

The spatial data resulting from vectorisation were analysed in terms of descriptive statistics with Microsoft Excel 2013 (see Annex). For each LC/LU class in 1830 and 2016, the individual total area in km² as well as its share on the total area in percent was calculated. This was done for the entire catchment as well as for the fluvial corridor only (HQ_{300} zone). By definition, the HQ_{300} flood zone includes all parts of rivers and streams. However, due to position errors in the Franziscean Cadastre some segments of rivers and streams were located outside of flood zones. Therefore, analysis of LC/LUs in historic and current HQ_{300} zones required some preliminary data adjustment.

For the historic situation, the areas of rivers and streams outside of the HQ_{300} zone and LC/LUs surrounding them were identified by applying a buffer analysis of 100m width around the limits of flood zones. The area of outlying rivers and streams was then added to rivers and streams located within the historic HQ_{300} zone. Of course, this leads to an incorrect, oversized HQ_{300} zone. Thus, the addition of external areas of rivers and streams had to be compensated by proportional subtraction from other LC/LUs within the HQ_{300} zone. For this purpose, the areal distribution of LC/LUs surrounding those external rivers segments was used for determination of individual subtractions within the HQ_{300} zone.
In general, a similar approach was used to adjust data from 2016. Here, for compensation of the area surplus, one third of the previously added area of running waters was subtracted from each of the three LC/LU types covering the largest area in the HQ_{300} zone (i.e. meadows and pastures, sparsely wooded land and forests), respectively.
For determination of LC/LU change, a transformation analysis was done with ESRI ArcGIS 10.6 producing a sheet listing the different LC/LUs and their areal development between 1830 and 2016. These values were copied in a separate sheet listing each LC/LU type with its respective transformation into other LC/LU types. After calculation of areas in km² and calculation of changes in areal percentage referred to total areas, this data was used for results.

5 RESULTS

In the following section, the results obtained with this methodology are presented. The first sub-chapter 5.1 describes absolute and relative changes in the area of LC/LU types between 1830 and 2016 in the entire upper Salzach catchment as well as the trajectories of land transformation for individual LC/LU types. In the second sub-chapter 5.2, absolute and relative areal changes of LC/LUs along the fluvial corridors as well as changes in the total area of HQ_{300} zones are presented. In order to estimate the potential hydrological effect of overall changes associated with those land transformations, the historic situation and hydrological implications of each LC/LU type is shortly described by means of a literature review in chapter 6.3. Finally, in chapter 6.3.9, a deduction of the potential hydrological changes is given based on the previously given literature information.

5.1 LC/LU CHANGES BETWEEN 1830 AND 2016 IN THE UPPER SALZACH CATCHMENT

As can be seen by comparing Figures 18 and 19 or the two detail maps in Figure 20, LC/LU considerably changed between 1830 and 2016. In 1830, forests covered the largest areas (28%, see Figure 21) of the upper Salzach catchment with a total of approximately 767km². Most of these forests were found in the subalpine zones along the northern Saalach catchment and along the Salzach valley. Similarly, meadows and pastures as well as sparsely wooded land (including fruit tree meadows and crooked wood), commonly used as livestock feeding grounds, were wide-spread LC/LUs in the montane to alpine zone covering 28% (748km²) and 17% (465km²) of the catchments surface, respectively.

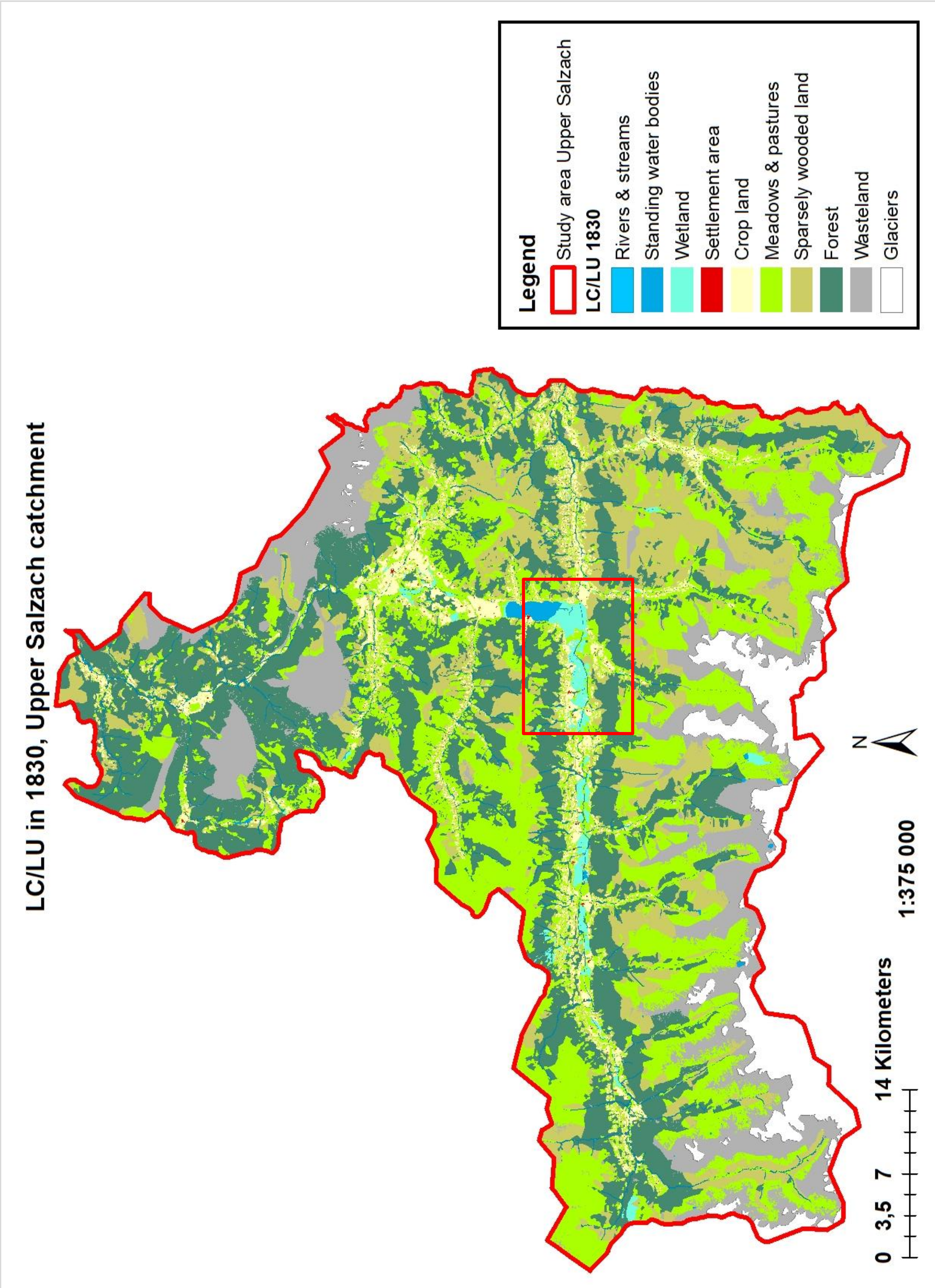

Figure 18*: Land cover/land use of the upper Salzach catchment in 1830. Red square: location of the detail maps in Figure 19.*

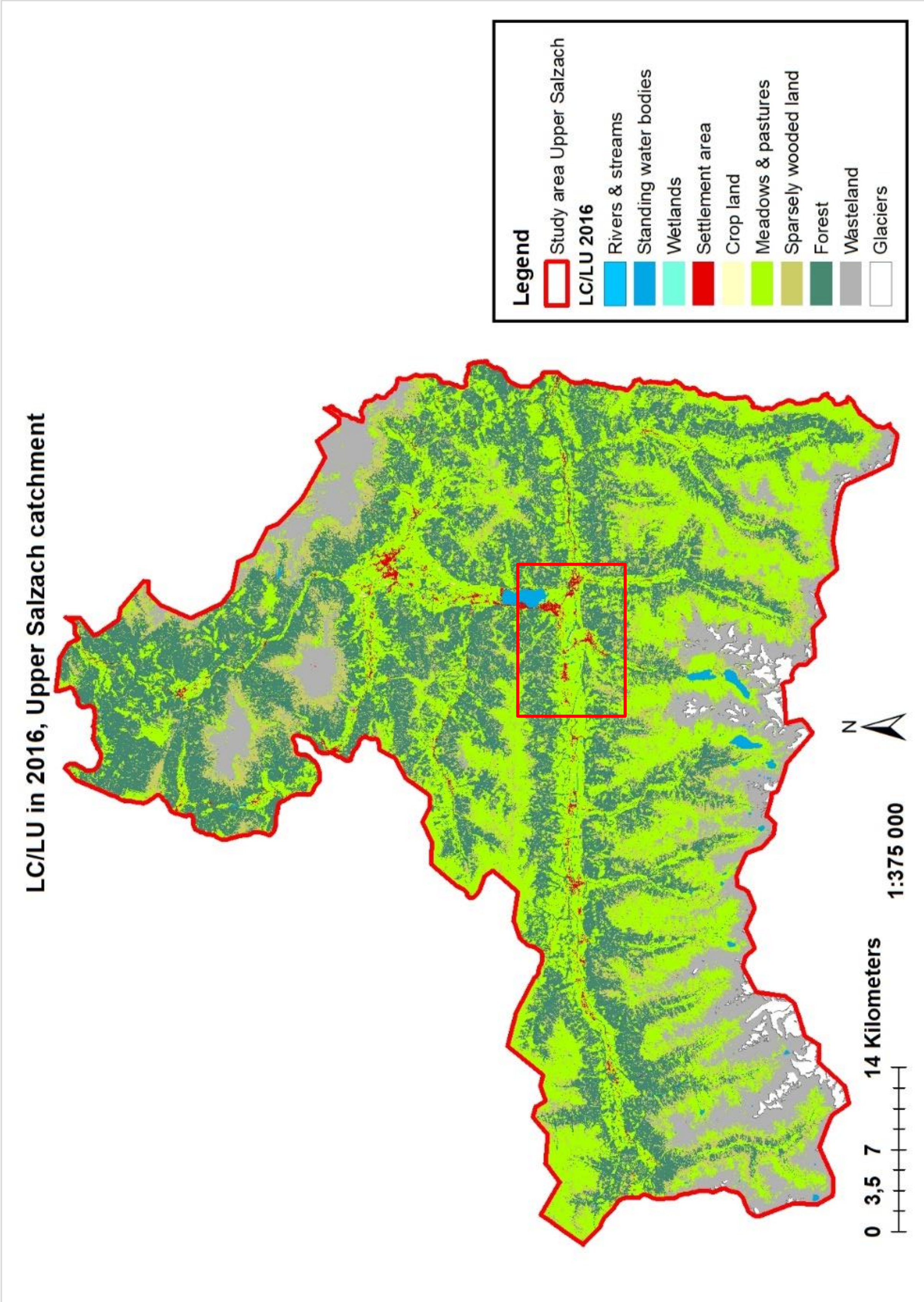

Figure 19: Land cover/land use of the upper Salzach catchment in 2016. Red square: Location of the detail maps in Figure 20.

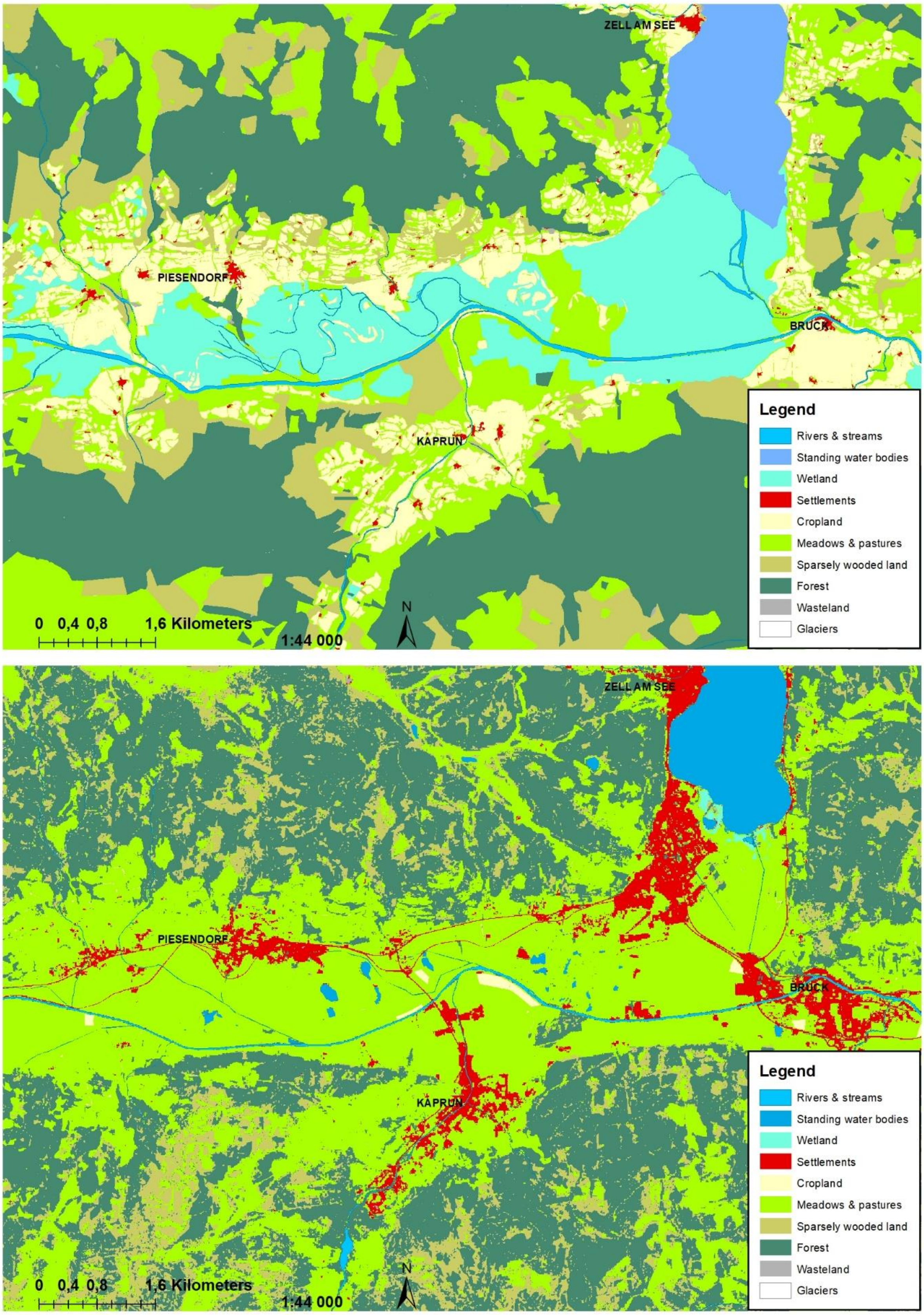

Figure 20*: Exemplification of LC/LU transformation between 1830 (upper map) and 2016 (lower map) in the flow section between Piesendorf and Bruck. See location of the detail in Figures 18 and 19.*

The highest altitudes were dominated by bare wasteland and glaciers, accounting for 13.5% (364km²) and 6% (164km²) of the total catchment, respectively. In contrast, wide reaches of the valley plains were cropland (5.1% of the total catchment, 139km²), which was not restricted to areas in direct proximity to fluvial corridors, but could also be found along hillsides of up to 1200-1300m a.sl. Such exploitation of steep, barren grounds being difficult to cultivate was necessary because a big share of potential agricultural soils along the Salzach valley was covered by swamps, precluding further exploitation for self-sustaining farming on which most people relied (see chapter 6.3.4). In those days, wetlands represented about 1.1% of the total upper Salzach catchment corresponding to an area of 30km². At the outset of major river regulation measures, the area of rivers and streams accounted for 0.6% (15.6km²) of the total catchment area, while standing water bodies covered 0.3% (7.7km²). Settlement areas represented the smallest areas with 0.1% of the total catchment, corresponding to an area of 3.7km². Vineyards, in contrast, were and still are totally absent in the study region, which is why they were excluded from representation in the Figures 21 and 22.

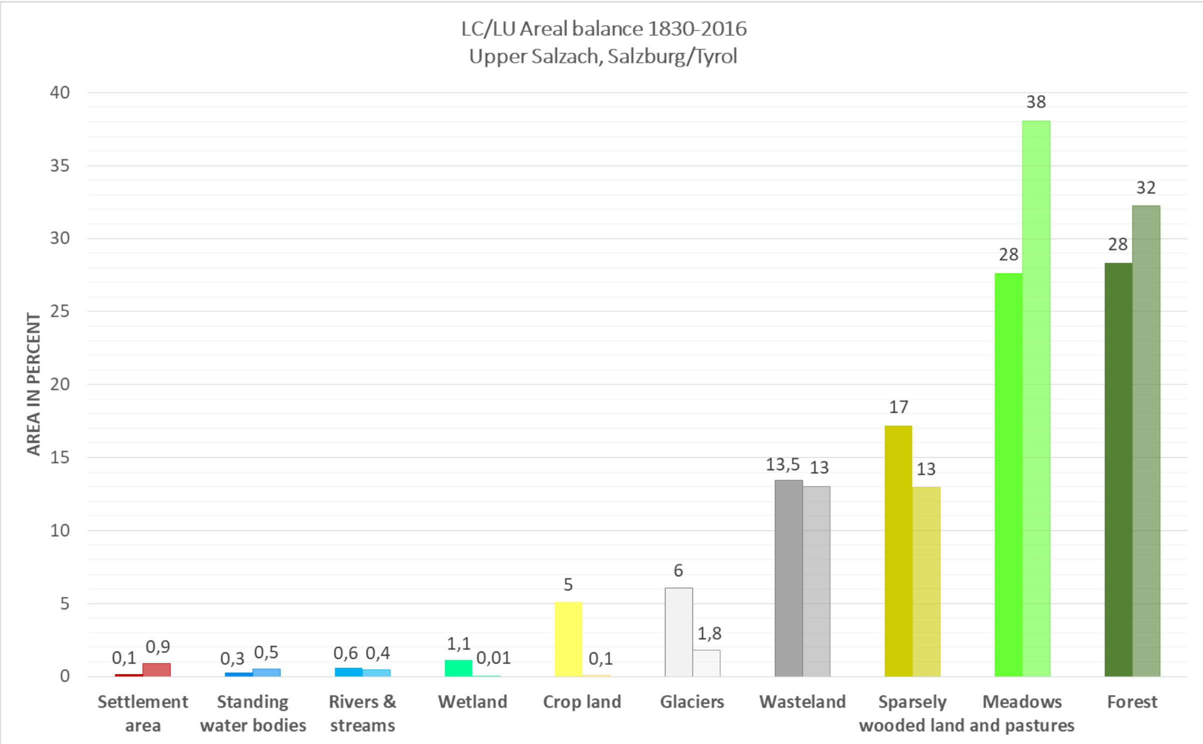

Figure 21*: Area of LC/LU in percent related to the total catchment area in 1830 (dark colours, left) and 2016 (bright colours, right), aligned from smallest LC/LU type to largest LC/LU types in 1830.*

Until 2016, forests significantly expanded from 28% to 32% (i.e. 871km²) of the total catchment. In relation to the total area of forests in 1830, this corresponds to an increase of 13.6%. Most forest growth took place on former sparsely wooded land as well as on meadows and pastures (see Table 9) in high altitudes, which often were used as feeding ground for livestock. As society shifted towards more industrialized agriculture, those mountain pastures were often being abandoned and finally got forested. Likewise, some areas of former wasteland are now wooded, which could be an effect of a warmer climate, allowing vegetation to colonize even higher altitudes. To a smaller extent, forests developed on those LC/LUs, which were heavily transformed, like e.g. on abandoned cropland, drained wetland as well as along narrowed and straightened rivers and streams. Yet more remarkable expansions were found for meadows and pastures, increasing from 28% to 38% (i.e. 1029km²) of the total catchment in 2016. This corresponds to an increment of 37.6% if compared to area extents in 1830. As shown by HOHENSINNER et al. (2021a), most meadows and pastures in higher altitude regions had been abandoned and got wooded, leading to an arithmetical downwards shift of the median elevation of grassland, so that increments are primarily focused to lower elevations. Here, the most considerable relative changes occurred on former cropland and wetlands. Thus, 90% of former cropland and around 77% of former wetland was transformed into grassland (meadows and pastures). Still, to a smaller extent, Alpine grassland now also colonizes former wasteland areas and even former glaciers.

Table 9*: Percentage of LC/LU in 1830 being transformed into other LC/LU types in 2016, e.g. 10% of former forests are now meadows and pastures. Values below 1% are only shown, if a LC/LU type in 1830 lost more than 99% of its former extent in 2016. Asterisk: Faulty values due to inconsistent delimitation of such areas in the historical and current data sources, see chapter 6.4.*

LC/LU 1830	Percentage	LC/LU 2016
Forest	72	Forest
	17	Sparsely wooded land
	10	Meadows and pastures
Meadows and pastures	67	Meadows and pastures
	18	Forest
	13	Sparsely wooded land
Sparsely wooded land	46	Meadows and pastures
	35	Forest
	18.5	Sparsely wooded land
Wasteland	67	Wasteland
	20	Meadows and pastures
	10	Sparsely wooded land
	2.7	Forest
Glaciers	66	Wasteland
	30	Glacier
	3.0	Meadows and pastures
Cropland	90	Meadows and pastures
	6	Settlement
	2.5	Forest
	0.5	Cropland
Wetland	77	Meadows and pastures
	8	Settlement
	7	Forest
	4.6	Standing water bodies
	2.7	Sparsely wooded land
	1.1	Rivers and streams
	0.1	Wetland
Rivers and streams	33	Meadows and pastures
	32	Rivers and streams
	20	Forest
	7	Sparsely wooded land
	6	Settlement
	1.5	Wasteland
Standing water bodies	76	Standing water bodies
	15	Meadows and pastures
	4.3	Settlement
	1.7	Wetland
	1.4	Forest
	1.1	Sparsely wooded land
Settlement*	56	Meadows and pastures
	38	Settlement
	4.0	Forest

In contrast to forests and grassland showing substantial area increments, sparsely wooded land was notably reduced by 24.7% (to 350km²) compared to their former extent. Only 18.5% of former sparsely wooded land remained unchanged, the rest was predominantly transformed into grassland or forest (succession). New sparsely wooded land has colonized former unwooded or bare land, such as meadows and pastures and wasteland in high altitudes. The latter colonisations, together with the succession of grassland on former wasteland and glaciers reinforces the assumption that climate change altered the distribution of vegetation in the upper Salzach catchment, leading to an upwards shift of vegetation zones. Owing to these temperature changes since the end of the Little Ice Age around 1860, glaciers declined by 70.2% (to 49km²), leaving behind large wasteland areas. However, many former wasteland areas (33%) have also been succeeded by vegetation so that the area of wastelands actually declined by 3.3% (i.e. to 352km²). In the valleys, strongest changes were found in the distribution of cropland and wetlands. Related to their former area, cropland declined by 98.8% (from 139km² to 1.7km²), while wetlands were nearly eliminated (from 30km² to only 0.2km², equivalent to a reduction of 99.3% of the former area). These tremendous losses resulted from the transformation of unprofitable arable land into meadows and pastures for livestock feeding as well as from drainage of wide-spread moors, reeds and swamps along the Salzach valley. Some of these areas had also been transformed into settlements or colonized by forests. A minor share of former wetlands is now covered by water bodies (i.e. rivers and streams, ponds and lakes). Owing to massive river narrowing and river straightening along the Salzach and the Saalach River since the beginning of the 19th century the area of rivers and streams declined by 22.4% from formerly 15.6km² to 12.1km² in 2016. Most of the former flow sections are now covered by grassland, forests or sparsely wooded land. A smaller fraction was transformed into settlements. However, it should be noted, that due to faulty representation of gravel banks adjacent to rivers and streams as settlement areas in the LISA map, the amount of settlements on former river segments might actually be significantly smaller. In contrast, the area of standing water bodies increased by 80.5% from formerly 7.7km² to around 14km² in 2016, as a result of the construction of reservoirs for power plants in the upper Salzach catchment. Settlement areas show the highest relative increase, rising from formerly 3.7km² in 1830 to 24km² in 2016, corresponding to a 6.5 fold increase. While settlement areas represented only 0.1% of the total area in 1830, they now represent 0.9%. However, the development of settlement areas should be interpreted with caution given the limitations of the LISA data set, i.e. mapping of larger infrastructure only. Former settlements might therefore not have been transformed into e.g. grassland as is indicated in Table 9, but might simply not have been taken into account in 2016 (The same applies, if small settlements in 1830 were mapped with insufficient accuracy, leading to faulty land transformations; for further information see chapter 6.4). Thus, it is suggested that the area of settlements in 2016 actually should be interpreted as a minimum. In reality, the area of settlements today might be even larger.

5.2 LC/LU CHANGES BETWEEN 1830 AND 2016 IN HQ_{300} ZONES

Alterations of LC/LUs along the fluvial corridors, i.e. in areas being flood-prone to 300-year floods (HQ_{300} zones), reflect general patterns of change in the total catchment. However, some LC/LU types show even more distinct shifts. As can be seen in Figure 22 and in contrast to the situation in the total catchment, meadows and pastures dominated the HQ_{300} zones in 1830. 31% (or 55km²) of the fluvial corridors were covered by grassland, whereas only 9% (or 16km²) were covered by (alluvial) forests. Similarly widespread, cropland made up about one fourth (or 44km²) of areas adjacent to rivers and streams.

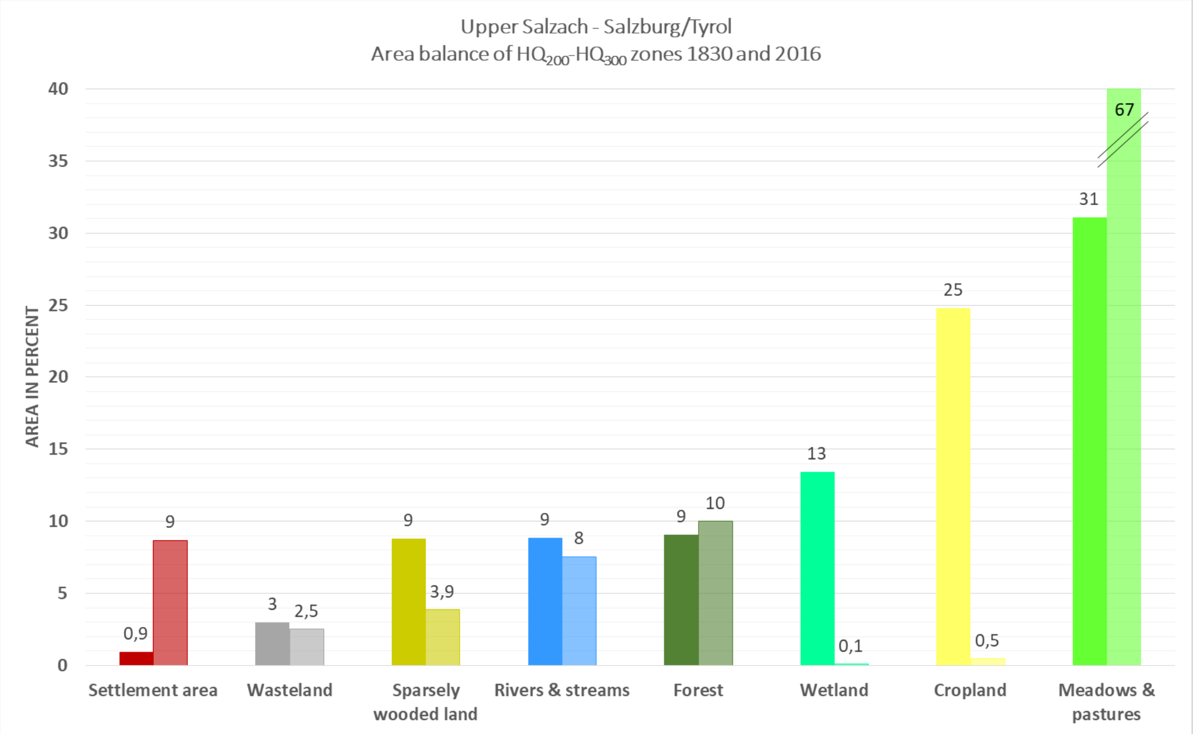

***Figure 22**: Area of LC/LU in percent related to areas of HQ_{300} zones in 1830 (dark colours, left) and 2016 (bright colours, right), aligned from smallest LC/LU type to largest LC/LU types in 1830.*

Likewise, wetlands covered wide areas along rivers and streams. Being dispersed over the entire valley section between Neukirchen and Bruck, they covered 13.5% (or a little less than 24km²) of the fluvial corridors. At that time, rivers and streams and sparsely wooded land both accounted for 9% (or 15,6km²) of the HQ_{300} zone. The smallest LC/LU types within the fluvial corridors were wasteland and settlement areas, representing 3% (5,3km²) and 0.9% (1,7km²) of the flood zones, respectively. As can be seen by comparison with abovementioned values, the share of settlements, as well as of other LC/LUs such as wetlands or cropland, was much higher along the fluvial corridors, if compared to LC/LU distribution in the total catchment.

Until 2016, 99.3% of former wetlands along the fluvial corridors had been lost to drainage. With less than 0.2km² left, wetlands have virtually vanished. Most of these areas were transformed into meadows and pastures. Along with drainage measures, systematic river regulation measures started at the beginning of the 19th century. This led to a truncation of rivers and streams of about 22.4% (to 12.1km²). Many areas of sparsely wooded land adjacent to rivers and streams got cleared, which might be explained by the transformation of former fruit tree meadows and woody pastures to more intense land uses, leading to a loss of 60.3% of the former area (from 15.6km² to 6.2km²). The area of alluvial forests, however, almost remained the same (then, as now 16km², equivalent to 9% and 10% of the HQ_{300} zones, respectively). At the same time, cropland has been abandoned and transformed into meadows and pastures, resulting in a 98.2% decrease of former arable land. Today, only 0.8km² of cropland remain in the HQ_{300} zone. The conversion of the aforementioned LC/LUs led to a considerable increase of meadows and pastures in the fluvial corridors. In the period between 1830 and 2016, the area of grassland increased by 95.3% from 55km² to approximately 107km². Nowadays, two thirds of the total fluvial corridors are covered by meadows and pastures. Moreover, the transformation of wetlands and river regulation measures cleared the way for urban expansion. Settlement areas grew substantially from formerly less than 1.7km² to 14km² in 2016, equivalent to an 8.2 fold increase. They now cover 9% of the fluvial corridors. In contrast, the area of wastelands in river surroundings barely changed and still amounts to 2.5% (i.e. 4km²) of the HQ_{300} zone.

Alongside these qualitative changes in LC/LU composition, human interventions also affected the extent of inundation areas over time. As can be seen in Figure 23, areas being flooded by a today's 300-year flood were significantly larger in 1830. Over time, the HQ_{300} flood zone got shortened by 16km² from formerly 177km² to 161km² in 2016, which corresponds to a reduction of 9%.

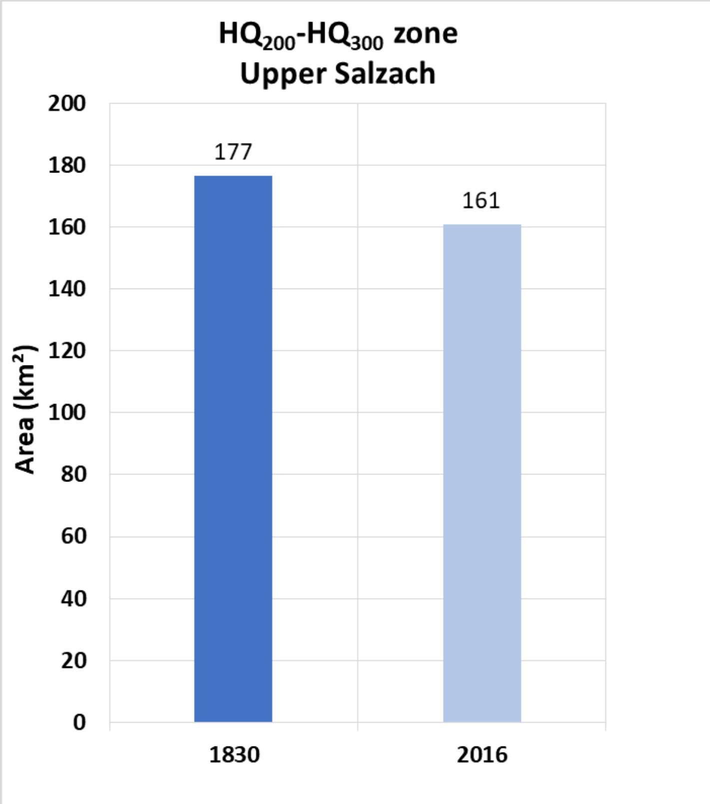

***Figure 23**: Extent of inundation areas being flooded by a 300-year flood in 1830 and 2016.*

6 DISCUSSION

In the following sub-chapters, the results of this work are compared with and discussed based on national and international literature. Furthermore, general considerations and limitations regarding the data used as well as future research needs are given.

6.1 TESTING HYPOTHESES RELATED TO LC/LU CHANGES IN THE TOTAL CATCHMENT

As was shown in chapter 5.1, the results corroborate hypotheses associated with LC/LU changes in the total catchment. Between 1830 and 2016, the settlement area was found to have seen a 6.5 times increase. This is in line with rates of change in the number of buildings reported by the PROVINCIAL GOVERNMENT OF SALZBURG (2016a) for the period 1817-2011. Compared to other European mountain ranges, as for example the Carpathian region, where settlement areas have doubled between 1820 and 1980 (LIESKOVSKÝ et al. 2018), this increase is remarkable. Noticeable increases in forest cover found in this study (+13.6% between 1830 and 2016 or 0.75% per decade between 1830 and 2010) seem to have been even more pronounced in the shorter period between the end of the 19^{th} century/beginning of the 20^{th} century and today. Thus, for instance, the PROVINCIAL GOVERNMENT OF SALZBURG (2016a) reported rates of forest expansion in Salzburg of more than 20% between 1881 and 2013. Similarly, BEBI et al. (2017), who assessed changes in forest cover in the European Alps between the 19^{th} and 21^{st} century found that the province of Salzburg ranged among the regions with greatest rates of forest expansion, i.e. +7.0% per decade since 1928 (since the availability of reliable data). In other regions of the European Alps with longer data records, such as in Bavaria or in the French Pre-Alps, accruals were more comparable with rates of forest expansion found in this work and amounted to +0.7% per decade since 1900 and +3.5% per decade between 1850 and 2013, respectively. Most of this forest expansion took place along steeper slopes (>30°) close to the natural treeline on former Alpine meadows and pastures (BEBI et al. 2017). This led to a decrease in Alpine grasslands in the Alpine region (see for instance DULLINGER et al. 2003, TAPPEINER et al. 2006, GEHRIG-FASEL et al. 2007), which also was confirmed in the study region (cf. HOHENSINNER et al. 2021a). The latter study represents an overall dataset of LC/LU change in all Austrian catchments analysed within the framework of PoCo-FLOOD. It was shown that the median altitude of grasslands sank by almost 300m. This was attributed to the abandonment of Alpine meadows in high altitudes as well as to the transformation of arable land to pastures in low-lying valley floors. Everywhere in the Alps, the area of cropland, thus, decreased by between 6% and 67% over the last two centuries. The more unfavourable the local conditions, the more arable lands were lost (TAPPEINER et al. 2006). In the upper Salzach catchment, almost 99% of all former croplands were transformed to other land uses (mostly grasslands), indicating that local conditions were particularly unsuitable for agricultural cultivation (cf. BFW s.a. b). This decline is even more pronounced than reductions of approximately 90% between 1881 and 2013 reported for the province of Salzburg (PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Similarly, formerly extensive wetlands along the Salzach valley and close to the city of Saalfelden were drained and converted to other land uses in order to optimise land occupancy. As a result, wetlands have virtually vanished and declined by more than 99%. By comparison, overall rates of long-term wetland loss in Europe was estimated at e.g. more than 54% (FINLAYSON AND SPIERS 1999) or more than 56% (DAVIDSON 2014) only. Likewise, glaciers have considerably declined. In the European Alps, glaciers were estimated to have lost almost 50% of their area between 1850 (last glacier maximum) and 2000 (ZEMP et al. 2008). Thereafter, in the years 2000-2014, glacier recession was observed at accelerating rates (e.g. FISCHER et al. 2015). In this period, European glaciers further lost more than 25% of their area (approximately 1.8% per year, SOMMER et al. 2020). In line with these large-scale developments, glacier areas in the upper Salzach catchment between 1830 and 2016 declined by 70.2%. However, this value is higher than the 65% decrease in glacier areas estimated with the datasets of GROß AND PATZELT 2015 (showing glacier extents in 1850) and BUCKEL AND OTTO 2018 (showing glacier extents in 2015), which were processed to cover the exact extents of the study region and, thus, the same glaciers as analysed in this work. The difference in glacier retreat may be attributed to a less precise methodology applied in this master's thesis. However, despite this decline - and other than expected - glacier retreat was not found to have led to an increase in wasteland areas. In fact, many former glacier areas have transformed to wastelands, but a slightly higher amount of former wastelands got vegetated in the period between 1830 and 2016, leading to a marginal reduction in wastelands of 3.3%. This indicates that succession occurs at faster rates than assumed. Increases in the area of standing water bodies associated to growing glacier lakes and newly built reservoirs, however, could be confirmed (+80.5% between 1830 and 2016).

6.2 TESTING HYPOTHESES RELATED TO LC/LU CHANGES IN THE HQ_{300} ZONE

Along fluvial corridors, hypotheses 2 are partly confirmed. In fact, changes in settlements were found to be even more pronounced (8.2 fold increase compared to a 6.5 fold increase in the total catchment). This is in line with findings of TOCKNER AND STANFORD (2002), who reported higher land use pressure along riparian areas worldwide, but especially in Europe. In the overall dataset of HOHENSINNER et al. (2021a), changes amounted only to a 7.5 fold increase, whereas along the Bavarian upper Main basin, for instance, a five-fold increase was found between 1850 and 2011 (FRÜH-MÜLLER et al. 2015). In contrast, wetland losses in the floodplain were found to be similar to catchment-wide changes, which also included trajectories of headwater wetlands. Thus, wetland drainage was shown to have been equally intense everywhere in the catchment. Other than expected, associated land reclamations have not caused a reduction in floodplain forests. Actually, floodplain forests slightly increased by 0.5% along fluvial corridors. Thus, like in other Alpine catchments, floodplain forests already must have been extensively cleared prior to 1830 (cf. MUHAR et al. 2019). Still, despite these insignificant quantitative increases it is to be assumed that former and present alluvial forests strongly differ in terms of qualitative characteristics, such as species composition or the mean stand age (e.g. KLIMO AND HAGER 2001). Along with drainages of valley floors, river regulation and flood protection measures were conducted, which significantely decreased the area of running waters as well as of the floodplains by 22.4% and 9%, respectively. These changes are less than could have been expected from previous studies focusing on changes in fluvial morphology since 1750 (cf. HOHENSINNER et al. 2021b) and even less than reductions in the overall dataset. In the overall dataset, the decline of running waters and floodplains amounted to 40% and 13%, respectively (HOHENSINNER et al. 2021a). The less pronounced declines in channel area may have been due to the fact that river morphology of the Saalach and Salzach river in 1830 was dominated by straight and oscillating single bed channels (cf. MUHAR et al. 1996), which – on a historical perspective – were shown to have changed less than multi-channel or meandering rivers (HOHENSINNER et al. 2021b). Furthermore, in 1830, many river regulation measures were already implemented. Thus, river morphology and dimensions of both the Saalach River and the Salzach River were not pristine (cf. MADER 2000). Also the loss of floodplain areas is small if compared to international literature stating, for instance, floodplain losses of – on average - two thirds (and up to 80 to 90%) of their former area along large rivers in Germany (BRUNOTTE et al. 2009, cited after FOLLNER et al. 2010), or more than 90% in many European countries, e.g in Switzerland (TOCKNER AND STANFORD 2002). However, as mentioned before, losses of the HQ_{100} zone in the upper Salzach catchment would most likely be much more pronounced than the 9% reduction of HQ_{300} zones and thus possibly be more comparable with declines stated above.

6.3 POTENTIAL EFFECTS OF LC/LU CHANGES ON RUNOFF BEHAVIOUR AND FLOOD REGIME

In the following sub-chapters, the potential hydrological effects of associated land transformations (research question 3) will be assessed first for individual LC/LU types and later on a wider perspective bringing together individual information to an overall estimation.

6.3.1 OPERATING PRINCIPLES AND LIMITATIONS

A catchment's flood response is the result of an interplay of numerous controlling factors, such as climate, topography, geology and soils, which set the boundary conditions for any kind of hydrological process. At a smaller scale, however, land transformation may also be an important driver of flood change (BRONSTERT et al. 2001), though its potential effect is subject to long-time scientific controversies (e.g. WEHREN et al. 2010, BLÖSCHL et al. 2018) and specifying the exact role of LC/LU on river floods is still elusive. This is due to the many dynamic and closely intertwined processes shaping the runoff response, which are hard to isolate and assess, making any analysis and prediction of impacts more difficult. Thus, many research gaps are still to be addressed to increase knowledge about the interaction of LC/LU change and flood change at the catchment scale (FAO 2002, ROGGER et al. 2017).
In general, changes in LC/LU and management practices may affect runoff in various ways. Many relevant mechanisms, processes and feedback loops are shown in Figure 24. In short, each LC/LU type affects the soil surface (e.g. its ground cover or surface roughness) and soil characteristics (e.g. infiltration capacities) differently and, thus, provides different above-ground, surface and subsurface water storage capacities (NIEHOFF 2001, HALL et al. 2014). These water storage capacities can be interpreted as hydrological reservoirs (e.g. interception storage, soil storage etc.) of different size, diverse filling and depletion modes and temporally varying filling degrees. The impact of LC/LU change on floods is largest in case it has led to a loss (or gain) of extensive or highly efficient hydrological reservoirs, e.g. by sealing (or reclamation) of thick, permeable soils. In contrast, it is small in case water retention capacities remained largely unchanged after land transformation (e.g. soil sealing on thin soils with only slightly permeable bedrock). This implies that the scale effect of LC/LU change is not only a function of the area being converted, but also depends on its location. Similarly, the effect of LC/LU is small if hydrological reservoirs are close to saturation prior to precipitation events, anyway (BRONSTERT et al. 2001, NIEHOFF 2001). Besides, depending on the distribution of individual LC/LU types in the catchment, soil water movements and flow paths to the main channel differ and, hence, runoff concentration may strongly vary (NIEHOFF 2001, BLÖSCHL et al. 2007, WEILER 2016). The effect of LC/LU change on floods, thus, not only includes the alteration of hydrological resevoirs, but also involves modifications in runoff formation, which may be accelerated or delayed (NAEF et al. 2002). Ultimately, this may affect the superposition of flood waters coming from different tributaries, thereby increasing or reducing flood peaks in the main channel (BURT 1989).
The most important hydrological effect of LC/LU change in terms of flood response is the enhancement or prevention of infiltration (NIEHOFF 2001). Natural vegetation cover – especially by forest – is generally attributed to highest infiltration capacities and, hence, to reduce and delay flood peaks (cf. BROWN et al. 2005). Soil sealing by urbanization or soil compaction by intense agricultural practices, in contrast, largely impede infiltration, thereby leading to increased local flood peaks (cf. BRONSTERT et al. 2001, WEILER 2016). In case LC/LU changes have reduced the infiltration capacities of soils, precipitation intensity and geology become the main determinant for surface (and flood) runoff. In contrast, if infiltration is completely inhibited by impermeable soil surfaces, LC/LU change becomes the key factor for runoff formation (NIEHOFF 2001).
The effect of any kind of LC/LU change is highest for small catchments with low antecedent soil moisture responding to intensive, convective rainfall events and becomes more and more negligible with increasing catchment size and/or more long-lasting, less intensive precipitation (NIEHOFF 2001, BLÖSCHL et al. 2018). The pronounced effect on small spatial scales is due to the limited scope at which

convective storms (during which high infiltration capacities are critical for runoff attenuation) and LC/LU changes normally take place (BRONSTERT et al. 2001). This constraint of important drivers to small scopes is the reason for the limited effect of LC/LU change on floods, which is restricted to small or - at best - medium floods (cf. BRONSTERT et al. 2001, BESCHTA et al. 2001, SALAZAR et al. 2012, BLÖSCHL et al. 2018). At larger scales, an increasing number of controlling factors and process interactions may impede the identification of any particular effects of local LC/LU change (FAO 2002, VIGLIONE et al. 2016) and advective precipitation events become more relevant for flood formation (BRONSTERT et al. 2002). During such long-lasting, large-scale precipitation events, soil saturation processes over large areas of the catchment become the dominant driver for flood formation (most often of high magnitude floods) and differences in infiltration capacities of individual LC/LU types are, thus, negligible (NIEHOFF 2001, BRONSTERT et al. 2002, BLÖSCHL et al. 2018). In contrast, with increasing catchment area concerned by flood inducing events as well as with increasing flood magnitudes, the characteristics of the stream network come to the fore (NIEHOFF 2001).
Thus, on balance, the most important parameters determining the potential effect of LC/LU change on floods are the precipitation type, infiltration characteristics as well as soil and bedrock properties.

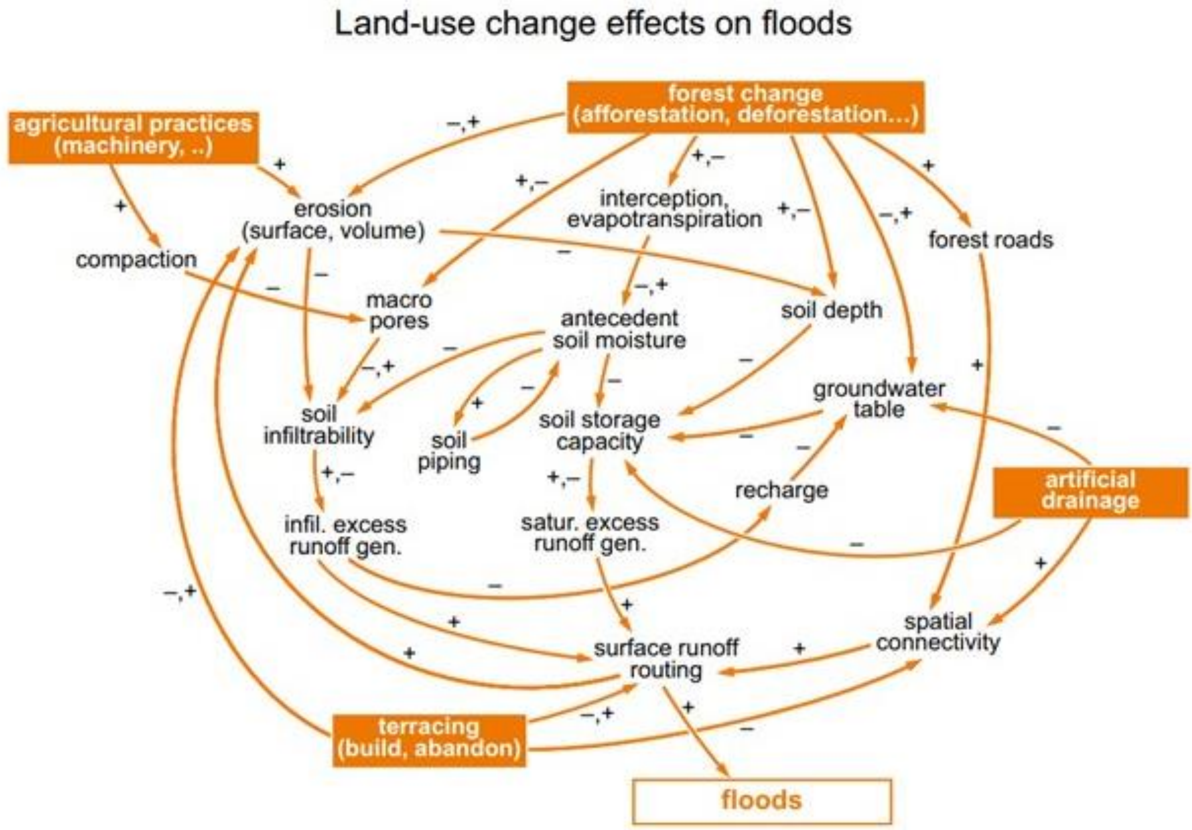

Figure 24: Schematic process interactions in land use change effects on floods at the catchment scale. Plus and minus signs indicate whether an increase in a variable increases or decreases another variable (ROGGER et al. 2017).

6.3.2 WASTELAND AND GLACIERS

Historically, glaciers were sometimes attributed to aggravate floods induced by heavy rainfall, e.g. by contributing important additional amounts of melting waters to rivers and streams of Pinzgau (LORENZ 1857) or by damming up glacial lakes, which caused severe flood damages in case of failure. Under cold climatic conditions, however, glaciers retain precipitation amounts over long periods of time of up to hundreds of years (FISCHER et al. 2018). One reason is their thick snow cover, allowing to accumulate not only solid precipitation, but also to absorb rainfall amounts of up to 50% of the snow covers water equivalent (DYCK AND PESCHKE 1995). Thus, the cumulative effect of buffering precipitation in the colder historic climate of 1830 in which glaciers in Pinzgau advanced rather than retreated (cf. last glacier maximum around 1860, FISCHER et al. 2015) is estimated to be higher than the potential risks of flood reinforcement or glacial lake outbursts. However, with progressively increasing temperatures due to climate change, glacier melt is amplified and an increasing number of glaciers is lost (cf. FISCHER et al. 2015, FISCHER et al. 2018). It takes time for soils to develop and for plants to colonize former glacier areas, so that for the following decades most of these spots are subsequently covered only by sparsely vegetated rocks (predominantely mosses and herbaceous taxa, FISCHER et al. 2019, cf. Table 8). Those bare rocks and shallow, sparsely vegetated or unvegetated soils in steep terrain limit the water retention capacity in high Alpine regions. In fact, in such environments, relevant infiltration processes are restricted to debris and deep rockfills (KIRNBAUER et al. 2008). Thus, although dependent on the catchment's geology and topography, water retention capacities are generally low and precipitation amounts most often are rapidly transmitted to subjacent areas (cf. LORENZ 1857, BRONSTERT et al. 2002, VERBUNT et al. 2005, KIRNBAUER et al. 2008). In karst regions, such as in the Saalach catchment, however, high amounts of surface runoff might directly percolate into the subsurface, locally reducing the volume of effective precipitation (cf. MADER et al. 1996). With further glacier retreat and transformation into wasteland, the precipitation buffering effect of glaciers will most likely gradually decrease, leading to more direct runoff responses in high mountain regions. In this regard, ALAOUI et al. (2013) found that increases in surface runoff due to climate change (i.e. increased snow and glacier melt) largely overweigh the attenuating effect of plant succession into higher altitudes. Thus, in a future with increasing temperatures, amplified glacier melt might, in some cases, initially contribute to critical increases in river discharges and, hence, flood peaks (BRAUN AND WEBER 2006, cf. chapter 2.3). However, after most glaciers have vanished, the runoff response of high Alpine regions is expected to be shaped primarily by topography and soil evolution as well as - to a lesser degree - by succession of plants.

6.3.3 SETTLEMENTS

As was shown in chapters 5.1 and 5.2, the upper Salzach catchment has experienced a substantial growth in sealed surfaces and urbanized areas, which, between 1830 and 2016, equals a relative increase from 0.1% to 0.9% of the upper Salzach catchment (equivalent to a 6.5 fold increase) as well as from 0.9% to 9% of its fluvial corridors (equivalent to an 8.2 fold increase). These rates of change are also reflected by official information. Accordingly, in the period 1817 to 2011, the number of buildings in Pinzgau rose from formerly approximately 4.300 to 25.556, corresponding to a sixfold increase (PROVINCIAL GOVERNMENT OF SALZBURG 2016a). However, these numbers do not consider the construction of roads or other infrastructure, which additionally augment surface sealing.

Owing to the more local nature of hydrological processes in urbanized areas and the straightforwardness of measurements, impacts of sealed surfaces on floods are well understood (ROGGER et al. 2017). Over many decades, extensive studies have broaden the knowledge base, which is, today, supported by broad scientific agreement (ESHLEMAN 2004). In this context, the term "sealed surfaces" in urbanized areas sums up all kinds of concreted or compacted grounds and infrastructure, e.g. roads, pavements, parking lots, buildings etc. On these surfaces, infiltration of precipitation is inhibited and directly transformed into surface runoff and/or conveyed to the sewage system, which might, in parts, drain water into receiving streams and rivers or might be overcharged in the course of heavy precipitation events (cf. HARMS 1986). However, it should be considered that the degree of surface sealing has significantly increased over time. While most streets and squares had been unpaved in the early 19th century, all are sealed and hinder infiltration today (HOHENSINNER et al. 2021a). Likewise, today, the amount of impervious surfaces in urbanized areas might be highly variable. Thus, in rural settlements and suburban areas, vegetation coverage generally is comparatively high and the share of impermeable areas is much smaller than in industrial areas or urban core areas. Therefore, runoff responses in historic and present settlement areas as well as in suburban settlements and highly sealed environments will most likely be different (cf. BRONSTERT et al. 2001). On an entirely sealed surface, for instance, 80% of precipitation amounts directly flow off as surface runoff, whereas on grassland, the share amounts to only 5% of precipitation sums (WEILER 2016).

In general, urbanization considerably increases infiltration excess overland flow and sewage system discharge and decreases interflow, baseflow and saturation excess overland flow. Thus, in combination with very low surface roughness on sealed surfaces, an increase in urbanization generally leads to faster surface runoff formation, accelerated runoff concentration, higher shares of direct flow and an overall increase in runoff maxima and volumes (NIEHOFF 2001). Since the early days of hydrological modelling, the same runoff reactions were also stated by other authors, who found reduced lag times as well as increased storm runoff volumes and flood peaks due to highly reduced infiltration capacities and surface roughness as well as rapid and efficient conduction of surface runoff to the sewage system or receiving waters (e.g. SALVINI AND KAMMERER 1961, HOLLIS 1975, HARMS 1986, CHOW et al. 1988).
After WEILER (2016), the magnitude of possible impacts of urbanisation on floods depends on the following factors: 1. The share of sealed surfaces in the catchment, 2. Their location in the catchment, 3. The catchment's area, 4. The runoff contribution of the respective areas prior to surface sealing, 5. The catchment's moistness prior to flood events and 6. The type of precipitation event and its magnitude. These statements are confirmed e.g. by VERBUNT et al. 2005, who found no significant increase in flood peaks at the catchment outlet when simulating a growth of residential areas of as little as 1.6% replacing grassland. Accordingly, they concluded that hydrological impacts related to this rate of urbanisation are restricted to the local scale, while being negligible further downstream. Similarly, HOLLIS (1975) showed that increases in soil sealing of less than 5% had no effect on floods of short recurrence intervals. In contrast, for higher relative increases in imperviousness, he found up to tenfold increases in flood magnitude. To this effect, clear examples are given by BRONSTERT et al. 2001, who confirmed considerably increasing flood peaks with increasing shares of sealed surfaces in the catchment, most notably for convective storm events and to a lesser extent also for advective ones. For instance, it could be shown, that – under historic conditions (1.3% settlement area in the catchment) - the runoff maximum after a convective storm event of short return period in the urban Körsch catchment (127km²) amounted to only a sixth of the present runoff maximum (25% settlement area in the catchment). Similar amplifications of flood runoff were also found for urbanisation scenarios in the more agricultural Lein catchment (115km², see Figure 25). Still, for their simulations, the authors did not adapt model assumptions for individual scenarios, i.e. the degree of soil sealing or the connectivity to sewage systems. Differences in runoff formation between the historic and the present state, may, thus, be even more pronounced.

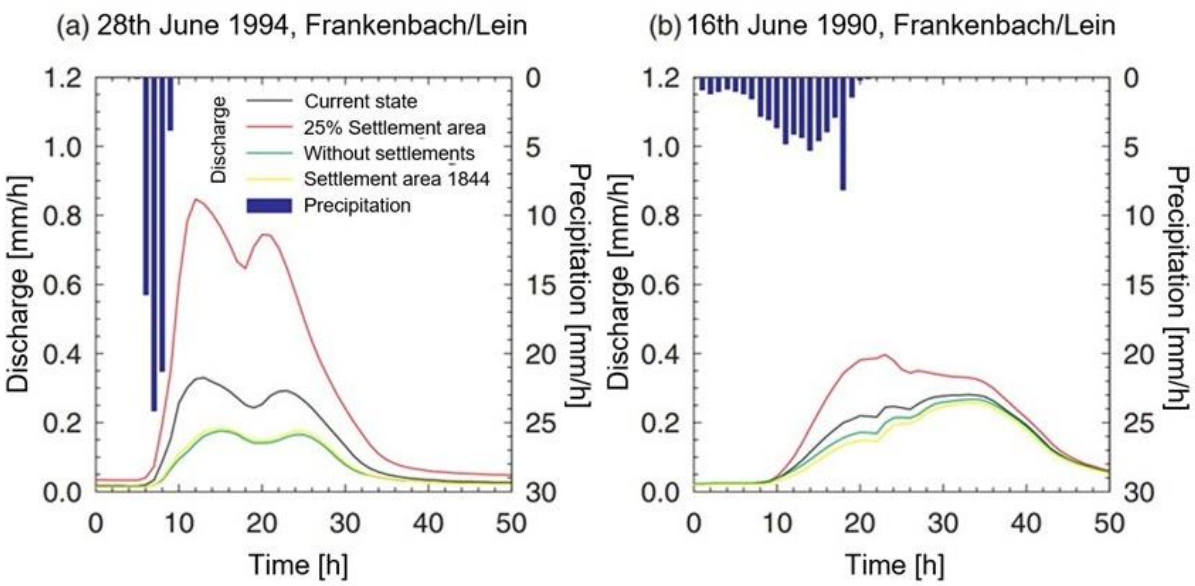

***Figure 25**: Simulation of runoff formation under different urbanization scenarios in the course of a convective storm event (left) and an advective precipitation event (right). Share of settlement areas in the catchment: 1844 = 0.8%; current state = 7.4%.* Modified after BRONSTERT et al. 2001.

Furthermore, BRONSTERT et al. (2001) confirmed the importance of the respective location of surface sealing in the Lein catchment. According to their findings, the geographical position of sealed surfaces might intensify the flood peak of floods with low recurrence intervals, alter the shape of the flood hydrograph as well as possibly increase flood volumes. The respective outcome depends on the location of the centre of precipitation and the impact on floods is highest in case the respective soils featured high infiltration capacities prior to surface sealing. Again, the effect of location was found to be strongest for short and intense, convective rainfall events. However, although being comparatively small, the amplification of flood peaks on sealed surfaces during advective precipitation events might also be of relevance for floods in large river basins.
In terms of any potential amplification of flood peaks, it was found that the effect of urbanisation decreased with increasing flood magnitudes, because during larger flood events, larger percentages of the catchment area contribute to runoff and soil saturation processes become the determinant factor for flood runoff (HOLLIS 1975, HARMS 1986).
Accordingly, the increase of settlement areas between 1830 and 2016 is expected to particularly enhance surface runoff formation and concentration during convective storm events and on a local scale, thereby reducing lag times and increasing storm runoff maxima and volumes of floods of small to medium magnitude. On a catchment perspective, however, the effect of settlements is expected to be negligible given the fact that they represent less than 1% of the total catchment area.

6.3.4 CROPLAND

Since the Middle Ages, mountainous regions in Pinzgau have been intensely used for agricultural purposes. Forests in high altitudes were extensively cleared to use these steep soils as pastures for livestock breeding (KOLLER 1975), which was and still is the main source of income for farmers in this region (PILLWEIN 1843, DÜRLINGER 1866, PROVINCIAL GOVERNMENT OF SALZBURG 2016b; cf. chapter 2.4). Some of these land reclamations had also been used for crop cultivation in altitudes of up to 1100m a.s.l. (DÜRLINGER 1866) or in even higher altitudes between 1200m a.s.l. and 1300m a.s.l (after own elevation measurements). Of course, such agricultural exploitation in general and former management practices on mountainous terrain in particular have had considerable implications on runoff formation and erosional processes, which are described and estimated in the following.
In general, runoff coefficients of agricultural lands and their effect on floods are shaped by individual characteristics of the vegetation cover, soil properties and management practices (BRONSTERT et al. 2001, WAGNER et al. 2009).
Regarding vegetation characteristics, relevant parameters determining the potential water storage capacities and flood attenuation of crops are, for instance, their evapotranspiration rates, surface roughness, leaf area index (LAI; leaf area in m² related to 1m² of soil area) and the related degree of soil coverage as well as their root penetration (BRONSTERT et al. 2001, FOHRER et al. 2001, WAGNER et al. 2009). The LAI and the degree of soil coverage determine the area on which interception is enabled and the degree to which the soil is protected against desiccation and siltation. Root penetration, in contrast, may improve soil water conditions. For instance, soils with intense rooting may reduce the antecedent soil moisture through transpiration, thereby increasing the water absorptive capacity of the soil. Additionally, roots stabilise the soil matrix and facilitate infiltration processes by creating preferential pathways. However, unfavourable soil properties, such as shortages in oxygen, moisture and nutrients or unsuitable grain size distributions (e.g. compacted, too fine or too coarse substrate) may impair rooting (BRONSTERT et al. 2001). Storage capacities provided by vegetation vary with the specific type of vegetation and depend on the season (development status, prior to harvest vs. after harvest; BRONSTERT et al. 2001, FOHRER et al. 2001). Accordingly, soil coverage and interception storage capacities are subject to temporal fluctuations with lowest contributions to flood attenuation between autumn (after harvest) and spring (before re-growth) (WEILER 2016, FOHRER et al. 2001, NIEHOFF 2001). In this regard, FOHRER et al. 2001 showed that the shorter vegetation period of crops and comparatively long periods of uncovered soils are the main reason for overall highest contributions to total stream flow and surface runoff as well as lowest rates of evapotranspiration, if compared to pastures

or mixed forests. Moreover, the authors confirmed the high sensitivity of surface runoff to soil cover (maximum canopy storage and LAI) during the growing season and showed that ground coverage of crops is especially critical for runoff generation during the season with highest rainfall amounts. Accordingly, the potential impact of extreme precipitation events varies with the growing season and the respective ground coverage of individual crop types. In this context, the duration of soil coverage over the year also plays an important role and differs for different crop types. For instance, cultivation of perennial forage acreage or winter barley results in a year-round soil coverage, while the cultivation of maize covers the ground only during four months of the year (LANDESAMT FÜR UMWELT, NATURSCHUTZ UND GEOLOGIE MECKLENBURG-VORPOMMERN 2002, WAGNER et al. 2009). In the worst case, crops germinate late in spring and are harvested late in the year, inhibiting the cultivation of intertillages or winter crops and causing long periods of open soils (WAGNER et al. 2009). However, it should be mentioned, that interception by different crop types allows only for a comparatively low amount of precipitation storage of rarely more than 3.4mm (HOYNINGEN-HUENE 1983). Thus, in relation to total precipitation amounts of flood-inducing events, the actual water storage capacity of vegetation by interception is small (NIEHOFF 2001).

Soil properties are governed primarily by the geologic parent material and management practices, which further affect the organic matter, biological activity, structural stability and the pore volume of soils, and hence, their infiltration and water-holding capacities (BRONSTERT et al. 2001, cf. WAGNER et al. 2009). Thus, improper soil cultivation, fertilisation or cultivation of crops with low interception storage may diminish infiltration and water storage capacities and accelerate runoff formation (NIEHOFF 2001). For instance, soils with low structural stability (i.e. sandy or silty soils, which are frequently found along the Salzach and Saalach valleys) are more vulnerable to the type and date of management practices (e.g. prior to a precipitation event), which may more easily cause soil compaction and a decrease in pore volume (WEILER 2016, BRONSTERT et al. 2001). However, due to other favourable characteristics, these type of soils are frequently cultivated, so that during uncovered episodes, desiccation or siltation may significantly reduce their structural stability, infiltration and water storage capacity (cf. NIEHOFF 2001, WEILER 2016). The magnitude of this tendency depends on numerous factors, such as on the cultivation methods applied, on the soil's water budget and on the intensity of heavy precipitation events (BRONSTERT et al. 2001). Still, the effect of agricultural management practices on floods was found to be limited to medium-sized floods. Therefore, floods with return periods above 100 years will not be prevented, attenuated or affected by any changes in cultivation patterns (WAGNER et al. 2009).

Taking into account vegetation and soil parameters, WAGNER et al. (2009) classified several cultivation types according to their contributions to floods into row crops (e.g. potatoes, beets, field beans and vegetables) with highest runoff coefficients, followed by cropland (cereals and legumes) causing medium runoff coefficients and grassland (pastures and permanent meadows) with the lowest contributions to surface runoff. They found that soils with gravelly and sandy substrate are most sensitive towards changes in management practices. On these soils, conversions of row crop cultivations or cropland to grassland might reduce surface runoff by 29% (sandy soils) to 65% (gravelly soils). For more cohesive soils, runoff coefficients are still reduced by 14% to 18%. Thus, the authors state that any conversion of row crops and conventional cropland to fallows, grassland or forests will, ultimately, decrease flood risk. In this context, grasslands are described as the most suitable of all agricultural land uses to minimize large-scale surface runoff and erosional processes. Flood prevention on grassland may only be further increased by conversion into un-grazed fallows or forests. In contrast, uncovered, conventional cropland and row crops with high interspaces temporarily contribute to surface runoff and siltation. In this regard, it was shown that despite a higher inclination of hillslopes in the upstream sections of the Trefflingfall catchment (Lower Austria), local soil characteristics and agricultural land use as grasslands led to higher flood prevention than in low-elevation downstream areas, where cropland and row crops dominated.

In former days in Pinzgau, most agricultural plots were used as so called "Egarten", meaning an agricultural management of cultivating crops over a short period of a few years, followed by a conversion into grasslands (or other land uses), which were then exploited for a comparatively longer period. Thereafter, grassland was re-transformed and, again, used as cropland. The total area of this kind of agricultural land in Pinzgau amounted to approximately 133km² (DÜRLINGER 1866, excluding data from Tyrol and the districts of Lend and Dienten), which corresponds well to results of cropland in the Fransciscean Cadastre (139km² in 1830). However, DÜRLINGER (1866) estimated that, on a yearly basis, only half of these agricultural areas had been exploited as cropland (66,5km²), while the rest, in reality, was used as grassland. Accordingly, on an annual perspective, only about 5% of all agricultural areas, actually would have been ploughed cropland. The rest (half of all Egarten plus meadows, pastures and swamps) would have been dedicated for livestock breeding. This implicates, that the true size of historic cropland might actually have been smaller than indicated in the Franziscean Cadaster, as it appears that such agricultural lands were not mapped according to their actual land use at the time of mapping, but rather according to a generic classification system, which summarized these alternating usages in an umbrella term as "cropland". Following FOHRER et al. (2001) and WAGNER et al. (2009), this shift towards – in reality - more grassland and less cropland, most likely, has had a positive effect on water retention capacities of soils in the historic condition. By limiting the extent of bare soil surfaces and the duration of uncovered periods to several years of more intense exploitation, this cultivation method may have led to lower surface runoff formation, if compared to permanent, conventional cropland. Furthermore, permanent soil coverage by grasslands also may have reduced the risk of siltation on silty soils in Pinzgau, which generally are described as being more vulnerable towards detrimental management practices (NIEHOFF 2001, WEILER 2016). These positive effects, however, may, to some extent, have been counteracted by increased soil compaction and trampling damages due to intense livestock grazing (PILLWEIN 1843, KOLLER 1975, BRONSTERT et al. 2001, LEITINGER et al. 2010, WEILER 2016, MAYERHOFER et al. 2017).

The most commonly cultivated crops were "Korn" (which is not further specified but most likely is a term used for rye, cf. PROVINCIAL GOVERNMENT OF SALZBURG 2016a, p.121) and oat. The cultivation of wheat was restricted to lower elevations and broader valley floors. To a minor degree, cultivated crop types also included peas, beans, linum and hemp. Potatoes and trifolium had, back then, only recently been introduced (since 1789), so that their cultivation was quite common but had no long history (PILLWEIN 1843, cf. PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Fruit farming occupied only comparatively small areas of land (approximately 0.83 km², DÜRLINGER 1866), whereas vineyards were inexistent throughout Pinzgau. Unfortunately, no detailed information about water storage capacities associated to most of these crops can be given. However, for commonly cultivated ones (rye, oat, wheat and potatoes), interception storage potentials range between 2.1mm and 3.4mm of open field precipitation (HOYNINGEN-HUENE 1983), while root depths barely attain more than 1m root depth (BRONSTERT et al. 2001), indicating comparatively low water retention capacities, when considering additional unvegetated episodes during the year.

Located along steep slopes and broader valley plains, agricultural soils, were very densely and continuously used, without making use of fallows to enable soil recovery. This intense exploitation was necessary to harvest enough provisions for livestock feeding during the winter season. Due to the complex terrain at many agriculturally exploited sites, management practices had to be adapted to local conditions. The typical cultivation method for soils in Pinzgau was ploughing. In mountainous terrain, where ploughing with draft animals was an unfeasible task, croplands were often furrowed and/or loosened manually by manpower (using a plough and/or hoes). However, such manipulations enhanced erosional processes along the hillslopes and were not recommended on shallow, rocky grounds (PILLWEIN 1843, see also MATHIEU 1998). Furthermore, plough marks created rills, which, depending on their extent and orientation relative to the hillslope, could accelerate surface runoff and, thus, runoff concentration (NIEHOFF 2001, WEILER 2016). The barrenness of mostly dry and sandy soils required a lot of fertilisers to maintain the cultivation of crops, whose dissemination was more challenging in this terrain. In this regard, it was common to pile up the manure, wait until it had frozen and to then distribute it in the fields. Of course, cropland in broad valley floors and along low-lying hillslopes was more fertile and easier to cultivate (PILLWEIN 1843). Nevertheless, cereal production in Pinzgau most often was insufficient and relied on grain supplies from other regions of Salzburg or from neighbouring countries for most of the time (PILLWEIN 1843, DÜRLINGER 1866, MADER 2000).

Overall, it is expected that the agricultural exploitation as "Egarten" somehow reduced the adverse effects on runoff formation, which is usually enhanced by conventional cropland management. However, as a long-time consequence of deforestation, amplified by the conversion of mountainous soils into intensely grazed pastures and cropland, contemporary authors state that mass movements in the 19th century, such as mudslides and landslides, were quite frequent (cf. PILLWEIN 1843, DÜRLINGER 1866), leading to a degradation and reduction of cultivable soils in higher altitudes and causing an abandonment of agricultural farmsteads and fields (DÜRLINGER 1866). Thus, it is assumed that in the case of Pinzgau the effect of cropland on floods was shaped primarily by the vulnerability of soils to e.g. ploughing, siltation, desiccation and avulsion and less by the actual vegetation cover. This vulnerability resulted from high yearly precipitation amounts, predominant regional soil types as well as high slope lengths and gradients (cf. LANDESAMT FÜR UMWELT, NATURSCHUTZ UND GEOLOGIE MECKLENBURG-VORPOMMERN 2002)

6.3.5 WETLANDS

In the mid-19th century, considerable shares of the valley floors along the Salzach valley were covered by swamps, inhibiting the exploitation of land by other land uses (PILLWEIN 1843). Hence, no efforts nor financial resources were spared to drain the valley plains of Pinzgau (MADER 2000). Thus, in 1866 already 18 drainage channels with a total length of at least 8 hours were established in the region (DÜRLINGER 1866). Of course, these saturated soils and their drainage most likely significantly altered the characteristics of floods in this region. Therefore, the following section provides an overview and estimation on how these areas and their drainage might have affected floods.

In general, wetlands are known to potentially affect the timing, volume and duration of floods as well as the peak flows. However, the term "wetland" includes many different land types (e.g. wet woodlands, reedbeds, peat bogs, fens etc.), each of which may have a different hydrological function, which is primarily defined by their landscape location, soil characteristics, topography, soil moisture and management. Depending on these conditions, wetlands may not only reduce but also enhance flooding (ACREMAN AND HOLDEN 2013). In this context, BULLOCK AND ACREMAN (2003) conducted a literature review assessing the findings of 169 wetland studies worldwide dating back to the period 1930-2002. Despite a majority of studies (82%) suggesting that wetlands reduced and/or delayed flooding, they found that headwater wetlands actually behave differently. In this regard, 41% of all studies on headwater wetlands (mostly from Europe) indicated that these wetlands increased flood peaks. It was shown that 55% of statements about flood event volumes and 62% of statements about wet period flows found that headwater wetlands increased the immediate response of rivers to rainfall, generating higher flood volumes, even without increasing the flood peak. These effects were explained by mostly saturated soils in headwater wetlands, conveying rainfall more rapidly to the river. Similarly KIRNBAUER et al. (2008), who investigated wetland areas along a headwater stream (Löhnersbach) in the Saalach catchment, highlighted the high runoff contributions of permanently saturated soils in direct proximity to running waters, transmitting large amounts of precipitation directly to the water body. Furthermore, for advective precipitation events, it was shown that some of the wetlands responded not only with immediate surface runoff, but also produced a second, delayed runoff peak of considerable duration and volume after precipitation had ceased. This second runoff peak was explained by subsurface flow processes deriving from groundwater. However, the authors emphasized on the different runoff reactions that individual wetlands exert. Thus, wetlands on sloping, shallow soils produced more direct runoff responses than those on deep and vegetated soils of flat valley planes. At large, the authors confirmed that runoff formation on wetlands is the dominant factor for regional flow and relevant for the entire catchment of Löhnersbach, irrespective of the antecedent soil moisture conditions or the magnitude of events. However, it should be noted that these wetlands constitute only 4% of the total catchment. In regions with higher relative shares of saturated areas, this effect may be even more pronounced.

In this regard, high infiltration rates and storage capacities for precipitation in wetlands are only to be achieved if the water table is below the surface (HOLDEN AND BURT 2002). Hence, flood reduction in headwater wetlands relies on a sufficiently low water level, providing enough capacity and responsiveness for rapid water storage. However, wetlands that are close to saturation for most part of the year rarely attenuate flood flows, but rather contribute to storm runoff and flooding by rapidly generating saturation-excess overland flow (PRICE 1992, ACREMAN AND HOLDEN 2013, cf. BRONSTERT et al. 2002). And even if wetlands normally reduce flood peaks during most part of the year, they may actually increase them during wet winter months, when they are fully saturated (BURT 1995). Under extreme circumstances, the whole basin may be saturated and flood magnitude is controlled primarily by rainfall. These catchment most likely form high flood peaks (ACREMAN AND HOLDEN 2013).

Likewise, more than one third of wetlands in the Salzach valley consisted of waterlogged swamps (KOCH-STERNFELD 1811), which were supplied by a highly raised groundwater table, rather frequent river floods and precipitation (cf. ACREMAN AND HOLDEN 2013). These wetlands were at least annually mowed and used for litter (PILLWEIN 1843), further reducing potential evapotranspiration and water loss. Taking into account the aforementioned findings on the hydrological effect of saturated wetlands, it is assumed that flood peaks and volumes were increased due to extensive areas of saturated wetland soils adjacent to the Salzach River. In the Saalach catchment, in contrast, major wetlands were restricted to comparatively small areas between Maishofen, Saalfelden and Maria Alm. Due to lacking historic information about the characteristics of these wetlands, their potential effect cannot be estimated.

At the beginning of the 19^{th} century, first drainage channels and ditches were constructed (MADER 2000, WIESBAUER AND DOPSCH 2019). The effect of drainages on floods, however, can be complex. Thus, on the one hand, they generally reduce soil wetness and lower the groundwater table, thereby increasing soil storage capacities and lag times while reducing flood peaks. On the other hand, they might accelerate runoff reactions and increase peak flows (ROBINSON 1990, HOLDEN et al. 2004, PATTISON AND LANE 2011, ACREMAN AND HOLDEN 2013, KADYKALO AND FINDLAY 2016). Accordingly, the net effect of drainages is difficult to measure. Their actual impact depends on a catchment's topography (slope and local vegetation) and the respective location of drainages (ACREMAN AND HOLDEN 2013) and varies with the source of soil wetness (groundwater vs. waterlogging) as well as with the respective soil types and drainage types (surface or subsurface drainage; ROBINSON 1990, WEILER 2016). In this regard, ROBINSON (1990) showed that drainage on highly permeable soils and/or by open ditches is more likely to intensify the runoff situation than drainage on (clayey) soils of low permeability and/or by subsurface drainages. However, the author states that in regions, whose water table had been near to the surface prior to the drainage, this measure will most likely result in its lowering, providing new water storage capacities during flood events and thereby reducing floods. Thus, it is assumed that intense drainage along the Salzach valley led to an amelioration of the flood situation and a reduction in flood risk.

6.3.6 WATER BODIES

Over centuries, rivers and streams in Pinzgau have been adjusted to human requirements. Long before the first documented river straightening in the early 16^{th} century, running waters were locally regulated e.g. for flood protection (levee construction, river bank protection measures) (MADER 2000), energy demands (rerouting, water abstraction) (HOHENSINNER et al. 2021b) and transportation (logging dams, river bank protection measures, bed load excavations) (WIESBAUER AND DOPSCH 2019). In the late 18^{th} and early 19^{th} century, however, engineers recognized the need for a more systematic approach to tackle the hydraulic and hydrological challenges of flood protection and land reclamation. Since then, extensive measures were implemented, which included river straightening and narrowing, river bed blastings, bed load excavations, bank protection, levee construction and wetland drainage (cf. chapter 2.4). The total area of rivers and streams got truncated by approximately 4km², which is equivalent to a loss more than 22% of the former area. Finally, the newly reclaimed land on the valley floors had become available for more intense land uses (MADER 2000). The extensive, unexploitable wetland areas adjacent to the rivers had become agriculturally exploitable grasslands. Likewise, barely profitable croplands in the river corridors were converted to meadows and pastures. Settlements extended into the newly flood-protected river corridors (cf. chapter 3.1 and 3.2). These interventions affected the flood regime of adjacent rivers in manifold ways.

On the one hand, altered LC/LUs on the floodplain led to changes in infiltration capacities and surface runoff. In this regard, it is assumed that increased infiltration capacities and saturation thresholds on drained swamps (cf. ROBINSON 1990) as well as increased water retention on grasslands compared to cropland (cf. WAGNER et al. 2009) were, to some extent, counteracted by increasing soil sealing (e.g. from formerly unpaved streets and squares to paved ones today) and growth of settlement areas (cf. BRONSTERT et al. 2001). However, as conversions of former wetlands and croplands to grasslands cover by far the largest areas in fluvial corridors along the Salzach and Saalach River (overall 107km²), it is believed that increased water retention on these more unsaturated, constantely and densely vegetated areas is more important for flood attenuation than the counteracting effect of increased settlement areas (overall 14km²). Another important aspect to consider is altered surface roughness by changes in riparian vegetation, which may significantly affect flood conveyance and attenuation (e.g. ANDERSON et al. 2006, THOMAS AND NISBET 2007, KISS et al. 2019). In this regard, wooded floodplains are considered to most effectively slow down flood waves, thereby retarding and reducing flood peaks further downstream, while lower vegetation, such as grasslands only play a negligible role in flood retardation (cf. ANDERSON et al. 2006, THOMAS AND NISBET 2007, O'CONNELL 2008). Along river corridors in the upper Salzach catchment the amount of alluvial forests has not changed since 1830 (now, as then about 16km²). However, considerable amounts of sparsely wooded land have been lost (about 9km² or 60% of the former area), so that today, floodplains along the Salzach and Saalach River are largely covered by grassy vegetation. Although being characterised by less dense vegetation coverage and, hence, lower surface roughness than forests, it was shown that sparsely wooded land may significantly slow down, retain and, thus, reduce flood waves, while the effect of grasslands on flood wave deceleration is small, causing comparatively more intense and flashier flood events (O'CONNELL 2008). Thus, related transformations of LC/LU along river corridors in the upper Salzach catchment may have similar effects. In the headwater sections, however, forest growth may have led to increased water retention and associated decreases in the flashiness of flood flows (cf. chapter 6.3.8).

On the other hand, the aforementioned river regulation and flood protection measures (e.g. straight, narrowed and incised channels accompanied by levees) led to a constriction of the former runoff area and a decoupeling of the river from its former floodplain area (WIESBAUER AND DOPSCH 2019). The area available for water storage of 300-year floods was significantly reduced by 16km², which is equivalent to a loss of 9% of its former area (cf. chapter 5.2). It should be kept in mind, however, that most flood protection measures are designed for 100-year floods, so that 300-year floods overrun most levees and dikes designed for 100-year events. The actual truncation of 100-year flood zones may, thus, be even more severe. In combination, river training and losses in flood retention areas led to an acceleration of flood runoff (flood conveyance) and potential increases in flood peaks in downstream regions (cf. BRIERLEY AND FRYIRS 2005, HOHENSINNER et al. 2018, WIESBAUER AND DOPSCH 2019). This problem was even more pronounced, as – a few decades ago – still a number of villages had not been sufficiently protected against floods (i.e. against 100-year events). For instance, flood defense measures in Mittersill only allowed protection from 20-year floods. Hence, the village was frequently flooded by greater events. After several severe floods in 2002, 2005 and 2013, a new paradigm in river engeneering was finally put into force. More than fifteen kilometres of the upper Salzach River channel got widened up by between 10 to 70m in the years 2001-2020. Whereever possible, i.e. along reaches with sufficient space available, additional retention areas were provided. Moreover, existing flood protection infrastructure got renewed, modernised or enhanced. Thus, villages like Mittersill, which were not yet provided with sufficient flood protection are now safe from floods up to 100-year recurrence intervals (WIESBAUER AND DOPSCH 2019).

Additionally to these interventions, a number of run-of-river plants and storage power plants with large reservoirs have been built since the early to mid-20th century in the region (cf. PROVINCIAL GOVERNMENT OF SALZBURG 2016c, ÖBB-INFRASTRUKTUR AG 2019, VERBUND HYDRO POWER AG 2013). For instance, the two largest of the four reservoirs of the Glockner-Kaprun group - Moserboden and Wasserfallboden in the Kapruner Ache catchment - comprise a storage volume of 84.9 million m³ and 81.2 million m³, respectively (VERBUND HYDRO POWER AG 2013), whereas the storage volume of the reservoirs in the Stubache catchment amounts up to 55 million m³ (Tauernmoossee) and 15.7 million m³ (Weißsee) (ÖBB-INFRASTRUKTUR AG 2019). Among other things (e.g. formation of glacier lakes), the construction of these storage power plants contributed to the considerable augmentation in area of standing water bodies, which increased from formerly approximately 8km² to about 14km² in 2016, corresponding to an increase of 80.5% of the former area. These reservoirs provide important storage capacities for flood attenuation in the region. For instance, LEBIEDZINSKI et al. 2020 showed the four reservoirs of the Glockner-Kaprun group reduced the flood peaks of maximum annual floods (in the period 2000-2015) on average by 78% at Kaprun (Kapruner Ache) any by almost 19% at Bruck (Salzach River). It was demonstrated that the mean annual available storage volumes are generally highest in spring and early summer (>125 million m³), but gradually decreasing thereafter with lowest storage capacities in September (about 35 million m³). Nevertheless, even the highest five day flood volume in August 2014, which was close to a 10-year flood (28.8 million m³) could be retained. Despite the smaller storage volume of the Stubache reservoirs, it is assumed that they play a similarly important role in attenuating smaller floods. The importance of reservoirs and other surface water bodies for flood retention of smaller floods is also highlighted by VERBUNT et al. 2005 and SALAZAR et al. 2012. However, the retention of larger floods may be limited by restricted storage capacities of reservoirs (VERBUNT et al. 2005). Thus, the potential flood reduction of large floods by small surface water bodies might be nearly zero (SALAZAR et al. 2012). According to these findings, it can be expected that the operation of storage power plants has led to an important reduction in small floods on a regional perspective.

6.3.7 MEADOWS AND PASTURES

As mentioned earlier, livestock farming and cattle breeding were and still are the main source of income for farmers in Pinzgau (DÜRLINGER 1866, cf. PILLWEIN 1843, PROVINCIAL GOVERNMENT OF SALZBURG 2016b). Then, as now, animal husbandry focused primarily on cattle and sheep and, to a lesser degree, goats, horses and pigs were kept, too (DÜRLINGER 1866, PROVINCIAL GOVERNMENT OF SALZBURG 2016b). Every year in the month of May, a ceremonial driving, bringing up livestock from the valleys to the mountain pastures, began. For the first few weeks, grasslands at lower elevations (so called "Frühalpen" or "Voralpen") were frequented until temperatures got warm enough to head for pastures in the High Alps (PILLWEIN 1843). In order to tap their full potential, big herds were introduced, intensely grazing these grasslands (KOLLER 1975). After several months, livestock was driven back down to their farmsteads in late summer to early autumn. However, mountain grasslands were not only used for grazing. They were also rather intensely exploited for hay harvest. In this regard, PILLWEIN (1843) reports on the techniques applied for mowing in steep terrain. He refers to farmers securing their steps by studded footwear or using ropes to mow even the most fathomless spots.

In total, the area of grasslands in Pinzgau amounted to approximately 1175km² in 1830. Thereof, approximately 193km² were classified as meadows, 232km² as common pasture and about 749km² as mountain pasture (without consideration of areas in Tyrol and the districts of Dienten and Lend) (DÜRLINGER 1866). Hence, the vast majority of areas (981km²) had been grazed. The remaining areas were not necessarily unexploited grassland, but rather might have been used for hay harvest (e.g. on wet meadows in Pinzgau, cf. PILLWEIN 1843). Today, Alpine pastures and mountain meadows still represent the most common grasslands in Pinzgau (397km²). However, compared to their former extent, today's mountain pastures have declined by almost 50%. By far, most of the meadows (195km²) in Pinzgau are now intensely used and mowed for several times over the year. In contrast, meadows being mowed only once in a year amount to only 4km². Pasture land, which formerly covered extensive areas, now only amounts to 60km². The remaining areas consist of disused grassland (55km²) and litter meadows (1,8km²) (PROVINCIAL GOVERNMENT OF SALZBURG 2016b). It should be noted, that the sum of grassland areas given by the latter publications differs from the total area of grasslands found in this work. Moreover, differing historical and present categorisations of grassland and land use types might impede reliable comparisons (PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Nevertheless, these values are used to give an impression of historic and present management practices.

Meadows and pastures consist of a variety of different grasses and herbs. Thus, on account of the respective soil conditions (water and nutrient supply, substrate), their LAI, soil coverage and root depth may vary strongly, leading to a high heterogeneity in hydrological responses among individual grasslands (BRONSTERT et al. 2001). In this regard, KIRNBAUER et al. (2008) summarized LAI values and soil coverage ratios for meadows and pastures found by previous studies in a sub-catchment of the Saalach River (at approximately 1900-900m a.s.l.). Accordingly, the soil coverage ratios attain values between 0.8 and 0.95 for different types of grassland, whereas the LAI varies seasonally and attains values between 1.5m²/m² in winter and up to 4m²/m² in summer. For grasslands at lower elevations, BRONSTERT et al. (2001) compiled literature stating values between 1.6m²/m² and 12.9m²/m². The resulting potential maximum precipitation storage by interception is stated in LEITINGER et al. (2010) and NIEHOFF (2001), who summarized values from literature ranging between 1mm and 3mm. With the exception of sand rush communities showing significantly shorter root depths (0.25m), average root depths for different types of grasslands range between 0.5m and 1.2m (ELLENBERG 1996). These characteristics result in surface runoff coefficients between 0.22 on gravelly, sandy soils and 0.76 on clayey and loamy soils or soils with impermeable or saturated layers (WAGNER et al. 2009). Compared to other land uses (e.g. bare soils and coniferous forests), these values represent intermediate values (cf. BRONSTERT et al. 2001, KIRNBAUER et al. 2008, WAGNER et al. 2009). Likewise, in terms of water retention, grasslands attain moderate values ranging between the ones of agricultural plots and forests (cf. FOHRER et al. 2001).

Their actual effect on hydrology is shaped primarily by the management practices applied. In this regard, pastures generally show higher surface runoff coefficients than meadows (WAGNER et al. 2009). However, depending on the intensity of use (e.g. grazing, single or multiple mowing) their impact on flooding may strongly vary (cf. LEITINGER et al. 2010). In this regard, grazing may lead to trampling damages and soil compaction, thereby reducing the infiltration capacity of soils and increasing surface runoff (cf. NIEHOFF 2001, PATT et al. 2011). Thus, LEITINGER et al. (2010) analysed the seasonal variability of soil physical and hydraulic properties as well as of surface runoff on abandoned areas (vegetated by graminoids, herbs and dwarf shrubs) and pastures in an alpine catchment in Tyrol. They found very low surface runoff coefficients (up to a maximum of 0.03) on abandoned areas throughout the year. In contrast, pastures showed strong seasonal variations of surface runoff coefficients. In autumn after the end of the grazing season, maximum runoff coefficients of 0.25 were found on pastures, which were caused by cattle trampling and associated soil compaction. Similar observations and conclusions are also stated in MAYERHOFER et al. (2017) for mountain pastures in the Austrian Alps. To that effect, LEITINGER et al. 2010 showed that cattle trampling significantly increased the soil's dry bulk density in the uppermost soil layer, thereby compacting macropores and reducing infiltration rates by more than 60%. Nevertheless, bulk density was found to recover during the winter season, which was attributed to freezing-and-thawing cycles and bioturbation processes, which, again, decreased soil compaction. The authors point out that increased surface runoff coefficients in late summer and autumn, when glacier melt and precipitation sums are highest, may lead to an increased flood risk in mountainous regions being drained by torrents. In this regard, the date and duration of grazing as well as livestock densities are decisive variables affecting surface runoff.

Accordingly, compared to the present situation, the intense use of meadows and mountain pastures in former days (cf. PILLWEIN 1843, KOLLER 1975) may have led to higher surface runoff contributing to flood events. Additionally to the above mentioned decline in mountain pastures of about 50% between 1866 and 2010 (cf. DÜRLINGER 1866, PROVINCIAL GOVERNMENT OF SALZBURG 2016b), many of these former grasslands were succeeded by woody vegetation. Thus, as shown in chapter 5.1, about 30% of the former meadows and pastures are now covered by sparsely wooded land or forest. In general, woody vegetation is attributed to the highest water retention capacities of LC/LUs and is often associated to attenuate floods (cf. chapter 6.3.8). To that effect, the replacement of former mountain meadows and pastures by wooded land ultimately may have reduced surface runoff and flood risk. This assumption is supported by findings of VERBUNT et al. (2005), who explored the hydrological effects of converting Alpine grasslands into forests in the Swiss Alps. After conversion, their hydrological simulations showed a clear reduction of soil moisture, surface and subsurface runoff due to increased evapotranspiration rates and higher interception losses. This effect was especially pronounced during the growing season (June to August) and at the valley bottom, whereas in higher altitudes, the decline in runoff was found to depend more on soil thickness, associated root depths and, hence, storage capacities. Similar results were also found by BIRD et al. (2003, cited after NISBET AND THOMAS 2006), who found up to 60 times higher infiltration rates under young native woodland compared to grazed pasture. Under compacted pasture, infiltration rates were readily exceeded during storm events, leading to rapid runoff and potentially higher flood flows. However, even though pastures may often show higher surface runoff coefficients than meadows (WAGNER et al. 2009), more intensely used grasslands on the valley floors (i.e. meadows being mowed several times a year), today, may be prone to soil compaction due to operations with heavy machinery. On compacted grasslands, infiltration rates would be similarly reduced, causing increased surface runoff and, hence, runoff contributions during flood events (cf. BRONSTERT et al. 2001). However, within the scope of this work, the extent of grasslands subject to such risks could not be estimated.

6.3.8 FORESTS

Deforestation has a long history in Salzburg, and more specifically, in Pinzgau. After forests at lower elevations had been cleared to gain land for settlements, livestock farming and cropland, continuous population growth and increasing agricultural demands led to further deforestation in progressively higher altitudes between the late 11th century and the mid-14th century. Henceforth, forests in more mountainous regions up to the timber line were cleared and transformed to numerous Alpine farmsteads ("Schwaighöfe") and mountain pastures (cf. DÜRLINGER 1866, KOLLER 1975). Additionally, important, resource-intensive industries developed from the 13th century onwards, namely salt mining in Hallein and Reichenhall (Bavaria), gold and silver mining in Gastein and Rauris and ore mining in many regions of Pinzgau. These industries required large amounts of wood, e.g. for salt refinery, gallery construction as well as for charring for smelt plants. Hence, the bulk of forests in the upper Salzach catchment (from Krimml to Lend) had been assigned to salt mining in Hallein and ore mining in Gastein and Rauris, whereas most forests in the Saalach catchment were allocated to the Bavarian saline of Reichenhall and regional mines (KOLLER 1975).
Forests along the Saalach River and its tributaries were the main wood supplier for the Bavarian salt production over many centuries (DÜRLINGER 1866). In the early 19th century, 870km² out of a total of 1060km² of land allocated to the saline of Reichenhall were situated in Pinzgau, of which 400km² were exploitable forests. The forests consisted, originally, of spruces, firs and important amounts of deciduous trees. The latter, however, were unwanted and, hence, had to be felled and replaced by coniferous trees, leading to a gradual change in species composition over time. Forests were harvested by clearing extensive areas at a time (so called "Großschlagwirtschaft"), felling trees from lower elevations to higher elevations and leaving trunks of a maximum height of 30cm. Up to the late 19th to early 20th century, the required amounts of wood were drifted down the streams and rivers of the Saalach catchment. For this purpose, trunks assigned to the saline Reichenhall were restricted to a maximum length of 87cm, whereas in the Unkenbach and the Saalach River, logs for other purposes were allowed to be up to 2.7m long. However, the discharges in many streams were insufficient to transport the numerous trunks. Therefore, logging dams were constructed allowing to retain sufficient amounts of water. This practice led to frequent artificial floods, which were reinforced by the momentum of logs. Ultimately, river banks got heavily eroded despite the fact that most banks of drifting streams and rivers had been stabilized by provisional wooden bank protection measures. Overall, on a yearly basis, between 30 000 Klafter and 40 000 Klafter (i.e. between approximately 55 000m and 75 000m, depending on Bavarian or Austrian standards) of logs were drifted to Reichenhall. Timber, that could not be brought by drifting waters were charred on site and brought to nearby mines (KOLLER 1975). As to the state of forests after century-long exploitation in the Saalach catchment, related publications state conflicting information. For instance, KOLLER (1975) cites a historic source from the mid-17th century, concluding that still enough exploitable forests existed. However, TREML et al. (1995, cited in WIESBAUER AND DOPSCH 2019) state that, at the beginning of the 17th century, stocks of wood had already been almost depleted, which is why a new

sole pipeline between the saline Reichenhall and Traunstein, a region still disposing of sufficient wood, was constructed. At the latest from the late 18th century onwards, the state of forests and their rejuvenation got increasingly worse. It was not until many decades later, after the development of rail traffic in 1860, that forests assigned to the saline of Reichenhall could be substituted by stone coal and, hence, could be preserved (KOLLER 1975).
Similar management practices and exploitation of forests could also be found along the Salzach valley. The forests consisted mainly of spruces, firs and larches, locally also with small stocks of beeches. However, being an unwanted tree species, the latter got superseded by coniferous trees over time. Over centuries, forests were harvested by clearing extensive areas at a time, leaving tree trunks of a maximum height of 30cm. Many of the clear-cut areas had been subsequently burned in order to both, destroy the roots of deciduous trees and to set up the soil for cereal cultivation for one or two years. Besides, other activities intervening with the natural rejuvenation of forests, such as mountain pastures on formerly forested land or forest pastures were common practice in former days. In order to preserve the forests of Pinzgau, these procedures got prohibited or restrained in the late 16th century. Still, as described further below, these regulations were barely reckognized. Following these forest management practices, in 1851, 88% of the total tree population in Pinzgau were spruces, being found up to elevations of 1500-1800 m a.s.l., which got harvested after 80-140 years. However, even in this comparatively late period of historic forestry, the rejuvenation of spruce stands in mountainous areas was impeded by pasture servitudes, inhibiting the emergence of young forests. Thus, owing to natural hazards and grazing, large clear-cut surfaces facing south most often remained treeless for 15 to 20 years. In contrast, rejuvenation on large clear-cut areas with northern aspect was abundant, so that mountain pastures had to be cleared every year. Larches represented 6% of the tree population in the mid-19th century and were found in altitudes between 900m a.s.l. and 1800m a.s.l., whereas beeches still represented 2%, grew up to elevations of 1200m and, thus, were restricted to the lowlands and Unterpinzgau. Pines, which formerly covered larger areas were now only sporadically found up to elevations of 2400m a.s.l. (KOLLER 1975). More or less all forests along the Salzach valley in Pinzgau were assigned to supply the saline of Hallein and the mines in Rauris and Gastein. Hence, considerable areas of forests along all major tributaries were cleared each year for their provision. Thus, all High Tauern tributaries and numerous streams from the Greywacke zone (e.g. Trattenbach, Nadernachbach, Mühlbach and Stuhlfeldnerbach) served as drifting waters. Along many of them (e.g. along the Obersulzbach, Hollersbach, Trattenbach, Mühlbach and Hüttwinklache), logging dams were constructed to allow drifting of logs of up to 1.20m length. Only if logs were not to be brought by drifting waters, they had to be charred on site. Similarly to the adverse effects of drifting seen in the Saalach catchment, this practice lead to massive bank erosion, which is why river banks along drifting waters had imperatively to be protected in order to minimise damages. However, notwithstanding all negative impacts of drifting, it was the standard practice for wood transportation until the late 19th and early 20th century. Without considering wood demands for mining purposes or any other uses, yearly wood requirements for salt production in Hallein amounted to 30 000 Klafter to 40 000 Klafter in the period between the 16th and early 19th century. Hence, as early as in the second half of the 16th century, wood was becoming a scarce resource in some places, e.g. along the Mühlbach and the Trattenbach. These shortages were aggravated by larger windthrows, which are historically documented. Thus, having witnessed a number of devastating natural desasters, which were attributed to deforestation, residents feared further landslides, mudslides and floods, and confronted the planned complete clearance of local forests. Approximately at the same time, in the late 16th and late 17th century, forests along the Rauriser Ache and the Wolfbach were almost completely depleted, respectively. In line with these developments, forests along the Gasteiner Ache (Pongau) also got depleted by the end of the 16th century, so that, henceforward, ore deriving from there had to be smelted in Lend with char from forests of Pinzgau. For the sovereigns, related concerns about shortages were the main reason for numerous regulations, e.g. of 1237, 1524, 1550, 1555, 1563, 1592, 1659, 1713 and 1755, aiming at securing the wood and char supply for all important industries, subjects and provincial towns of Salzburg. However, hardly anyone respected these prescriptions, which is also the reason for the frequent actualisations in forestry law. Every forestry law from 1550 onwards adduced that forests got progressively devastated due to the self-interests of subjects derogating forest growth and

ascertained further losses in the total area of forests on the benefit of meadows and pastures. Accordingly, knowing violations, unauthorised clearances and displacements of the timberline for the benefit of mountain pastures were common practice. In this regard, the archbishop of Salzburg, Wolf Dietrich, reached out to its subjects in 1592, complaining about the pervasive, heavy squandering of wood by unauthorised, improper and careless tree fellings. He states that in many cases, inaccurate felling of one specific tree led to the downthrow of 15-20 others and that forest damages were further aggravated by the careless transportation of tree trunks, injuring surrounding trees, which were then often subject to windthrows. As a result from forest clearances in both directions – uphill and downhill - only a comparatively small stripe of forests remained along many hillslopes. In the subsequent years, up to the early 19th century, poor rejuvenation in higher altitudes, forest damages and natural hazards still limited and reduced the amount of exploitable forests. Thus, in order to reduce fellings, wood saving measures were implemented since the mid-18th century (KOLLER 1975).

In 1866, the total area of forests in Pinzgau amounted to approximately 733km² (DÜRLINGER 1866).

Since then, forested land increased between 1881 and 2010-2013 from formerly 697km² to between 954km² and 1180km² (PROVINCIAL GOVERNMENT OF SALZBURG 2016a and 2016b). Most of these forests are coniferous forests, which are prevalent throughout Pinzgau. However, along some tributary valleys of the Salzach and on large areas of the northern Saalach catchment, mixed forests and scattered stocks of small broad-leaved forests can also be found (data from CORINE LANDCOVER 2018, cf. EUROPEAN ENVIRONMENT AGENCY 2017). In addition to increases in the total area of forests in Pinzgau, forest growth is now twice as high as in the late 19th century and increased from formerly 313 493 solid cubic metres (and 4.5% per hectare and year) to 675 000 solid cubic metres (and to 8.4% per hectare and year). However, it should be noted, that more exact measuring methods in present days may impair comparisons (PROVINCIAL GOVERNMENT OF SALZBURG 2016a). Still, these differences are remarkable and certainly have led to changes in the hydrological response of both catchments. Thus, in the following, an overview of the potential effects of forests on floods is given.

The effect of forests on water yield and floods relies on a number of different factors and their combination. Thus, on the one hand, it is the combined effect of high interception storage capacities, retaining water above-ground as well as of high evapotranspiration rates, which reduce soil moisture, thereby increasing soil water storage capacities. On the other hand, intense root penetration, bioturbation and accumulation of humus build up macropores and preferential pathways, which increase soil permeability, infiltration rates and water storage capacities, thereby reducing surface runoff (cf. HEWLETT 1982, NISBET AND THOMAS 2006, WEILER 2016, BLÖSCHL et al. 2018).

Similarly to any other LC/LU, the water retention capacity of forests may considerably vary depending on e.g. the dominant tree species (deciduous vs. coniferous), their LAI and their root depths (cf. BRONSTERT et al. 2001, NISBET AND THOMAS 2006). In this regard, highest LAI and interception storage capacities are found in evergreen coniferous forests, whereas lowest values are found in seasonally defoliated deciduous forests. Accordingly, the LAI in coniferous forests ranges between 3.8m²/m² and 19.2m²/m² with a maximum interception storage between 3mm and 5mm, whereas the LAI of mixed forests ranges between 2m²/m² and 12m²/m² with a maximum interception storage capacity of 2.5mm to 4.5mm (cf. literature compilation by BRONSTERT et al. 2001). Maximum root depths range between 0.4m and 1.5m in coniferous forests and between 0.7m and 1.5m in mixed and deciduous forests, respectively. The lowest values are obtained by spruces (0.4m to 0.8m) (literature compilation by MÜNCH 1993, cited after BRONSTERT et al. 2001). As can be seen by contrasting these values with values obtained by other LC/LUs (see previous chapters), the aforementioned parameters show maximum values in forests.

This is also the reason why forests are generally attributed to attenuate floods (cf. CALDER AND AYLWARD 2006). In this regard, BROWN et al. (2005) provided a literature review compiling publications on the effects of vegetation change on the water yield. Thus, HIBBERT (1967) as well as BOSCH AND HEWLETT (1982) who reviewed small experimental catchments in temperate zones found that a reduction in forest cover resulted in an increase in water yield, while increasing forest cover led to a decrease in water yield. In this regard, SAHIN AND HALL (1996) confirmed that a 10% reduction in coniferous forest cover resulted in a more pronounced increase in mean annual water yield (+20 to

+25mm), than a similar reduction in deciduous hardwoods (+17 to +19mm) or scrub (+5mm). Although many of these studies focused on the effects of vegetation change over the first five years after treatment, HORNBECK et al (1993) showed, that these effects could be prolonged by controlling regrowth, while uncontrolled regeneration of forest cover rapidly diminished the increased streamflow in 3-10 years.

However, when comparing, for instance, interception storage capacities to precipitation volumes causing floods, it is evident that even maximum values of forests will only negligibly reduce effective precipitation amounts (NIEHOFF 2001, NISBET AND THOMAS 2006). Also on a broader perspective, recent studies have highlighted the limited impact of forests on floods (BESCHTA et al. 2000, BRONSTERT et al. 2001, CALDER AND AYLWARD 2006, KOHL et al. 2008, SALAZAR et al. 2012, ALAOUI et al. 2013, WEILER 2016, BLÖSCHL et al. 2018). In this context, it was shown, that measurable effects of forests were restricted to small catchments and floods with low recurrence intervals, i.e. deforestation was found to increase peak flows of 1 to 5-year floods. For larger floods and larger catchments, however, the effect of deforestation got negligible (cf. BESCHTA et al. 2000, WEILER 2016, BLÖSCHL 2018). For instance, BESCHTA et al. (2000) found that deforestation in small watersheds (60-101ha) in Oregon, USA, increased the peakflows of one-year floods on average by 13-16%, whereas its effect already considerably diminished for 5-year floods whose peak flows were increased on average by 6-9%. For flood events with recurrence intervals above 5 years no significant effect of deforestation could be found. Also in larger basins (62-640km²) no strong evidence confirming that deforestation affected flood peaks was found. Likewise, SALAZAR et al. (2012) found that the potential effect of afforestation on peak flow reduction decreased with increasing event magnitudes. In the Kamp catchment (Austria) forests reduced peak discharges of small floods by up to 30%, while in the Upper Iller catchment (Southern Germany) flood peak reductions of small to medium floods ranged only between 2% and 8%. These lower contributions compared to the Kamp catchment were attributed to shallower soils being underlayn by less permeable bedrock, which generate considerable amounts of subsurface flow (cf. following section). Similar results were also found by BLÖSCHL et al. 2018, who investigated the effect of afforestation of grasslands on peak flow in the Inn catchment. They found, that even a drastic replacement of grasslands by trees (i.e. a conversion of 1000km²) reduced the peak flow of a 100-year flood and a 1000-year floow only by 4.4% and 4.8%, respectively. Thus, the attenuating effect of forests on large floods is comparatively small and does not change much with further increasing flood magnitudes. This is due to the fact that large floods in larger catchments are generally caused by long-lasting rainfall events over wide areas of the river basin. During these precipitation events, runoff is generated by saturation excess in a number of catchments rather than by infiltration excess. Thus, increased infiltration capacities provided by afforestation play a minor role, compared to soil moisture conditions and the height of the groundwater table. In contrast, infiltration capacities are an important factor in situations, where runoff is generated by infiltration excess, e.g. in the course of short and intensive rainfall events, which frequently cause flooding in small catchments and/or on soils of low permeability. Thus, as changes in LC/LUs affect infiltration capacities rather than saturation parameters, the effect of forest changes (and of LC/LU in general) on floods is strongest during short, intensive storm events in small catchments causing small floods and decreases with more long-lasting precipitation events, increasing flood magnitude and increasing catchment area (BRONSTERT et al. 2001, BLÖSCHL et al. 2018).

In addition to these general limitations, the hydrological effect of changes in forest cover also depends on other factors, such as on the relative catchment area affected by afforestation or deforestation, management practices applied, as well as on climate and altitude (cf. BRONSTERT et al. 2001, NISBET AND THOMAS 2006). Thus, in most small catchments forest cover has to be reduced by more than 20% to result in a measurable change in streamflow. Even so, water yield changes are strongly affected by climate (BOSCH AND HEWLETT 1982, STEDNICK 1996) and soils (HEWLETT 1982, VERBUNT et al. 2005, WEILER 2016), with most sensitive responses on runoff components being found in high rainfall areas (BOSCH AND HEWLETT 1982) and valley plains, as opposed to mountain regions. In this regard, it was shown that simulated afforestation of pastures reduced total runoff by 287mm at the valley bottom and by only 174mm at 2200m a.s.l. This also indicates that differences in runoff formation between pastures and forests decrease with increasing altitude (VERBUNT et al. 2005). On the one hand, this is due to longer periods of soil saturation due to extended periods of snowmelt and lower evapotranspiration in colder mountain climates (>2000m a.s.l.). Therefore, the potential water retention by vegetation in mountain regions will initiate later in the year, as compared to lowland regions. Thus, any significant differences in runoff generation between forests and pastures are detectable only during several months between early summer and autumn, when both vegetation types might contribute to flood attenuation. However, during these months, clear differences in runoff generation were be observed, i.e. lower runoff formation on wooded soils (VERBUNT et al. 2005). On the other hand, comparatively low storage capacities in mountainous regions with shallow soils and coarse substrate limit the root growth and potential water retention of any plants. Hence, rapid subsurface runoff formation may occur irrespective of the type of vegetation (BRONSTERT et al. 2001, VERBUNT et al. 2005, AlAOUI et al. 2013). In contrast, in valley plains with deeper soils, conversions from pasture land to forest significantly reduced subsurface flow. Regarding overland flow, afforestation of pastures led to significant decreases by interception and change rates remained constant over all altitudinal zones. (VERBUNT et al. 2005).

In many cases, forest management may have a stronger impact on runoff formation than the presence or absence of forests themselves (cf. CALDER 1992, NISBET AND THOMAS 2006, WEILER 2016, EUROPEAN UNION 2018). In the past, such operations included e.g. the clearance of extensive areas at a time ("Großschlagwirtschaft"), the gradual replacement of deciduous trees by coniferous trees, widespread improper felling and transportation of individual trees, burning of cleared areas and subsequent usage as cropland, forest pastures and the abstraction of forest litter for animal husbandry (KOLLER 1975). Each of these practices is attributed to rather increase runoff formation than to be neutral or to reduce it. For instance, leaf litter (needles) in coniferous forests and forest fires may induce hydrophobic reactions on soils, thereby increasing surface runoff and erosional processes (WEILER 2016). Other activities, such as logging and clearing or grazing may result in soil compaction, reduced infiltration capacities and retarded rejuvenation of forests, which all may increase surface runoff formation (cf. CALDER 1992, NISBET AND THOMAS 2006, LEITINGER et al. 2010). By using former forest stands as cropland or by removing forest litter for animal husbandry, soils may become unprotected against the erosive forces of raindrops, which may lead to a clogging of surface micropores and macropores, thereby generating an impermeable crust, which, again, reduces infiltration and increases surface runoff (cf. CALDER 1992, ESHLEMAN 2004). Nowadays, forest management practices, such as the employment of heavy machinery, the construction of forest roads and drainages are known to potentially increase surface runoff due to soil compaction, surface sealing and faster runoff concentration (cf. CALDER 1992, BRONSTERT et al. 2001, WEILER 2016). However, due to restrictions of this work, no detailed information about these parameters can be given. Nevertheless, the following statements can be made: Today, a considerable share of the total forest area in Pinzgau serves as protection forests against natural hazards. For instance, from all economically exploitable forests managed by Austrian Federal Forests in Pinzgau (i.e. 344km² out of a total of 720km²), 33% are assigned as protection forests. The vast majority of these areas are excluded from economic use and must be maintained with special care (ÖBF 2016). While most forests in Pinzgau are still harvested by clear cutting of areas >500m² (BFW 2021), logging and wood removal are now often conducted by cable yarding, i.e. with minimal encroachment of forest soils (ÖBF 2016). Similarly, other historical practices known to negatively affect the water retention capacity of forest, such as burning of cleared areas, lost their legitimacy. And in contrast to past situations, associated legal prohibitions are now acknowledged. Thus, the human pressure on forests has, to some degree, diminished. Similarly, the pressure on other LC/LUs, such as on grasslands has eased. For instance an increasing number of ancient mountain pastures in Austria got abandoned and succeded by forest, which is one of the reasons for the continuous forest growth over the last decades, especially in high altitudes above 1800m a.s.l. (cf. BFW 2011).

Despite the fact that forests may have only a limited impact on floods, especially in mountainous terrain, historic sources about the state of forests, their management and associated and documented consequences of deforestation (e.g. mudslides, landslides and floods) suggest that forest clearances did have a significant impact in the upper Salzach catchment, which was not restricted to water retention. Forests did also stabilize the soils on steep slopes and protected them against temperature and moisture extremes, which reduced erosion and landslides (cf. JEWITT 2005, JAMES AND LECCE 2013, FRYIRS

AND BRIERLEY 2013). Thus, the removal of forests and their conversion to pastures might not only have caused increases in surface runoff, total streamflow, peak flow and flood risk in general (cf. FOHRER et al. 2001, ESHLEMAN 2004) but might also – and most importantly - have amplified erosional processes (cf. BORK et al. 1998, DOTTERWEICH AND DREIBRODT 2011). An increasing amount of denuded hillslopes were exposed to elementary physical forces, which enhanced further denudation (cf. DOTTERWEICH 2008) and resulted in increasing amounts of natural hazards in Pinzgau being reported by numerous historic sources. Many of them attributed this rise in mass movements and related detrimental hydrological developments to extensive deforestations in the past (cf. WIESBAUER AND DOPSCH 2019). For instance, KOCH-STERNFELD (1811) states that the paludification of valley plains in Pinzgau was entailed 500 years ago (i.e. in the 14^{th} century) and was reinforced by continuous violent fellings in the tributary valleys of the Salzach River and by improvident use of logging dams. The waterlogged swamps, in turn, most likely reinforced flooding. Thus, beyond its effect on river discharge, deforestation had far-reaching consequences, which all affected the frequency and magnitude of natural desasters in the catchment. Today, forest growth and more sustainable and provident forest management practices most likely have, to some degree, led to a more favourable hydrological situation. Still, new land uses such as ski slopes may locally counteract these developments (KOLLER, 1975, KOHL et al. 2008).

6.3.9 ESTIMATED OVERALL EFFECT

Following the information given in the previous, preliminary chapters about historic and present LC/LUs as well as their management, general statements about the potential effects of changes in LC/LU on runoff behaviour, responding to research question no. 3, can be made. In this context, it is important to highlight that historic LC/LUs did not only affect runoff parameters, but also – and most importantly – erosional processes in regions prone to physico-chemical weathering and, on average, high yearly precipitation amounts (cf. BORK et al. 1998, DOTTERWEICH AND DREIBRODT 2011, JAMES AND LECCE 2013, as well as FRYIRS AND BRIERLEY 2013 elucidating the role of LC/LU change on erosional processes). In combination, this geologic prospensity to disintergration and the rainy climate entailed the pronounced hydrologic sensitivity of the region towards detrimental, historic land management practices. The most fatal of all land management practices was large-scale deforestation along the mountainsides of all major tributary catchments of the Saalach and Salzach River, which not only led to increased (surface) runoff, but also to a loss of vegetative erosion control and, thus, more frequent mass movements. It was the resulting combination of increased tributary discharges and bedloads, which caused the progressive paludification of large areas along the Salzach valley. Thus, amplified erosion along clear-cut hillslopes and resulting higher inputs of debris into the Salzach River caused a gradual aggradation and local superelevation of the river bed and, thus, a phreatic rise, which procured the formation and growth of adjacent waterlogged swamps and increased the flood risk for all communities in direct proximity to the river. By not sufficiently allowing the rejuvenation of forests, e.g. by transforming clear-cut forests into permanent (alpine) meadows and pastures or cropland, these tendencies got further aggravated and historic sources state frequent mass movements, e.g. on hillside croplands. Hence, despite the fact that forests might have actually only a small hydrological impact on regional floods, it is quite apparent that their continuous removal over many centuries along exposed hillsides had started a cause-and-effect chain, which eventually contributed to significant increases in flood discharges and flood risk (cf. chapter 2.4). For the Saalach, in contrast, reliable data about historic floods is missing and, thus, similar conclusions cannot be drawn.

Today, the intensity of land use in high alpine regions has, to a certain degree, diminished. Vast areas of former alpine pastures, i.e. at least 50%, have been abandoned. Many of these formerly intensely grazed grasslands are now succeded by a considerable encroachment of trees and forests into higher altitudes. In addition, former clear-cut forest areas have rejuvenated and are now managed in a more provident manner, which contributes to the considerable forest growth stated in the previous chapters and which limits negative impacts of deforestation on soils. Reconsidering the previously stated hydrological effects of these LC/LUs and their management, it is expected that such extensive replacements now provide generally higher water retention capacities, reduced (surface) runoff and lower stream discharges as well as lower erosion potential compared to historic conditions. In addition water retention capacities in high alpine catchments were further increased by new land uses, i.e. storage power plants, which were introduced in the 20^{th} century. As was shown, reservoirs of storage power plants may considerably reduce flood runoff on a local to regional perspective. In contrast, somehow counteracting this general trend towards increased water retention capacities in high mountain regions, glacier retreat is expected to significantly increase local runoff not only because of glacier melt, but also because it continuously uncovers shallow wasteland soils, which provide only little water retention capacities. Furthermore, it is plausible that the loss and degradation of glaciers buffering precipitation may have led to faster and more pronounced runoff reactions, as compared to the historic situation.

Along valley plains and fluvial corridors, on the other hand, LC/LU changes have been even more pronounced (cf. chapter 5.2). For the purpose of taking maximum economic advantage of the surroundings, large areas had to be transformed. For instance, most river sections of the Saalach and Salzach River had been straightened and narrowed in order to facilitate river bed incision, flood protection and the drainage of valley floors. As a result, the area of rivers and streams had been considerably retrenched from formerly almost 16km² to 12km² today. Following a shorter (thus more inclined) and more narrow flowpath, flow velocities increased. In addition, in the years after implementation, both rivers got progressively decoupled from their floodplain and, thus, not only lost important shares of their former runoff area, but also large areas of potential flood retention zones adjacent to the river. Thus, the constriction and loss of runoff areas as well as of flood retention areas is expected to have caused an acceleration of floodwaters and increases in flood peaks in downstream regions. In addition, the area and degree of surface sealing has considerably increased throughout the valleys of Pinzgau since 1830. From a total of formerly 1.7km², the area of settlement areas located in the HQ_{300} zone increased to 14km² today. Likewise, the area of outlying settlement areas has strongly increased, too. Following the information given in the previous chapters, this growth in sealed surfaces is expected to have led to local increases in surface runoff and, thus, local contributions to floodwaters along river corridors of Pinzgau. In contrast to these flood reinforcing effects of LC/LU change along valley plains, other transformations in LC/LU, such as the conversion of cropland into meadows and pastures are expected to rather have attenuated surface runoff formation and to generally provide higher water retention capacities today. Of course, the actual hydrological impact of such conversions depends on todays management practices applied (e.g. the use or disuse of heavy machinery on meadows) and on the nature of individual soils, which could not be investigated in detail within the scope of this work, but which may also cause strongly divergent runoff responses (e.g. due to soil compaction). Similar but even more pronounced hydrological effects are expected to have arisen from the drainage of extensive, waterlogged swamps along the Salzach valley and their conversion into meadows and pastures. In accordance to literature information stated above, these drainages are estimated to have led to an overall higher water retention capacity and, thus, reduced surface runoff and flood runoff contributions. Taking into account the basic conditions under which historic floods had taken place (e.g. lower water retention capacities in deforested sub-catchments, locally superelevated river banks, high groundwater tables, large saturated swamp areas etc.) as well as numerous historic sources reporting on frequent, severe flood events, it is assumed that, overall, flood magnitude has decreased on the regional scale due to the cessation of detrimental, historic land management, which reinforced erosion processes and runoff formation.

6.4 GENERAL CONSIDERATIONS

Using historic sources and maps requires consideration of potential biases and limitations. In general, historic documentary sources or measured data, e.g. about floods, get progressively scarcer the further one goes back in history. Beyond this issue of often relying on a very limited number of historical sources, historic flood records also tend to be limited to the most severe damaging events, while omitting more frequent floods of lower magnitude. For flood frequency analysis, such biased and incomplete historic flood records are deficient. For the purpose of comparing historic and present extreme flood magnitudes, as it was done in this work, this bias would be rather expedient. Still, it may be an unfeasible task, too. On the one hand, this is due to the descriptive quality of many documentary sources, making any quantification of historic flood discharges impossible. On the other hand, historic flood marks, which would allow a conversion of historic flood water levels to present flood discharges, have become defective due to human alterations in the river system or on the respective buildings (HALL et al. 2014). In the study region, historic flood marks to estimate historic flood discharges were lacking. Thus, an attempt to exemplify historic flood discharges along the Salzach River was done by providing historic flood discharges converted according to the only serviceable historic flood marks along the Salzach River in Burghausen, located at the most downstream end of the catchment. Of course, the historic flood response at Burghausen had been shaped by highly differing boundary conditions of climate, topography, geology, soils and LC/LU and may, thus, proscribe any comparisons with historic flood discharges in the upper Salzach catchment. Still, these historic flood discharges at Burghausen were illustrated in order to give an impression to what extent historic flood magnitudes exceeded those of extreme flood events in the 20th and 21st century (e.g. HQ_{100}). Considering all information given by historic documentary sources about the circumstances under which floods had taken place, it is most plausible that historic flood magnitudes in Pinzgau (upper Salzach catchment), similarly, must have been higher than today (cf. MADER 2000, WINDING AND VOGEL 2003 WIESBAUER AND DOPSCH 2019). Likewise, the cartographic basis of the historic LC/LU map - the Franziscean Cadastre - may feature biases, inaccuracies and inhomogeneities, which need to be considered. Consisting of thousands of map sheets depicting individual parcels of land in all provinces of the Austrian monarchy, a large number of military cartographers was assigned to the mapping procedure. Although being instructed with clear and detailed specifications on how to survey the respective lots of land, the mere number of cartographers and actors involved (FUHRMANN 2007), inevitably, resulted in different levels of accuracy among individual field works and, thus, in inhomogeneities. Still, the overall accuracy of the Franziscean Cadastre was comparatively high, with average errors in length of about 1.3m in 100m mapped distance and 4.9m in 2000m mapped distance (ULBRICH 1961). Primarily being designed as a tool for land taxation, not all areas within a region had to be mapped in an equally detailed manner (ULBRICH 1961, FUHRMANN 2007). A focus was set on the more intensely used valley plains, while high altitude regions at the transition to wasteland were represented in a rather sketchy way, which lacked detail. For instance, although vegetation naturally fades out at the limits of its natural range (FISCHER et al. 2019), the Franziscean Cadastre depicts the transition zone between sparsely wooded land, alpine meadows and wasteland by sharp limits. This delimitation may have artificially expanded or reduced the true size of historic LC/LUs in high alpine regions and, hence, associated changes are to be interpreted with care. In addition to these issues, further inhomogeneities arose from the georeferencing procedure, which frequently led to distortions, overlays and gaps along rivers and streams as well as along borders of cadastral municipalities and map sheets. In order to reduce associated mapping errors to a minimum, supplementary historic maps had to be used, for instance the online version of the Franziscean Cadastre on www.mapire.eu. Still, most often, those sources showed similar distortions, so that e.g. historic river widths and river courses had to be approximated. Overall, the sum of these factors may have led to incorrect results at the local scale. Thus, in order to assess the accuracy of historic LC/LU representations and to estimate the potential error associated with their reconstruction, HOHENSINNER et al. (2021a) compared mapping results of the Jamtal valley (54.3km², Tyrol) based on the Franziscean Cadastre and the Kulturenskelettkarte to mapping results of a separate detail analysis conducted by ATZLER (2021).

In the latter study, the historical land cover was reconstructed over multiple time steps (2015, 1970, 1921, 1870, 1820), using the "regressive-iterative" GIS method (HOHENSINNER et al. 2013), which allows a more robust reconstruction of former LC/LU distributions than reconstructions that solely focus on one specific point in time (e.g. 1830). It was found that the reconstruction of LC/LUs, which was based only on the Franziscean Cadastre and the Kulturenskelettkarte tends to underestimate the area of most LC/LU types. For instance, the historic area of settlements and cropland were underestimated by 15% and 10.4% (percentage of deviation in relation to the detailed GIS analysis), respectively. Similarly, the area of running waters was identified to be 10.5% smaller than in the detail analysis, whereas grassland and wasteland were found to be underestimated by 6.5% and 1.9%, respectively. The low potential error of the latter is related to the integration of present wasteland areas from 2016, which most probably already had existed in 1830, thereby enhancing the accuracy of representation in the historic dataset. Thus, the true surface area of these LC/LU types, actually, may have been correspondingly larger than represented in the historic map and values presented in chapters 5.1 and 5.2 would be higher. This also affects the rates of change of the respective LC/LU types between 1830 and 2016 (cf. Figures 21 and 22), e.g. lower increases in settlement areas and grassland and even higher reductions in croplands and running waters. In contrast, the historic area of forests was shown to be overestimated by 4%. Accordingly, forests in 1830 may have been even smaller than was found in the present work and forest growth up to the year 2016 may be correspondingly higher. The most error-prone of all LC/LU types was sparsely wooded land, which was overestimated by 48%. Representing an intermediate state between grassland interspersed with trees and dense forests, this high potential error is due to the not necessarily well-defined, consistent and congruent attribution of sparsely wooded land in both, the historic mapping as well as present satellite data. The area values of this LC/LU type shown in chapters 5.1 and 5.2, may, thus, be much too high. Correspondingly, associated decreases of historic sparsely wooded land up to the year 2016 would, in fact, be less pronounced or inexistent (HOHENSINNER et al. 2021a).

Beyond these shortcomings in the historic data, the present LC/LU dataset of 2016 also entails potential pitfalls, which need consideration. It consists of a patchwork of different datasets, which were to be brought together because the data basis – the LISA land cover map of 2016 – either did not reproduce a number of LC/LU types or represented them fragmentarily, lacking sufficient accuracy and detail. This is the case, e.g. for meadows and forests, whose classification and representation was found to be very inaccurate. Likewise, the classification of settlement areas, in many cases, was defective. Gravel banks along larger rivers, for instance, were erroneously accounted to settlement areas. Although many of these areas have been eliminated by a subsequent insertion and clipping of running water bodies into the data set, still some of these wrongly attributed settlement areas have remained. On the other hand, an important amount of settlement areas had not been integrated into the LISA dataset. For instance, not holding a sufficiently large area, smaller settlements and isolated homesteads were overlooked in the classification process. Parks and small gardens, which were integrated in historic settlement areas were attributed to different LC/LU types in the present dataset. Thus, even when considering the remaining artificial settlement areas along larger rivers, the present settlement area should be interpreted as a minimum area, which, in reality, is larger. Accordingly, both the historic and present settlement areas are considered to be underestimated. Still, as both values, in reality, would be higher, rates of change in the total area of settlement between 1830 and 2016 are expected to not change much. In addition, both, the inaccuracy in representing settlement areas as well as the differing definition of settlement areas (i.e. including or excluding e.g. green spaces) affect the results on how settlement areas have developed between 1830 and 2016. In this regard, the transformations of settlement areas shown in Table 9 have to be interpreted with care. Other than suggested, it can be assumed that almost all historic settlement areas have remained until 2016 and that, at most, a small share of former settlement areas has transformed to grassland or forests. Similarly, results for sparsely wooded land, which is not accurately defined, should be interpreted with care, as it is unclear to which degree historic and present sparsely wooded land may be comparable.

Aside from these issues in data quality, reliable estimations of changes in the study region's flood regime due to the isolated effect of LC/LU change are also made difficult by the nature of hydrological processes

themselves. Climate, topography and geology are the primary determinants, which set the preconditions for hydrological processes and their susceptibility to change in response to e.g. land transformation. Depending on the interplay of these factors, hydrological responses of individual regions within a catchment to the same type of LC/LU change may be highly diverse (BRONSTERT et al. 2001). This adds complexity to the hydrological effect of LC/LU change at the catchment scale, at which its effect, most often, already is small and superimposed by other factors and, thus, hard to detect (FAO 2002, BLÖSCHL et al. 2007, VIGLIONE et al. 2016). And even at the local scale, at which LC/LU change has the most pronounced effect, hydrological processes are highly complex and isolating the effect of LC/LU change may be difficult. Thus, due to the number of factors and scopes to be considered (see also chapter 6.1), global statements about the effect of LC/LU change on floods are illegitimate (BRONSTERT et al. 2001, NIEHOFF 2001, ROGGER et al. 2017).
Besides, LC/LU change is not the only anthropogenic activity, which, in the past, has altered local flood risks. In fact, the present flood situation in the study region is the result of a combined effect of LC/LU change, river regulation measures and climate change acting in parallel (BRONSTERT et al. 2002, BLÖSCHL et al. 2007, MERZ et al. 2012, VIGLIONE et al. 2016). A summary of relevant processes, variables and drivers of flood change associated with these factors was provided by MERZ et al. 2012 in Table 10. While some drivers of flood change act simultaneously and at the same spatial scales, others may operate at different temporal and spatial scopes. Thus, the actual flood response may vary with the period and area under consideration, accentuating the need for a more holistic analysis.

***Table 10**: Drivers of change in flood hazard and associated variables (MERZ et al. 2012).*

Compartment	Processes	Variables	Drivers of change
Atmosphere	Meteorological forcing of catchment water fluxes.	Temperature, total precipitation, precipitation intensity, snow cover, snowmelt, seasonal distribution of climatic variables, seasonality of floods.	Natural climate variability at different time scales, anthropogenic climate change.
Catchments	Runoff generation and concentration.	Infiltration capacity, runoff coefficient, water storage capacity.	Urbanization, deforestation, wildfires, agricultural management practices, drainage of wetlands and agricultural areas, construction of flood retention basins.
Rivers	Flood wave propagation, superposition of flood waves.	River morphology, conveyance, roughness, water level, discharge, inundated area.	River training, reduction in river length, construction of dikes, groynes and weirs, operation of hydropower plants and reservoirs.

While land transformations (e.g. changes in infiltration capacities) are important drivers for flood changes in small catchments and at low flood magnitudes, river regulation measures (e.g. river training and associated losses in flood retention areas) become relevant factors at larger catchment scales and for floods of higher magnitudes. This is due to the general tendency of larger settlements at larger catchment scales, which, along larger rivers, require large-scale flood protection works (BLÖSCHL et al. 2007, VIGLIONE et al. 2016). As early as in the late 19th century, the Salzach River had already been regulated for the most part (WIESBAUER AND DOPSCH 2019). Although river training measures are convenient for reducing local flood risks in upstream sections, their downstream effects, most often, are quite the contrary. Here, changes in upstream river morphology (i.e. reductions in the wetted area, river bed roughness and sinuosity of the river) generally led to increased flood celerities and faster flood wave propagation, while the loss of upstream natural retention areas may, eventually, cause increased flood peak volumes and, thus, increased flood risks in these downstream regions (RAMESHWARAN AND WILLETTS 1999, ACREMAN et al. 2003, ACREMAN AND HOLDEN 2013, HALL et al. 2014, SCHOBER et al. 2020). However, if controlled flood retention polders are present, peak attenuation of extreme floods may be larger today, than it was before river regulation, because of a more efficient activation of the available retention space (SKUBLICS et al. 2016). The actual impact of river training on floods, thus, varies locally (SCHOBER et al. 2020). Large hydropower reservoirs such as those in the Stubache and Kapruner Ache catchment, in contrast, are generally attributed to reduce runoff peaks of small to medium floods by retaining flood volumes (VERBUNT et al. 2005, HALL et al. 2014, LEBIEDZINSKI et al. 2020). Although being most pronounced in small basins, reservoirs may also contribute to the reduction of small to medium floods at the mesoscale, while having no significant effect on the attenuation of extreme floods as well as in large catchments (cf. LEBIEDZINSKI et al. 2020). Thus, overall, the effect of river engeneering measures on floods in the study region appears to be very pronounced and needs to be taken into account in future research projects assessing changes in flood risks between the pre-industrial period and present conditions. Still, the main driver of flood change is climate (and climate change, e.g. changes in precipitation intensities and amounts), which is dominant at almost all scales (BLÖSCHL et al. 2007, VIGLIONE et al. 2016). By reason of the scope of this work, climate implications on the flood situation and flood change were not compiled in detail. Nevertheless, it has to be taken into account when estimating the relative role of land transformations on hydrological conditions in the catchment. Over the last centuries up to recent decades, alterations in temperature and precipitation characteristics have significantely affected the study region's flood regime (cf. chapter 2.3, cf. HALL et al. 2014). Climate variability associated with fluctuations of these primary climate parameters led to an alternation of flood-rich and flood-poor periods. In the study region, such flood-rich periods have been found e.g. between 1500-1516, 1564-1576, 1636-1660 and 1788-1792 (BLÖSCHL et al. 2020). Being determined by the antecedent soil moisture as well as the type and intensity of precipitation, the relative hydrological role of LC/LU during these wetter climate periods may be limited. Still, detrimental land use management had an important impact on the catchment's susceptibility to erosion. Thus, by this mechanism, i.e. by enhanced erosion along deforested hill slopes in the course of heavy rainfall events, causing mass movements and, eventually, river bed aggradation, it is expected that LC/LUs have further reinforced flooding during flood-rich periods (cf. HALL et al. 2014). However, future climate change is projected to be much more pronounced than observed climate changes of the last 250 years (SCHÖNER et al. 2014). In a warmer climate with altered precipitation patterns (AHRENS et al. 2014, CHIMANI et al. 2016a and 2016b) e.g. less snowfall, more rainfall (GOBIET et al. 2014, NACHTNEBEL et al. 2014, ZAMG 2017, SCHÖNER et al. 2018, HANZER et al. 2018) and potentially more frequent and more intense convective storm events (APCC 2014, BLÖSCHL et al. 2017, BECSI AND LAIMIGHOFER 2018a and 2018b, WALTL 2018) and, thus, different flood-inducing mechanisms (BMLFUW 2009, HOLZMANN et al. 2010, BLÖSCHL et al. 2017) the relative impact of LC/LU on runoff formation should be re-evaluated (cf. BRONSTERT et al. 2001, BLÖSCHL et al. 2007, BMNT 2018). Beyond alterations in the runoff and flood regime of rivers and streams in the region (KUHN AND OLEFS 2007, WEBER et al. 2009, HOLZMANN et al. 2010, LAGHARI et al. 2012, GOLER et al. 2016, HANZER et al. 2018), climate change will also affect LC/LU itself, e.g. by causing glacial retreat, inducing upwards shifts of vegetation limits or exerting pressure on forests (windthrows, bark beetles, forest fires). These aspects are expected to become progressively important in determining erosional and hydrological processes in high alpine regions (BFW 2011, BMNT 2018) and, thus, need consideration in future hydrologic research associated with LC/LU change.

For the present work, the complexity of hydrological effects associated with land transformations allows, at most, a rough estimation of changes in the flood regime of the upper Salzach catchment between 1830 and 2016, but cannot provide clear answers at this stage. However, the here presented data will provide the basis for a spatially distributed rainfall-runoff model, which will simulate and assess the hydrological consequences of land transformations in the catchment and, eventually, will allow more profound and robust insights into the topic.

7 CONCLUSION

The aim of this work was to assess changes in land cover and land use (LC/LU) between 1830 and 2016 in the upper Salzach catchment, Austria, in order to estimate related changes in runoff formation and flood risk. In the study region, this might be of special interest, since - in the past - it had been subject to a considerable number of severe floodings associated to certain types of LC/LU change and detrimental land use management practices. Over centuries, extensive areas of forests along the study region's valleys and mountainsides were cleared for salt production in Hallein and Reichenhall as well as for gold and silver mining in Rauris and Gastein. Adding to this, wood was in high demand as contruction material and for domestic purposes. After their clearance, most former forest areas had been transformed into permanent (alpine) meadows and pastures or cropland, which inhibited their rejuvenation. This way, as early as in the second half of the 16th century, exploitable forests had become a scarce resource in some sub-catchments. Up to the early 19th century, poor rejuvenation in higher altitudes, forest damages and natural hazards still limited and reduced their amount. Situated in a mountainous region of regionally easily weathered bedrock and climatically favoured physico-chemical wheathering (e.g. due to high yearly precipitation amounts or frequent freeze-thaw cycles), the hydrological and erosional consequences of deforestation and detrimental management practices over centuries in the upper Salzach catchment appeared to be very pronounced. Lacking root penetration and soil protection by tree canopies, the stability of soils and slopes as well as water retention capacities got highly reduced. On the one hand, this led to frequent mass movements accumulating debris into Salzach tributaries. On the other hand, precipitation events rapidly entailed drastically increased runoff, transforming mountain streams into fast-flowing torrents with high tractive power, which now eroded also coarser bed load fractions into downstream areas. The material got deposited in the confluence sections with the Salzach River, whose gradient between Krimml and Bruck was too low for providing sufficient bedload transport capacities to allow the relocation into downstream regions. Failing to erode the material, which gradually built up, the river bed of the Salzach River was progressively lifted, locally causing superelevated river banks of about 1.5m height difference with regard to the river surroundings. Correspondingly, groundwater levels were lifted, too, and valley floors began to transform into (often waterlogged) swamps. The low water retention capacity in the mountainous sub-catchments in combination with the superelevated river banks and high groundwater tables also led to frequent severe floodings of the valley floors, extensively inundating them and, thus, intensifying paludification between Neukirchen and Bruck. Knowledge of these historic baseline conditions - which represent a very unfavourable flooding situation - is fundamental, when interpreting LC/LU changes between 1830 and 2016 in terms of their hydrological role.

In order to assess how the flooding situation has changed due to land transformations, a comparison of LC/LU distributions derived from the digitisation of the Franziscean Cadastre from 1830 with the Sentinel-2 based LISA High Resolution Land Cover Map (Level II) of 2016 was conducted and included 1. LC/LU changes on a catchment-wide perspective and 2. LC/LU changes along fluvial corridors.

Regarding LC/LU changes on a catchment-wide perspective, it was found that the upper Salzach catchment had undergone comprehensive transformations since the onset of industrialisation. Until 2016, the areas of many LC/LUs have been altered in a way, which is generally associated with increased flood risk. Settlements, today, make up 6.5 times larger areas than 190 years ago. Owing to massive river straightening and narrowing, the area of rivers and streams had been truncated by 22.4%. Glaciers have lost 70.2% of their former area, leaving barren wasteland, which, very slowly is recolonized by vegetation. On the other hand, many LC/LU types, which were historically associated to reinforce floods, have been abandoned and converted. For instance, extensive wetlands (i.e. often waterlogged swamps) and cropland areas along the valleys and mountainsides (up to 1200m a.s.l.) declined by 99.3% and 98.8%, respectively. The vast majority of these areas, i.e. 77% and 90%, respectively, got transformed into grasslands. This contributed to the considerable increase of grasslands between 1830 and today, which amounts to 37.6%. Many abandoned alpine meadows and pastures (31%) and sparsely wooded lands (35%) in high altitudes got (densely) wooded, being conducive to a forest growth of

13.6%, as compared to their former area. Despite being constantly exposed by melting glaciers, the area of wastelands has rather decreased (by 3.3%) than being extended, because large areas of former wasteland (33%) got succeeded by vegetation. Moreover, new land uses have emerged, i.e. large reservoirs of storage power plants in the Stubache and Kapruner Ache catchments, which were shown to considerably reduce flood runoff of small to medium floods on a local to regional perspective. Together with the formation of glacial lakes, this contributed to an almost doubling (+80.5%) of the area of standing water bodies between 1830 and 2016.

Alterations of LC/LUs along the fluvial corridors, i.e. in areas being flood-prone to 300-year floods (HQ_{300} zones), reflected general patterns of change in the total catchment. For instance, just as was the case on the catchment-wide perspective, the decline of wetlands, which formerly covered 13% of the fluvial corridors amounted to 99.3%. Similarly, the decrease of croplands (98.2%), formerly covering 25% of the HQ_{300}-zone, was shown to be comparable with relative changes in the total catchment. However, some LC/LU types showed even more distinct shifts. For instance, as compared to growth rates on a catchment-wide perspective, settlement areas experienced an 8.2 fold increase along fluvial corridors. They now represent 9% of the HQ_{300} zone. In contrast, vast areas (i.e. 60.3%) of sparsely wooded land have been lost. On areas formerly covered by wetlands, cropland and sparsely wooded land, extensive grasslands were established. Thus, the area of meadows and pastures increased by 95.3%, now covering 67% of the HQ_{300} zone. Other than in the total catchment, the area of alluvial forests did not change much (+0.5%) over the last 190 years. In addition to these qualitative changes in LC/LU composition, the aforementioned truncation of running waters by river regulation and flood protection measures also affected the extent of inundation areas over time. Accordingly, the HQ_{300} zone got shortened by 16km², equivalent to a loss of 9% of their former extent.

For reasons of differences in the intensity of land use, the potential changes in runoff formation and flood risk were estimated individually for valley floors and for high alpine regions.

Along the valleys and fluvial corridors, the potential hydrologic effect of LC/LU change between 1830 and 2016 is determined by antagonistic land transformations. Due to river regulation measures, most river sections of the Salzach and Saalach River, today, follow a shorter (thus more inclined) and more narrow flowpath, resulting in increased flow velocities. In addition, both rivers got progressively decoupled from their floodplain and, hence, not only lost important shares of their former runoff area, but also lost large areas of potential flood retention zones adjacent to the river (as was specified above). Both, the constriction and loss of runoff areas as well as of flood retention areas are expected to have caused an acceleration of floodwaters and flood propagation as well as increases in flood peaks and, thus, flood risks in downstream regions. Further amplifying local flood risks, the increased area and degree of surface sealing is expected to considerably contribute to local (surface) runoff in the course of precipitation events and, thus, to locally augment floodwaters along river corridors of the upper Salzach catchment. In contrast to these flood reinforcing effects of LC/LU change along valley plains, other - and by far larger - land transformations, such as the conversion of cropland into meadows and pastures are expected to rather have attenuated surface runoff formation and to generally provide higher water retention capacities today. Similar but even more pronounced hydrological effects are expected to have arisen from the drainage of extensive swamps along the Salzach valley and their conversion into meadows and pastures. These drainages are estimated to have resulted in an overall higher water retention capacity and, thus, reduced surface runoff and flood runoff contributions.

In high alpine regions, the extensive replacement of large areas of formerly intensely used meadows and pastures by trees and forests on the one hand as well as the rejuvenation of former clear cut forests, which, today, are managed in a more provident manner on the other hand are expected to have resulted in generally higher water retention capacities, reduced surface runoff and lower stream discharges as well as lower erosion potential compared to historic conditions. In addition, local water retention capacities are further increased by storage power plants in high alpine catchments, which are assumed to considerably reduce runoff peaks of small to medium floods on a local to regional perspective. In contrast, somehow counteracting this general trend towards increased water retention capacities in high mountain regions, glacier retreat is expected to significantly increase local runoff not only because of glacier melt, but also because it continuously uncovers wasteland soils, which generally provide only little water retention capacities. Furthermore, it is plausible that the loss and degradation of glaciers may have led to faster and more pronounced runoff reactions in response to rainfall, as compared to the historic situation.

Altogether, considering that the historic baseline situation in 1830 was characterized by frequent and severe floods due to detrimental land management over centuries (thus, representing a very unfavourable flooding condition), it is assumed that, overall, the flood risks have decreased on the regional scale due to a more provident land management today. Until 2016, historically low water retention capacities in many tributary catchments have most likely been increased and high erosion rates have most likely been reduced due to forest expansion. Locally significantely superelevated river banks and high groundwater tables were lowered by river regulation. Thus, large waterlogged swamps covering extensive areas of the valley floors were drained and converted to grasslands, thereby most likely contributing less to runoff than historically. It is expected that the effects of these transformations overweigh the effects of modern flood reinforcing LC/LU changes, such as urbanization. In this respect, the upper Salzach catchment would represent an exception in terms of changes in flood risk associated with modern land transformations. However, in a future with increasing land consumption (e.g. for settlement areas and infrastructure) as well as with altered climate conditions (e.g. precipitation amounts and/or intensities) the relative role of LC/LU on the runoff behavior and flood regime needs to be re-evaluated.

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11 ANNEX

SALZBURG/TYROL Upper Salzach catchment	1830	2016	SALZBURG/TYROL Upper Salzach catchment	in historic HQ300 (corrected)	in present HQ300	Area within 100m-buffer outside of historic HQ300	Area in historic HQ300 according to GIS
Total area study region [m²]	**2 704 382 551**	**2 704 382 551**	**Area in HQ300 [m²]**	**176 610 703**	**160 711 660**	**104 966 226**	**176 610 703**
	1830	**2016**		**1830**	**2016**		
Settlements	3 711 388	24 221 838	Settlements	1 665 010	13 944 154	76 216	1 666 535
Running waters	15 605 043	12 134 528	Running waters	15 605 043	12 134 528	not included	13 504 978
Standing water bodies	7 686 104	13 856 836	Standing water bodies	0	0	168 813	0
Wetlands	29 960 549	214 927	Wetlands	23 748 618	165 233	288 546	23 754 391
Meadows and pastures	747 903 626	1 029 463 575	Meadows and pastures	54 952 559	107 409 663	29 306 425	55 542 272
Cropland	138 925 500	1 684 692	Cropland	43 811 236	765 026	3 441 029	43 882 048
Vineyards	0	0	Vineyards	0	0	0	0
Sparsely wooded lands	465 341 951	350 497 553	Sparsely wooded lands	15 563 521	6 205 608	23 503 029	16 033 748
Forest	766 656 567	871 183 997	Forest	15 980 804	16 060 929	45 691 971	16 894 966
Wasteland	364 187 686	352 150 618	Wasteland	5 283 911	4 026 520	2 391 904	5 331 766
Glaciers	164 404 136	48 973 987	Glaciers	0	0	98292	0
Area balance study region [km²]	**2 704**	**2 704**	**Area balance HQ300 [km²]**	**177**	**161**		
	1830	**2016**		**1830**	**2016**		
Settlements	3,7	24	Settlements	1,7	14		
Running waters	16	12	Running waters	16	12		
Standing water bodies	8	14	Standing water bodies	0	0		
Wetlands	30	0,2	Wetlands	24	0,2		
Meadows and pastures	748	1 029	Meadows and pastures	55	107		
Cropland	139	1,7	Cropland	44	0,8		
Vineyards	0	0	Vineyards	0	0		
Sparsely wooded land	465	350	Sparsely wooded land	16	6		
Forest	767	871	Forest	16	16		
Wasteland	364	352	Wasteland	5	4		
Glaciers	164	49	Glaciers	0	0		
Area balance study region [%]	**100**	**100**	**Area balance HQ300 [%]**	**100**	**100**	**100**	**Subtraction in m²**
	1830	**2016**		**1830**	**2016**	Distribution key (%)	
Settlements	0,1	0,9	Settlements	0,9	9	0,07	1 525
Running waters	0,6	0,4	Running waters	9	8	not included	not included
Standing water bodies	0,3	0,5	Standing water bodies	0	0	0,16	3 377
Wetlands	1,1	0,01	Wetlands	13	0,1	0,27	5 773
Meadows and pastures	28	38	Meadows and pastures	31	67	27,92	586 335
Cropland	5	0,1	Cropland	25	0,5	3,28	68 845
Vineyards	0	0	Vineyards	0	0	0,00	0
Sparsely wooded land	17	13	Sparsely wooded land	9	3,9	22,39	470 227
Forest	28	32	Forest	9	10	43,53	914 162
Wasteland	13	13	Wasteland	3	2,5	2,28	47 855
Glaciers	6	1,8	Glaciers	0	0	0,09	1 967
						100,00	**2 100 066**
							Area of running waters within 100m buffer zone outside of historic HQ300