Historical changes in floodplains of prealpine rivers

A GIS-based analysis in southern Bavaria


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Mémoire de dominante

Gestion des Milieux Naturels

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Abstract

Les rivières en tresses, caractérisées par la présence de canaux séparés par des bancs de graviers, appartiennent aux milieux naturels les plus menacés en Europe. La régulation des cours d'eau au cours du siècle dernier visant à lutter contre les inondations et accroître la production d'électricité a conduit à une perte de la dynamique naturelle. En Bavière, les conséquences de la linéarisation et des seuils successifs se traduisent par une diminution des surfaces de graviers et une incision du lit, entraînant la modification d'habitats prioritaires. Cette étude se propose de quantifier la diminution de la surface des graviers sur une période de 150 ans en prenant en compte également l'évolution de la végétation du lit majeur. Elle est fondée sur une analyse SIG à partir de cartes anciennes et de photos aériennes. Il a été constaté que la surface de gravier disparue avoisine les 80%, avec une disparition plus importante en région préalpine et que les stades végétatifs pionniers, porteurs d'espèces protégées, se font de plus en plus rares.

Braided rivers, characterised by small channels separated by gravel bars, belong to the most threatened natural environments in Europe. The regulation of water courses over the last century for flood control and hydroelectric production led to the loss of their natural dynamic. In Bavaria, straightening of rivers and construction of successive weirs have resulted in the decrease of gravel bar area and the deepening of river beds, leading to modification of valuable natural habitats. This study aimed to quantify the decrease in gravel bar area over 150 years, based on a GIS-analysis of historic maps and aerial photographs and taking into account the evolution of floodplain vegetation. The analysis indicates that the gravel bar area has decreased by around 80%, with a higher decrease in the prealpine region. It also found that pioneer vegetation stages, which potentially support protected species, are increasingly scarce.

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1. Introduction

1.1 Morphological characteristics of braided rivers

Paleogeographic studies have shown that during the late glacial period, braided rivers were the most widespread river landscape in Europe (Wiederhekr et al. 2007). More precisely, the braided gravel-bed rivers are often located in temperate piedmont and mountain-valley areas (Tockner et al. 2006).

They are characterised by a morphology of small channels separated by gravel bars that can also be described as a shifting mosaic of channels, ponds, bars, and islands (Stanford, 1998, Poole et al., 2002, Ward et al., 2002).

Several studies have identified the optimal conditions for the formation of braided channels, including an abundant supply of sediment, rapid and frequent variations in water discharge (with floods and periods of water distress), and erodable banks of non-cohesive material (Church & Jones, 1992).

The best example of a braided river in Europe is the Tagliamento River in northern Italy that has retained a part of its natural dynamic and where flood dynamics can still reconfigure the spatial environment (Kollmann et al. 1999, Tockner et al. 2003).

1.2 Braided rivers in Bavaria

The following study examines different rivers in Bavaria (the study sites are fully described in Material and Method). The rivers targeted by the study are the braided rivers of the Bavarian alpine and pre-alpine region, which are located at the southern end of the Danube River ("Donau" in German) as shown in Figure 1, and have their source in the northern Limestone Alps. (Böhm et al., 2006)

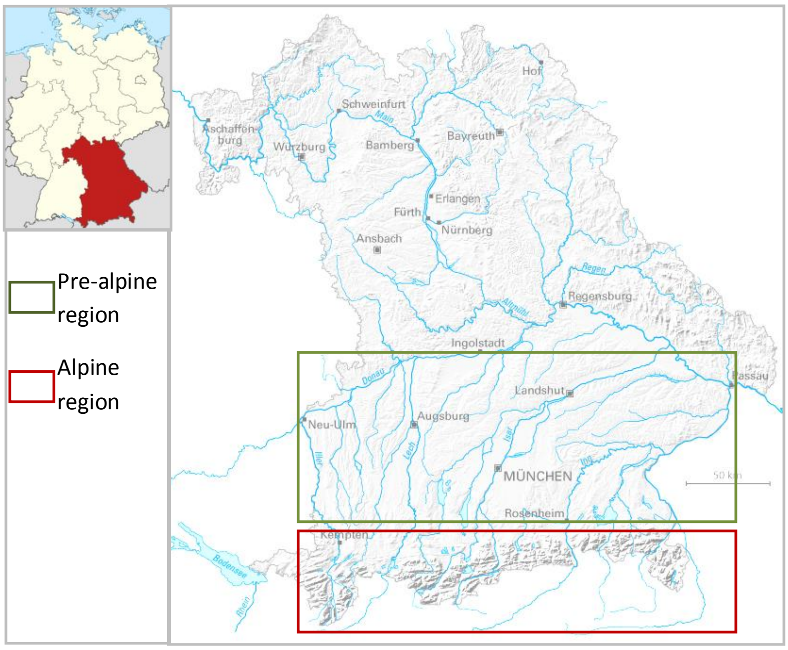

Figure 1:Map of the main Bavarian rivers (source: Bavarian Flood Information Service, HND) and localization of the pre-alpine and alpine sections

After leaving the Alps, the rivers run through a Flysch zone and then enters a moraine landscape. The substratum of the lower part of the rivers is formed by sandy sediments of the Molasse. (Böhm et al., 2006). The high sediment bedload during flooding periods is responsible for the braided morphology with gravel bars. (Fischer 1966, Jerz et al 1986, Schauer 1984).

1.3 Ecological value

These types of landscape provides a highly dynamic habitat when in a good ecological state. Tockner et al. (2006) have also identified hostile characteristics of braided rivers such as frequent floods and periods of water stress, low organic content and high fluxes of temperature and humidity. The dynamic is mostly seasonal but can be at a more stochastic rhythm. The constant redistribution of the spatial arrangement leads to the construction of a complex system of biotic and abiotic elements often called shifting habitat mosaic (SHM) (Stanford, 1998; Poole et al., 2002; Ward et al., 2002). This mosaic depends on the form of the river, the geological substratum, but also on local factors such as deadwood in the river or flow accelerations (Wiederkehr et al., 2007).

In terms of vegetation, the regular redistribution of sedimentary material assures a constant renewal and the creation of new habitats (Reich, 1994). Therefore, there is a high percentage of pioneer vegetation stages on fresh gravel bars (Tockner et al 2006), which have organisms that have adapted and now even depend on the turnover. For this reason, there are some species that can be found only along the braided rivers of the prealpine and alpine regions. Some of these species only survive on gravel bars and only some of those can tolerate human interference, if the interference is limited(Reich, 1994). The small Eurasian shrub *Myricaria germanica is* especially relevant for us: entirely confined to active zones, this species is threatened with extinction in Europe and only remains on the shore of some Bavarian rivers (Müller, 1991).

Beyond the gravel bars and the regularly flooded areas with pioneer vegetation, there are other forms of vegetation organized as follows (as described by Müller, 1991): pioneer shrubs flooded almost each year (willow, alder); pine-willow shrubs and grey alder woods flooded every 3 years; pine woods and alder-ash woods rarely or never flooded. Outside the flood area, we might find pine woods, ash-elm woods, as well as semi-natural grasslands as a result of pastoral activities or litter utilization.

1.4 River regulation and loss of the natural dynamic

The regulation of water courses in Bavaria started at the end of the 19th Century to protect the population from floodING and for hydroelectric production (Reich, 1994). The straightening of the Isar River started at that time downstream from Munich and as a result, this section of the river lost its natural character decades ago. Arztet (2008) describes that section as a straight line with a water bed that is deeper and a groundwater level lower than they would have been historically.

The upper Isar, far upstream from Munich, was also impacted by human activities. In 1923, almost 25m^3/s of water began to be diverted at the barrage of Krün to the hydropower station of Walchensee, leaving the river almost dry 300 days of the year (Reich 1994, Schödl 2005). About 20 kilometers downstream from Krün, where the reservoir lake of Sylvenstein was built in 1958-59 to reduce the flood peaks, the sediment load is fully blocked. Consequently, the area of gravel bars has sharply decreased downstream (Jerz et al. 1986). A few sections of braided river still remain but the vegetation cover has changed with the influx of willow-alder shrubs. There has also been a negative impact on the spatial arrangement of suitable habitat units: in braided rivers, the gravel bars overlap or are close to each other but there are now up to 250 m long interruptions separating the gravel bars (Bravard et al. 1989, Church & Jones 1992). This makes recolonization more difficult and disturbs the balance between extinction and colonization. Endangered species losses have been observed on these sections.

By the 1990s, Reich (1994) had stated that in Bavaria the floodplains of braided rivers were habitats threatened with extinction and all the relict areas were suffering from human interferences that were affecting the river dynamics.

1.5 Restoration

The remaining gravel bars and vegetated islands, being among the most endangered landscape elements worldwide (Tockner et al. 2006), seem like a priority for protection and their status raises questions about conservation and monitoring methods. These habitats are very sensitive to channelization, gravel extraction, and flow regulation, therefore restoration of the natural hydrogeomorphic dynamics is the most important protective action (Reich 1994, Tockner et al 2006).

The literature provides several examples of projects and stakeholders involved in the restoration. For instance, Arztet (2008) described a project in Bad Tölz in 1994 involving the Bavarian authorities and the local hydropower station to raise the minimum water flow. Other restoration measures suggested include the removal of bank protection to foster the natural erosion and transport of sediment, the active restructuration of bed sills, and the involvement of forestry services in the restoration of softwood alluvial plains (Arzet et al. 2008). Sometimes the difficulty lies in getting stakeholders from different domains to work together: foresters, flood protection services, hydropower stations, nature conservation stakeholders. There may also be a conflict of interests. Sonnenschein (1999) illustrates this when she refers to the "Teilrückleitung": the decision in 1990 to divert less water at the barrage of Krün in order to give it back to the natural river bed. She states that the resulting losses for hydroelectric production amounted to several million Deutsche Marks (1 million DM > 510 000€) per year, which led to the reduction of workforces at hydropower stations.

In the 2000s, Tockner and Stanford (2002) wrote that although a huge amount of detailed environmental knowledge has been compiled, up to 60% of all restoration projects are still ineffective (Tockner & Stanford, 2002). The main reasons they identified for this were a "missing-link" between the natural and social sciences and a lack of reference data from near-pristine ecosystems, which constrains the understanding and replication of ecosystem processes.

1.6 Problem statement

This study aims to remedy the lack of reference data from near-pristine ecosystems of braided rivers described earlier by quantifying the evolution of gravel bar area on the Bavarian rivers at different points in time. For a better understanding of the ecosystems, the vegetation of the floodplain will also be taken into account.

The study sites are located at different distances from the river source, some in the alpine region and some in the prealpine region, in order to assess if there are regional disparities and which locations are the most alarming from a nature conservation perspective.

When studying the Tagliamento, the Italian river that retains the natural dynamic and complexity of a braided river in a pristine stage, Kollmann et al. (1999) observed that the active zone of the river was largest on the upper part, a few kilometers away from its source. Therefore we expected that the gravel bar area on the Bavarian rivers would also be greater in the upper parts than at the sources or the middle parts. Furthermore, given the higher population and concentration of human activities in the prealpine region, we expected to observe a greater decrease in the gravel bar area along these sections.

The map below (Figure 2) presents our study environment and illustrates the locations described in the introduction.

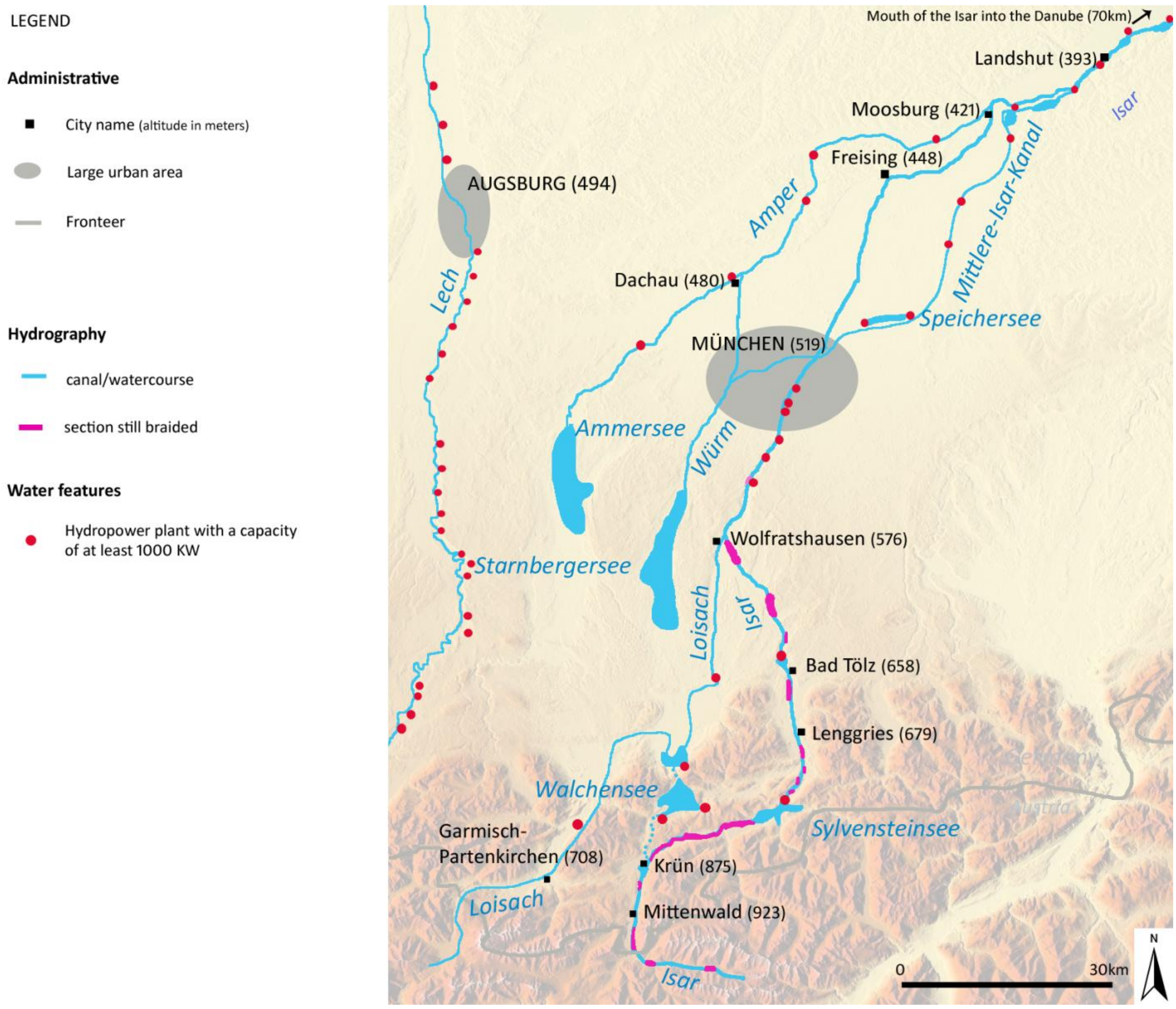

Figure 2: Synthesis map of the whole study area with its hydrographic and hydropower features. (<u>sources</u> : relief map: openstreetmap.org, hydropower stations: Bavarian Environment Services (LFU), braided section of the rivers: rough estimation based on observations of remaining gravel bars with Google Earth)

2. Material and method

2.1 Choice of the study sites

2.1.1 The Hotspot-Project

The study sites were chosen to be related to the Hotspot-Project Alpine riverscape. There are Hotspot regions in whole of Germany, from the Baltic sea to the Alps, and they cover 11% of the total area of the country. The different regions were determined during a research and development project of the German Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN), in which the rarity and the threat to species and habitats were taken into account.

The Hotspot-Project Alpine riverscape involves 18 local partners of nature conservation, public administration and businesses, with WWF as coordinator. The main goal is to conserve the remaining biological diversity along the rivers through conservation measures but also to work on the acceptance of the revitalization measures. The focus is on the riverscapes and floodplains of the Lech river, the Ammer river, the Loisach river and the Isar river, and their importance for the biological diversity.

2.1.2 The involvement of the Chair of Restoration Ecology

The Chair of Restoration Ecology at the Technische Universität München (TUM) is involved in the scientific evaluation of this Hotspot-Project through several projects to estimate and improve the quality of nature conservation of this region. The targeted areas in the present study are related to three of these projects:

-Grazing management project in the floodplains of the Isar: development of monitoring methods of the grazing activities for the control of the encroachment of woody vegetation based on vegetation samples and the presence of valuable endangered species

-Re-introduction of the German tamarisk (*Myricaria germanica)* on the Lech river: description of the the initial state of the river, development of conservation measures and establishment of monitoring methods (specie on Figure 3)

-Conservation and re-introduction of *Chondrilla chondrilloides* : understanding the repartition of this specie to find its optimal conditions and bring new seeds to suitable areas in the field (specie on Figure 4).Figure 3

Figure 3: Picture of a German Tamarisk *(Myricaria Germanica*) re-introduced at the Lech river (photo: J. Crabot)

Figure 4: Picture of *Chondrilla Chondrilloides* in Friedergries (photo: A. Zehm)

The map on Figure 5 shows the location of the five study areas and to which project they are related.

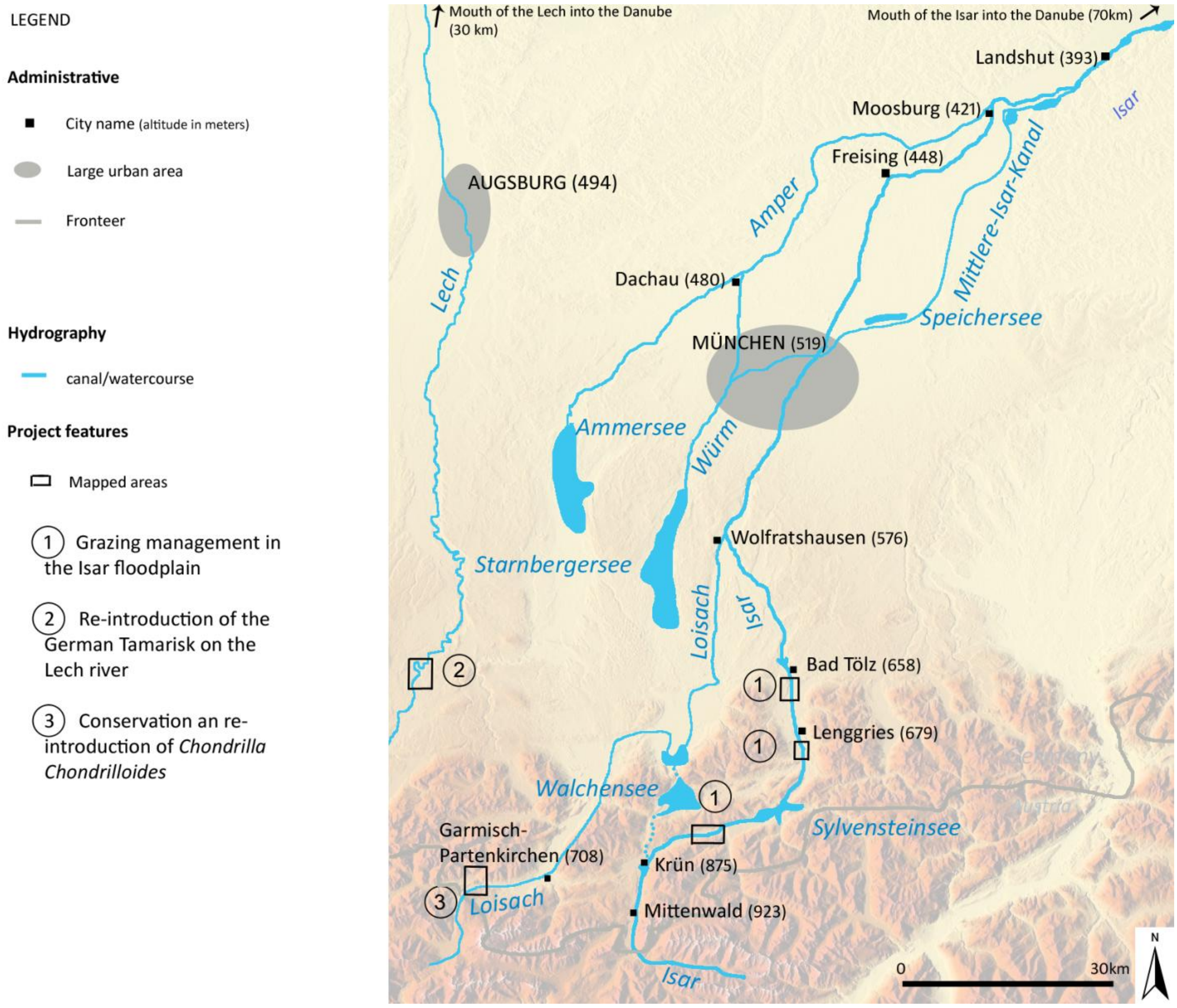

Figure 5: Map of localization of the study sites (source of the relief map: openstreetmap.org)

2.2 Description of the study sites

The study focuses on five study sites which are presented below from South to North, following the direction of the current. The connection between each study site and the different Hotspot-projects is mentioned here to justify the choice of the targeted areas but it will not be developed in the study: the main objective is the quantification of the decrease of gravel bars rather than the analysis of its consequences for nature conservation. The perspective it may offer for these projects will nevertheless be mentioned in the discussion.

2.2.1 Friedergries

Friedergries is a limestone debris cone of national importance in the Bavarian limestone Alps, with ecosystems typical of gravel bars. It presents a richness in rare plant species and near-natural forest communities. Unlike the other study sites, the study area here is rather large than long because we were interested in the evolution of the vegetation beyond the strict limits of the floodplain. Another difference is that we consider here a small stream at its source, the Friederlaine, and not a large river.

Figure 6: The Friederlaine flowing through Friedergries (Photo: J. Crabot)

Project related	**Re-introduction of *Chondrilla Chondrilloides***
Altitude	840 – 935 m
River	Friederlaine, small stream tributary of the Loisach river
Length of the study area	1,6 km
Conservation	-Part of the Nature reserve "Ammergauer Alpen" since 1963 -Natural forest reserve since 1978 -Natura 2000 FFH + Birds* (Ammergebirge)

* Fauna-Flora Habitat Guideline and Birds Directive

2.2.2 Vorderriss

Vorderriss, located between the barrage of Krün and the Sylvenstein reservoir lake on the upper Isar, is one of the last remaining sections of near-natural braided river in Germany. This part of the Northern limestone Alps displays an extreme natural richness: 11 species of the Annexe II, 24 habitat types of the Annexe I of the Fauna Flora Habitat (FFH)-Classification and 15 bird species of Annexe I of the Birds directive.

Project related	**Grazing management in the floodplains of the Isar**
Altitude	741 m
River	Isar
Length of the study area	2 km
Conservation	-Natura 2000 FFH + Birds (Karwendel mit Isar) -Landscape conservation area

Figure 7: Isar in Vorderriss, one of the last sections of near-natural braided river in Germany (Photo: J. Crabot)

2.2.3 Lenggries

Lenggries is located on a corridor of habitats from the Alps down to the Danube longer than 100km. It is covered with habitats with rare specious of animals and plants protected at European level and on this basis, classified Natura 2000. This study site is on the upper part of its river like Vorderriss but it is at the limit between alpine and prealpine region.

Figure 8: Deep bed and woody vegetation along the Isar in Lenggries (Photo: J. Crabot)

Project related	**Grazing management in the floodplains of the Isar**
Altitude	679 m
River	Isar
Length of the study area	2,7 km
Conservation	-Natura 2000 FFH (Oberes Isartal) -Landscape conservation area

2.2.4 Bad Tölz

Bad Tölz belongs to the same Natura 2000 site than Lenggries, it is a few kilometers downstream from the precedent study site and differs from it with a much larger floodplain area.

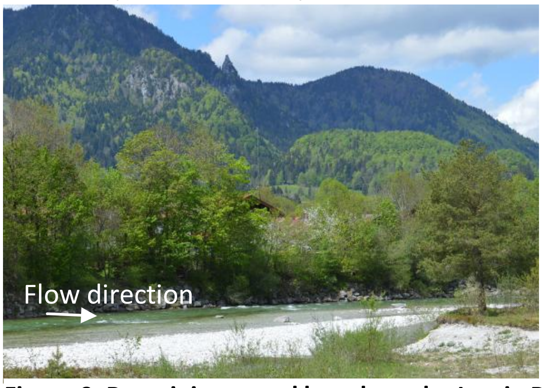

Figure 9: Remaining gravel bar along the Isar in Bad Tölz (Photo: J. Crabot)

Project related	**Grazing management in the floodplains of the Isar**
Altitude	658 m
River	Isar
Length of the study area	3,1 km
Conservation	-Natura 2000 FFH (Oberes Isartal) -Landscape conservation area

2.2.5 The Litzauer Schleife

This site is situated on the middle part of another river, the Lech. It is the last unregulated section on the Lech with floodplain woods, gravel bars, alkaline fen and low-nutrient grasslands.

Figure 10: Bend of the Lech at the Litzauer Schleife and diversity of vegetation patches (Photo: J. Crabot)

Project related	**Re-introduction of the German Tamarisk**
Altitude	720m
River	Lech
Length of the study area	6,8 km
Conservation	-Natura 2000 FFH + Birds (Litzauer Schleife) -Landscape conservation area

The objective of this study is to quantify the evolution of gravel benches area on the different study sites. To this end, relevant data were ordered at the Bavarian Office for Surveying and Geographic Information (Landesamt für Digitalisierung, Breitband und Vermessung Bayern), including historic maps and orthophotos of 2009 in the first place.

2.3.1 Historic maps

The modern topographic surveys in Bavaria started in 1808. Over the 19th century, "Urpositionsblätter" (original position sheets) were drawn in a 1:25 000 scale, covering the whole territory of Bavaria. The selected maps respectively date back to 1838 for the study area on the Lech river, 1864 for the three areas on the Isar river, and 1826 for the tributary of the Loisach river. The total surface of such a map is 87 km². The colors or even the legend may be slightly different between two maps because they were established by different authors and over a long period. They were delivered on a digital support and already georeferenced, which means aligned to a known coordinate system.

2.3.2 Orthophotos of 2012

To assess the current situation of gravel bars, recent orthophotos were ordered. An orthophoto is an aerial photograph that was geometrically corrected to perfectly fit Earth's surface and have a high spatial accuracy. The resolution of these documents is 20 centimeters. One orthophoto is a digital document with an area of 0,22 km², that is why many different were necessary to cover one study area: for example, the Litzauer Schleife required 33 images. They are composed of three channels: red, green and blue but without near-infrared channel. This last type of channel could have been interesting to analyse the vegetation types but given that this type of information is not available for other forms of data (simple aerial photographs), the near-infrared channel was not mandatory.

2.3.3 Aerial photographs of the 1960's and 1980's

As it will be described below, it became clear during the digitizing that further data would be needed in addition to the historic maps and the recent orthophotos. Therefore, aerial photographs of the 1960's and the 1980's were ordered for each study sites. These years were chosen for technical reasons: to minimize the number of aerial photographs needed (one for some study areas, three for others) and to have a sufficient quality for the photo-interpretation. At this time, no orthophoto was available and the aerial photographs required a georeferencing. This was processed on ArcGis 10.2 of ESRI and the RMS error obtained at this stage was in average 1 meter. The RMS error or Root Mean Square error, reflects the average accuracy of the digital representation and in this case, 1 meter is reasonable given the original data and the purpose of the study. These photographs are not orthorectified, their orthorectification would have needed additional data (such as the digital elevation model) and time.

2.3.4 Former similar studies of 2012

Two bachelor thesis were achieved at the chair in 2012 with similar objectives.

The work of Verena Christina Weitmann focuses on gravel bars and gravel islands on the Middle Isar (section of the Isar river in the North of Munich). She had historic maps taken from an article of Seibert, 1962, which were representing the gravel bars and the different types of vegetation at different times of the 19th century, and aerial photographs taken at different times of the 20th century. She used a 1:1 000 scale for the digitizing work and then analysed the following parameters: number of gravel bars and islands, area of gravel bars and islands, shape index described in the paragraph 2.5.1 Choice of indicators.

The bachelor thesis of Valerie Moos dealt with the gravel and sand bars of five different alpine rivers of Bavaria. For each river, 5 sites in prealpine region and 5 sites in alpine region were randomly selected with ArcGis: there were 50 sites in total, each study site being a circle with a diameter of 1km. The analysis over time was based on the comparison between historic maps (the so-called “Urpositionsblätter”) and orthophotos of 2009. The scale of digitizing was 1:2000 for the historic maps and 1:800 for the orthophotos. She studied the gravel bar area (comparison pre-alpine and alpine regions), the correlation between current and historic bars, and the correlation between gravel bar area and the number of constructions (dams…). The Table 2 at the end of this chapter sums up the similarities and differences between these two studies and the present one.

2.3.5 Additional data

In the first place, vegetation and deadwood samplings were envisaged. The master students carried out vegetation samplings following different protocols according to their project, it would also have been possible to work with them for the analysis but it would have been complicated if each set of data is different. Furthermore, the digitizing work has been more time consuming than expected and already provided enough material to analyse.

2.4 Digitizing

The extraction of the data in an analyzable form, from the maps and photographs into polygons for which we know the characteristics, goes through the digitizing of these documents on the geographic information system ArcGis 10.2 of ESRI.

2.4.1 Strategic choices : mapping key, sector limits and digitizing scale

The first step is to choose the different categories that will be mapped and to establish a mapping key. For the relevance with the master thesis related to my study sites, focusing on plant species and plant communities, it is interesting to map the gravel bars but also the different types of vegetation. For this purpose, in the limit of the technical possibilities of photo-interpretation and given the characteristics of floodplains of braided rivers, the following categories are used during the digitizing:

– water course

– gravel bars

– herbaceous areas: it corresponds to the first stage of succession, these areas are still very opened, eventually with pioneer species and sometime a few woody species, the dynamic of colonization is still highly reversible

– softwood floodplain: higher rate of woody plants with species withstanding the regular floods, such as willows, ashes and alders.

– hardwood floodplain: the next stage in the succession, with a vegetation well established, and a higher diversity in the tree species.

During the digitizing work, it can be sometimes difficult to make the difference between the two last categories. If it is not possible to make a clear difference by recognizing the type of trees (sometimes the form or the color of willows can be very characteristic but not always), the density of shrubs and the height of the trees helps to choose the category. Indeed, we will suppose that the higher and the thicker the vegetation is, the more rarely it was disturbed by floods and on this basis, it can be categorized as “hardwood floodplain”.

Nevertheless it was noticed that the information of the historic maps on the types of vegetation are too vague for this categorization. Indeed, a dotted line or a different color is used to delineate the boundary between a gravel bar and a vegetated area, and in some cases slightly different colors are used to distinguish different forms of vegetation but not systematically, as illustrated in Figure 11.

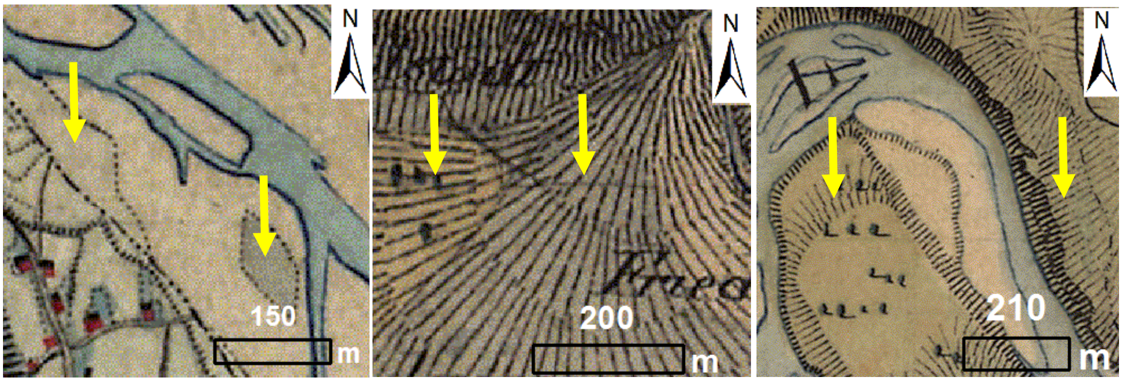

Figure 11: Differences in the representation of the vegetation on the different historic maps. From left to right: Lenggries 1864, Friedergries 1826, Litzauer Schleife 1838. Source: LDBV BY)

It is therefore decided to keep the different categories of vegetation for the mapping of the orthophotos but to take the historic maps into account just to map the gravel bars. To have historical points of reference for the vegetation, this is the moment where it is decided to order additional data as described in paragraph 2.3.3.: the aerial photographs of the 1960's and 1980's.

For each area, the sector that is digitized corresponds only to the floodplain, not further. The limits are sometimes clear: roads, buildings, relief but sometimes not and it is possible in some cases that the total area of the floodplain is slightly overestimated. A finer boundary would require to analyse the tree species in the field of each study site.

As regards the scale for the digitalization, to be coherent with one of the former studies and to have comparable results, the same scales are used: 1:2000 for historic maps and 1:800 for orthophotos. Working on these documents, this choice of scales appears to be relevant with the resolution available.

2.4.2 The different steps in using the software

Once this is decided the digitizing work can begin, based on the mapping key presented in Annexe 1. It consists in using the Editor tool of ArcGis, creating a layer (or representation of a given geographical data) of polygons . A value is assigned to each polygon to describe it – in the present case, one of the category described above.

Field trips where photos were taken took place on each study site and professionals (WWF, consultancy office in environment, Bavarian Academy for Nature Protection and Rural Conservation (ANL)…) with a good knowledge of the area were present: it also helped to decide how the different areas should be categorized.

In the first place, the historic maps and the recent orthophotos are mapped. After having mapped the aerial photographs of the 1960's and 1980's as well, the digitizing work of each area on each date is checked and updated to be sure to have homogeneous data.

The digitizing is proceeded very carefully to create a very reliable polygon layer: much small errors can come from manual editing of adjacent polygons and to avoid this, tools like "auto-complete polygons" are used. But despite such careful work, it is frequent that some small geometry problems remain. Therefore, two tools of ArcGis were used to make sure such problems were fixed: Repair Geometry and Integrate. The first one inspects each features to fix problems such as overlapping polygons of polygon with a null geometry and the second one makes sure that two adjacent polygons have coincident boundaries (if not, it merges them in a tolerance given in input).

2.5 Quantitative analysis

Having now polygon layers for each of the 5 targeted areas and for each of the 4 dates, the question is raised of how to extract the information and how to analyse it using relevant parameters. In first place, it is about choosing simple indicators arising from the characteristics of the polygons, as presented in the following paragraph.

2.5.1 Choice of indicators

One of the objectives is the comparability of the results with the two former studies, for this purpose the indicators they used are also measured here. In addition to that, the results have to bring some relevant information for the different master thesis and to this end additional indicators are chosen, especially as regards the vegetation. The following indicators are calculated for each study area and for each year.

- Total area of each category (gravel bars, herbaceous area, softwood floodplain, hardwood floodplain). The aim is to quantify the decrease of gravel bars and study the evolution of the vegetation, the first index to look at is naturally the total area. It was also used in the precedent studies.
- Shape Form Index. Dealing with complex and fragmented habitats, such indicators provide information on some aspects of biodiversity at a landscape level. There are many different shape indexes but the Area-Weighted Mean Shape Index (AWMSI) was kept. It is an average perimeter-to-area ratio for a landscape, weighted by the size of its patches. With this index, larger patches are weighted more heavily than smaller patches.

Équation 1: Formula of the Area-Weighted Mean Shape Index (AWMSI)

$$AWMSI = \sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(\frac{0.25p_{ij}}{\sqrt{a_{ij}}}\right)(\frac{a_{ij}}{TA})\right]$$

where pij is the perimeter of the patch ij, aij the area of the patch ij, i=1,…,m is the number of patch types, j=1,…,n is the number of patches and TA is the total area of landscape.
It doesn't have units and its values are greater or equal to 1. When AWMSI=1, all patches of the landscape are squares and AWMSI increases without limit with the complexity of the patch shapes.
This indicator was used in the first study but not the second one, because the second one just mapped gravel bars and this index requires to map the whole landscape.

- Neighborhood Index. In a good ecological state and with a remaining wild dynamic, the landscape of a braided river has an ordered succession in the forms of vegetation. Nevertheless, in a very disturbed riverscape, it is possible to observe a different structure of the vegetation. The neighborhood index allows to get some information such as: if we consider a herbaceous polygon in one study area, which adjacent patches will be more likely to be found. In this study, we chose to measure the total outline shared between each category.
- Floodplain area. As explained in paragraph 2.4.1, there was an uncertainty on its exact limits and the results may be slightly impacted but the evolution of the total floodplain area may improve our understanding of the global evolution.

Special braid indicators exist, such as the average number of braids on several transverse sections (Howard et al, 1970) or the total length of the channels divided by the length of the main channel (Mosley, 1981) but the targeted rivers are not enough braided anymore to justify the use of such indicators.

After measuring each parameter, the absolute value of the difference between the different years is calculated. The difference between the most ancient and the most recent material is also calculated to assess the total impact over a period of approximately 150 years. The relative difference is also calculated to be able to compare the different study sites because they have variable total area, using the formula: (Parameter(ancient)-Parameter(new))/Parameter(ancient)*100.

2.5.2 Segmentation of the study areas

In order to have finer results, beyond the absolute value for the different parameters on each study site, it is decided to segment the study sites in equal parts. Rather than comparing the total values between the different years, it allows to compare the area of each category respectively on each segment and obtain a finer comparison. It provides an average value of the parameter for the different study sites and makes possible a statistical analysis.

Technically, as shown in Figure 12, a line was drawn in the middle of the study area, split in regular segments of 100 meters and perpendicular lines were drawn at the limits of each segment. Then a tool of ET Geowizard, a set of editing tools for ArcMap, was used to split the existing polygon layers according to these lines. After a few spatial joins, the polygon layers is cut and has all its attributes.

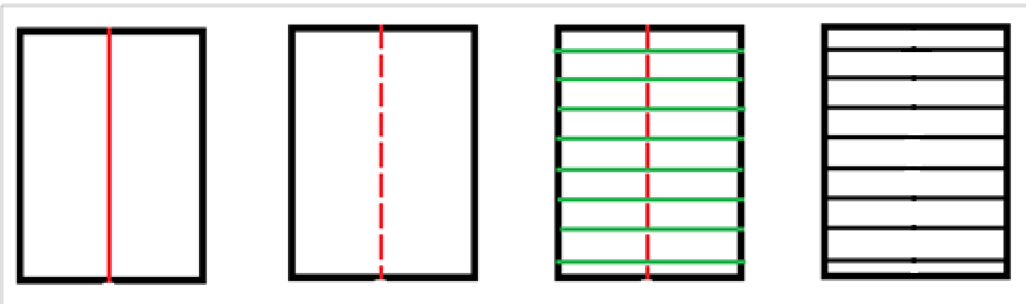

Figure 12: Scheme illustrating the steps of the segmentation in ArcGis.

The sections have the same characteristics in each study area.

2.6 Precision and verifications

2.6.1 Precision of the digitizing and buffer method

During the work on ArcGis, it became clear that the interpretation, the luminosity of the pictures and other external parameters could induce an important bias in the digitizing. Therefore, a method found in the literature on a similar project (Brien, 2006) was applied to estimate the consequences of this digitizing error on the results.

As regards the limit of polygons between gravel bar and water course, many repetitions of a channel boundary were carried out. Then, the different segments were compared and the variability in the digital representation that we obtained is the digitizing error, in meters. For the different photographs, a digitizing error of 0,43 m was found which is reasonable in comparison to the results found in the literature (Brien, 2006). As regards the vegetation, the digitizing error was estimated in a more pragmatic way, because the error was underestimated with the repeated digitizing : indeed, the variability for vegetation is more due to thoughtful interpretation than optical error. An error of 5 meters was chosen.

The next step is to apply this estimated error to the area of the polygons. This goes through the use of buffers. For the minimum area, a new polygons layer was generated by using inside buffers and for the maximum area, outside buffers were generated.

Having a minimal and a maximal area, the consequence in terms of interpretation of the results is that the total area of each category can be given with a confidence interval. This will only reflect the variability due to the digitizing error. To apply these results to the calculation of the decrease of the area between the year 1 (y1) and the year 2 (y2), the following formula is used:
Positive error of the decrease = Maximal Area (y1) – Minimal Area (y2)
Negative error of the decrease = Minimal Area (y1) – Maximal Area (y2)
It is a pessimistic estimation of the consequences of the digitizing error because it supposes that the area was highly overestimated in one case and highly underestimated in the other.

2.6.2 Verification of the water parameters

Another source of uncertainty is the water level : for two different water levels, the apparent surface of gravel bars can vary significantly. For this purpose, the water parameters provided by the site of the Bavarian Flood Information Service (Hochwassernachrichtendienst in Bayern, HND) were controlled.
A measurement station was chosen close to each study site, then the water discharge and the water level in the five chosen stations were compared at the different days on which the different aerial photographs were taken. In addition to that, the site provides data on the average values in summer, in winter and over a year. Therefore, to put the results into perspective, the final comparison graphics will also show the usual average and extreme values in summer because aerial photographs are mostly taken between June and September. There was not always data available, especially for the 1960's.
The table in Annexe 2 shows the different stations chosen and on which exact dates the data were collected for the water parameters.

2.7 Statistical analysis

The statistical analysis can be conducted using the data extracted from the segmentation. The data set consists of five samples (the five study sites) of *n* elements (the sections), where *n* is different in each sample. The variable considered will be the different areas of each category.

Study sites	Number of sections (*n*)
Litzauer Schleife	53
Bad Tölz	31
Lenggries	27
Vorderriss	21
Friedergries	16

Before deciding which statistical test will be used to analyse the differences between the samples, a few tests have to be carried out on the whole data set. For instance, an ANOVA on the decrease in gravel bar area of the different study sites would be interesting because it is a strong and common statistical test to know if the samples are significantly different from one another, but it requires that the data set follows a normal distribution and that the different groups have an homogeneous variance.

Therefore, a test on the normality was conducted and the Kolmogorov-Smirnov test was chosen for this. To test the homogeneity of variances, the Levene test was conducted. The results are presented in Table 1.

Table 1: Statistical test on the normal distribution and the homogenous variance of the data set

	Data set : decrease in gravel bar area			
	1828-2012	1828-1960	1960-1980	1980-2012
Kolmogorov-Smirnov test (p-value)	0.0347	0.0209	0.0187	1.264 e-04
Levene-test (p-value)	0.0065	0.1188	3.837e-09	3.302 e-04

For each series of the data set, the p-value of both tests is lower than 0,05. It means that at a 5% significance level, we can affirm that these series do not follow a normal distribution and do not have an homogeneous variance. A transformation of the data set with the logarithm function to achieve a normal distribution was considered but the data set having negative and null values, the transformation was not a success, even using a constant. The same tests were also conducted on the data set series of each vegetation type (Annexe 4): they have neither a normal distribution nor an homogeneous variance.

In such cases, it is recommended to use a non-parametric test. Firstly, to measure if there is any difference between the different study sites for one series (for instance the decrease between 1960 and 1980), the Kruskal-Wallis test is used, which is appropriate when there are more than two groups to analyse. If the p-value is low, at least one study site is different from the others. In this case, the next appropriate test to conduct is the Dunn test, comparing pairwise the study sites. It is the relevant test when group sizes are not equal and when a Kruskal-Wallis test was conducted: it uses the same ranking and the hypothesis of the Kruskal-Wallis test.

In addition to that, in order to analyse the impact of the geographic localization on the current situation of the gravel bars, we will calculate the correlations between different parameters and the distance to the source.

2.8 Similarities and differences with the former studies

This study following two others, presented in paragraph 2.3.4, we decided to confront our results. Before this, it is necessary to fully understand the similarities and differences between all these projects to know to what extent the results can be compared, they are therefore presented in Table 2. In this study, the choice of the study areas, their number and the choice of the categories to map is closer to Verena Weitmann's work. Nevertheless, there was no statistical analysis conducted and in this way, our project is more similar to Valerie Moos' Work.

Table 2: Sum up table of the differences between the former studies and the present one

	Bachelor thesis of Verena Christina Weitmann (January 2012)	**Bachelor thesis of Valerie Moos (September 2012)**	**Present study**
Choice of the study sites	Related to an article: Seibert, 1962.	Randomly selected with ArcGis	Related to Hotspot-Project
Location of the study sites	In prealpine region, in a very anthropized area	In prealpine and alpine region	Mostly in alpine region
Number of study sites	2	5 rivers * (5 areas in alpine + 5 areas in pre-alpine region) = 50 sites	5
Material	-Historic maps (article of Seibert) at 3 different dates -Aerial photographs of the 70's, the 80's and the 90's -Orthophotos of 2009 (7 dates in total)	-Historic maps (Urpositionsblätter) -Orthophotos of 2009 (2 dates in total)	-Historic maps (Urpositionsblätter) -Aerial photos of the 60's and the 80's -Orthophotos of 2012 (4 dates in total)
Area of one site	390 ha and 310 ha	1 circle of 1km of diameter (78 ha)	Depends: from 150 ha to 300 ha. One site is divided into sections of 6 ha.
Mapped categories	Gravel bars Water courses Softwood floodplain Hardwood floodplain	Gravel bars	Gravel bars Water courses Herbaceous areas Softwood floodplain Hardwood floodplain
Digitizing scale	1:1000	1:800 (orthophotos) 1:2000 (historic maps)	1:800 (orthophotos) 1:2000 (historic maps)
Measured parameters	-Number of islands -Total area of gravel bars -AWMSI	-Total area of gravel bars -Number of dams on the studied rivers	-Total area of each category -AWMSI -Neighborhood index
Statistical analysis	None	-Normality: Kolmogorov test -Homogeneity of the variance: Levene test -Differences between the samples: Kruskal-Wallis and Mann-Whitney test -Correlations: recent/ancient gravel bar area, gravel bar area and dams	-Normality: Kolmogorov test -Homogeneity of the variance: Levene test -Differences between the samples: Kruskal-Wallis and Dunn test -Correlations: decrease / distance to the source

3. Results

3.1. The digitized maps

The first results of the study are the digitized maps for each study site at each date, 20 maps in total. Although no precise quantitative information is delivered at this stage, it gives a first impression and can bring interesting qualitative information for stakeholders on these areas. Indeed, they may be interested in analyzing which area developed in which way, which is not the purpose of the present study. The Figure 13 displays an example of the evolution that can be observed using the maps and all the maps are available in Annexe 3.

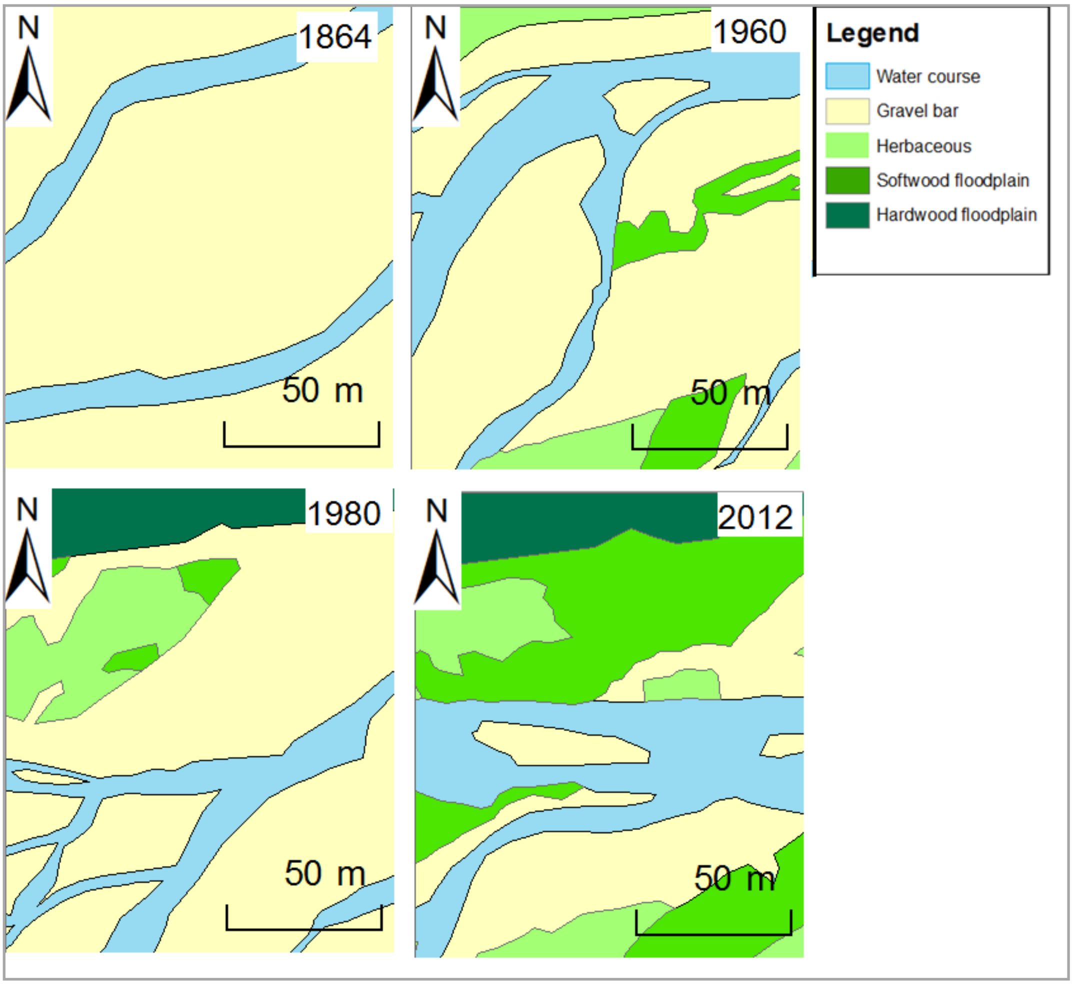

Figure 13: Same section of the digitized maps of the study site Vorderriss at each date.

The form and the location of the channels are highly variable but looking at the different maps of Figure 13, we can see that the general trend is the encroachment of vegetation, especially of the woody type. This observation also applies to the other study sites.

Moreover, the study site Bad Tölz shows a particularity. Between 1864 and 1960 the Isar river took a sinusoidal form. As regards the study site Friedergries, a major change happened between 1960 and 1980: in 1960, most of the open gravel areas were in the eastern part of the study site with a large herbaceous area on the South and in 1980, the open gravel areas are in the western part and the former large herbaceous have turned into bushes.

Other utilizations of these maps are possible. For instance, if we consider the project of re-introduction of *Chondrilla chondrilloides* in Friedergries, points with coordinates where the specie was observed are available. It is possible to extract the characteristics of the maps at each date at these exact locations and it provides information on the history of the sites where we tend to find the specie: it may help to understand better its distribution area.

3.2. Analysis of the gravel bar area

3.2.1. Absolute area and decrease on the whole study site

The first step of the quantitative analysis is to look at the evolution of the absolute gravel bar area.

After the extraction from ArcGis to Excel, we sum all the areas of the polygons categorized as "gravel bars" to obtain the total gravel bar area on each study site and for each year. Based on these results, the relative decrease was calculated (Figure 14). Negative values would indicate that the gravel bar area has actually increased. On Figure 14, error bars were added: they are the results of the work on the digitizing error with the buffer method. It means they don't reflect other sources of uncertainty such as the fluctuating water parameters.

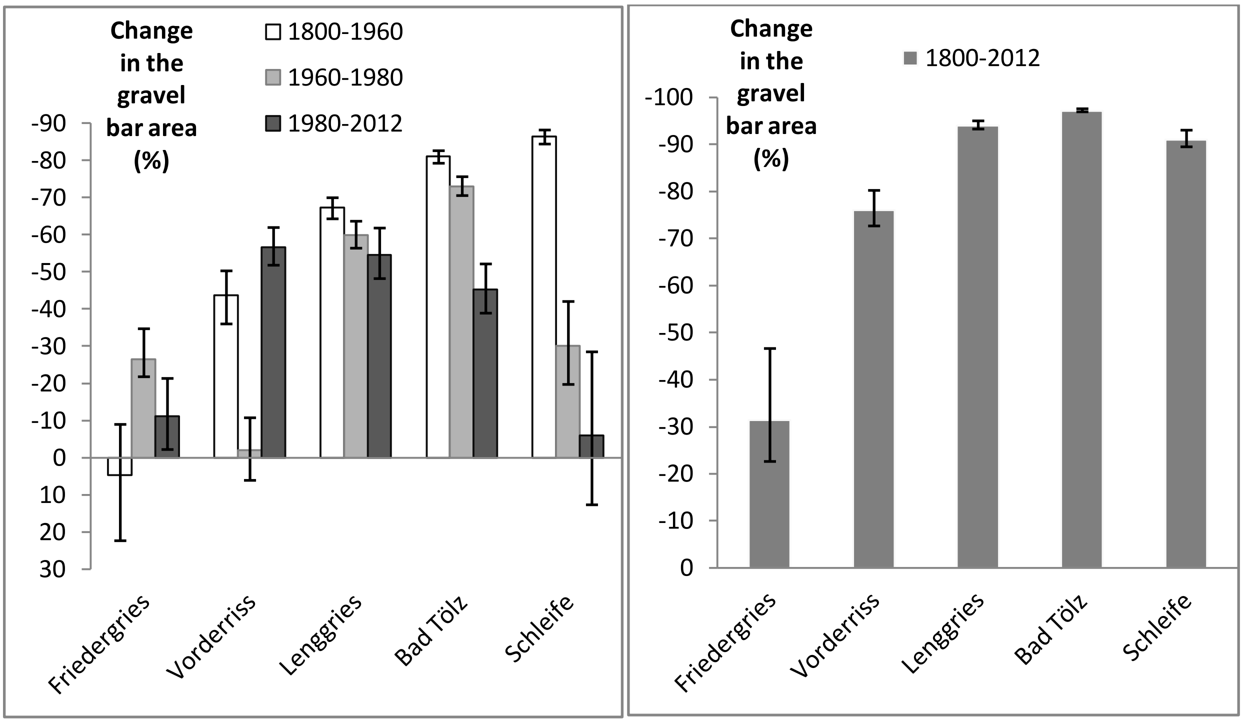

Figure 14: Right: decrease of the absolute gravel bar area of each period (1800-1960, 1960-1980, 1980-2012). **Left: decrease on the whole study period** (1800-2012). The error bars only reflect the uncertainty due to the digitizing error.

For the three last study sites, the decrease in gravel bar area on the whole study period (Figure 14, right) exceeds 90%. Nevertheless, it is only around 30% in Friedergries and 70% in Vorderriss. If now we look at the evolution on each period in between, except for Friedergries and Vorderriss, most of the reduction of the area happened between the 1800s and 1960. It was between 1960 and 1980 for Friedergries, and between 1980 and 2012 for Vorderriss.

As regards the digitizing error bars, most of the observations stay true if we take them into account. Some bars display an increase of the gravel bar area (Schleife 1980-2012, Vorderriss 1960-1980, Friedergries 1800-1960): it is not impossible, it may be due to a very different water level at that time, to gravels that were upstream and were transported to the study site or to recent floods that freed gravel bars from its vegetation. Nevertheless, the error bars were calculated in a way that overestimates the digitizing error and they should be considered with caution.

The different study periods have very different length, therefore we weighted the results per decades (Figure 15) to have information on the speed of the process.

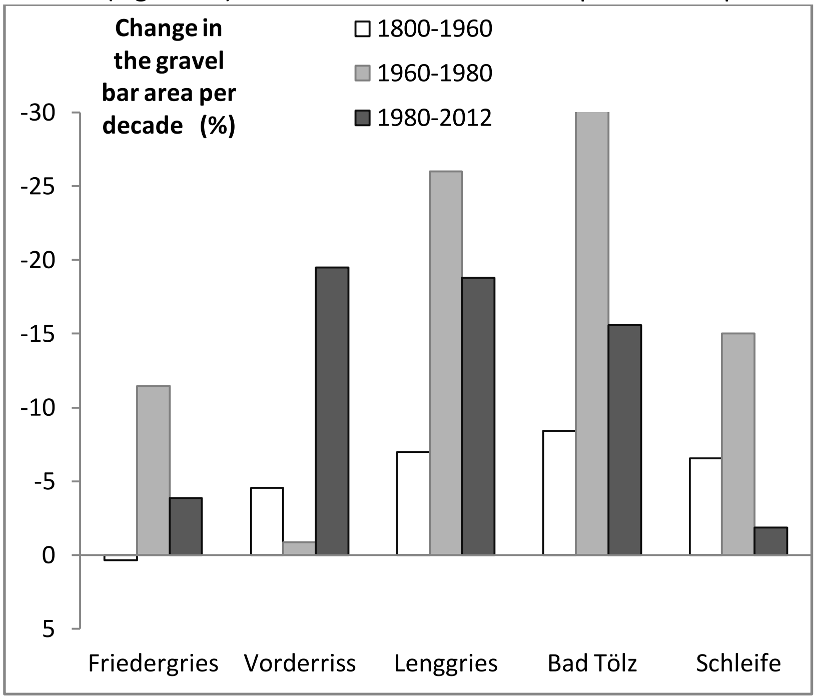

Figure 15: Change in the gravel bar area per decade on each period

The most important and rapid transition stays 1960-1980 for Friedergries and 1980-2012 for Vorderriss. However, for the three last study sites, we notice this time that the most rapid change seems to have happened between 1960 and 1980, with about 15% decrease in gravel bar area per decade in the Litzauer Schleife and more than 25% per decade for Bad Tölz and Lenggries.

3.2.2. Statistical analysis after segmentation

The segmentation allows to have a finer comparison of the decrease in gravel bar area between the different study sites. The sections on the different study sites have the same size.
Working on the sections, if we had used the relative decrease in percent using the following formula:

$$[\text{area}_{\,(year\ 1)} - \text{area}_{\,(year\ 2)}] / \text{area}_{\,(year\ 1)} * 100$$

many errors would have appeared due to null values and we would have lost some data. For this paragraph, it is therefore decided to only consider the decrease as [area $_{(year\ 1)}$ - area $_{(year\ 2)}$] in hectares. But to compare the decrease in gravel bar area over time on the different study sites, we need to know the initial state. To this end, the Figure 16 displays the gravel bar area in the 1800s.

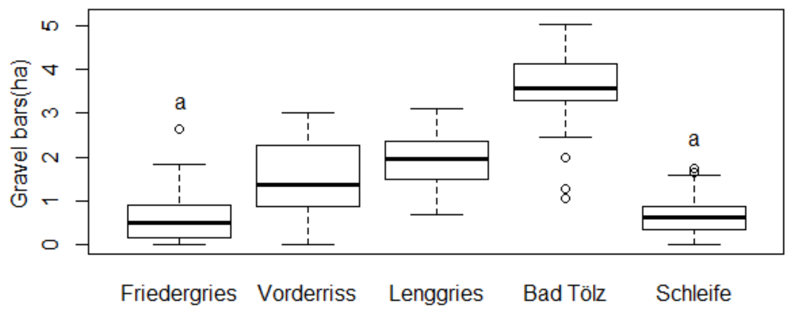

Figure 16: Gravel bar area per section in the 1800s. Letters indicate similarities (p-value of Dunn test >0.05), boxes without the same letter were significantly different.

After achieving the Kruskal-Wallis and Dunn tests, we find that the study sites had significantly (5% significance level) different gravel bar area per section in the 1800s, except the Litzauer Schleife and Friedergries which were similar. Bad Tölz had a significantly higher gravel bar area, followed by Lenggries and Vorderriss.

Now that the initial state is known, the decrease can be considered (Figure 17 to Figure 20).

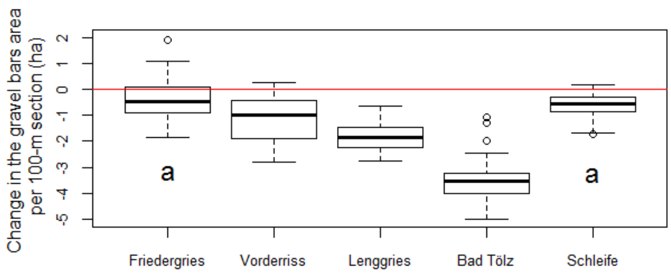

Figure 17: Decrease of the gravel bar area on the whole period: 1800s-2012

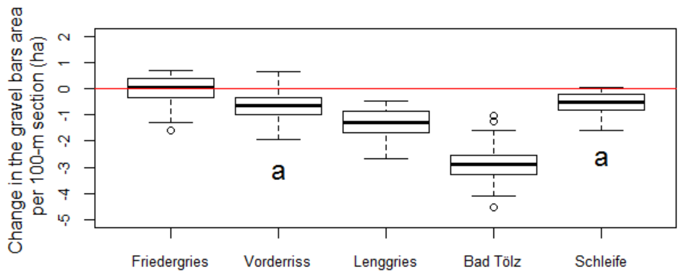

Figure 18: Decrease of the gravel bar area between the 1800s and the 1960's

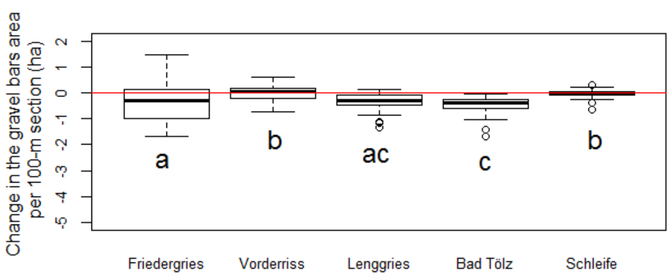

Figure 19: Decrease of the gravel bar area on the period 1960-1980

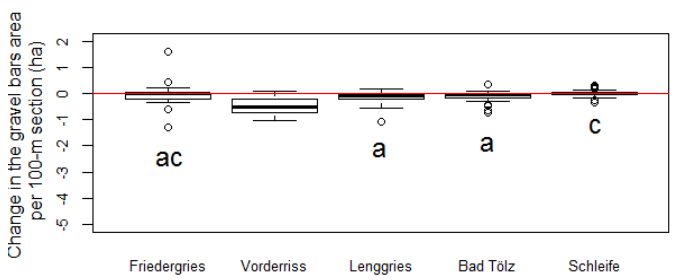

Figure 20: Decrease of the gravel bar area on the period 1980-2012

For the whole study period, from the 1800s to 2012, the decrease in gravel bar area was significantly different for all the study sites except between the Litzauer Schleife and Friedergries, to which the Dunn test gave a high p-value 0.3690 (the following paragraph refers to the results of the Dunn tests, presented in Annexe 4). This is surprising compared to the results of the first paragraph where the Schleife was much higher than Friedergries but the results were in percentage at this time.

The Figure 17 (change 1800s-2012) and Figure 18 (change 1800s-1960) are quite similar to the Figure 16 (gravel bar area 1800s). This is not surprising because in paragraph 3.2.1 we found that for three of the study sites, the decrease of gravel bar area on the whole period was beyond 90% and looking more precisely at each time frame, the major shift was mostly between the 1800s and 1960.

On the period 1960-1980, for each study site except Friedergries, the decrease appears lower than for the last period (Figure 19). This confirms also the observations of paragraph 3.2.1. In addition to that, Friedergries shows a very high variance.

At last, as regards the decrease observed between 1980 and 2012, Vorderriss is the only site to stand out, significantly higher than the others. This also confirms the observation of paragraph 3.2.1.

In a general way, the conclusions of paragraph 3.2.1 were confirmed: the major decrease in gravel bar area happened between the 1800s and 1960 and it was reduced of its quasi-totality in three study sites, the major change happened between 1960 and 1980 for Friedergries and between 1980 and 2012 for Vorderriss.

Nevertheless, we have some additional information. The average decrease on the Litzauer Schleife reaches zero quite fast, but it was also very low from the beginning. On the opposite, the decrease in Bad Tölz is especially high, but it was also the site with the largest gravel bar area in the 1800s. Furthermore, the high variance of Friedergries and the boxplot almost centered around zero shows that while some gravel bars disappear on some sections, other appear in other sections – the general trend staying the decrease of the total area.

3.2.3. Correlations

The following paragraph aims to analyse the impact of the geographic localization on the current situation of the gravel bars. On the basis of the results of Tockner et al. (2003) for the Tagliamento river, a wild alpine braided river, we expect to find, on the historic maps displaying a remaining natural dynamic, a maximal gravel bar areas on the upper part. We also expect to observe a larger decrease with a higher distance to the source, the prealpine regions being more populated and disturbed.

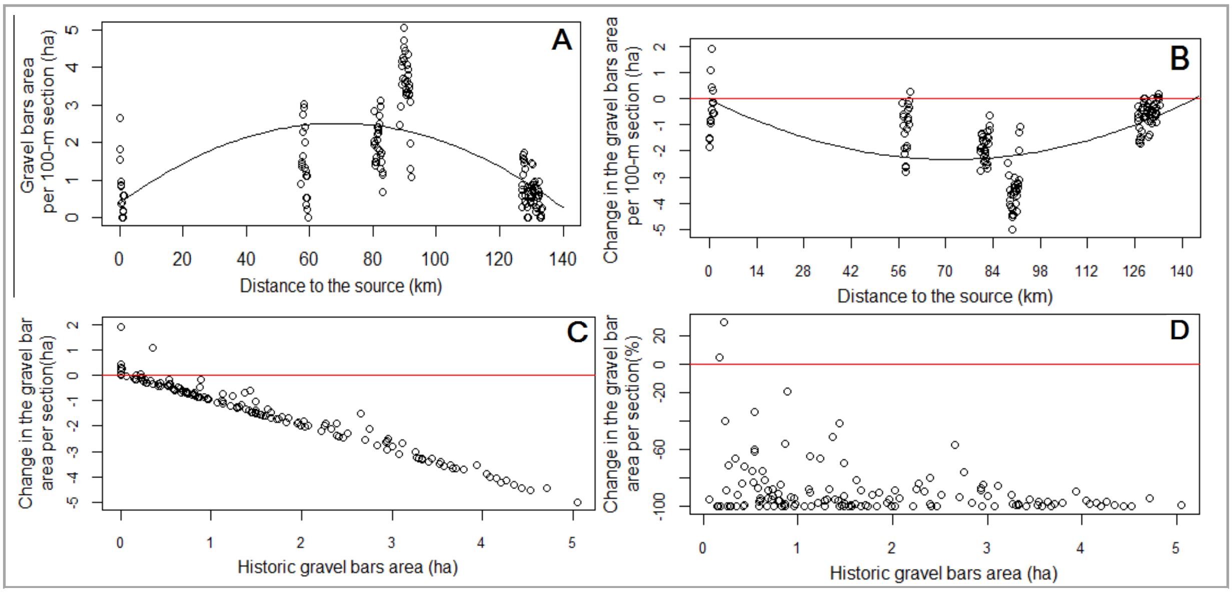

Figure 21: A: Correlation between the historic area and the distance to the source. R=0.41, p < 2,2e-16**. B: Correlation between the decrease of the gravel bars area and the distance to the source**. R=0.39, p < 2,2e-16
C: Correlation between the decrease of the gravel bars area (ha) and the historic availability in gravels. R= 0,98
D: Correlation between the decrease of the gravel bars area (%) and the historic availability in gravels

As expected, the historic gravel bar area, at a time when the Isar had still a natural dynamic, reaches a maximum but it is rather in the upper-middle part of the river (Figure 21 A).

The total decrease in gravel bar area is highly correlated to the historic availability in gravels (Figure 21 C and D): the more there was gravels, the more it decreased.

3.2.4. Verification of the water parameters

To put these first results into perspective, the average summer water parameters are confronted to the parameters observed when the aerial photographs, main support of this study, were taken.

As displayed on Figure 22, all photographs were taken at days with similar water discharges and around the normal average for Bad Tölz and Lenggries. Data of the 1960s are missing for Vorderriss and Friedergries, but the same observation can be made on these study sites for 1980 and 2012. Nevertheless, the values of the Litzauer Schleife are quite different and higher than the normal average in summer, this may have an impact on the results. Indeed, the decrease of the gravel bar area on the Litzauer Schleife may have been underestimated between 1960 and 1980, and between 1980 and 2012.

Many data of the 1960s and 1980s are missing to complete the Figure 23 which shows the water levels but it mostly leads to the same conclusions than the Figure 22. However, there is a slight difference for Bad Tölz where the values of 1980 and 2012 are lower than the normal average and quite distinct from one another. It means the decrease in gravel bar area in Bad Tölz between 1980 and 2012 may have been overestimated (impossible to state something unequivocally for 1960).

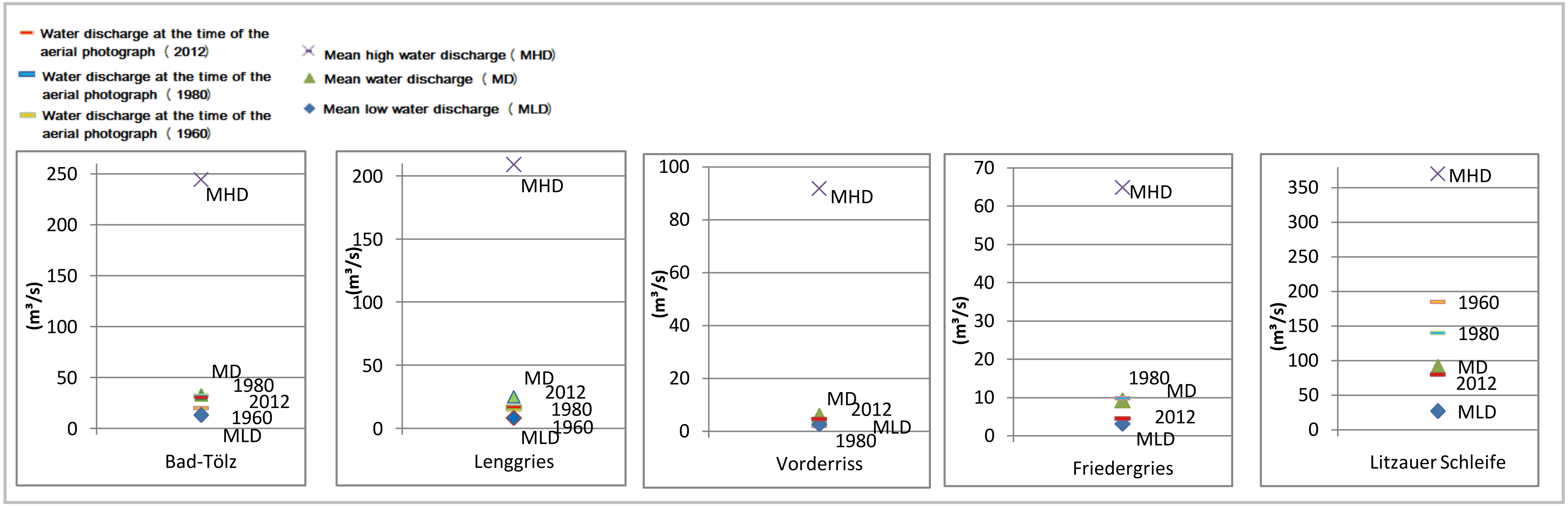

Figure 22: Comparison of the usual water discharge in summer and on the different days when the photos were taken

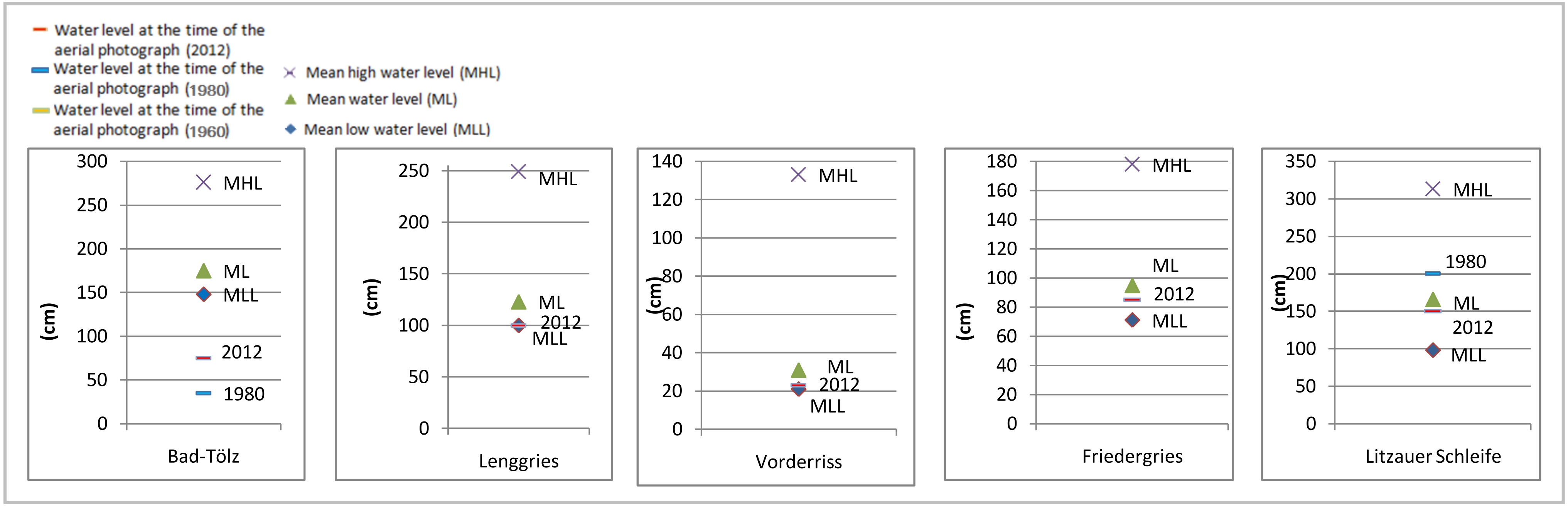

Figure 23: Comparison of the usual water level in summer and on the different days when the photos were taken

3.2.5. Comparison with former studies

We recall as introduction to this paragraph that the Litzauer Schleife is on the Lech river, Bad Tölz, Lenggries and Vorderriss on the Isar river and Friedergries on a tributary of the Loisach river. The Schleife is in prealpine region, Bad Tölz and Lenggries are on the limit between prealpine and alpine region and Vorderriss and Friedergris are in alpine region.

- *Reminder of the main results of the projects of 2012*

Regarding the project of Verena Weitmann, the only usable data relevant to be in this paragraph are the two graphs displaying the total gravel bar area on her two study sites, Garching and Oberhummel. These sites are located on the Isar, in the North of Munich where the river was strongly disturbed. The decrease, not available in the study, is calculated from the graphs using the axis as scale (Table 3). No further statistical data are available for this project.

Table 3: Decrease in gravel bar area calculated from the graphics of Verena Weitmann

	Decrease in the gravel bar area (%)	
	Garching	Oberhummel
1810-1900	40	83
1900-1960	90	11
1960-1970	-43	13
1970-1980	50	14
1980-1990	20	0
1990-2009	50	33
1810-2009	98	92

A table in Valerie Moos' project gives an overview of her measurements, it was simplified for the purpose of our study (Table 4). The relative decrease is the lowest for the Lech and Isar rivers.

Table 4: Decrease in gravel bar area observed in Valerie Moos' study

	Decrease in the gravel bar area (%)				
	Iller	Wertach	**Lech**	**Isar**	Inn
1800s-2009	89	89	78	79	100

Valerie Moos also studied separately the alpine region and the prealpine region of each river. It showed, among other things, that the gravel bar area on the Isar has significantly more decreased in the prealpine region than in the alpine region. In prealpine region, of all rivers, the gravel bar area on the Isar River has decreased the most and in alpine region, on the Isar and the Lech.

- *Confrontation with our results*

First of all, let us compare the results on the decrease in gravel bar area for the Isar river. For Bad Tölz and Lenggries we had a total decrease beyond 90% which is closer to the results of Weitmann. It is interesting to note that Bad Tölz, Lenggries and Weitmann's study sites are located rather in the prealpine region (Bad Tölz and Lenggries on the limit) and in areas with many human activities. On the other hand, Vorderriss, which is in the alpine region, had a value closer to 70% and to Moos' value (Table 4). The observation that the decrease of gravel bar area for the Isar river is significantly more important in the prealpine than in the alpine region applies quite well to our results for the Isar.

Moreover, if we look at the changes on Weitmann's sites on the different periods, the major shifts happened before 1960 for Garching and before 1900 for Oberhummel. It goes along the same lines as our results for the sites in prealpine region.

As regards the Lech river, the value obtained on the Litzauer Schleife was about 90% which is much higher than Moos' value. Nevertheless, she had 9 other study sites on the Lech river, 5 of which were in alpine region were the decrease in gravel bar area tends to be lower.

- *Comparison with Valerie Moos' correlations*

Another data provided by Moos' study are the correlation between historic and recent gravel bars after a log transformation. She found a positive correlation in alpine region (r_S=0.666) and in prealpine region (r_S=0.505). We had no strong correlation between the areas in the 1800's and the current area. It may be due to the fact that she had much more sites in alpine region, which were sometimes less disturbed and whose current gravel bar area may reflect better the historic area.

To conclude this paragraph, the values obtained in this study on the decrease in gravel bar area is consistent with the former studies and strengthen some of the hypothesis of Valerie Moos: the higher decrease in the prealpine region for the Isar river and a correlation with the past gravel bar area. It is comforting to note that three studies carried out by different persons with sensible different protocols lead to coherent results.

3.3. Analysis of the area of each vegetation type

The analysis on the different vegetation types will follow the same approach than the analysis of the gravel bar area. The maps in the 1800s were digitized only with a "vegetation" category, no fine comparison is possible with these years. There are no similar data to be compared in the former studies. We recall here that "herbaceous" refers to the areas with a woody vegetation below 20% of cover; "softwood" to areas with a woody vegetation over 20% and a vegetation cover of softwood species over 50%; "hardwood" to areas with a woody vegetation over 20% and a vegetation cover of softwood species below 50%.

3.3.1. Absolute area and evolution on the whole study site

The evolution of the area of the different vegetation types was firstly calculated by summing the area of the polygons of each category on the whole study site (Figure 24). The error bars reflect the possible digitizing error (buffer of 5 meters around the actual polygons).

We can see that between 1960 and 1980, the herbaceous area decreased everywhere ; it was mostly to the benefit of the softwood area. In this period, the hardwood area increased or remained quite stable.

Between 1980 and 2012, there is no general trend for the evolution of herbaceous area but the softwood area rather increased or remained stable. The hardwood area generally remained quite stable.

In the Litzauer Schleife, the last increase of the herbaceous area doesn't seem to be at the expense of the other vegetation types, it may have rather encroached on gravel bars.

Bad Tölz really stands out. Its evolution is strongly characterized by the transition from softwood to hardwood on both periods of time.

The area of each vegetation type remained quite stable in Lenggries.

Vorderriss and Friedergries show a similar evolution of the area of each form of vegetation, mostly the transition from herbaceous area to softwood area. The hardwood area in Friedergries is very high because the site was not as easy to cut than the others and we were interested in the evolution of vegetation outside the direct floodplain area.

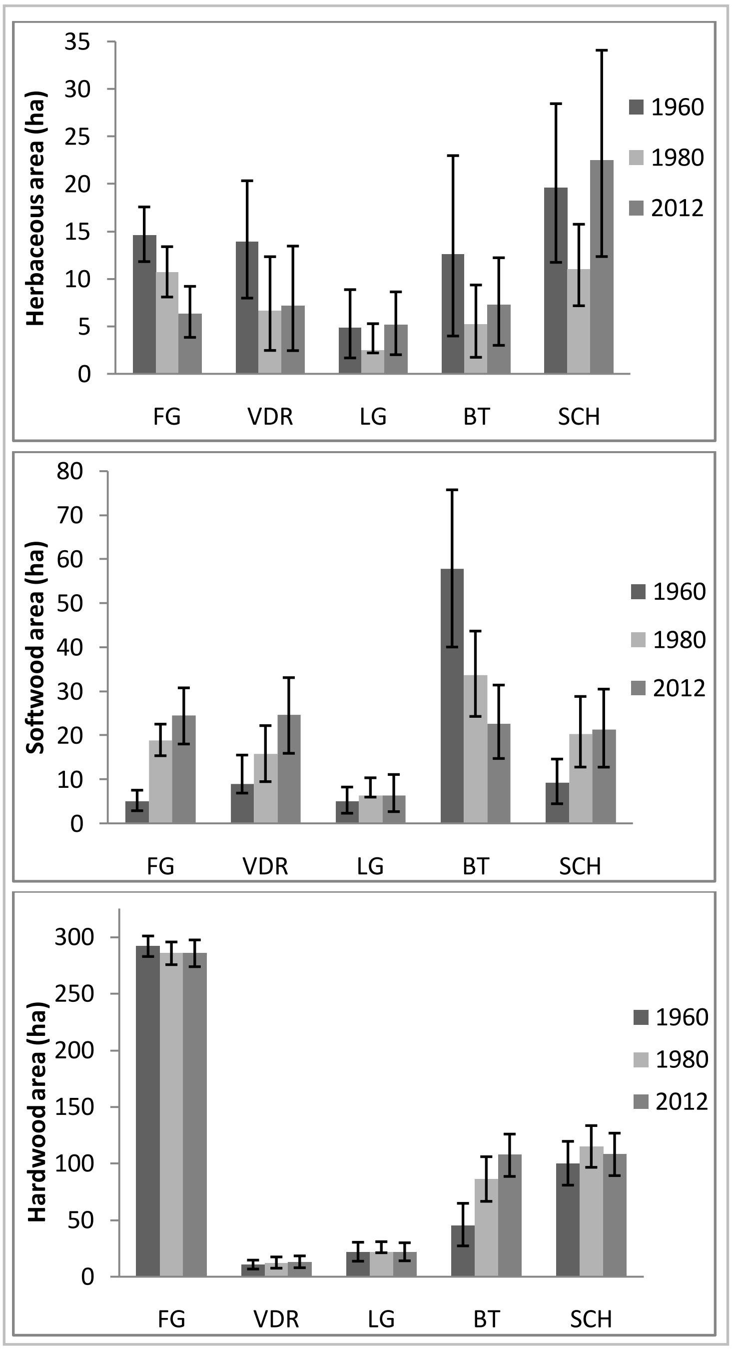

Figure 24: Evolution of the area of the different vegetation types over the 20th century (herbaceous on the top, softwood in the middle, hardwood in the bottom). The error bar reflects only the digitizing error. (FG: Friedergries , VDR: Vorderriss, LG: Lenggries, BT: Bad-Tölz, SCH: Schleife)

The error bars on Figure 24 do not allow to contradict most of our observations. They are quite high for the herbaceous area which was smaller than the other categories and for which a 5 m-buffer changes greatly the area.

To understand better the relations between each vegetation form and their relative importance in the floodplain, they were all presented in percentage of the total area on Figure 25. The precedent observations seem to be confirmed. We can add that in Bad Tölz and Vorderriss, the herbaceous area decreased more than the gravel bar area. The changes mostly happen between 1960 and 1980.

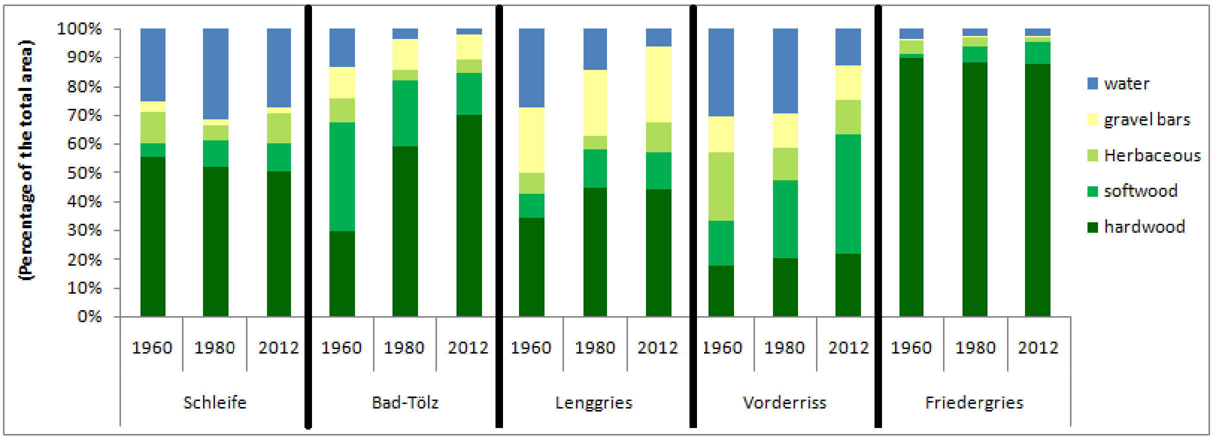

Figure 25: Relative occupation of the gravel bars, water course and the different types of vegetation in the floodplain

It is not possible to analyse the evolution of the different types of vegetation since the 1800s, but we can at least compare the evolution of the total area of vegetation in the floodplain. Between the 1800s and 1960, the total vegetated area was quite stable for the Litzauer Schleife (+2,5%), Lenggries (-2,1%) and Friedergries (-1,1%) but it doubled for Bad Tölz (+99,3%) and more than double in Vorderriss (+119,0%).

For a better understanding of this evolution, we look at the evolution per decade of the total floodplain area (Figure 26). Differences within 1% may be due to the difficulty of clearly delineate the floodplain as described in Chapter 2. However, the floodplain area was significantly reduced in Lenggries, especially between 1960 and 1980, and in Bad Tölz before 1960.

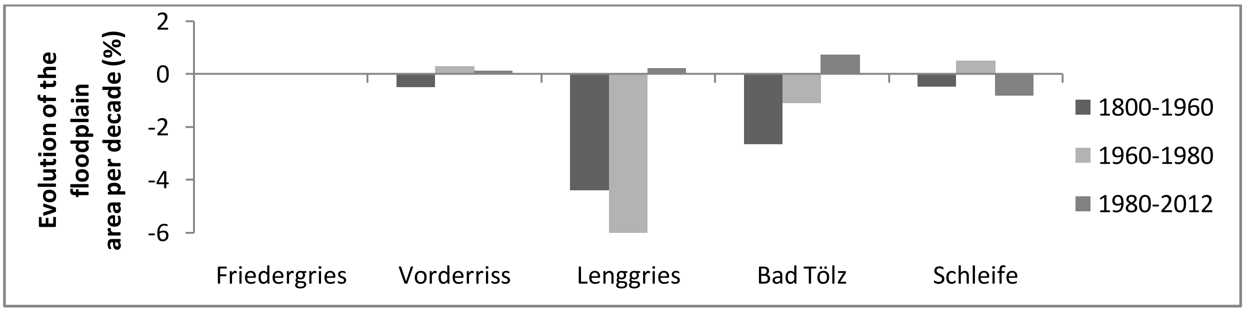

Figure 26: Evolution per decade of the total floodplain area.

3.3.2. Statistical analysis after segmentation

The statistical analysis of the evolution of the area of each vegetation type was displayed the same way as for gravel bars (Figure 27). Before looking at the decrease, the “initial state” was checked, like in paragraph 3.2.2.: the boxplots of each vegetation type in 1960 were established and statistical tests were carried out (Annexe 4) to analyse the differences.

In 1960, as regards the herbaceous area, the study sites are ranked in two groups : Bad Tölz, Vorderriss and Friedergries with a higher herbaceous area, Friedergries having an especially high variance; the Litzauer Schleife and Lenggries are similar to one another with lower herbaceous area.

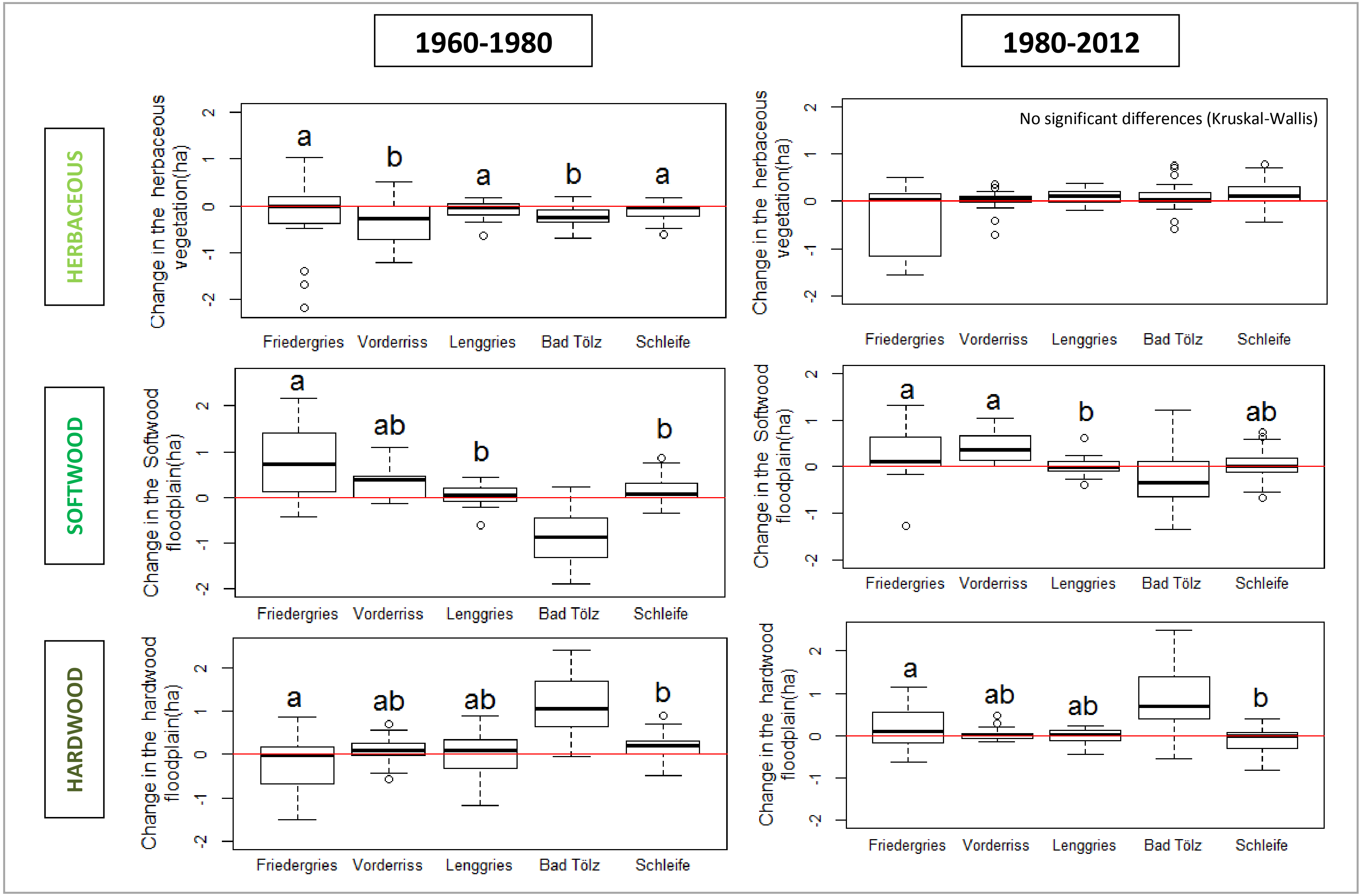

Figure 27: Decrease in hectare of the area of each vegetation type per section for both periods 1960-1980 and 1980-2012.

This is already a difference with the precedent paragraph where the Litzauer Schleife seemed to have a higher herbaceous area. The segmentation may have smoothed disparities along the river.
As regards the softwood area in 1960, Bad Tölz is followed by Vorderriss, significantly different from the others although it was not so clear on the last paragraph.

Now that the vegetation in 1960 was checked, we can look at Figure 27 and the evolution over the late 20th century. Between 1960 and 1980, all study sites have a similar decrease of the herbaceous area, Bad Tölz and Vorderriss a bit more than the others (statistical tests in Annexe 4) but they had a larger herbaceous area in the first place. Furthermore, the changes in the area of each vegetation type and the groups of study sites observed are similar to what we saw in paragraph 3.3.1.

In conclusion to this paragraph, the statistical analysis confirmed the observations made in paragraph 3.3.1, with the transition from herbaceous to softwood on some sites and from softwood to hardwood on others. It brought new information on the Litzauer Schleife, for which some changes are not so strong as displayed in Figure 24, and on the disparities within the different study sites (variances). Indeed, Bad Tölz and Friedergries seem to display many disparities. In addition to that, the statistical tests often showed that the Litzauer Schleife and Lenggries have low and similar values for the evolution of the vegetation types.

3.4. Shape form index

In the following paragraph, the question of the complexity of the landscape is raised. The Area-Weighted Mean Shape Index (AWMSI) was calculated for each maps (Figure 28) and we had the values of AWMSI of Verena Weitmann in the form of graphs. We recall that the higher the AWMSI is, the more complex the patch shapes of the landscape are.

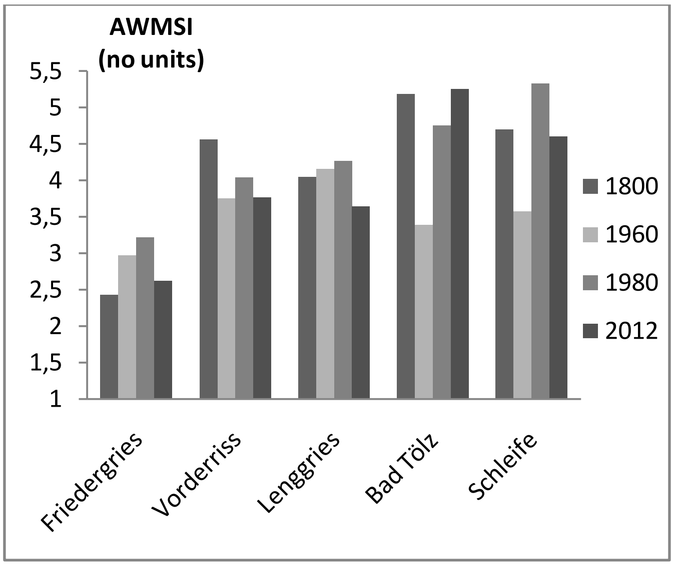

Figure 28: Area-Weighted Mean Shape Index (AWMSI) calculated for each digitized maps.

Firstly, considering the absolute values of the AWMSI on our sites and on Weitmann's sites, we noticed that her values almost never exceed 2 and our values are always above.

Several explanations are possible :

- The complexity of the landscapes in Garching and Oberhummel is indeed lower than in our study areas. Looking at the maps available in Weitmann's report, it seems to be possible, the river being early and strongly disturbed and linearised.
- The formula of the AWMSI was differently understood. In this formula (Choice of indicators, page 16), the total sum is divided by the "total landscape area". Yet we choose to map only the floodplain area, which is often decreasing in time, when Weitmann mapped a fixed area for each year. Her maps from the 1970s to the 2000s display unmistakably a larger area than only the floodplain : her AWMSI is calculated on a larger landscape and is therefore lower.
- There is a difference in the precision of the digitizing work. This is certain because she mapped the aerial photographs on a 1:1000 scale and a 1:800 scale was used in our study.

In addition to that, the fact that the AWMSI in Weitmann's report is applied to a larger area than the floodplain with polygons for the roads and private gardens means that the complexity observed may not reflect the only complexity of the natural environment but also of the human environment (except if she proceeded differently which is not mentioned). It does not seem relevant to further compare and we will now consider the Figure 28 alone.

The value of the 1800s for the AWMSI are to be taken with caution because the digitizing of the historic maps are much less precise than for the photographs. Except in Lenggries and Friedergries, it strongly decreased everywhere between the 1800s and 1960. The historic map of Friedergries is quite imprecise.

Between 1960 and 1980, the AWMSI increased everywhere but only moderately in the three first sites. In Bad Tölz, it even skyrocketed and continued to skyrocket between 1980 and 2012 whereas it decreased everywhere else.

Aside from the comparison of temporal variations of the AWMSI, it is interesting to do a geographic comparison of the index. It seemed that Friedergries had the lowest AWMSI and the Schleife the highest. Therefore we calculated the Pearson correlation between the AWMSI of 2012 and the distance from the source in kilometer, we found a coefficient of 0,821.

3.5. Neighborhood index

The results of the analysis of the polygons neighborhood is presented in Table 5. For each category of patches, the cell indicates what is the adjacent category the more likely to be found. A simple color code was used to make the reading easier. The historic maps were not included in this analysis because there was not enough information about their vegetation.

Table 5: Main neighbor for each category on the different maps (except the historic map)

		Friedergries	Vorderris	Lenggries	Bad Tölz	Schleife
Gravel bars	1960	Hardwood	Water	Water	Water	Water
	1980	Hardwood	Water	Water	Water	Water
	2012	Hardwood	Water	Water	Water	Water
Herbaceous area	1960	Gravel bars	Softwood	Gravel bars	Softwood	Hardwood
	1980	Softwood	Softwood	Softwood	Hardwood	Hardwood
	2012	Softwood	Softwood	Softwood	Hardwood	Softwood
Softwood floodplain	1960	Hardwood	Herbaceous area	Hardwood	Hardwood	Hardwood
	1980	Hardwood	Herbaceous area	Hardwood	Hardwood	Hardwood
	2012	Hardwood	Hardwood	Hardwood	Hardwood	Hardwood
Hardwood floodplain	1960	Gravel bars	Softwood	Softwood	Softwood	Softwood
	1980	Gravel bars	Softwood	Softwood	Softwood	Softwood
	2012	Softwood	Softwood	Softwood	Softwood	Softwood

As regards the gravel bars, it was expected that the water course will be the main neighbor. For Friedergries, on the contrary, hardwood is the main neighbor. This is also not surprising because there is only a small stream in Friedergries but very widespread forests. Lacking information, we will later look at the second most frequent neighbor of gravel bars in Table 6.

Except for the Litzauer Schleife, the Table 5 confirms that the trend is the encroachment of woody vegetation everywhere. If we look at the categories in contact with the herbaceous areas, it switched from softwood to hardwood in Bad Tölz and to gravel bars to softwood in Lenggries and Friedergries. In Vorderriss, the category mostly in contact with the softwood areas switched from herbaceous to hardwood area and in Friedergries, the hardwood areas were mostly juxtaposed to gravel bars and are now rather in contact with softwood.

Table 6: Second most frequent neighbor of gravel bars

		Friedergries	Vorderris	Lenggries	Bad Tölz	Schleife
Gravel bars	1960	Herbaceous	Herbaceous	Herbaceous	Softwood	Herbaceous
	1980	Water	Softwood	Hardwood	Hardwood	Softwood
	2012	Softwood	Softwood	Herbaceous	Hardwood	Herbaceous

This table shows that the zones in contact with gravel bars are varying greatly. The encroachment is confirmed in Bad Tölz, Vorderriss and Friedergries like earlier. There is no clear trend for the Schleife and Lenggries where the vegetation changed again between 1980 and 2012.

4. Discussion

4.1. Discussion on the results

The discussion of the results is structured in two parts: first a discussion on the general trends we observed; followed by a discussion on the specific situation at each study site.

Our results showed that the decrease in gravel bar area was high at every site but there were significant differences between the study sites, with decrease ranging from from 30% to 90%. The change of gravel bar area over time at the Schleife, Bad Tölz and Lenggries sites was high in each case and similar to one another, while Vorderriss and Friedergries stood out as different. This is consistent with the hypothesis that prealpine regions were more impacted than alpine regions, as Valerie Moos (2012) had expected. This might be due to the fact that prealpine areas was straightened earlier to protect the populations there (scarcer in the Alps) and to the need for electricity for the populations higher in the Prealps. The calculations of the correlations even allowed a further observation on the geography of the phenomenon: when the Bavarian rivers still had their natural dynamic, the gravel bar area reached an optimum on the upper part of the rivers, like observed by Tockner et al. (2003) on the Tagliamento.

The evolution of floodplain vegetation is more uneven between the study sites and seems to depend more on very local events than on region-scale events. Local events can include urbanization, pastoral activities or more specific events like the return of water to the river bed of Vorderriss. For the Schleife and Lenggries, there was not a very marked change in the areas for each type of vegetation, but at the other sites there was a clear trend of encroachment by woody vegetation: a transition from herbaceous to softwood in some cases, and rapid transition from softwood to hardwood in others. The deepening of the river bed is involved in this process: with the pioneer areas not being flooded enough, the woody vegetation is able to develop and stabilise (Gilvear et al. 2007). Organic water pollution may also lead to an acceleration of the aging of the vegetation. Indeed, Jürging & Patt (2005) showed that the nutrient load increases with the distance to the source, what can be explained by the concentration of agricultural activities, and this fosters the number and abundance of competitive and ruderal species.

The study showed that at most of the study sites, the complexity of patch shapes increased between 1960 and 1980: it may be related to the fragmentation of the gravel bars, the encroachment of the softwood areas and the fragmentation of the herbaceous area. The following decrease of the shape complexity after 1980 may correspond to the softwood area and the hardwood area that grow and homogenize the landscape. We also found that the further we go from the source, the more complex the landscape is becoming.

- *Friedergries*

In Friedergries, gravel bar area was found to have decreased by up to 30%, which is far less alarming than the other study sites. The main changes in the distribution of the gravels and vegetation areas occurred between 1960 and 1980. The large area of herbaceous vegetation has decreased to the benefit of softwood species. The high variance observed shows there are disparities within the study site and looking at the maps (Annexe 3) we note there is indeed a high East-West variability.

These observations are consistent with the history of Friedergries (Kortenhaus, 1987). Historically, the stream flowed to the south-east, which we noticed on the map from 1826. But in the 1930s the stream almost flowed directly to the South (Doposcheg, 1938) and during World War II, a dam was built at the top of Friedergries to make sure it flows entirely to the south-east again to avoid mudflows in Griesen, a village downstream. Our study shows that this construction did not have a strong impact on the total gravel area. At the beginning of the 1960s, the dam broke and the stream flowed to the south-west (Kortenhaus, 1987). This explains the significant shift observed in the maps and statistical analysis after 1960. After 1983, the stream moved further to West. Our study did not find a significant decrease in the gravel bar area after this. Nevertheless, while the decrease in the gravel bar area has stabilised, the softwood area has been growing sharply at the same time.

For the period up until the 1980s, the observations for Friedergries are rather positive: the gravel materials were constantly being relocated and this assured a natural dynamic suitable to valuable plant species and communities. However, over the last 30 years, a large section of the gravel has not been redistributed and this has led to a large woody encroachment, which could be harmful to pioneer plant species of interest.

In terms of management for the re-introduction of *Chondrilla chondrilloides*, the analysis of the past events and its consequences on the evolution of each landscape patch might help to understand the distribution of the specie. Moreover, if it is ever considered to re-introduce the specie elsewhere, the analysis between the gravel bar area and the distance to the source could help to discriminate which site is more interesting than the other: indeed we showed that some sites had a higher historical availability in gravels and that some had a faster and more important decrease, it could be taken into account.

- *Vorderriss*

In Vorderriss, the decrease in gravel bar area is lower than at other sites on the Isar but still measures 70% for the study period. Like at most sites, the decreases occured before 1960. Furthermore, Reich (2009) states that human activities might have been disturbing the bed-load balance in this sector since approximately 1850. As our historic map is from 1864, it means our first measurements might represent a river with an already slightly damaged dynamic. Nevertheless, the main impact on the gravel bar area appears to be the construction of the barrage of Krün 12 km upstream of our study site in 1923. We showed that the total vegetation area doubled between 1864 and 1960. Following construction, the water flow downstream the barrage of Krün was not enough to redistribute the gravel bars and maintain the pioneer stages of vegetation. It allowed willows to establish and the river banks to become stabilised (Reich, 1994).

It is interesting that the decrease in gravel bar area is nearly null between 1960 and 1980. It seems that the phenomenon stabilised. As our study site is located on a 70-km²-wide catchment area and the annual precipitations rise to 1500 mm (hnd-bayern.de), there might have been enough water flow to achieve a balance, despite the water loss in Krün.

However in this period of time, the study showed a major shift in the herbaceous area. While it was quite large in 1960, it had sharply reduced in favor of the softwood area by 1980. If we had earlier data on the 20th century, it would maybe indicate that this observation is the continuation of a phenomenon that has been going on for decades.

A major decision occurred between 1980 and 2012: from 1990, the water flow in Krün has been partially returned to the natural bed.

Our study observed that the highest decrease in the gravel bar area over the late 20th century was between 1980 and 2012 (above 50%). This indicates that despite the return of water flow and the very high floods of 1999 and 2005, the dynamic of the river could not be restored. This seems to be confirmed by the observations of Reich (2009) and Plachter (1998). The return of this water may even have been counterproductive to a certain extent, supporting the growth of willows. The returned flow would not be enough in itself if the sedimentation does not get its natural dynamic back. And this can’t happen if the gravel material has already been removed.

- *Lenggries and Bad Tölz*

Both of these study sites are quite close together compared to the others: only a few kilometers away from one another. The same total decrease in gravel bar area was measured at both these sites, over 90%, and they had the same pattern of evolution, with the majority of the decrease occurring before 1960. This is not surprising given the geographic proximity of the two sites and given the fact that there is no additional weir between the two sites. In reality , the transition is like to have mostly occured between 1912 and 1938 (Speer 2015, quoting data from the Water Management Office (WWA)-Weilheim): at this time, a new river course was built for the Isar and the cut banks (where most of the erosion happens) were consolidated. Most of the high water should have flowed into the channel that was built and the rest into the floodplain. In the beginning, the floodplain was being flushed with water at each time it flooded but the Isar deepened soon in the shorter course. Once that occured, there was enough volume in the river bed to contain the high waters and most of the floodplain went dry. The construction of the barrage of Krün in 1923 surely would have had a great impact here as well. In addition to that, the construction of the Sylvenstein reservoir lake in 1959 led to a further decrease in gravel bar area.

The area of each type of vegetation has not changed significantly at Lenggries, this stands in contrast to Bad Tölz where the softwood area decreased greatly to the benefit of hardwood species. Between 1960 and 1980, there was also a significant decrease in herbaceous area at Bad Tölz. Comparing the total vegetation area at Lenggries with the historic maps shows a stable evolution but the total vegetation area at Bad Tölz has more than doubled. This means that for Bad Tölz, the gravel bar area has been reduced by the encroachment of woody vegetation. The same is not true at Lenggries: on this site, the whole floodplain area decreased.

Speer (2015) provides information on the restoration measures that were taken in Lenggries and Bad Tölz from the 1990s. In Lenggries in 1997, the vegetation and the humus soil was removed on some areas, the aim being to remobilise gravel bars during floods over the next 10 years. They knew there was a risk that the vegetation would grow again if floods failed to appear, which is what happened when we look at our results: there was no major change to the vegetation and the gravel bar area keeps decreasing noticeably. In Bad Tölz, between 2012 and 2015, shrubs were mechanically removed on a 12-ha wide area and it will be interesting to follow the evolution of the vegetation area afterwards (orthophotos of 2015 are not available yet).

- *The Litzauer Schleife*

On the Litzauer Schleife, the gravel bar area along the Lech has decreased by more than 90% over the whole study period, occuring mostly before 1960. Valerie Moos observed a decrease of 78% between the 1800s and 2009 on the Lech but with a high variance between her 10 sites, it confirms that the Schleife is a sector of the Lech that has been especially damaged.

Our statistical analysis showed that there was no significant decrease in gravel bar area after 1960. However, looking at the water parameters, we found that these decreases (between 1960 and 1980 and between 1980 and 2012) may have been underestimated. Moreover, we would have expected that the construction of three hydropower stations upstream from the Schleife would have impacted the gravel bar area after 1960: a station was built 8 km upstream in 1966, another 11 km upstream in 1966, and one 17 km upstream in 1970 (source: websites of E.On and AÜW, the operating companies). It is possible that the gravel bar area in 1960 was already too low to observe a significant decrease after construction of these stations, or that nature conservation stakeholders actually managed to preserve this site. Amongst other things, their actions have successfully prevented the construction of an additional hydropower station in the sector in the 1960s (Deutinger, 2001).

No sharp change in the vegetation area was found here for any of the vegetation types but looking at the maps (Annexe 3) we see that vegetation distribution changes regularly, which shows that the river remains relatively dynamic here. The limits of the floodplain have not changed but in this sector the river is very deep and the slopes are not conducive to human activities.

4.2. Discussion on the methodology

The method of photo-interpretation implies an inherent bias : we map what we see from an aerial view, but the real ground cover is sometimes hidden. This was especially true for Friedergries where high trees grow directly in the river bed and so are difficult to delineate. Another bias of the method is the cartographer's interpretation, especially if not an expert. To avoid this problem, the mapping key was established after looking at each study site (through pictures and in the field), which was then strictly followed. The different digitized maps were also regularly reviewed to make sure the categories were mapped in an homogeneous way.

The limits of the floodplain may have been overestimated on some study sites where they were not clearly delineated by private gardens, roads or buildings. However, this would only impact the results for hardwood area, being almost systematically at the outer limit of the floodplain, and this would not strongly impact the interpretation of our results.

With such a method, it is not possible to overcome the limitation resulting from large fluctuations in the water parameters. A way to overcome this would be to increase the number of study sites and sampling dates to reduce the eventual disparities. But the more practical limits of time and financial costs did not allow for this. If the data were sufficient, a correction of the gravel bar area taking into account water level would be interesting. This is not possible here given the lack of historic data (1800s and 1960s). This may be possible for studies focusing only on aerial photographs of 1980 and later.

To assess the gravel material, we used orthophotos and aerial photographs. For several study sites that were very flat, there would be no important differences. It may have an impact for the Schleife which is deep and Friedergries which has a steep slope. However the error would be rather on the limits, in the sectors with higher trees and higher reliefs: this would impact the limits of the hardwood area which often didn't change much between the different years.

The study sites were chosen to be related to the Hotspot-Project. This means they are threatened natural environments but also that there is still something to be saved. Consequently, it is possible that the decrease observed is actually an underestimate when compared to other sites along the targeted rivers.

5. Conclusion

The study meets a requirement of the Water Framework Directive which suggests to establish reference conditions for surface waters by using historical data and to assess the impact of human activities. It quantified a process on Bavarian rivers that had been qualitatively described in literature and confirmed the almost total decrease in gravel bar area over the last 150 years in prealpine region.

In terms of management, the better understanding of the floodplain dynamics is essential to address restoration and conservation purposes. Strategies which don’t take it into account could be inefficient or counterproductive as illustrated by the situation in Vorderriss and partial negative consequences of the water flow returned into the natural bed without restoration of the gravel input.

The assessment of the situation at different points in time and the connection made with historic facts proved how strong human interferences can impact the natural environment. In Friedergries in the past it also led to positive consequences and it let us hope that future actions taken by nature conservation stakeholders may be able to slow down the current trend. Moreover, the quantification offered in the present study could be a tool in discussions with political authorities and help stakeholders to set quantified goals on the areas to restore.

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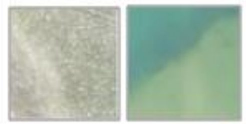
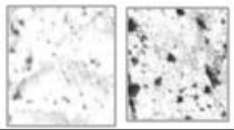
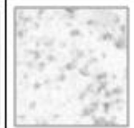
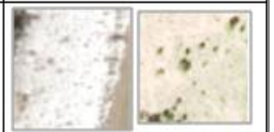
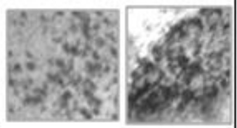
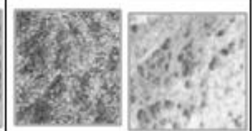
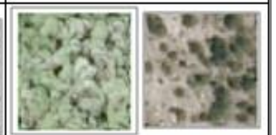
Table of Annexes

Annexe 1: Mapping key

Category	Description	Section on a 1:800 scale		
		1960	1980	2012
Gravel bars	Water cover < 50 % No vegetation visible			
Water course	Water cover > 50 %			
Herbaceous	Vegetation visible lower than 1 meter (no relief, no shadows) Woody vegetation < 20%			
Softwood	Woody vegetation >20% Softwood species (willow, ash... : light color, wavy form) >50%			
Hardwood	Woody vegetation >20% Softwood species <50% Darker color, heterogeneous aspect, star-shaped if resinous			

Annexe 2: Verification of the water parameters

- **Research of the relevant data: water stations and dates**

Study site	Closest water station	Days on which the aerial photographs were taken		
		1960s	1980s	2012
Litzauer Schleife	Lechbruck / Lech	09.09.1960	25.07.1980	24.07.2012
Bad Tölz	Water discharge: Bad Tölz KW / Isar Water level: Bad Tölz B472 / Isar	22.08.1960	24.09.1983	29.06.2012
Lenggries	Lenggries / Isar	10.09.1960	24.09.1983	27.07.2012
Vorderriss	Rißbachdüker / Isar	09.09.1959	19.09.1983	20.08.2012
Friedergries	Garmisch o. d. Partnachmündung / Loisach	17.06.1960	09.08.1983	27.07.2012

- **Values for the water discharge (m^3/s)**

		Litzauer Schleife	Bad Tölz	Lenggries	Vorderriss	Friedergries
Average values in summer	Low water discharge (LD)	12,2	7	3,38	0,52	1,72
	Mean low water discharge (MLD)	26,8	13	8,16	2,66	3,14
	Mean water discharge (MD)	91,6	33	25,3	5,94	9,27
	Mean high water discharge (MHD)	370	244	209	91,8	64,9
	High water discharge (HD)	971	582	608	291	182
Values on the days of the photos	1960s	185	20	17,5	Unknown	Unknown
	1980s	140	32	15	2,1	9,8
	2012	80	30	17	4,7	4,5

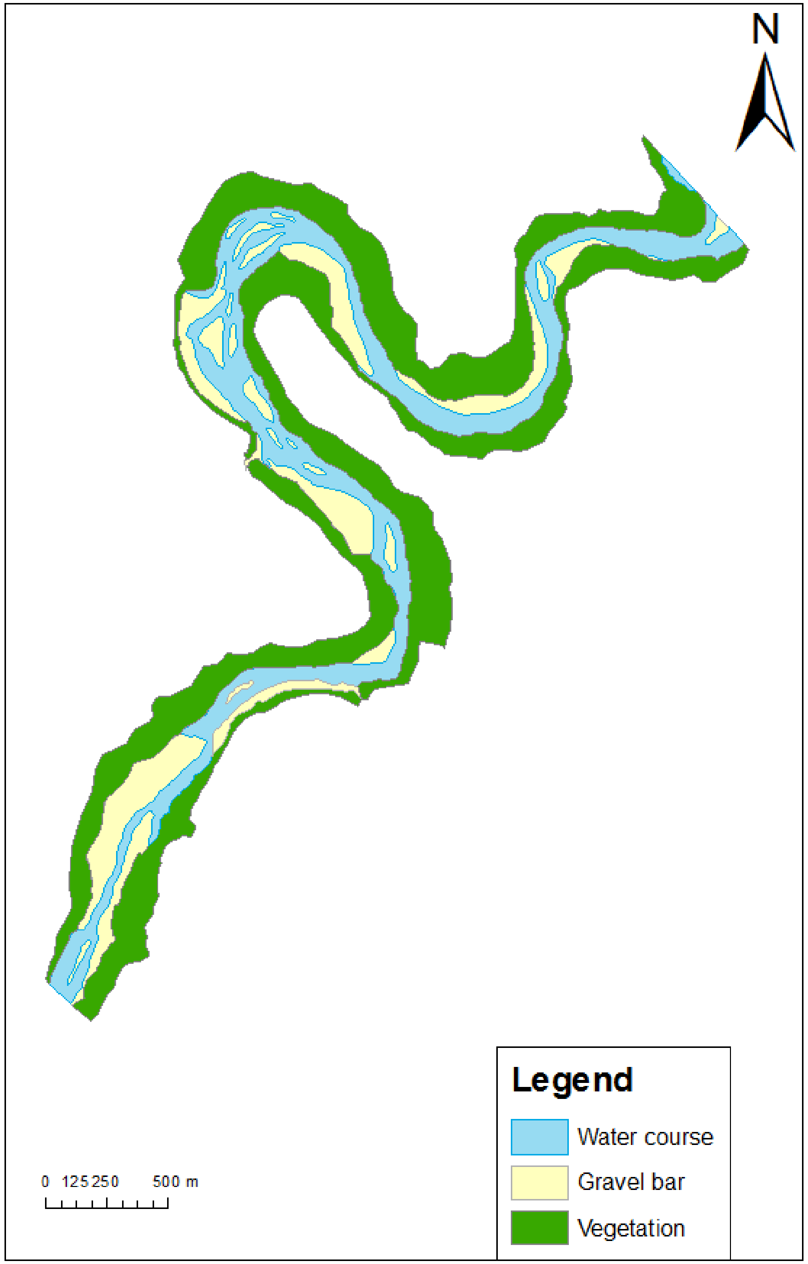
- **Values for the water level (cm)**

		Litzauer Schleife	Bad Tölz	Lenggries	Vorderriss	Friedergries
Average values in summer	Low water level (LL)	74	130	75	15	50
	Mean low water level (MLL)	98	148	100	21	71
	Mean water level (ML)	166	175	123	31	95
	Mean high water level (MHL)	313	276	249	133	178
	High water level (HL)	457	300	421	252	288
Values on the days of the photos	1960s	Unknown	Unknown	Unknown	Unknown	Unknown
	1980s	200	35	Unknown	Unknown	Unknown
	2012	150	75	100	23	85

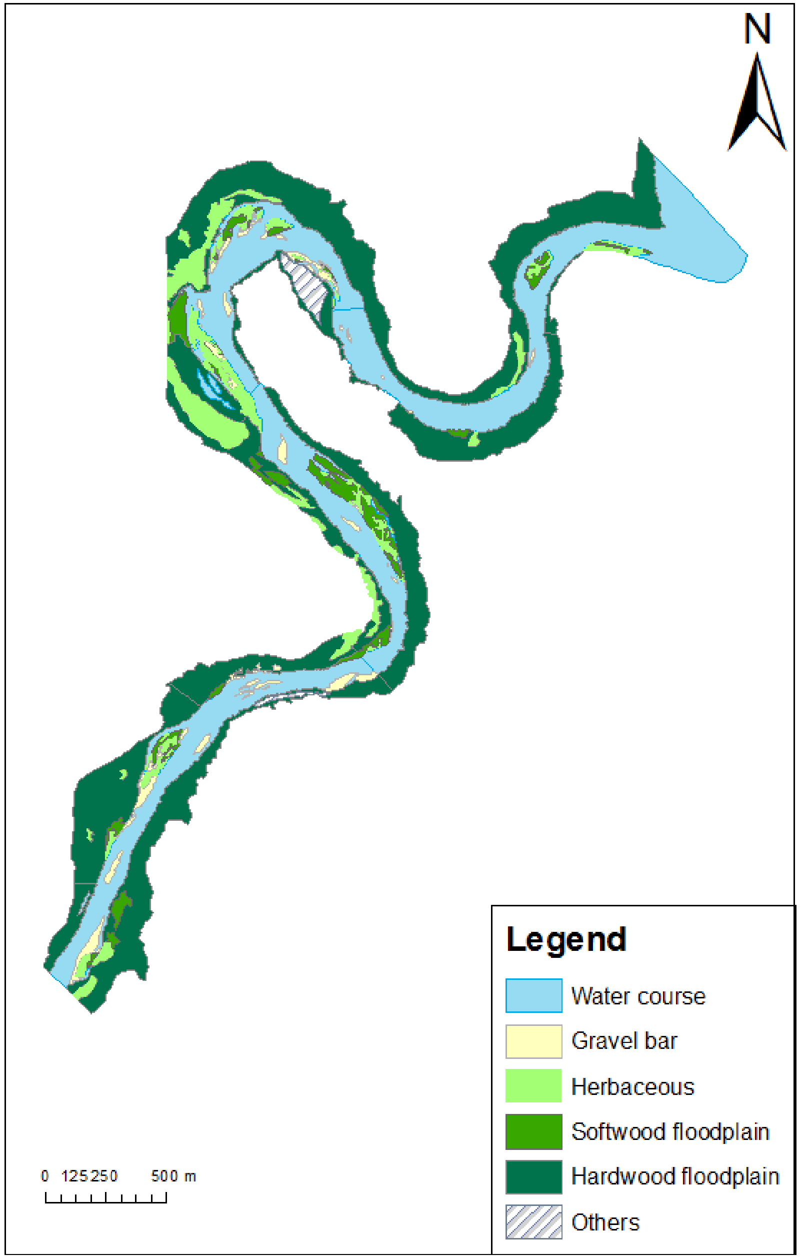
Source : http://www.hnd.bayern.de/

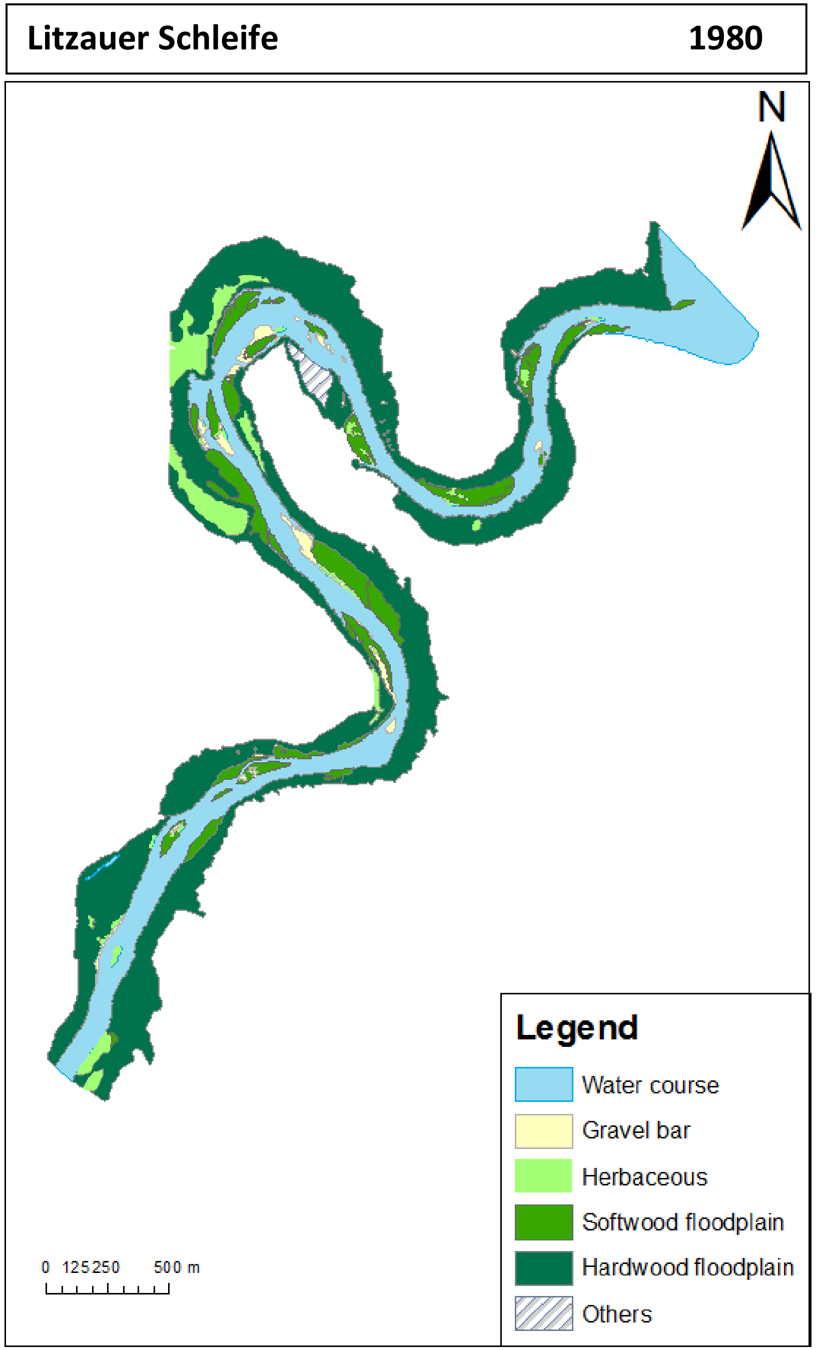
Annexe 3: Digitized maps of each study site and for each year

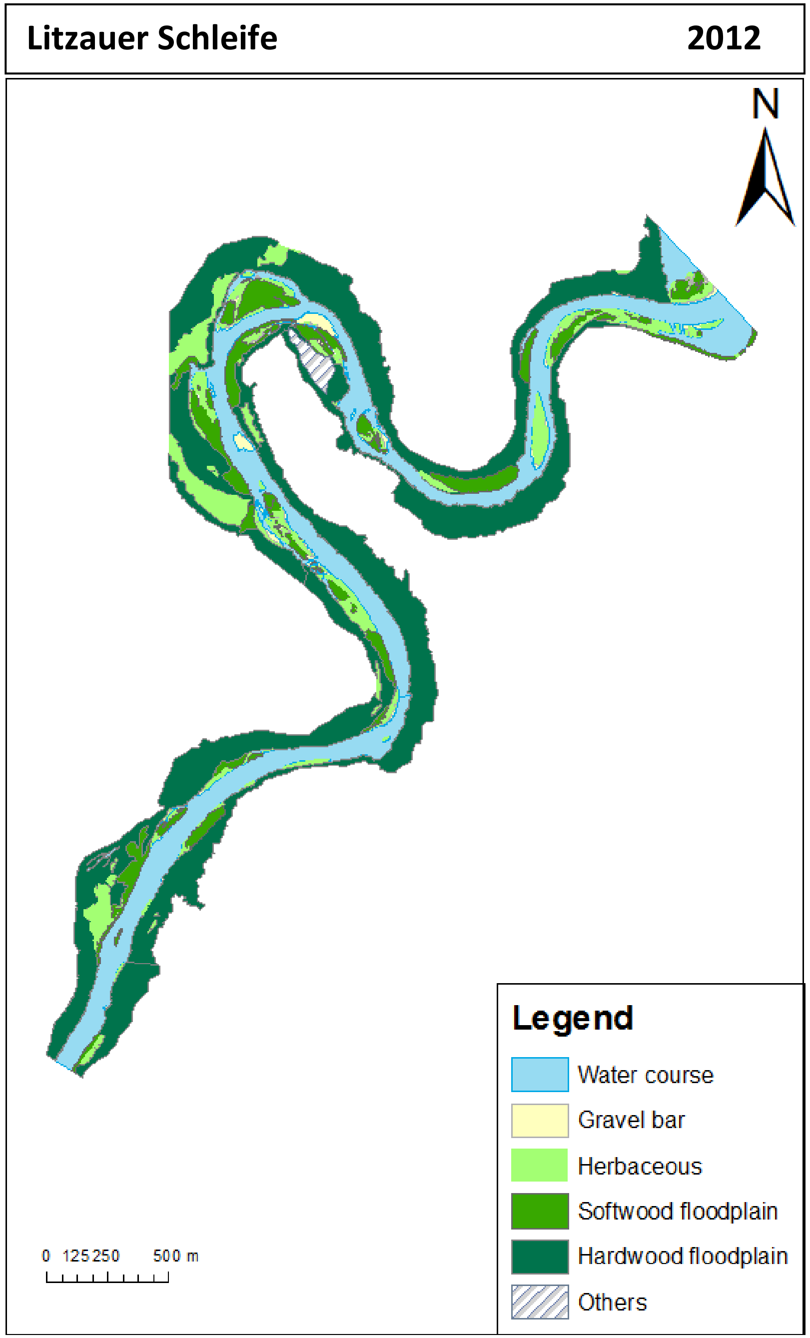
Litzauer Schleife **1838**

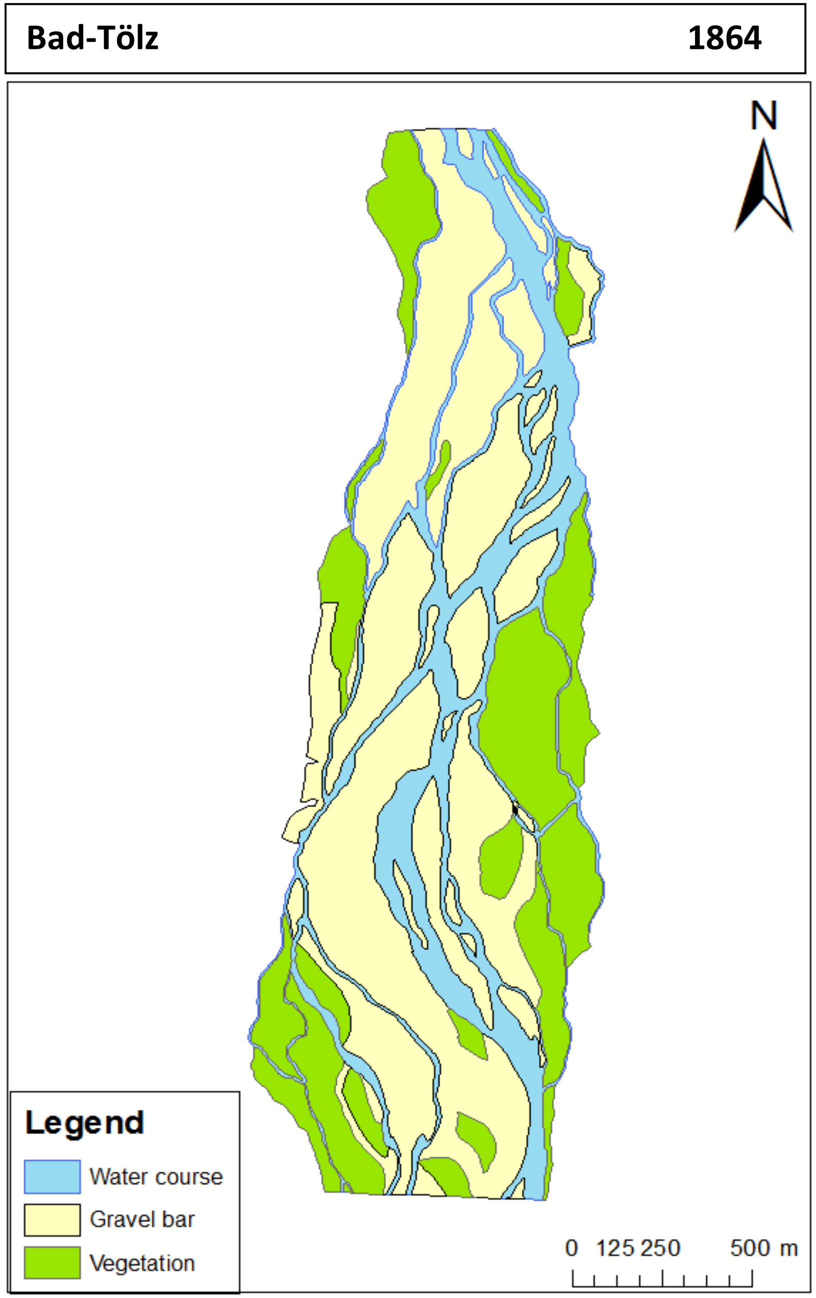


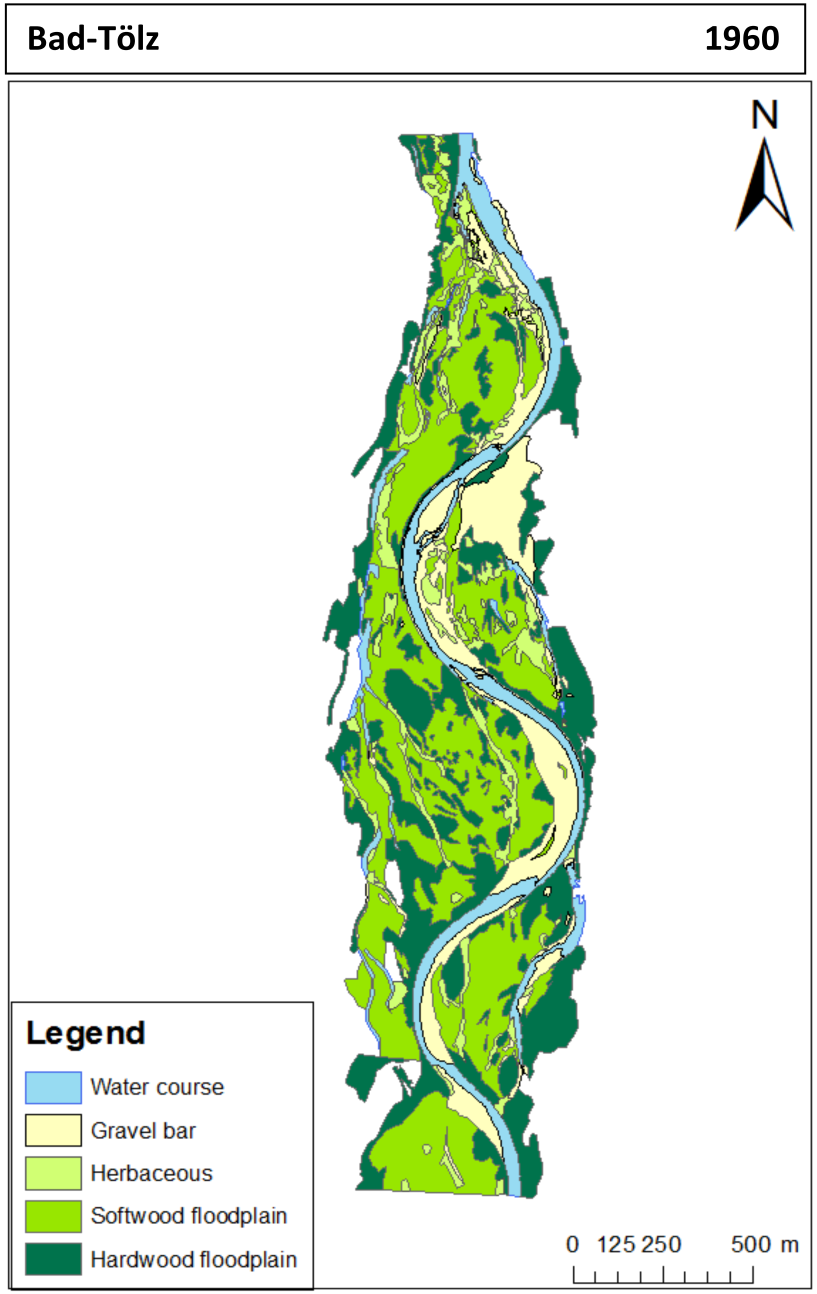
Litzauer Schleife **1960**

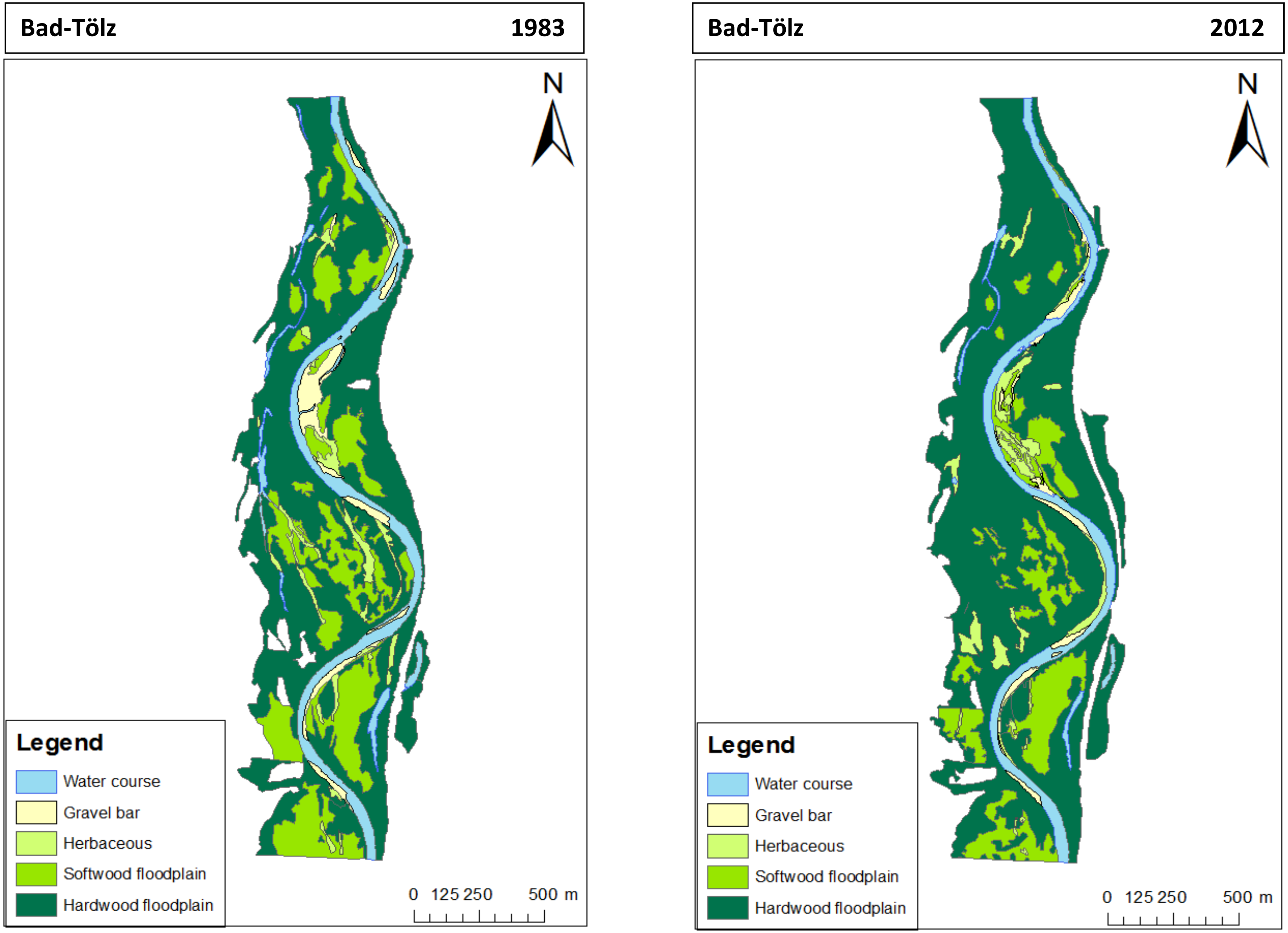


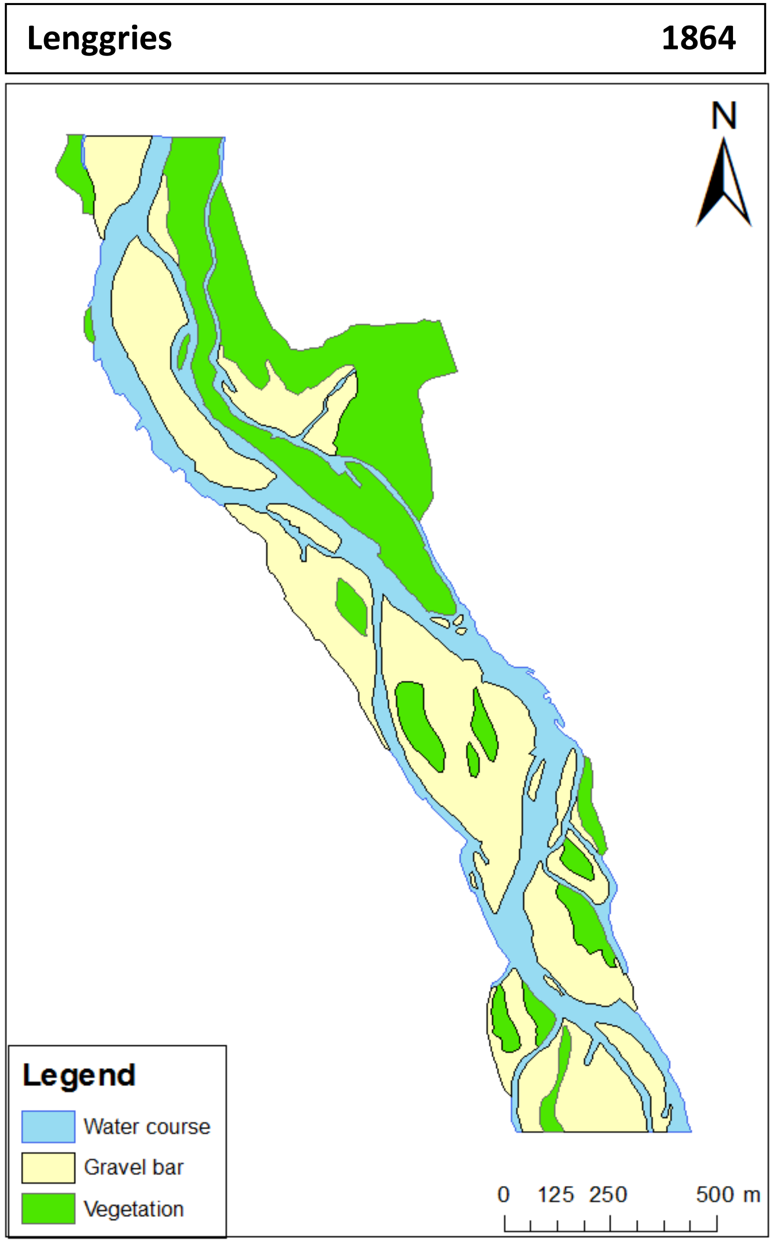

Litzauer Schleife
1980
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
Others
0 125 250 500 m

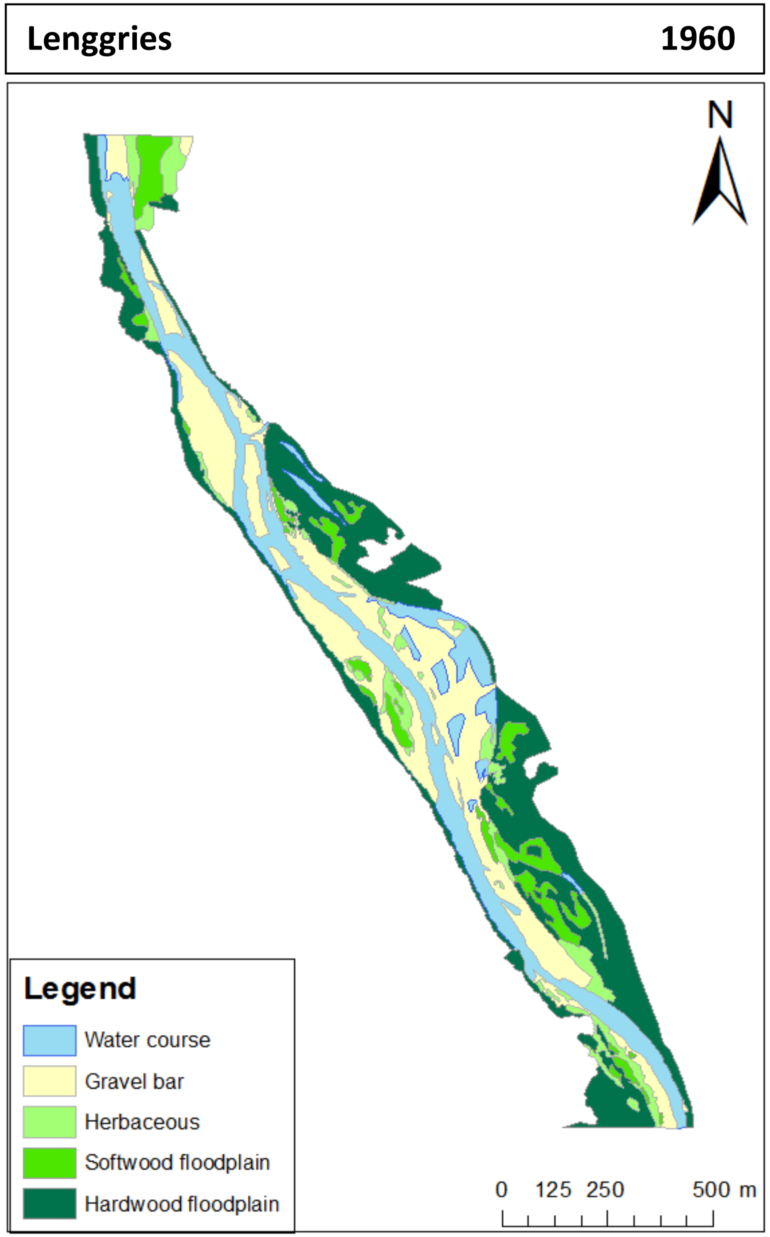

Litzauer Schleife
2012
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
Others
0 125 250 500 m

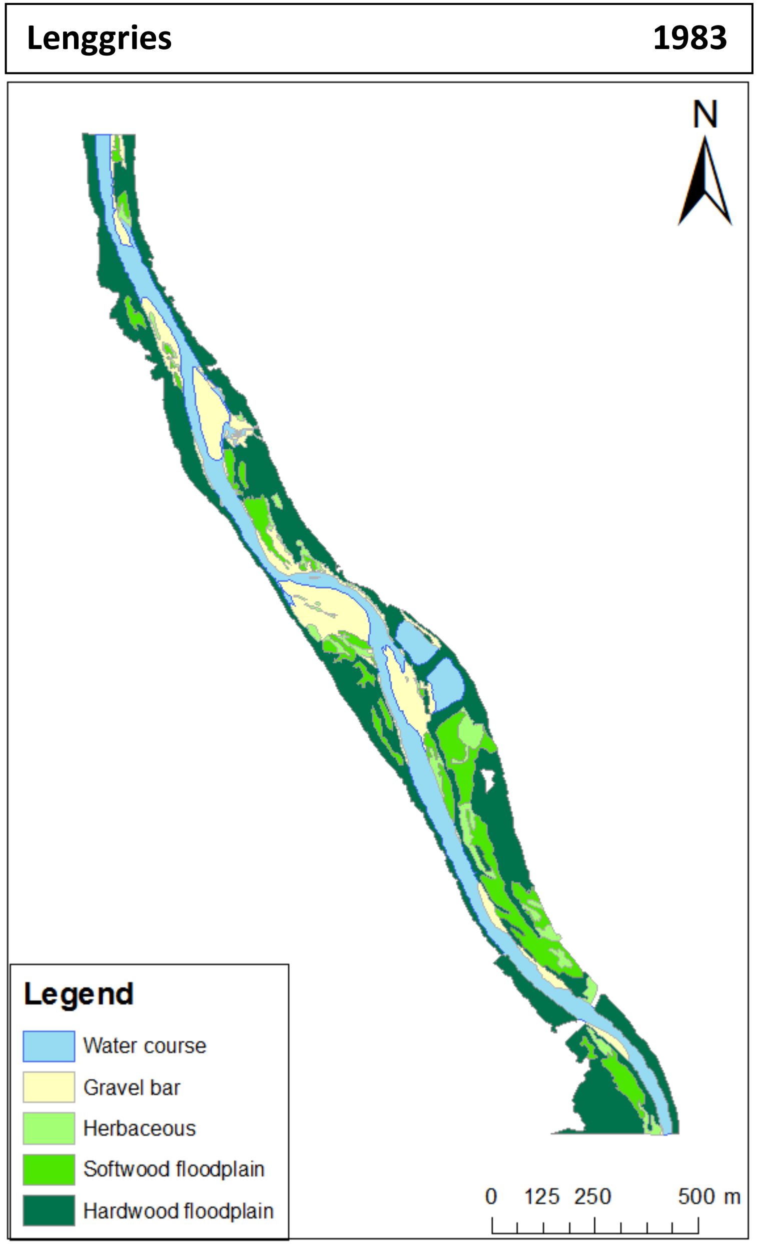

Bad-Tölz
1864
N
Legend
Water course
Gravel bar
Vegetation
0 125 250 500 m

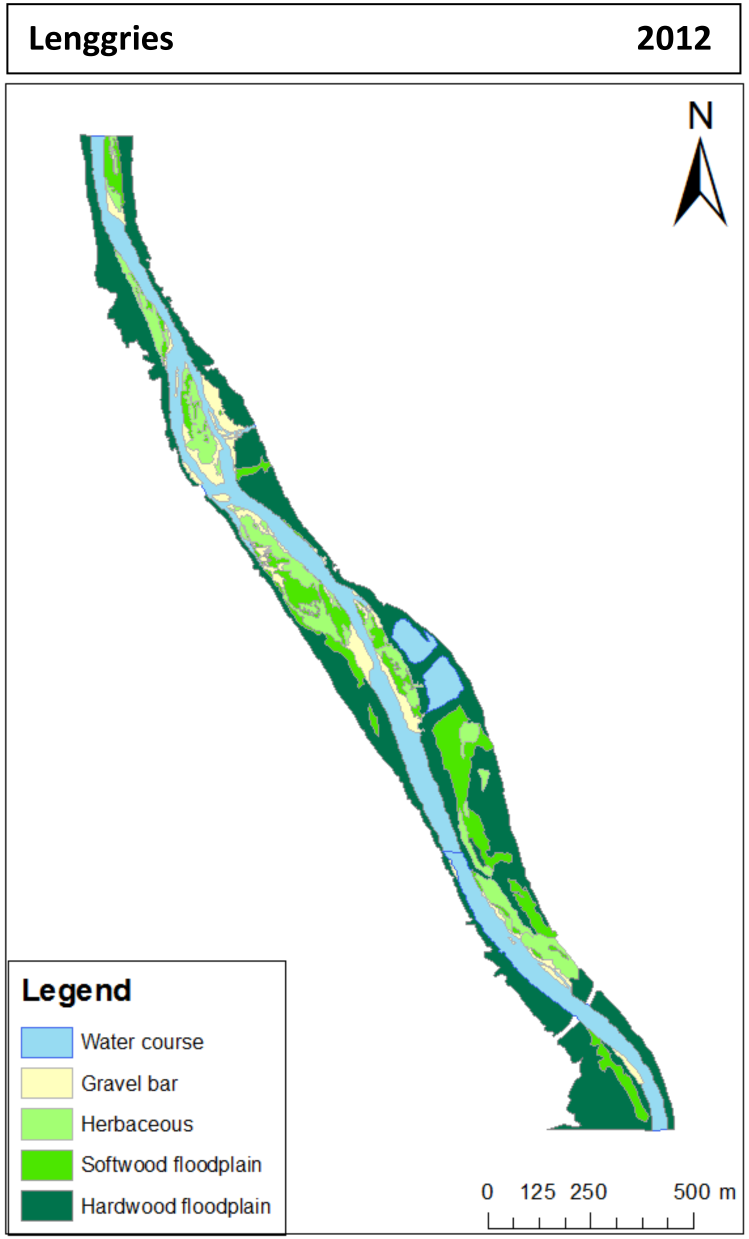

Bad-Tölz
1960
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m

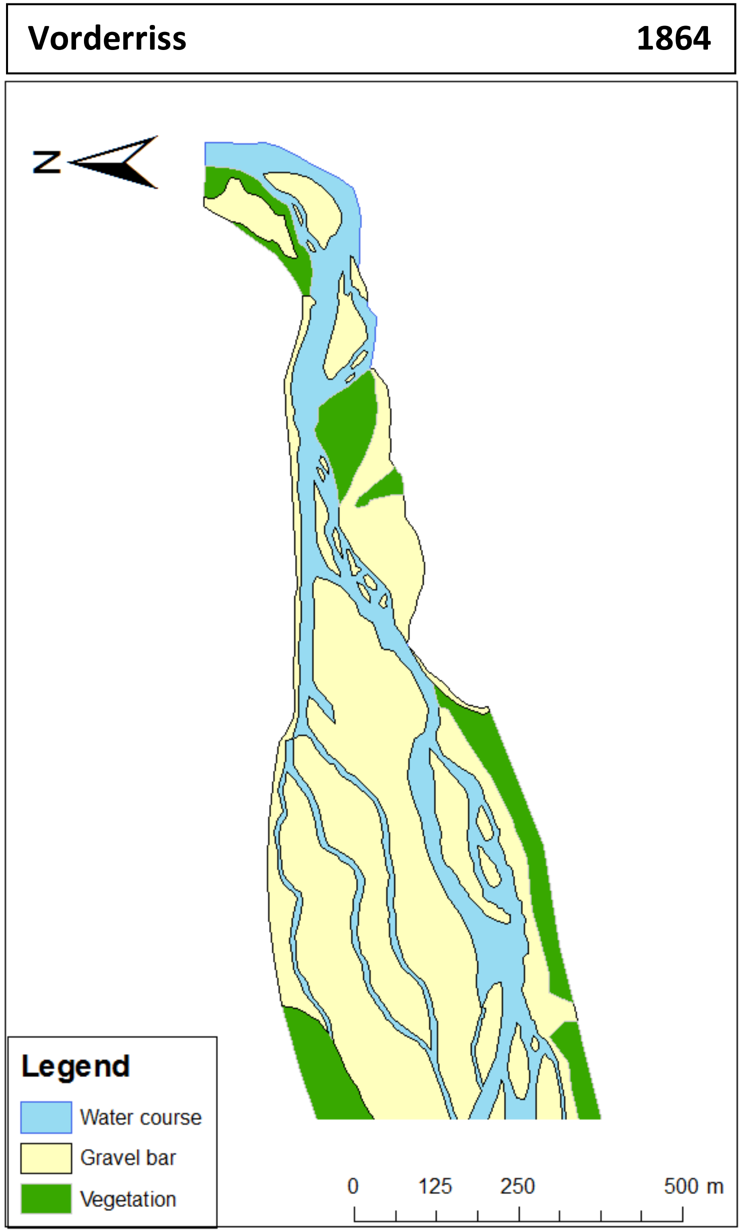

Bad-Tölz
1983
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m
Bad-Tölz
2012
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m

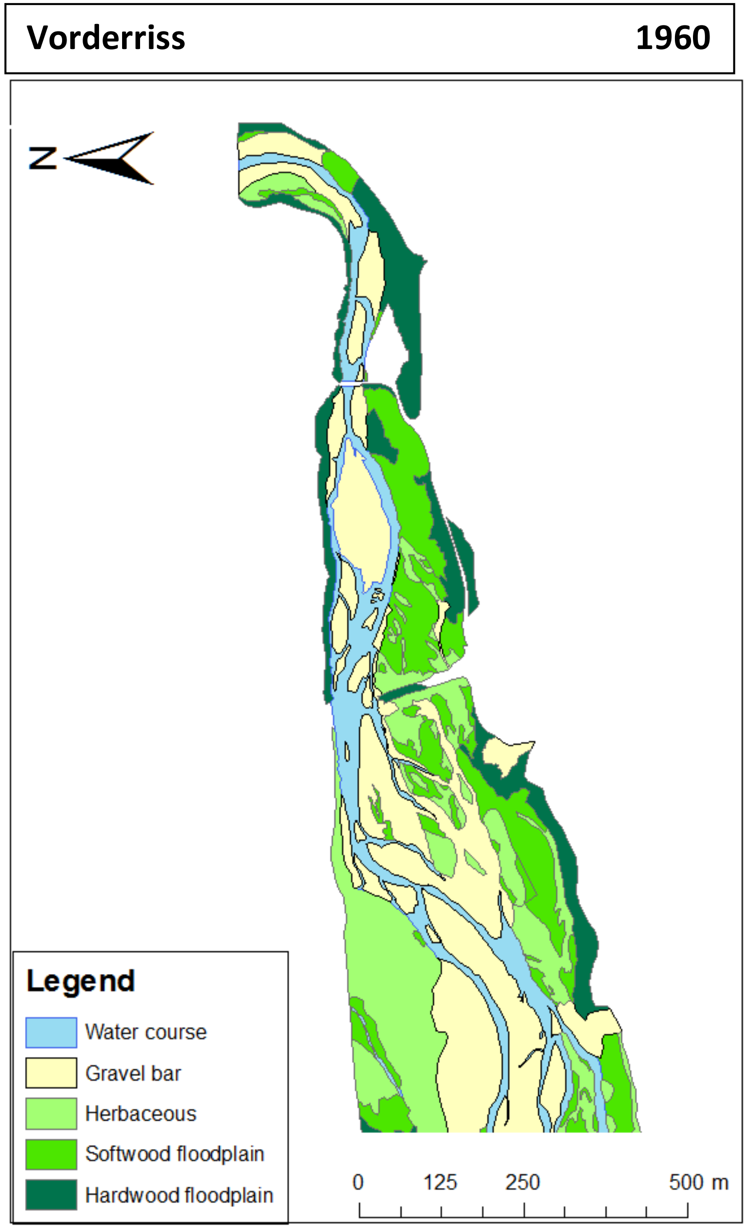

Lenggries
1864
N
Legend
Water course
Gravel bar
Vegetation
0 125 250 500 m

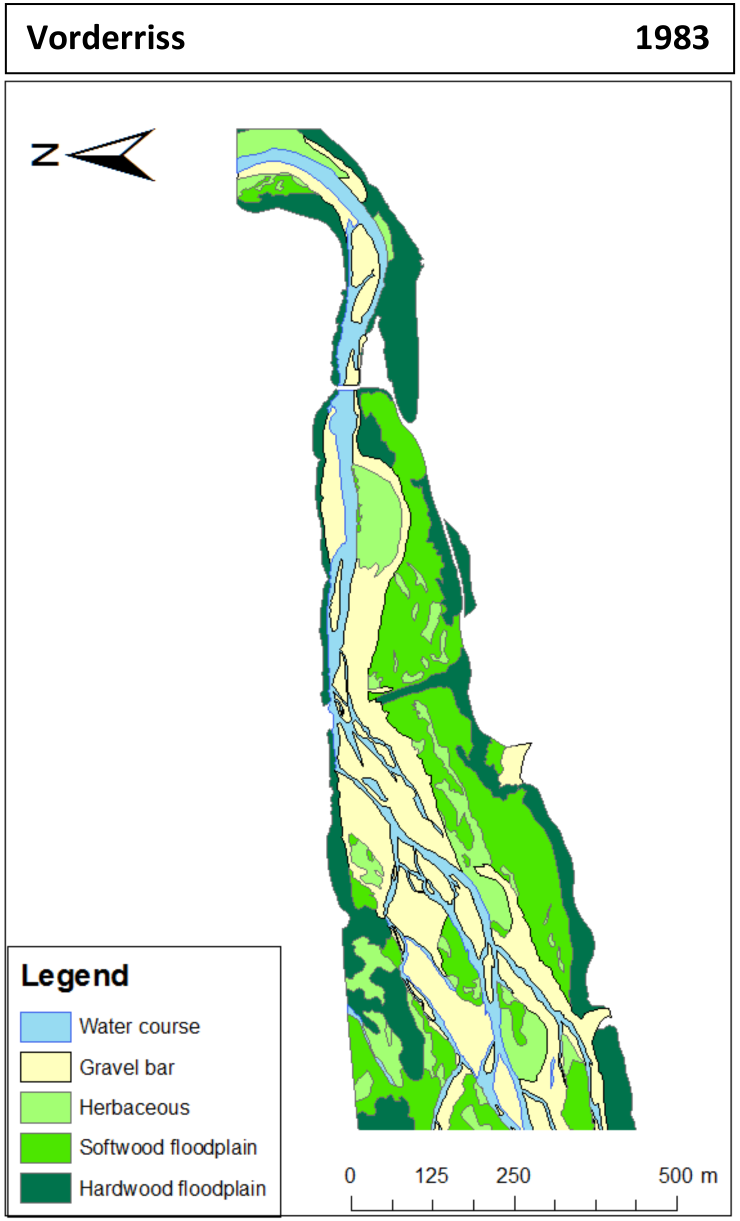

Lenggries
1960
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m

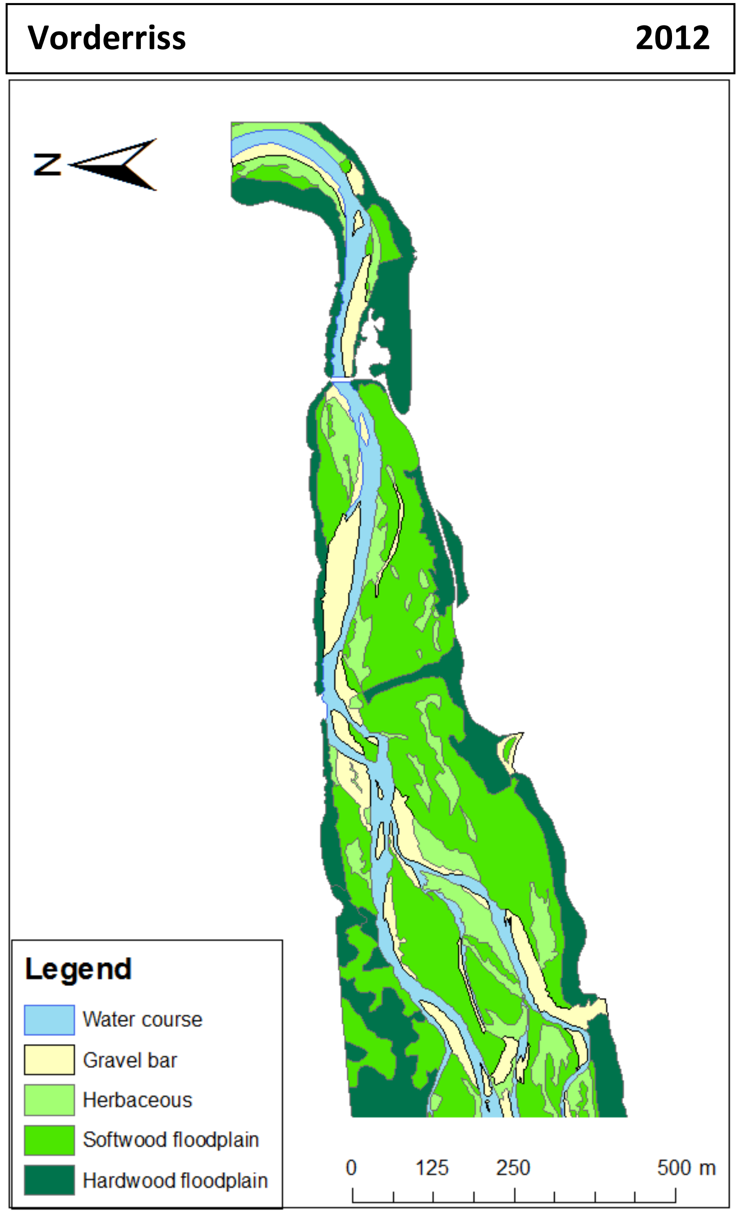

Lenggries
1983
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m

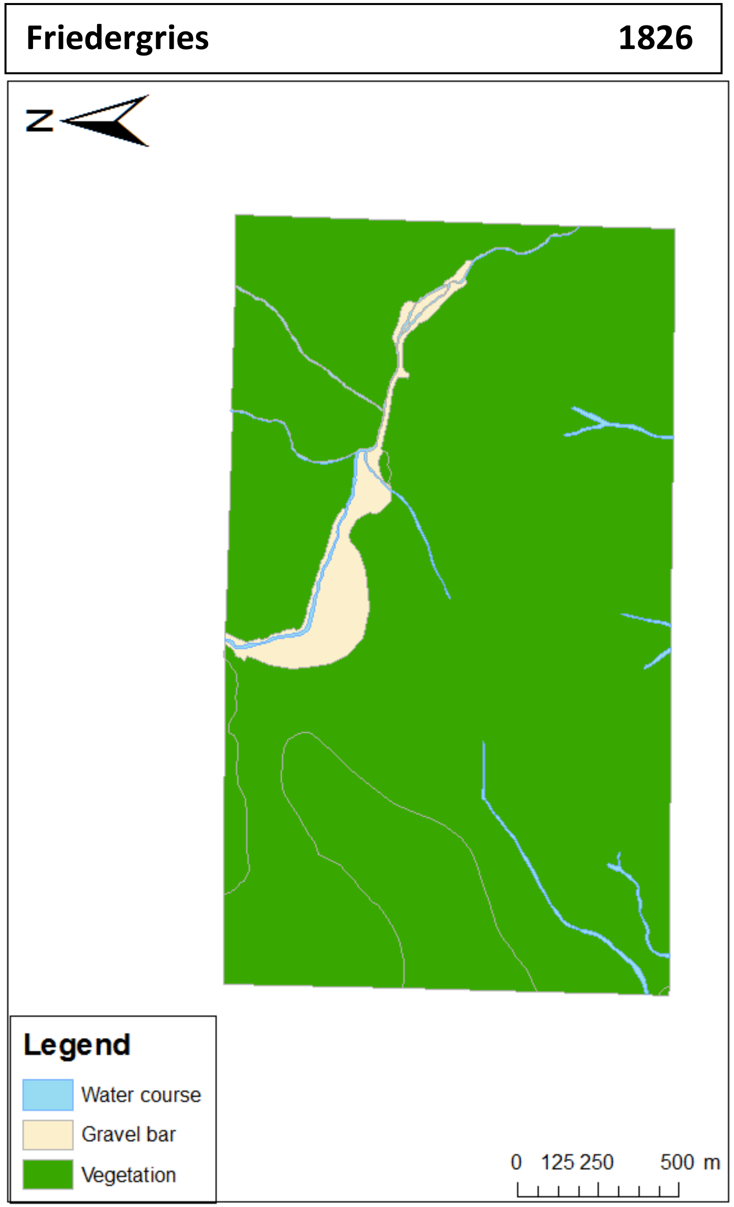

Lenggries
2012
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0 125 250 500 m

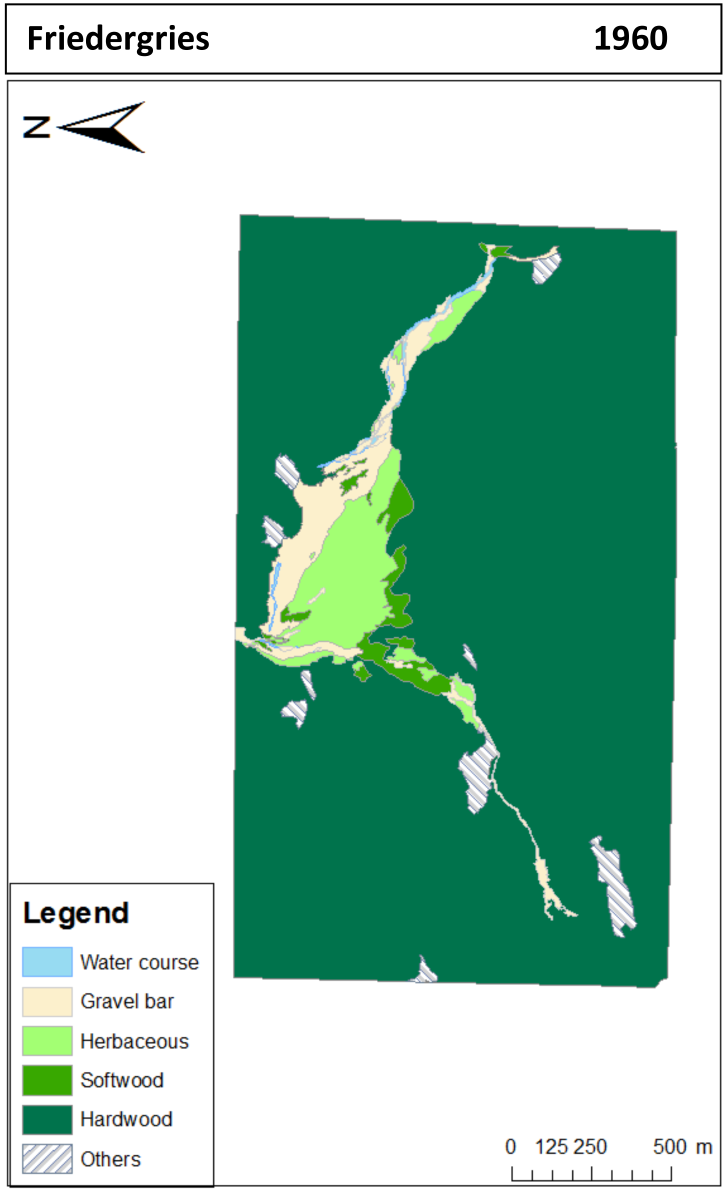

Vorderriss
1864
N
Legend
Water course
Gravel bar
Vegetation
0
125
250
500 m

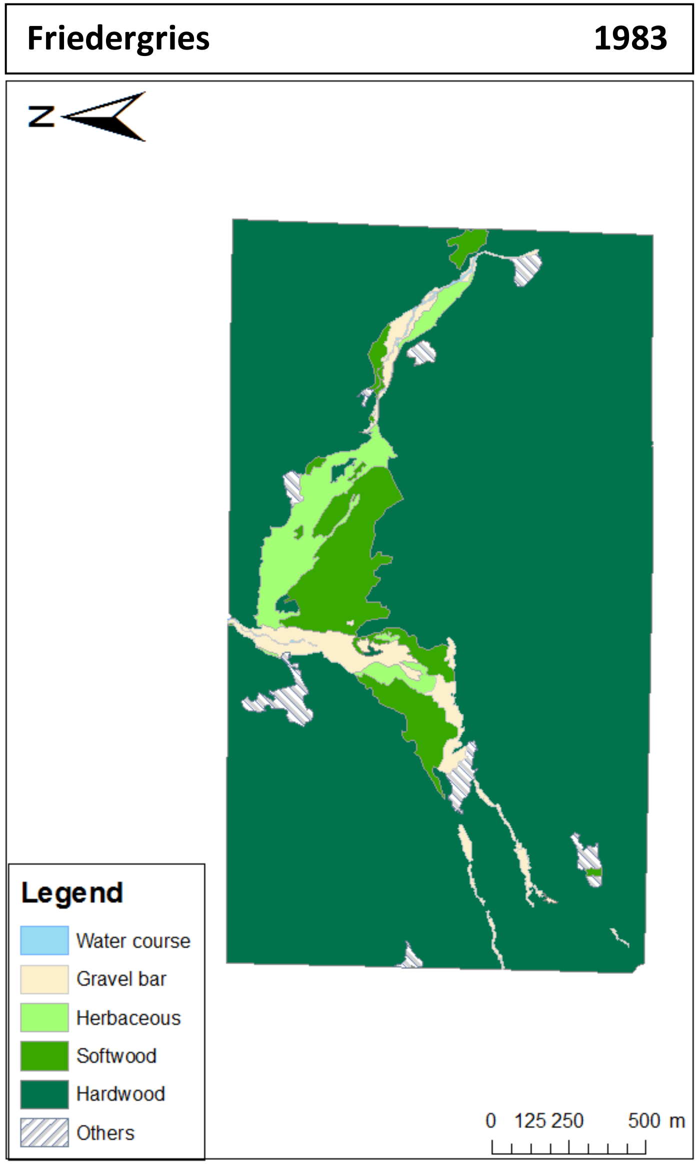

Vorderriss
1960
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0
125
250
500 m

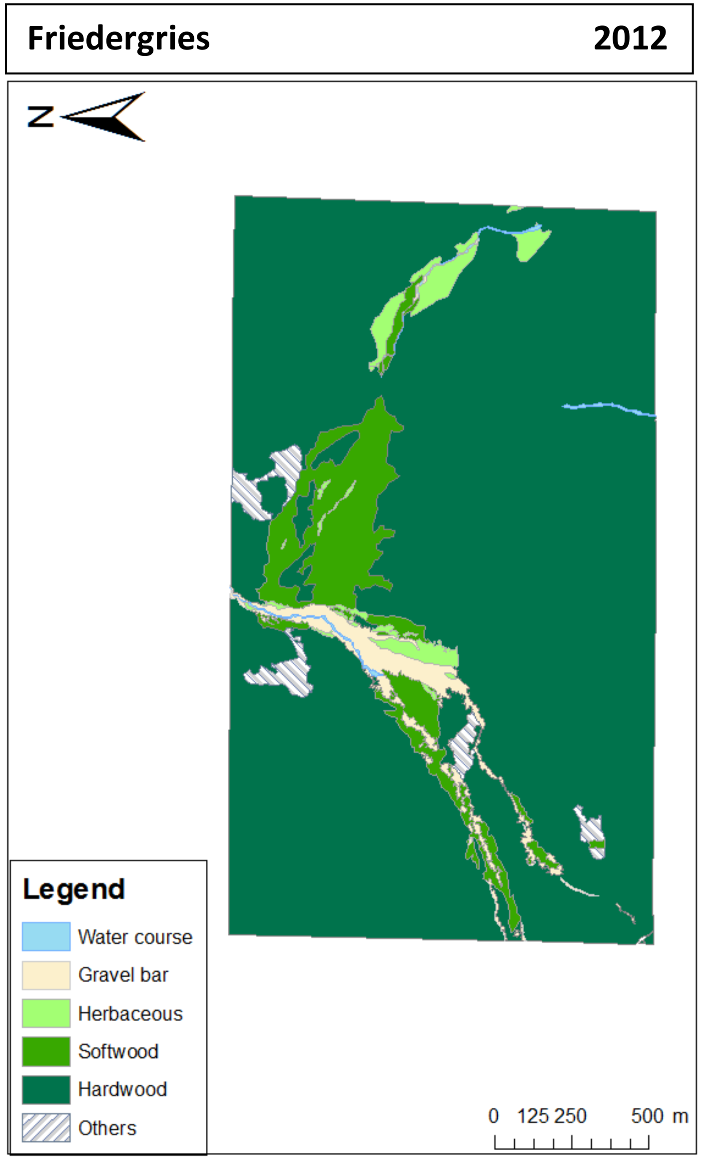

Vorderriss
1983
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0
125
250
500 m


Vorderriss
2012
N
Legend
Water course
Gravel bar
Herbaceous
Softwood floodplain
Hardwood floodplain
0
125
250
500 m


Friedergries
1826
N
Legend
Water course
Gravel bar
Vegetation
0 125 250 500 m


Friedergries
1960
N
Legend
Water course
Gravel bar
Herbaceous
Softwood
Hardwood
Others
0 125 250 500 m


Friedergries
1983
N
Legend
Water course
Gravel bar
Herbaceous
Softwood
Hardwood
Others
0 125 250 500 m


Friedergries
2012
N
Legend
Water course
Gravel bar
Herbaceous
Softwood
Hardwood
Others
0 125 250 500 m

Annexe 4: Statistical tests

Tests on the gravel bar area

Dunn's test 1800s

Z test statistic p-value	Schleife	Bad Tölz	Lenggries	Vorderriss
Bad Tölz	8,886597 0,0000			
Lenggries	5,194300 0,0000	-2,967642 0,0015		
Vorderriss	2,881801 0,0020	-4,480414 0,0000	-1,667179 0,0477	
Friedergries	-0,182513 0,4276	-6,696647 0,0000	-4,057797 0,0000	-2,396130 0,0083

Test on the decrease in gravel bar area

Test de Kruskal-Wallis

1800s-2012	1800s-1960	1960-1980	1980-2012
p-value < 2.2e-16	p-value < 2.2e-16	p-value = 3.466e-09	p-value = 4.336e-07

Test de Dunn 1800s-2012

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-6,750439 0,0000			
Lenggries	-2,924137 0,0017	4,146581 0,0000		
Schleife	-8,768039 0,0000	0,334540 0,3690	-5,129358 0,0000	
Vorderriss	-5,195347 0,0000	1,837130 0,0331	-2,401000 0,0082	1,994213 0,0231

Test de Dunn 1800s-1960

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-7,801124 0,0000			
Lenggries	-3,293593 0,0005	4,863469 0,0000		
Schleife	-7,943782 0,0000	2,121751 0,0169	-3,929791 0,0000	
Vorderriss	-5,902420 0,0000	2,209577 0,0136	-2,753565 0,0029	0,496408 0,3098

Test de Dunn 1960-1980

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-2,294855 0,0109			
Lenggries	-1,370114 0,0853	1,095904 0,1366		
Schleife	-5,809199 0,0000	-2,128306 0,0167	-4,029959 0,0000	
Vorderriss	4,740653 0,0000	-1,908765 0,0281	-3,365307 0,0004	-0,102026 0,4594

Test de Dunn 1980-2012

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-0,513370 0,3038			
Lenggries	0,149694 0,4405	0,625795 0,2657		
Schleife	-2,651326 0,0040	-1,547632 0,0609	-2,702132 0,0034	
Vorderriss	3,187401 0,0007	3,190888 0,0007	2,960693 0,0015	5,818613 0,0000

Tests on the vegetation types

Test on the normality and the variance of each vegetation data set

	Evolution of the herbaceous area		Evolution of the softwood area		Evolution of the hardwood area	
	1960-1980	1980-2012	1960-1980	1980-2012	1960-1980	1980-2012
Kolmogorov (p-value)	0.004238	1.967e-06	0.001491	0.02053	0.01146	0.000629
Levene (p-value)	1.163e-07	3.18e-07	3.301e-10	0.0001716	0.01146	0.000629

Test on the herbaceous vegetation

	Area in 1960	Area Evolution 1960-1980	Area evolution 1980-2012
Kruskal-Wallis	0.0002733	0.02375	0.1883

Dunn's test area in 1960

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-0,182704 0,4275			
Lenggries	-2,918487 0,0018	-2,256835 0,0120		
Schleife	-3,423871 0,0003	-2,509175 0,0061	-0,002977 0,4988	
Vorderriss	0,013053	0,180600	2,653142	3,012085

Dunn's test decrease area 1960-1980

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-1,999191 0,0228			
Lenggries	-2,380335 0,0086	-0,035472 0,4859		
Schleife	-2,503546 0,0061	0,172931 0,4314	0,255962 0,3990	
Vorderriss	-0,139256 0,4446	1,735915 0,0413	2,018307 0,0218	2,042735 0,0205

Dunn's test decrease area 1980-2012

No test because Kruskal-Wallis hypothesis was accepted: all groups are similar.

Test on the softwood floodplain

	Area in 1960	Area Evolution 1960-1980	Area evolution 1980-2012
Kruskal-Wallis	< 2.2e-16	4.306e-14	2.932e-07

Dunn's test area in 1960

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-5,116171 0,0000			
Lenggries	-5,894955 0,0000	0,073265 0,4708		
Schleife	-8,549515 0,0000	-1,215369 0,1121	-1,567469 0,0585	
Vorderriss	-3,001276 0,0013	2,189788 0,0143	2,418049 0,0078	4,178610 0,0000

Dunn's test decrease area 1960-1980

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-7,054540 0,0000			
Lenggries	-4,509568 0,0000	3,120455 0,0009		
Schleife	-6,296676 0,0000	2,621694 0,0044	-1,000869 0,1584	
Vorderriss	-6,182882 0,0000	1,278155 0,1006	-1,925858 0,0271	-1,255356 0,1047

Dunn's test decrease area 1980-2012

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	-3,439427 0,0003			
Lenggries	-1,678817 0,0466	1,955088 0,0253		
Schleife	-2,642045 0,0041	1,617375 0,0529	-0,657509 0,2554	
Vorderriss	-5,657925 0,0000	-1,628250 0,0517	-3,977018 0,0000	-3,884725 0,0001

Test on the hardwood floodplain

	Area in 1960	Area Evolution 1960-1980	Area evolution 1980-2012
Kruskal-Wallis	4.159e-11	4.926e-11	1.622e-11

Dunn's test area in 1960

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	3,840658 0,0001			
Lenggries	-3,052166 0,0011	-6,293963 0,0000		
Schleife	-0,973254 0,1652	-4,931759 0,0000	2,488945 0,0064	
Vorderriss	-4,421684 0,0000	-7,328618 0,0000	-1,533659 0,0626	-4,019615 0,0000

Dunn's test decrease area 1960-1980

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	6,034912 0,0000			
Lenggries	5,670618 0,0000	-1,156860 0,1237		
Schleife	5,396178 0,0000	-2,235164 0,0127	-1,152917 0,1245	
Vorderriss	5,124441 0,0000	-1,233773 0,1086	-0,152716 0,4393	0,884870 0,1881

Dunn's test decrease area 1980-2012

Z test statistic p-value	Bad Tölz	Friedergries	Lenggries	Schleife
Friedergries	3,575509 0,0000			
Lenggries	5,201481 0,0000	0,851342 0,1973		
Schleife	7,307054 0,0000	1,933599 0,0266	1,196766 0,1157	
Vorderriss	4,732029 0,0000	0,713441 0,2378	-0,109446 0,4564	-1,220902 0,1111

<u>Boxplots of the area of each vegetation type in 1960</u>