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REFORM

REstoring rivers FOR effective catchment Management

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Summary

Background and Introduction to Deliverable 2.1.

Work Package 2 of REFORM focuses on hydromorphological and ecological processes and interactions within river systems with a particular emphasis on naturally functioning systems. It provides a context for research on the impacts of hydromorphological changes in Work Package 3 and for assessments of the effects of river restoration in Work Package 4.

Deliverable 2.1 of Work Package 2 proposes a hierarchical framework to support river managers in exploring the causes of hydromorphological management problems and devising sustainable solutions. The deliverable has four parts. Part 1 provides a full description of the hierarchical framework and describes ways in which each element of it can be applied to European rivers and their catchments. Part 2 includes thematic annexes which provide more detailed information on some specific aspects of the framework described in Part 1. Part 3 includes catchment case studies which present the application of the entire framework described in Part 1 to a set of European catchments located in different biogeographical zones. Part 4 (this volume) includes catchment case studies which present a partial application of the framework described in Part 1 to a further set of European catchments.

Summary of Deliverable 2.1 Part 4.

Part 4 of Deliverable 2.1 provides four partial applications of the framework described in Part 1 to case study catchments (River Tweed, UK; River Loire, France; River Tagliamento, Italy; Rivers Lech and Lafnitz, Austria). These case studies are mainly confined to the delineation and characterisation phases of the framework, but they incorporate additional environmental settings to the complete case studies provided in Part 3.

Acknowledgements

REFORM receives funding from the European Union's Seventh Programme for research, technological development and demonstration under Grant Agreement No. 282656. We gratefully acknowledge the following for their constructive reviews: Gary Brierley, Judy England, Ángel Garcia Canton, Fernando Magdaleno Mas, María Isabel Berga Cano.

Table of Contents

This document is part 4 of a 4 part report and contains four partial applications of the Hierarchical Framework proposed in Part 1.

Catchment Case Study 6

The River Tweed: a large, Northern European gravel bed river

Robert C. Grabowski[1], Iain D. M. Gunn[2], Matthew T. O'Hare[2] and Angela M. Gurnell[1]

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1. Introduction

The River Tweed case study demonstrates how the hydromorphological assessment framework can be applied to a study reach. Often managers need detailed information on a particular reach to support management and planning decisions. Time and cost prohibit the full characterisation of all of the reaches in a catchment, but information is still needed from wider spatial scales to fully understand the hydromorphological processes operating at the reach scale. In these situations the application of the hierarchical assessment framework can be adapted as suggested in Section 1 of Deliverable 2.1 Part 1: the assessment focuses on the particular reach, the segment in which it is located and the segment immediately upstream, all of the landscape units, and the catchment. This approach ensures that changes in hydromorphological characteristics that have occurred upstream and downstream of the reach are included in the assessment as they may affect the flow of water and sediment to and within the channel which would influence the form and behaviour of the river at the study reach.

1.1 The River Tweed

The River Tweed is a gravel bed river flowing through the Borders region of southern Scotland, and which in its lower course forms the administrative border between Scotland and England (Figure 1.1). The River Tweed is famous for its salmonid fisheries and is protected under multiple national and international legislation: The Scotland Act 1998 (River Tweed) Order 2006, the EU Freshwater Fish Directive and the EU Habitats Directive.

The main stem of the River Tweed is delineated into six waterbodies for Water Framework Directive (WFD) monitoring and reporting (Table 1.1). Ecological status is rated from bad to moderate currently but is expected to progress to good status by 2027. Pressures on the River Tweed are primarily hydromorphological, e.g. water abstraction and morphological alterations, but issues with point and diffuse source pollution also exist.

This hydromorphological assessment of the River Tweed focuses on a stretch of river in the upper catchment rated as having bad ecological status caused by hydromorphological pressures, and which has been identified as a potential vulnerable flood risk area (PVA 13/04, SEPA). This catchment case study follows the initial stages of the hierarchical framework and includes the delineation of spatial units and indicators of past and present condition. As suggested in Deliverable 2.1 Part 1, the sections covering the characterisation of spatial units and characterisation of temporal change were skipped and the relevant information was incorporated into the indicators section. The Tweed case study finishes with the indicators section and does not continue to the interpreting condition and trajectories of change stage of the framework because of insufficient data for the reach-scale indicators. The case study provides a Scottish example of the types of existing data that can be used to conduct the initial phases of the hierarchical framework, and also highlights the importance of high-quality geomorphological survey data for a robust assessment of hydromorphological condition.

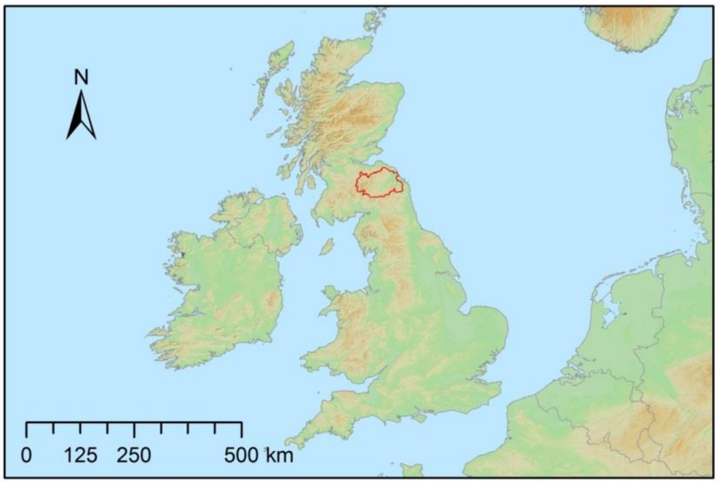

Figure 1.1 The River Tweed catchment, outlined in red, is located in southern Scotland.

Table 1.1 WFD waterbodies defined for the River Tweed

Name	ID	Length (km)	Ecological Status	HYMO status	Pressures (Objective by 2015)
Source to Talla Water	5205	13.99	Moderate	Moderate	Morph. alterations (Moderate) Abstractions (Good)
Talla Water to Scotsmill	5204	31.87	Bad	Bad	Abstraction (Bad) Impoundment (Poor)
Scotsmill to Ettrick Water	5203	28.97	Bad	Bad	Abstraction (Bad) Point source pollution (Good)
Ettrick Water to St Boswells Burn	5202	21.89	Poor	Poor	Abstraction (Poor) Point source pollution (High)
St Boswells Burn to Coldstream	5201	33.96	Moderate	Moderate	Abstraction (Moderate) Diffuse source pollution (Moderate)
Coldstream to tidal limit	5200	18.59	Moderate	Good	Morph. alterations – riparian vegetation (Good) Diffuse source pollution (Moderate)

2. Materials and Methods

2.1. Datasets

A selection of remotely sensed and national datasets was used in the delineation and characterisation processes (Table 2.1).

2.1.1. Mapping

Ordnance Survey (OS) maps for the River Tweed catchment were obtained from the Digimap service[1]. The MasterMap Topography Layer is a high resolution digital map series that contains layers for 9 different themes of objects, such as buildings, roads, vegetation type and water features (updated 2012). Position accuracy depends on the location of the feature; urban data has a horizontal accuracy of 1.0 m and rural data 2.5 m (equivalent to the OS 1:2500 maps). It is provided in GML format and was converted to ArcGIS shapefile using the InterpOSe software from Dotted Eyes[2].

A historical Ordnance Survey map and the current Mastermap topography digital map were used to investigate changes in reach planform characteristics. The historical map is part of the 1st National Grid map series for the UK. The large-scale (1:2500) map was obtained as digital map tiles in tif format from the Digimap service. A UK Ordnance Survey map at 1:2500 scale represents rivers to scale when they are 2 m wide, and has an absolute accuracy of ±2.8 m.

2.1.2. Aerial imagery

Delineation and characterisation of the reach and geomorphic units were supported by satellite imagery from Google Earth. Images from 2007 were the primary source of data, as they were the most recent images to cover the entire catchment (Copyright © 2014 Getmapping plc).

2.1.3. Elevation

The Profile DTM is a 10m resolution Digital Terrain Model (DTM) generated from the OS Land-Form Profile contour data (5m contours, 10m in mountainous areas), which is based on 1:10,000 scale mapping (updated 2009). DTM height accuracy is less than or equal to half of the contour interval (2.5 m), absolute accuracy of contours is on the order of +- 1.0 m root mean square error. Tiles (5 km x 5 km) were obtained from Digimap1 in a GeoTIFF format and mosaicked in ArcGIS 10.0. Licence permits academic use for UK researchers only.

High resolution digital elevation models (DEMs) based on LiDAR surveys were obtained from the Scottish Environment Protection Agency (SEPA) for the majority of the study section on the River Tweed. LiDAR, or light detecting and ranging survey, uses a laser scanner to obtain data point clouds of the topography of the land surface. Two DEMs were obtained as ASCII Grid format: a digital surface model (DSM) which represents the elevation of all natural and anthropogenic structures in the landscape such as trees,

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[1] Digimap. http://edina.digimap.ac.um, accessed on 15-March-2013)

[2] InterpOSe software by Dotted Eyes. http://misoportal.com/data/interpose-for-digimap/

buildings and roads; and the underlying DTM. The DSM and DTM have a horizontal resolution of 1 m and a vertical accuracy of better than 0.1 m (RMSE = 0.050).

2.1.4. Geology

A digital map (1:625,000 scale) of the bedrock and surficial geology of the UK was obtained from the British Geological Survey. The geology is generalised from a larger 1:50,000 'poster' map of UK geology (version 1, 1977 and 1979). Accuracy is 1 mm on the poster, which equates to 625 m on the ground. The data is freely available from the BGS website [3] or One Geology Europe[4].

2.1.5. Soil

The soil dataset was obtained from the European Soil Portal run by the European Commission's Joint Research Centre (JRC)[5]. The vector dataset of the European Soil Database (ESDB) (version 2) was downloaded in a joined shapefile that contains the attributes from the Soil Geographical Database of Eurasia (SGDE) (scale 1:1,000,000), Pedotransfer Rules Database (PTRDB), Soil Profile Analytical Database of Europa (SPADBE) and the Database of Hydraulic Properties of European Soils (HYPRES). Soil Typological Units (STU) are grouped into Soil Mapping Units (SMU) to display attributes. Three derived PTRDB attributes were used in the analysis: soil erodibility, soil hydrology and water regime.

The Pan-European Soil Erosion Risk Assessment map (PESERA) was used to estimate fine sediment input into the river. PESERA is a process-based model that quantifies soil erosion by water based on rainfall, topography, soil characteristics and land cover (based on CORINE from 1989, see below for more details). The soil loss estimates (t ha^{-1} yr^{-1}) are freely available in GeoTIFF format from the JRC[6].

[3] British Geological Survey. http://www.bgs.ac.uk/products/digitalmaps/digmapgb_625.html, accessed on 15-March-2013.

[4] One Geology Europe. http://geoportal.onegeology-europe.org/geoportal/viewer.jsp, accessed on 14 April 2014

[5] European Soil Portal. http://eusoils.jrc.ec.europa.eu/, accessed on 15-March-2013.

[6] PESERA. Joint Research Centre. http://eusoils.jrc.ec.europa.eu/ESDB_Archive/pesera/pesera_data.html, accessed on –March-2013.

Table 2.1 Primary datasets used in the delineation and characterisation of the River Tweed.

Property	Dataset	Format	Resolution	Version	Source
Mapping	MasterMap	GLM	1:1250	2013	Ordnance Survey (UK)
	1st National Grid Survey	TIF	1:2500	1966	Ordnance Survey (UK)
Aerial imagery	Satellite	Online	variable	2000-2012	Google Earth
Elevation	Profile DTM	GeoTIFF	10 m	2009	Ordnance Survey (UK)
	LiDAR	ASCII GRID	1 m		SEPA
Geology	Bedrock & Superficial	Shapefile	1:625,000		British Geological Survey (UK)
	Superficial	Shapefie	1:1,000,000		OneGeologyEurope
Soils & aquifers	European Soil Database	Shapefile	1:1,000,000	2006	Joint Research Centre (EC)
Soil erosion	PESERA	GeoTIFF	1 km		Joint Research Centre (EC)
Land cover	CORINE	GeoTIFF	100 m	2006	European Environment Agency
	Countryside Survey	GeoTIFF		1990, 2000, 2007	
River flows & flood extent	Mean Daily	Discharge	4 stations		SEPA
	Flood extent (1 in 200yr)	Shapefile	1:25,000		SEPA
Vegetation & sediment	River Habitat Survey	Survey	108 sites		Environment Agency (UK)
	Mean Trophic Rank	Survey	4 sites		Centre for Ecology & Hydrology (UK)

2.1.6. Aquifers

Groundwater data were downloaded as shapefiles from JRC's European Soil Portal[7]. The datasets are based on maps produced in a 1982 study by the European commission (1:500,000 scale). Theme 1 relates to aquifer coverage, and is the only theme included in these analyses.

2.1.7. Land cover and land use

The CORINE Land Cover (CLC) dataset was produced by the European Topic Centre on Spatial Information and Analysis and is made freely available as raster and vector datasets on the European Environment Agency website[8]. It is a pan-European dataset collected in 2006 by the SPOT-4/5 and IRS P6 LISS III satellites. Geometric accuracy of the satellite imagery is less than 25 m, and of the CLC data is less than 100 m. Thematic accuracy of the land cover theme is greater than 85%. The first and second levels of land classification were used in this spatial characterisation section.

The temporal analysis of land cover used historical land cover maps and county agricultural statistics. Recent changes in land cover were examined using the UK Countryside Survey digital land cover maps for 1990, 2000 and 2007. The 25-m resolution GeoTiffs were obtained from Edina Digimap[1], and thematic classes were aggregated to match those used in the Corinne land cover dataset and recommended in Section 5 of Deliverable 2.1 Part 1.

2.1.8. Hydrology – rainfall and discharge

Rainfall statistics, river flow summaries and mean daily flow records were obtained for river gauging stations on the River Tweed from SEPA. Gauging station factsheets provide annual and monthly mean, min and maximum rainfall and runoff (1959-2012); the daily flow hydrograph; a flow duration curve; river flow statistics (e.g. mean annual flood); and catchment characteristics.

River flow analyses concentrated on records from gauging stations within or near the study section: Lyne Ford, Peebles and Boleside (Table 2.2). The downstream-most gauging station at Norham was used for catchment summaries (e.g. water yield). Flood extents shapefiles were obtained from SEPA. The flood extents are part of the national flood hazard maps and are intended to support community-level flood risk management. They are based on a digital terrain model and a 1-d flood inundation model, and give an indication of the spatial extent of floods inclusive of flood defences. Three levels of risk are modelled: low (1 in 1000 year flood), medium (1 in 200 year flood), and high (1 in 10 year flood). The medium risk layer was used to represent the current floodplain (i.e. defended extent that incorporates flood defences). This extent was then modified based

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[7] A Digital Dataset of European Groundwater Resources at 1:500,000. (v. 1.0), data from a project by the European Crop Protection Association, based on data originating from a study performed by the European Commission (1982 , EUR 7940 EN), European Soil Portal http://eusoils.jrc.ec.europa.eu/ESDB_Archive/groundwater/gw.html, accessed on 15-March-2013.

[8] Corine Land Cover v. 2006. http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2, accessed on 15-March-2013.

on the LIDAR DTM to estimate the maximum floodable area extent. Flood extents are freely viewable online[9].

Table 2.2 Gauging stations in the River Tweed catchment.

Gauge	River - Site	Data type	Period of Record	Catchment Area	Grid Reference
21005	Tweed at Lyne Ford	Mean daily	1961 – 2012*	373	NT2059739747
21003	Tweed at Peebles	Mean daily	1959 - 2012+	694	NT2582140017
21006	Tweed at Boleside	Mean daily	1961 - 2013	1500	NT4982333376
21009	Tweed at Norham	Mean daily	1962 - 2013	4390	NT8983647709

Missing years: *2002, 2003 and 2005; +2008 and 2009

2.1.9. Field survey datasets

Two sources of field survey data were used to quantify various segment- and reach-level characteristics, including channel dimensions, bed and bank material/modifications, riparian and aquatic emergent vegetation, and geomorphic features.

The River Habitat Survey (RHS) is a standardised survey used by the Environment Agency to assess the physical structure of rivers and streams. The survey is based around a 500 m long reach, and involves a combination of general site characterisation, regularly spaced spot-checks (10 per reach) and a final sweep-up survey. A broad array of features are recorded during the survey, including valley form, channel dimensions (e.g. bankfull width and depth), bed and bank material, river flow types, geomorphic features (e.g. vegetated and unvegetated bars), land-use, riparian and aquatic vegetation, and artificial features. A total of 108 surveys are available for the River Tweed.

The Mean Trophic Rank Survey (MTR) was designed to assess the trophic status and eutrophication impact of rivers according to the aquatic vegetation (i.e. aquatic macrophytes) growing within the channel. The species and percentage cover of the macrophytes are recorded along 100 m stretches of river. Physical data on channel width, depth, bed substrate, shading by riparian trees and flow types (referred to as habitats in this method) are recorded. This information is then used to calculate a mean trophic rank for each survey. MTR survey data were provided by CEH and four of the survey sites were located within the study reaches. Unfortunately, physical data were not available for these sites, so the use of MTR data was limited to plant species and percentage cover.

2.2. Delineation and characterisation methods

For detailed methods on the delineation and characterisation procedures, please see the Deliverable 2.1 Part 1 (Sections 4 and 5) and the River Frome case study annex.

[9] Flood extent map, SEPA, http://map.sepa.org.uk/floodmap/map.htm, accessed on 25-July-2014.

3. Delineation of the Spatial Units

3.1. Region

The region is a large geographic area that contains characteristic assemblages of natural ecological communities that reflect broad climate patterns. This scale is important because it is these climate patterns and natural land covers that are the primary controls on all spatial scales of hydromorphological processes. The region was identified from online maps and publications of biogeographic regions in Europe (www.globalbioclimatics.org; EEA 2002).

The River Tweed is located in the Borders Region of southern Scotland and northern England, which lies within the Atlantic European biogeographic region (Figure 3.1). The climate is characteristically mild and humid and strongly influenced by the Atlantic Ocean.

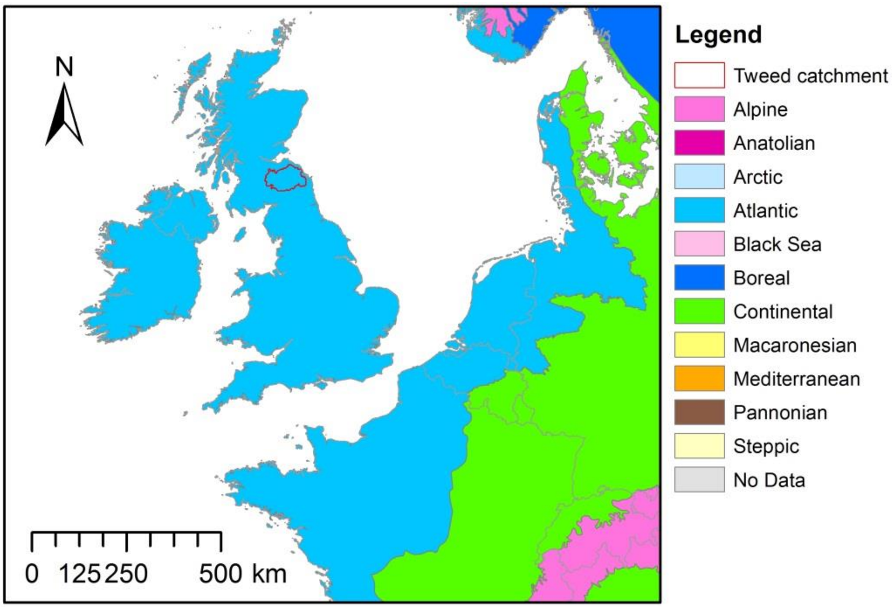

Figure 3.1 The biogeographic regions of Europe (Data: European Environment Agency © Council of Europe 2012)

3.2. Catchment

A catchment is an area of land that is drained by a river and its tributaries. The Tweed catchment was delineated based on topographic divide using the watershed delineation procedure in ArcGIS and the Profile DTM (10 m resolution).

The River Tweed is a large, mid-altitude, siliceous catchment according to the WFD typology (catchment area to normal tidal limit = 5,021 km^2, mean elevation = 264 m) (Figure 3.2).

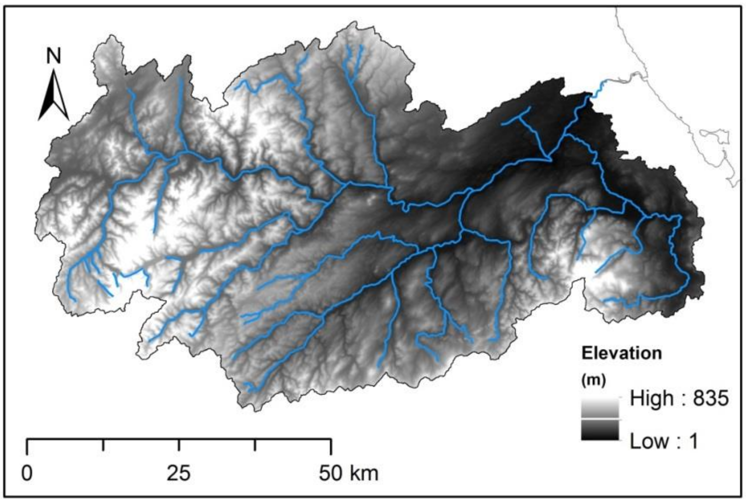

Figure 3.2 The River Tweed catchment is a large, mid-altitude catchment according to the WFD typology (Ordnance Survey data © Crown Copyright/database right 2012).

3.3. Landscape units

Landscape units are portions of the catchment with similar morphological characteristics. The catchment is divided into landscape units that are broadly consistent in terms of their topography, geology and land cover, as these factors determine the hydrological responsiveness of a catchment and the source and delivery of sediment to the river system (Figure 3.3). The River Tweed was delineated into three landscape units (Table 3.1). Landscape unit 1 encompasses the headwater, which is a mid-altitude area with mostly impervious siliceous bedrock and forest/scrub land cover. Landscape unit 2 is a transition zone between the hilly headwaters and the lowland areas, and was differentiated primarily based on a change in geology with glacial till becoming dominant. Landscape unit 3 is predominantly low elevation with glacial till geology and arable land cover dominant, but the southern portion of the unit is mid-altitude with an igneous geology.

Table 3.1 Characteristics of the three landscape units

Landscape units	1	2	3
Area (km^2)	1822	1541	1092
Elevation (WFD bands - % area)			
< 200 m	8%	38%	74%
200 - 800 m	91%	62%	26%
> 800 m	0%	0%	0%
Geology (dominant)			
Bedrock	Sandstone / Wacke	Sandstone / conglomerate	Limestone
Surficial	Alluvium, Till, Peat	Glacial till	Glacial till
Dominant land cover	Forest / scrub	Forest / scrub	Arable land

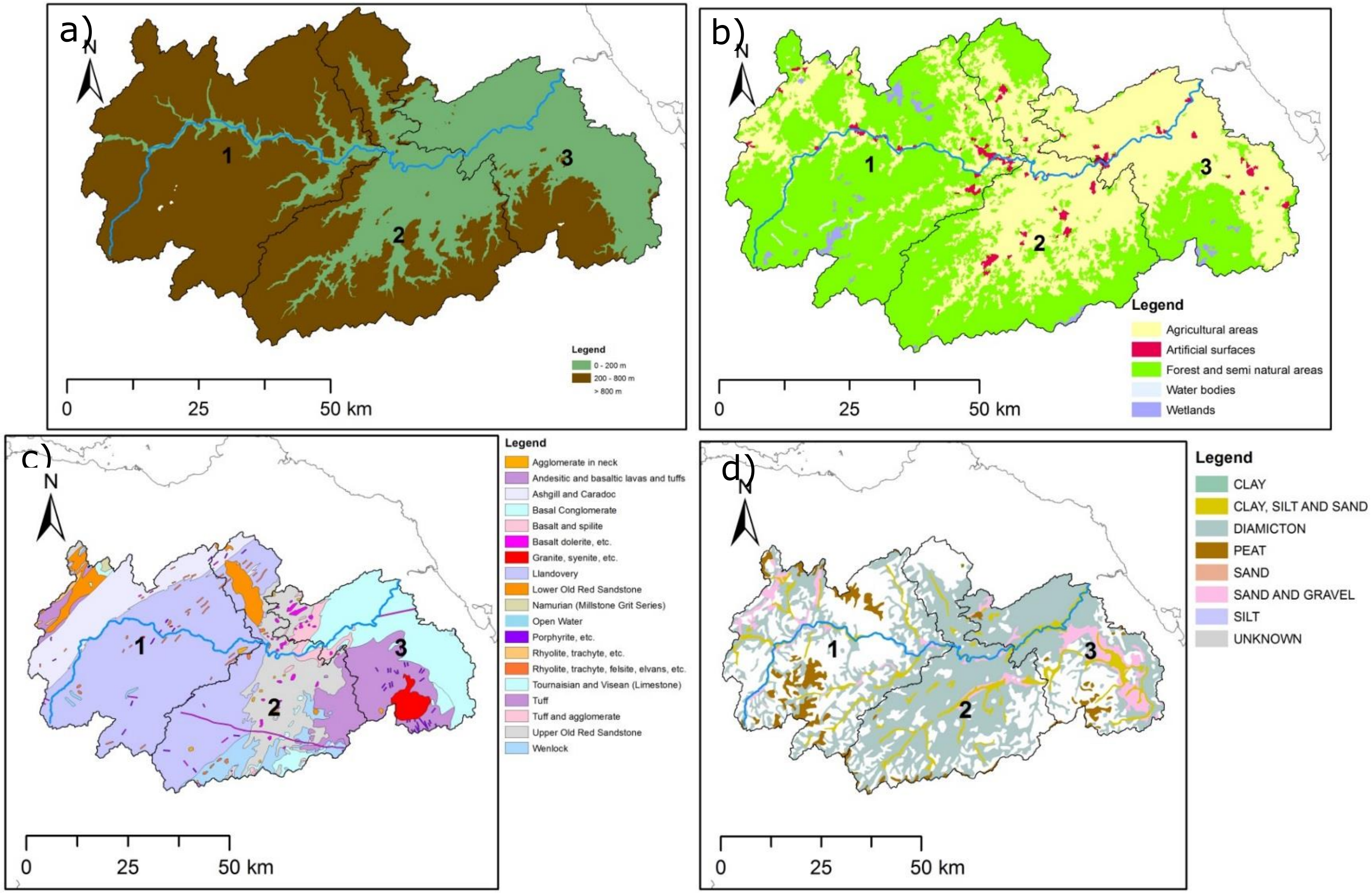

Figure 3.2 Landscape unit characteristics: a) elevation (WFD classes) (Ordnance Survey data © Crown Copyright/database right 2012), b) Corine level 1 land cover (© EEA 2013), and c) bedrock and d) surficial geology (based on DiGMapGB-625, with the permission of the British Geological Survey).

3.4. Segments

River segments are sections of the river network that are subjected to similar valley-scale influences and energy conditions. Delineation is based on major changes in valley gradient, major tributary confluences and valley confinement. A long profile of elevation and drainage area was used to set the segment delineation preliminarily, which was refined for the study section based on valley confinement (Figure 3.4). The River Tweed was delineated preliminarily into eight segments. The study area spans between the towns of Peebles and Galashiels (40 – 74 km downstream). Further examination of the valley setting in this section revealed that at 60 km the valley narrows significantly (width change, 195 to 119 m wide; confinement index change, 11.05 to 4.14), thereby warranting a further segment delineation. As stated in Section 1 of Deliverable 2.1 Part 1, if the hydromorphological assessment is to focus on a particular section of river then the segment in which it is located and the one upstream should be characterised. The study section spans Segments 3 and 4, and Segment 2 is characterised to support the assessment (Table 3.2). N.B. The delineation for the other segments remains preliminary and further subdivision may be necessary to account for changes in valley setting or to align with other administrative boundaries (e.g. WFD waterbodies).

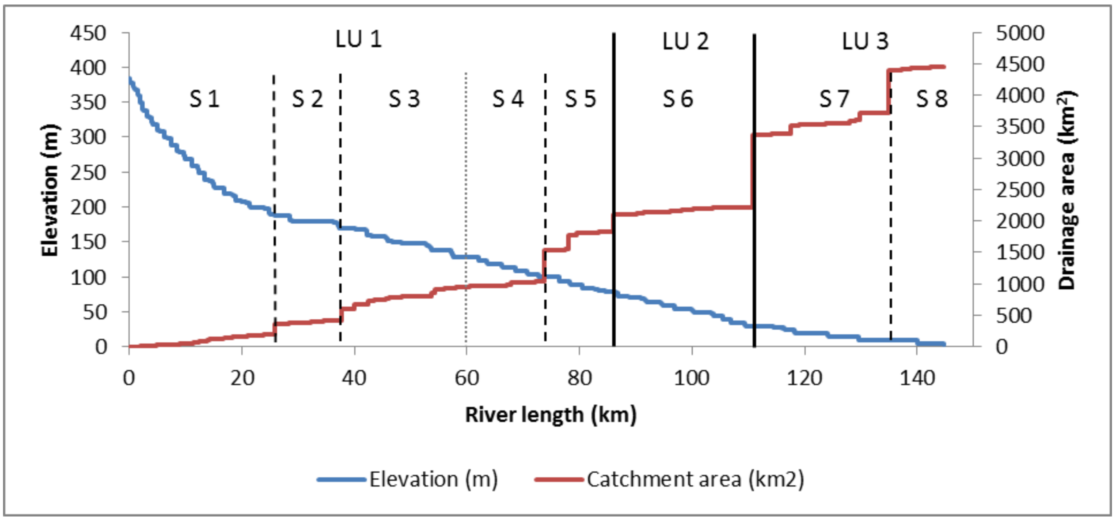

Figure 3.4 The River Tweed was delineated preliminary into eight segments based on increases in catchment area caused by major confluences and changes in valley confinement. The study section lies within segments 3 and 4 (Ordnance Survey data © Crown Copyright/database right 2012).

Table 3.2 Characteristics of the selected segments

Segments	2	3	4
Increase in drainage area at u/s confluence	87%	44%	n/a
Valley confinement	Unconfined	Partly confined	Partly confined
Valley gradient	0.0017	0.0019	0.0020
Segment length (km)	10.979	23.691	13.911

3.5. Reaches

The reach is the scale at which most people view and interact with the river, and the scale at which most restoration projects are focused. Hydromorphologically speaking, it is a section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent set of process-form interactions. In other words, the controlling factors that we identified in the earlier delineation steps produce characteristic patterns and landforms in the channel and floodplain, like river meanders and gravel bars. Delineation is based primarily on channel planform but also the presence of flow/grade control structures, resulting in a discrimination of river reaches according to a set of simple types.

Reach delineation for the Tweed was based on changes in valley setting and the presence of bed/grade control structures, as channel planform did not vary in the study area. Segment 4 remains a single, partly confined reach (Table 3.3).

Table 3.3 Characteristics for the reaches within the study section. *N.B. Reach 4 appears sinuous but is classified as straight because the channel follows the planimetric course closely.

Reaches	3a	3b	3c	3d	4
Valley confinement	Partly confined	Partly confined	Unconfined	Unconfined	Partly confined
Confinement index	7.42	4.22	12.83	11.05	4.14
Channel gradient	0.0017	0.0018	0.0016	0.0023	0.0019
Sinuosity index	1.06	1.11	1.07	1.08	1.04
Braiding index		1.03	1.01	1.01	1.00
Anabranching index		1.03	1.05	1.04	1.07
Structure at DS end		weir	weir		
River type	3	3	3	3	2
Threads	Single	Single	Single	Single	Single
Planform	Sinuous	Sinuous	Sinuous	Sinuous	Straight*

4. Indicators of present and past condition

4.1. Catchment

4.1.1. Catchment area

The River Tweed has a catchment area of 5,021 km^2 at the normal tidal limit. There are no major water diversions, so this represents the actual and functional catchment area. The River Tweed is a large-sized catchment according to the definition used by the WFD.

4.1.2. Water yield and runoff ratio / coefficient

According to flow summaries for the downstream-most river gauging station (Norham, catchment area 4390 km^2), average yearly rainfall is 1011 mm and average yearly runoff is 583 mm for the period 1962 – 2013, yielding a runoff ratio of 0.58.

4.1.3. Geology and land cover

The Tweed catchment is composed predominately of siliceous bedrock and surficial geology (i.e. glacial till) (95%) (Figure 3.3 c and d). Organic geology (i.e. peat) is found in 5% of the catchment, and calcareous and mixed geology in 0%.

Land cover consists predominately of forests and semi-natural areas (54%) (Table 4.1). Agricultural areas comprise 43% of the catchment, and wetlands and artificial surfaces 1% each, according to the 2006 Corine dataset. Recent change in land cover was assessed using the UK Countryside Survey (25 m resolution) with subclasses aggregated to coincide with Corine Level 1 classes. No change in general land cover types has occurred in the last 2 decades (Table 4.1).

Table 4.1 Recent change in land cover according to the UK Countryside Survey.

Land cover	1990	2000	2007
Forest and semi-natural	61%	54%	59%
Wetlands	1%	1%	1%
Artificial	1%	1%	1%
Agriculture	36%	43%	39%
Inland water	0%	0%	0%

4.2. Landscape unit

4.2.1. Exposed aquifers and Soil / bedrock permeability

Substantial differences exist in the % area of exposed aquifers between the landscape units according to the European Groundwater Resource dataset (Figure 4.1, Table 4.2). Landscape unit 1 had the lowest proportion of area with an unconfined aquifer (5%) and Landscape unit 2 had the greatest (40%). Groundwater storage in alluvium represents a small amount of the area of the landscape units, but may be locally important within river segments.

<u>Soil permeability</u>, as assessed with the hydrogeology parameter from the European Soil Database, shows no significant variation by landscape unit; permeable soil substratum covers between 66-70%.

Table 4.2 Hydrological characteristics at the landscape unit scale. Characteristics in bold font are the indicators specified in Deliverable 2.1 Part 1.

Landscape units	1	2	3
Aquifer (% area)			
Single, unconfined	5%	40%	23%
Single, mixed (unconfined/confined)	0%	0%	30%
Alluvium	5%	5%	13%
Nil	89%	54%	34%
Permeability classes (% area)			
Permeable soil substratum	70%	69%	66%
Affected by groundwater (at least seasonally impermeable)	8%	10%	22%
Upland / mountain	22%	21%	11%

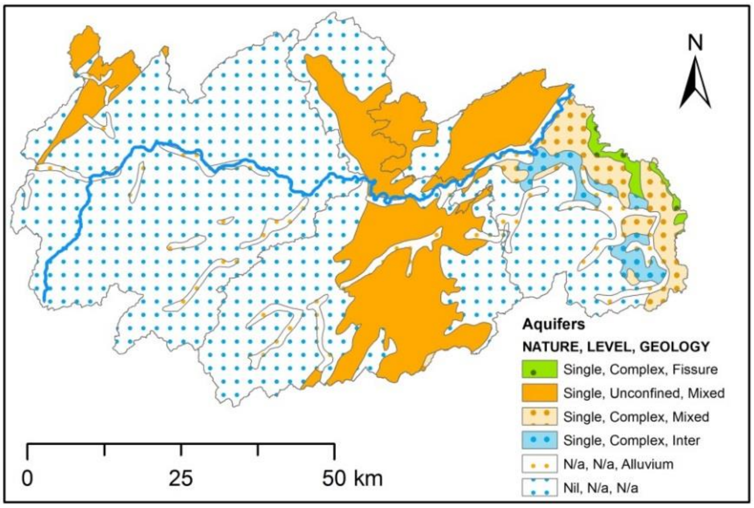

Figure 4.1 Aquifers within the Tweed catchment classified according to its nature, level and geology. For the hydromorphological assessment, exposed aquifer is defined as one with an unconfined level (JRC).

4.2.2. Land cover

Landscape units differ substantially in land cover (Table 4.3). Landscape unit 1 is composed predominantly of scrub and/or herbaceous vegetation (54%), Landscape unit 3 arable land (50%), and Landscape unit 2 contains an approximately equal mix of the two classes.

Land cover in all three landscape units is predominantly associated with an intermediate runoff production potential (Table 4.4). Landscape unit 1 has the highest proportion of area with both delayed and rapid runoff potential due to the greater area covered by forests and bare rock, respectively.

The historical analysis of recent change in land cover reveals that Landscape unit 1 has experienced an increase in the area covered by forests and pastures, and a decrease in scrub and/or herbaceous vegetation since 1990 (Figure 4.2). There are no clear trends for Landscape units 2 and 3, though Landscape unit 2 shows more fluctuations over time particularly for scrub and/or herbaceous vegetation.

Table 4.3 Land cover for the landscape units (% area, Corine Level 2)

Landscape unit	**1**	**2**	**3**
Artificial			
Urban fabric	1%	1%	0%
Industrial, commercial and transport units	0%	0%	0%
Mine, dump and construction sites	0%	0%	0%
Artificial, non-agricultural vegetated areas	0%	1%	1%
Agricultural			
Arable land	4%	29%	50%
Pastures	19%	19%	19%
Heterogeneous agricultural areas	0%	0%	1%
Forests			
Forests	16%	16%	3%
Scrub and/or herbaceous vegetation associations	54%	35%	23%
Open spaces with little or no vegetation	4%	0%	1%
Wetlands - Inland wetlands	2%	0%	1%
Waterbodies - Inland waters	0%	0%	0%
Glaciers and perpetual snow	0%	0%	0%

Table 4.4 Runoff production for landscape units in percent of area, based on land cover types (Corine level 2).

Landscape unit	**1**	**2**	**3**
Rapid	5%	1%	2%
Intermediate	77%	83%	94%
Delayed	18%	16%	4%

Figure 4.2 Recent changes in land cover from the UK Countryside Survey, aggregated to align with Corine Level 2 classes for Landscape units (a) 1, (b) 2, and (c) 3.

4.2.3. Sediment production

Average soil erosion rates based on the Pesera model are lowest in Landscape unit 1, highest in Landscape unit 3 and intermediate for Landscape unit 2 (Table 4.5). Whilst estimated soil erosion is primarily low to moderate along the main stem of the River Tweed, it is more severe further away from the channel, particularly in the agricultural areas of Landscape units 2 and 3 (Figure 4.3). Potential coarse sediment production was assessed using the EU landslide susceptibility dataset (Table 4.5). All landscape units had a high proportion of area classified as moderately or highly susceptible to landslides, but Landscape unit 1 was the only to have area classified as very highly susceptible (15%). A survey of Google Earth imagery for the catchment did not reveal clear evidence of mass movements. Gullying was visible in a few tributaries and often associated with land cover change (e.g. logging), but no landslides, torrents or other mass movements were identified. A more thorough analysis using high resolution topography or aerial imagery would be needed to accurately assess the percentage area of each landscape unit occupied by areas of sediment production.

As per the guidelines in Deliverable 2.1 Part 1, since only a small section of the river in a single landscape unit (1) is being assessed, all high or medium blocking structures within the landscape unit must be identified. Except for two weirs that are accounted for in the segment-scale analysis, there are no other blocking structures on the main stem of the

River Tweed. However, tributaries are impacted by blocking structures. Of particular note are several reservoirs in the uplands. The large Talla and Fruid reservoirs are found on tributaries that drain to Segment 1 of the Tweed; West Water and Baddinsgill reservoirs are on tributaries of the Lyne Water whose confluence with the River Tweed marks the start of Segment 3; and the large Meggett reservoir is on a tributary of the Ettrick Water whose confluence with the Tweed marks the start of Segment 4.

Table 4.5 Indicators of sediment production at the landscape unit scale.

Landscape unit	1	2	3
Average soil erosion rate (Pesera, t. ha-1. y-1)	0.42	1.38	1.90
Average soil erosion severity (Pesera)	Low	Moderate	Moderate
Landslide susceptibility			
Very low	11%	14%	29%
Low	14%	19%	29%
Moderate	32%	35%	15%
High	29%	32%	26%
Very High	15%	0%	0%

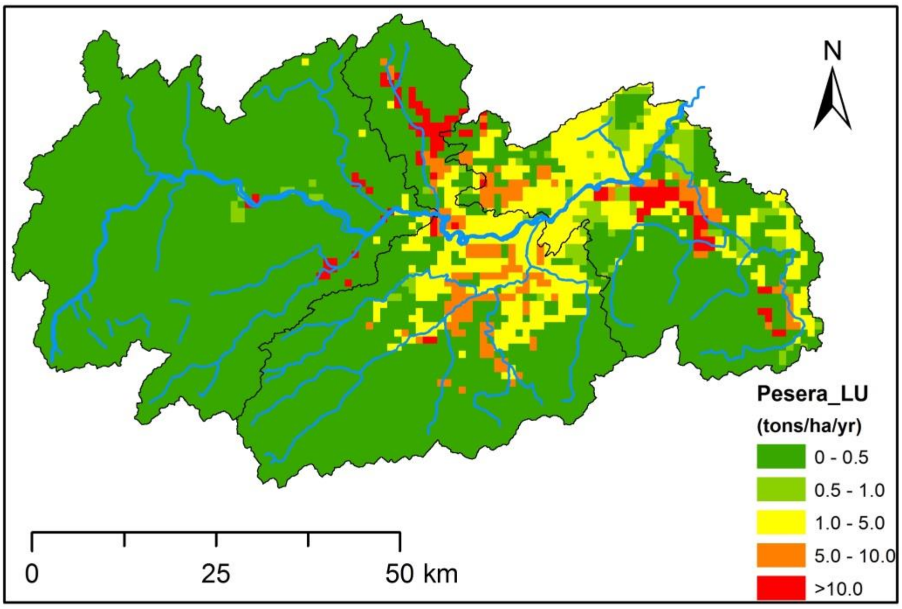

Figure 4.3 Predicted soil erosion rates based on the Pesera model.

4.3. Segment

4.3.1. Water flow

The only gauging station that is within the study area is in Segment 3 at Peebles. The Lyne Ford gauging stations is immediately upstream of the start of Segment 2, and upstream of the confluence with Lyne Water. The Boleside gauging station is immediately downstream of the end of Segment 4, and downstream of the confluence with Ettrick

Water, a large tributary with average daily flow equivalent to that of the Tweed at Peebles.

The flow regime type is perennial stable (groundwater) for Segment 3, and perennial runoff for the gauging stations that are adjacent to the study stretch (Table 4.6). IARI method classifies Segment 3 as stable because it has a lower coefficient of variation (DAYCV) than the other sites, which means that flows are less variable. The landscape unit is composed predominantly of impervious Palaeozoic and igneous formations, which one would expect to support a runoff dominated flow (i.e. flashy). However the valley in Segment 3, downstream of Peebles, has significant surficial deposits that support an alluvial aquifer (Figure 4.1) that could be responsible for the moderated flows.

Average monthly flows at all three gauging stations demonstrate a similar pattern in flow over the year (Figure 4.4). Flows are greatest in the winter (Jan) and lowest in the summer (July) which mirrors temporal patterns in rainfall for the area.

Morphologically meaningful discharges are presented in Table 4.6.

Extreme flow (discharge and month of most frequent occurrence) are presented in Table 4.7. Temporal patterns in extreme flow mirror those for average monthly flows; extreme low flows are most common in the summer an early autumn (June to September), whilst extreme high flows are most common in late autumn to winter (October to January)

Hydropeak frequency was not assessed due to lack of suitable hydrological information. Whilst no dams or reservoirs are present along the main channel, the operation of reservoirs located along tributaries within Landscape unit 1 could possibly result in hydropeaking, and more information is needed.

Monthly-averaged naturalised flow data were available for the three gauging stations from the start of the records to the end of 2000. Naturalised and actual flow records over this period were compared to determine the impact of reservoirs on river flows. The impact is greatest at the Boleside gauging station in terms of total reduction in average monthly flows (Figure 4.5a), but is greatest at the Lyne Ford station in terms of percentage reduction of naturalised flow (Figure 4.5b). The greatest impact on average monthly flows occurs in the autumn (September and October) (Figure 4.5b).

Table 4.6 River flow indicators for gauging stations within and adjacent to the study segments

Segment - Station	1 - Lyne Ford	3 - Peebles	5 - Boleside
Flow regime type	Perennial runoff	Stable (groundwater)	Perennial runoff
Average annual flow (m^3 s^{-1})	9.55	16.00	37.10
BFI	31.46	30.67	27.03
Morphologically meaningful discharge (m^3 s^{-2})	0.45	0.66	0.59
Qp_{median}	83.56	128.85	314.50
Qp_2	83.24	124.89	282.63
Qp_{10}	129.79	177.63	440.03

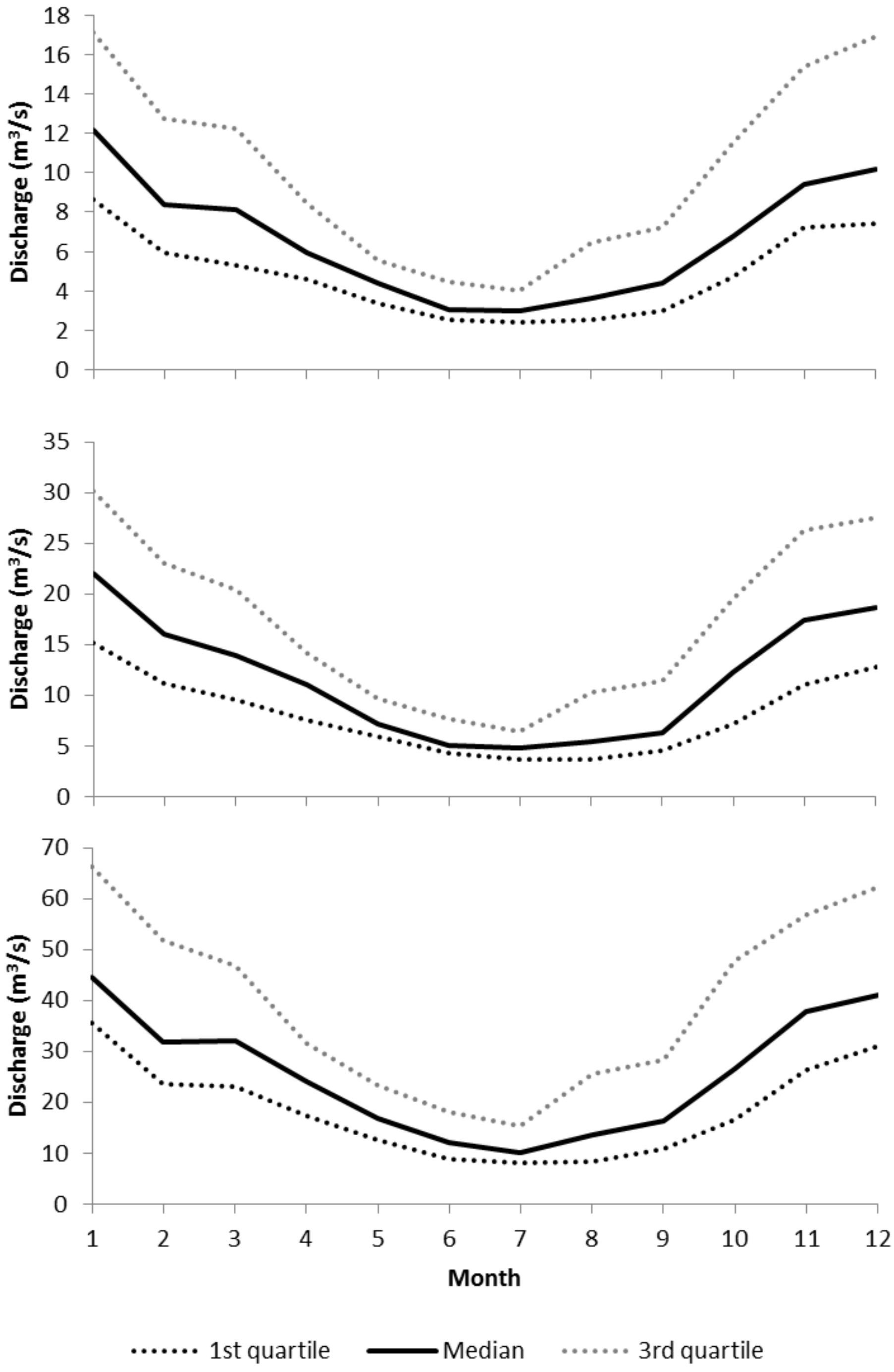

Figure 4.4 Monthly flows for the gauging stations at (a) Lyne Ford – Segment 1, (b) Peebles – Segment 3, and (c) Boleside – Segment 5.

Table 4.7 Annual extreme short-term (1-day) and long-term (30-day) flows (m^3 s^{-1}) and month of occurrence, reported for the 1st quartile (Q1), 2nd quartile (i.e median, Q2) and 3rd quartile (Q3).

Segment - Station	1 - Lyne Ford			3 - Peebles			5 - Boleside		
	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3
Minimum									
1-day	1.62	1.87	2.172	2.696	3.182	3.61	5.013	6.24	7.212
	Jun	Aug	Aug	July	Aug	Sep	June	July	Sep
30-day	2.081	2.444	2.92	3.199	3.98	4.658	6.84	8.28	9.633
	July	July	July	Aug	July	July	July	July	July
Maximum									
1-day maximum	56.27	81.95	101.3	91.89	114	143.7	229.9	295.8	370.7
	Nov	Dec	Jan	Oct	Dec	Jan	Oct	Nov	Jan
30-day maximum	18.91	24.15	28.85	30.57	39.51	48.47	72.26	93.76	105.7
	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan	Jan

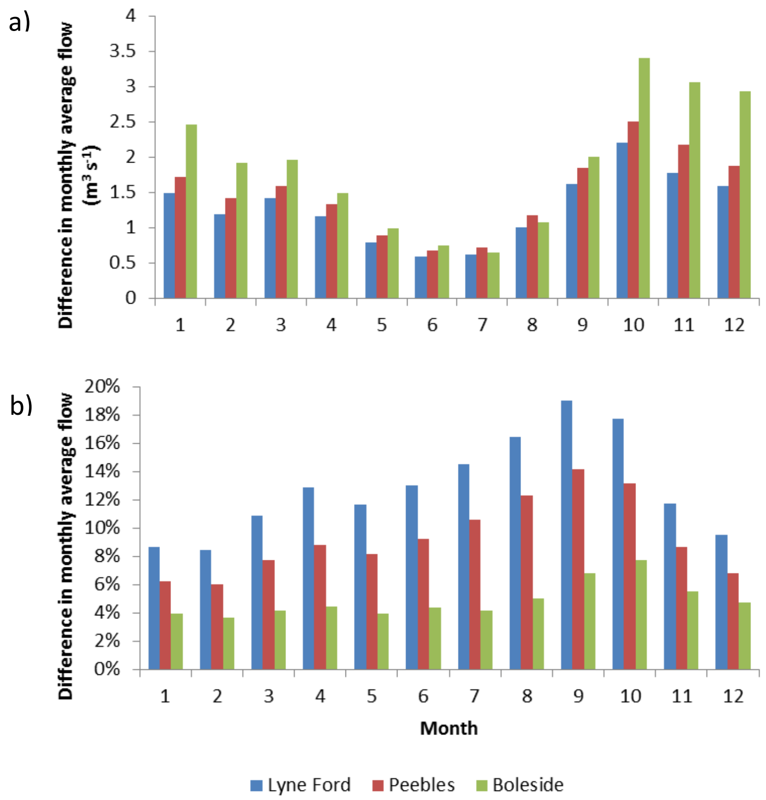

Figure 4.5 The difference between monthly average naturalised and actual flow reported in (a) absolute terms, discharge (m^3 s^{-1}), and (b) as a proportion of the naturalised flow.

4.3.2. Sediment flow

Eroded soil delivered to the channel was estimated at 0.053, 3.77 and 0.20 t km^{-1} yr^{-1} for Segments 2, 3 and 4 respectively based on the Pesera model and a 500 m buffer around the river (Table 4.8).

No land surface instabilities connected to the River Tweed were identified in Segments 2 - 4.

A sediment budget analysis was conducted by SEPA using the STREAM methodology, with the specific stream power model run using a Qp_2 discharge. The results of the model show Segment 2 is predominantly experiencing moderate deposition, Segment 3 has stretches prone to high bed erosion but also others where moderate to high deposition is likely; and Segment 4 is predominantly a high erosion stretch (Table 4.8).

The River Tweed has very few blocking structures; the study section has only 2 weirs assessed to be of medium impact along its 49 km length. No high impact spanning structures were identified in the study section; Segments 2-4 had three, six and two medium impact bridges, respectively (Table 4.8).

Table 4.8 Indicators associated with sediment flow to and within the channel at the segment scale.

Segment	2	3	4
Eroded soil delivered to the channel (Pesera, 500 m buffer, t km^{-1} yr^{-1})	0.053	3.77	0.20
Land surface instabilities	0	0	0
Sediment budget (STREAM, % of river length)			
High erosion	0%	32%	72%
Moderate Erosion	3%	9%	6%
Balance	40%	9%	9%
Moderate Deposition	55%	22%	0%
High Deposition	2%	28%	13%
Blocking structures			
High impact	0	0	0
Medium impact	0	2	0
Spanning structures			
High impact	0	0	0
Medium impact	3	7	2

4.3.3. River morphology adjustment

Indicators that represent constraints on river channel dynamics for the Tweed (average valley gradient, valley confinement and river confinement) are listed in Table 4.9.

Indicators of river morphology adjustments reflected in the extent of naturally-functioning riparian vegetation can be found in Table 4.10, including average riparian corridor width, proportion of riparian corridor under functioning riparian vegetation, riparian corridor continuity and riparian corridor vegetation cover / structure. Riparian vegetation was assessed using the UK Ordnance survey Mastermap high resolution map dataset that identifies natural and artificial land cover.

Table 4.9 Indicators that represent constraints on river channel dynamics

Segment	2	3	4
Average valley gradient	0.0017	0.0019	0.0020
Valley confinement	Unconfined	Unconfined	Partly confined
River confinement	Low (15.57)	Low (10.96)	Medium (4.01)

Table 4.10 Indicators of river morphology adjustment as represented by the extent and vegetation cover of naturally-functioning riparian vegetation

Segment	2	3	4
Average riparian corridor width (m)	333	324	144
Proportion of riparian corridor under naturally functioning riparian vegetation (% area)	27%	10%	25%
Riparian corridor continuity	34%	25%	75%
Riparian vegetation cover			
Mature	38%	70%	78%
Intermediate	4%	9%	3%
Early	57%	21%	19%
Overall assessment	Intermediate	Intermediate	Intermediate

4.3.4. Wood production

The % active channel edge bordered by living/dead trees is 13, 19, and 56% for Segments 2-4, respectively.

4.4. Reach

4.4.1. Flooding

The % floodplain accessible by floodwater is reported in Table 4.11. Despite a large number of embankments, floodwaters can access almost the entire floodplain of the River Tweed in the study reaches.

Table 4.11 Proportion of the floodplain accessible by floodwaters (1 in 200 year flood)

	3a	3b	3c	3d	4
Floodable area – 1 in 200 year flood (km^2)	0.5876	0.2950	5.0137	1.2407	1.9742
Floodplain area (km^2)	0.5555	0.2922	4.9227	1.2321	1.9518
% floodplain accessible by floodwater	95%	99%	98%	99%	99%

4.4.2. Channel self-maintenance / reshaping

Indicators of channel self-maintenance / reshaping are presented in Table 4.12.

Table 4.12 Indicators of channel self-maintenance and shaping for the study reaches of the River Tweed

	3a	3b	3c	3d	4
Specific stream power (W m^{-2})					
Qp_2	49	61	69	121	123
Qp_{median}	50	64	74	131	136
Qp_{10}	73	92	105	185	189
Bed sediment size	Gravel / Pebble	Cobble	Cobble	Cobble	Cobble
Bank sediment size	Earth	Earth	Earth	Earth	Earth
Channel gradient (m m^{-1})	0.0017	0.0018	0.0016	0.0023	0.0019
Confinement index	7.42	4.22	12.83	11.05	4.14
Mean bankfull channel width (m)	38	36	39	33	43
Mean bankfull channel depth	1.5	1.2	1.8	1.7	2.2
W:D Ratio	25	31	21	19	20
Sinuosity Index	1.06	1.11	1.07	1.08	1.04
Braiding Index	1.00	1.03	1.01	1.01	1.00
Anabranch Index	1.01	1.03	1.05	1.04	1.07
River Type	13	13	13	13	13

Presence of channel and floodplain features typical of the river type

All of the study reaches are classified as unconfined, single-thread, sinuous gravel-bed rivers (type 13). Potential morphological units according to Table 7.3 of Deliverable 2.1 Part 1 are pools, riffles, and large alternate (continuous) point bars closely confining the low flow channel. Data from RHS surveys indicate that riffles and bars are found in all reaches, but pools were uncommon (Table 4.13)

% area of the bankfull channel occupied by bars, benches and islands was assessed using channel outlines from the current high resolution OS digital maps, and consequently only consider the area occupied by islands. The percentage area occupied by islands was 0%, 2%, 4%, 1% and 3% for Reaches 3a-4 resepctively. Aerial imagery was only available for the one year (2007). Turbid waters and shading by riparian trees complicated the identification and delineation of channel geomorphic features, and consequently aerial imagery was not used to characterise the indicator.

Table 4.13 Channel geomorphic features assessed from River Habitat Surveys.

	3a	3b	3c	3d	4
Riffles and pools (per km)					
Pools	6.0	4.0	2.2	3.3	3.1
Riffles	0.0	2.0	0.4	0.0	0.0
Proportion of spot-checks reporting features					
Pools (no perceptible flow)	0.0	0.0	0.0	0.0	0.0
Riffles (unbroken standing waves)	0.3	0.1	0.3	0.1	0.1
Point bars (per km)					
Unvegetated point bars	1.0	0.0	0.2	0.0	0.2
Vegetated point bars	1.0	0.0	0.0	0.7	0.0
RHS spot-checks reporting features					
Mature islands	0%	20%	10%	0%	10%
Unvegetated bars (mid-channel, point and side)	10%	10%	10%	10%	0%
Vegetated bars (mid-channel, point and side)	10%	0%	10%	20%	20%
RHS surveys (n)	2	1	11	3	11

4.4.3. Channel change / adjustments

The presence of eroding banks (% active channel bank length) is presented in Table 4.14.

Table 4.14 The proportion of RHS spot-checks with eroding banks and the proportion of RHS sites were vertical bank profiles were extensive.

	3a	3b	3c	3d	4
Eroding banks (% of spot-checks)	10%	0%	35%	27%	5%
Vertical bank (extensive) (% of sites)	25%	100%	14%	50%	23%
Number of surveys	2	1	11	3	11

Results from historical analysis of reach planform shows that the channel has narrowed in the last 40+ years (Table 4.15). Channel length and sinuosity remained unchanged over this period, and a reduction in channel area was attributable to a reduction in channel width. In particular, the reduction in average channel width for reaches 3a and 3c is likely large enough to exceed the uncertainty in the map derived values. There was no significant change in braiding or anabranching indices.

Table 4.15 Temporal changes in channel position and width

	3a	3b	3c	3d
Channel area (ha)				
1966	7.93	8.43	46.63	11.87
2013	6.63	8.02	42.53	11.32
Net change (%)	-16.4%	-4.9%	-8.8%	-4.6%
Average channel width (m)				
1966	31.5	29.6	32.0	31.5
2013	26.3	28.2	29.2	30.0

Due to a paucity of reach-scale survey data, we were not able to quantify indicators related to the presence of geomorphic units indicative of narrowing, widening, deepening, etc, and vegetation encroachment.

Width of erodible corridor, erodible channel margin and the proportion of river bed that is artificially reinforced is presented in Table 4.16.

The number of high/medium/low blocking and spanning structures is presented in Table 4.17.

Table 4.16 Reach-scale indicators of the erodible corridor, erodible channel margin and bed reinforcement. Characteristics in bold are the indicators specified in Deliverable 2.1 Part 1.

	3a	3b	3c	3d	4
Erodible corridor					
Width (m)	101.1	86.6	217.7	197.2	124.4
Multiples of bankfull channel width	3.8	3.1	7.1	6.6	3.5
Erodible channel margin (%bank length)					
Banktop levees	27%	0%	9%	17%	1%
Set-back levees within 0/5 bankfull width	2%	23%	5%	1%	1%
Hard bank reinforcement	0%	0%	0%	0%	0%
Soft bank reinforcement	3%	0%	4%	5%	0%
Infrastructure within 0.5 bankfull width	4%	12%	16%	11%	14%
Erodible channel margin	35%	34%	34%	33%	17%
Proportion of artificially-reinforced river bed	0%	0%	0%	0%	0%

* RHS survey data gives higher values of artificial bank material than the spatial dataset provided by SEPA: 0%, 15%, 8%, 13%, and 6% for reaches 3a-4 respectively.

Table 4.17 The number of blocking and spanning structures in the study reaches classified by their impact on their impact on the longitudinal continuity of water and sediment flow.

	3a	3b	3c	3d	4
Blocking structures					
High impact	0	0	0	0	0
Medium impact	0	1	1	0	0
Low impact	0	0	0	0	0
Spanning structures					
High impact	0	0	0	0	0
Medium impact	1	1	4	1	2
Low impact	0	1	3	0	1

4.4.4. Vegetation succession

Limited data were available to assess aquatic vegetation extent. Mean trophic rank surveys had been previously conducted at four locations within the study reaches, and they give a snapshot of the dominant aquatic vegetation species and their percent cover at one point in time (Table 4.18).

Table 4.18 Percent cover data for the major macrophyte species recorded in the 4 MTR surveys previously conducted in the study reaches by CEG.

Reach Site	3a Manor Cove	3c WCB	3c Horsbrugh	4 Old Tweed Bridge
Phalaris arundinacea	0.1-1%	<0.1%	2.5-5%	25-50%
Sparganium erectum	n/r	n/r	<0.1%	1-2.5%
Ranunculus penicillatus ssp. pseudofluitans	25-50%	0.1-1%	0.1-1%	25-50%
Myosotis scorpioides	n/r	<0.1%	1-2.5%	0.1-1%
Scirpus sylvaticus	n/r	n/r	<0.1%	1-2.5%
Hildenbrandia rivularis	5-10%	n/r	n/r	n/r
Platyhypnidium riparioides	5-10%	n/r	n/r	n/r

Aquatic vegetation patchiness – no data were available to assess this characteristic.

Aquatic vegetation species are listed in Table 4.19. MTR data indicate that *Phalaris arundinacea* is the most common emergent macrophyte and *Ranunculus penicillatus* ssp. *pseudofluitans* and related species are the most abundant submerged macrophyte (Table 4.18). Other common aquatic species include *Sparganium erectum*, *Myosotis scorpiodes*, *Scirpus sylvaticus*, the rock-encrusting algae *Hildenbrandia rivularis* and several species of aquatic mosses including *Platyhypnidium riparioides* (Table 4.19).

The presence of aquatic-plant dependent geomorphic units / features was not assessed due to insufficient data.

The proportion of the riparian corridor under mature trees, shrubs and shorter vegetation, and bare soil is listed in Table 4.20. The vegetation in all of the study reaches is predominantly mature trees, though reaches 3a and 3d have high proportions of grass and wetland.

Lateral gradient in riparian vegetation cover classes and patchiness in riparian vegetation cover types were not assessed. The riparian corridor is narrow and disconnected, and no clear patterns in lateral gradients were evident in the Mastermap-derived classification. Patchiness within the vegetated area cannot be assessed with the dataset.

No riparian tree surveys were available from the project partners (SEPA and CEH), so dominant riparian tree species cannot be assessed.

No existing data were available to assess the presence of wood- or riparian tree-dependent geomorphic units.

Table 4.19 Aquatic vegetation species identified in MTR surveys

Species	Type	Form
Brachythecium sp	Aquatic	moss
Caltha palustris	Aquatic	Emergent/herb
Cardamine hirsuta/flexuosa	Riparian	herb
Cladophora aegagropila	Aquatic	green algae
Cladophora glomerata	Aquatic	green algae
Eleocharis palustris	Aquatic	emergent / rush
Epilobium sp.	Riparian	herb
Fontinalis antipyretica	Aquatic	moss
Fontinalis squarnoisa	Aquatic	moss
Hildenbrandia rivularis	Aquatic	rock-encrusting algae
Hygroamblystegium fluviatile	Aquatic	moss
Juncus effusus	Aquatic/Riparian	emergent / rush
Leptodyctium riparium	Aquatic	moss
Mimulus guttatus	Riparian	herb
Myosotis scorpioides	Aquatic//Riparian	emergent / herb
Myriophyllum alterniflorum	Aquatic	moss
Pellia sp.	Riparian	liverworts
Persicaria amphibia	Aquatic	emergent / herb
Phalaris arundinacea	Aquatic//Riparian	emergent / graminoid
Platyhypnidium riparioides	Aquatic	moss
Ranunculus (sect Batrachian)	Aquatic	submerged
Ranunculus penicillatus ssp. *pseudofluitans*	Aquatic	submerged
Rorippa sylvestris	Riparian	herb
Scirpus sylvaticus	Riparian	emergent / sedge
Sparganium erectum	Aquatic	Emergent / bur-reed
Symphytum officinale	Riparian	herb
Valeriana officinalis	Riparian	herb
Veronica anagallis-aquatica	Aquatic//Riparian	Emergent / herb
Veronica beccabunga	Aquatic	emergent / herb

Table 4.20 Proportion of the riparian corridor under mature, intermediate and early vegetation, and bare earth/sediment.

	3a	3b	3c	3d	4
Mature vegetation (Trees)	60%	79%	69%	56%	78%
Intermediate (Shrubs)	0%	3%	11%	2%	3%
Early (Grass / Wetland)	40%	18%	20%	41%	19%
Bare	0%	0%	0%	0%	0%

4.4.5. Wood delivery

RHS data indicate that fallen trees and large woody debris are present in most reaches within the River Tweed (Table 4.21), however, no site had extensive wood or fallen trees (>33% of reach area). No data were available to assess the abundance of wood in the riparian corridor.

Table 4.21 Wood delivery: Percentage of RHS surveys where fallen trees or large woody debris was present in the study reach.

	3a	3b	3c	3d	4
Fallen trees - present	100%	100%	36%	0%	45%
Large woody debris - present	50%	100%	45%	33%	82%
Number of surveys	2	1	11	3	11

Catchment Case Study 7

Hydromorphological assessment of the River Loire (France): a large West European river

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Irstea Lyon

1. Introduction

This document applies three stages of the hierarchical hydromorphological assessment framework described in Deliverable 2.1 Part 1 to a large sand-bed river to:

- Delineate the river and its catchment into spatial units (Section 2)
- Characterise the current hydromorphological condition of the spatial units (Section 3)
- Characterise some representative reach and morphological units using hydraulic parameters (Section 4)

To support these key stages in applying the methodology, we also introduce the River Loire catchment (Section 1.1), and provide a very brief technical summary of the data sources and methods used in the delineation and characterisation stages (Section 1.2).

1.1 The River Loire

The River Loire is a lowland, sand-bed river located in the western part of France. It is the longest river in France (1,012 km) and it drains an area of 117,054 km^2, or more than a fifth of France's land area. It rises in the highlands of the southeastern quarter of the Massif Central in the Cévennes range at 1,350 m, flows northwards for over 1,000 km through Nevers to Orléans, and then west through Tours and Nantes until it reaches the Bay of Biscay (Atlantic Ocean) at St Nazaire. Its main tributaries from upstream to downstream are the Allier, Cher, Vienne et Maine. The River Loire is characterized by an upstream piedmont section, significantly influenced by two dams (Grangent and Villerest Dam) that are used for flood regulation (together with another on the Allier River), then by a section with a multiple channel configuration downstream of the confluence with the Allier River, a short meandering section upstream of Orléans, and a multiple channel system with the presence of numerous vegetated islands and sand bars in the downstream section. The River Loire has a highly variable hydrologic regime with very low discharge during the summer and high magnitude flows in winter and spring. At Gien, located 564 km downstream from the source, flood events with a return period of 2 years correspond to a discharge of 1600 m^3/s.

The Loire has been described as "constantly under threat of losing its status as the last wild large river in France". The reason for this is that due to its great length and the possibility of extensive navigation, which severely limits the scope of river conservation. The Loire has the highest phytoplankton diversity among French rivers, includes nearly every freshwater fish species of France, including many migratory ones, and it also hosts about 64% of nesting bird species of France. Since the 1990s, the 'Loire Nature' projects have helped in embarking upon restoration to the river's ecosystems and wildlife.

In this report, we use the hierarchical assessment framework to investigate the hydromorphological condition of the River Loire. This application of the hierarchical framework, although incomplete, could be used for a variety of purposes; for example to identify significant hydromorphological pressures in the catchment, to support and interpret ecological surveys, or to inform catchment management decisions or restoration options.

1.2 Material and methods

1.2.1 Datasets

A selection of remotely sensed and national datasets was used in the delineation and characterisation processes (see Table 2.1 of the catchment case study 1).

The regional environment agency (DREAL Centre) have regularly monitored two hundred sites to record water levels at low and high flows since 1978. Aerial photographs taken during low flow conditions are available for 1955, 1984, 1995, 2002 and 2010. A topographic survey of the Middle Loire River was undertaken in 1995. Cross sections, surveyed every 2 km on average, cover the main channel and can be extended laterally with floodplain data extracted from Lidar data collected in 2003.

There are several hydrometric stations along the loire River. The main ones used for this study are Gien (1936-2012), Langeais (1985-2012), Saumur (1988-2012).

The methods for delineation and characterisation are based on the guidelines described in Deliverable 2.1 Part 1 Sections 4 and 5. The hydromorphological assessment framework consists of three main phases: delineation, characterization and the assessment of indicators of hydromorphological condition. Its implementation on the Loire is described in this document with complementary parameters obtained from numerical modelling and a comparison of reach boundaries identified with the framework and with some statistical tests.

2. Delineation of the Spatial Units

Figure 2.1 provides an overview of the framework. The criteria for distinguishing and characterizing the different spatial units are available in Deliverable 2.1 Part 1 sections 4 and 5. The boundaries of the spatial units' boundaries and the characterization of each unit are provided below.

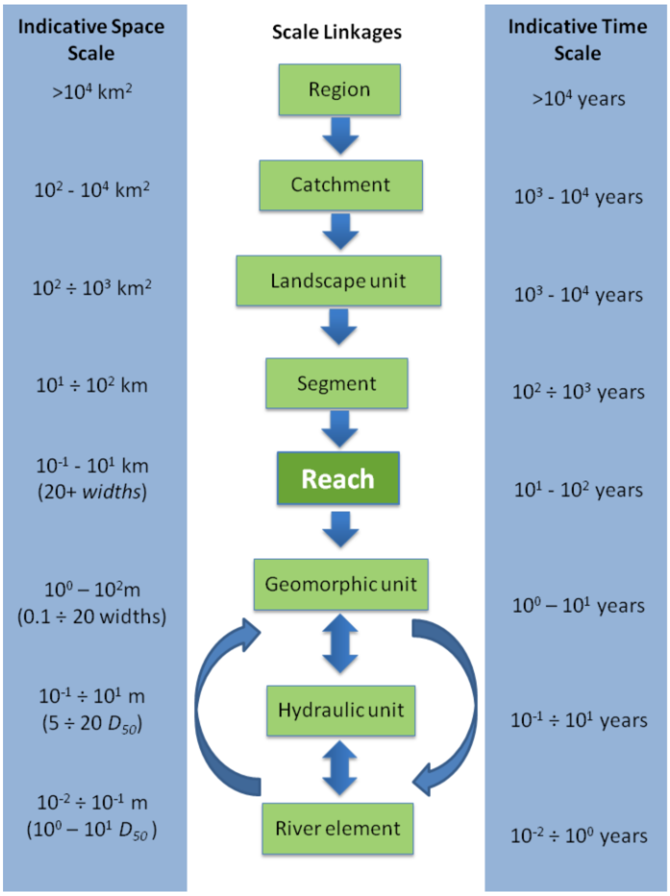


Figure 2.1 Hierarchy of spatial scales for the European Framework for Hydromorphology, including indicative spatial dimensions and timescales over which these units are likely to persist (image from QMUL).

2.1 Region

At this scale, macro features of biogeography and hydroclimate are considered. In the context of the Water Framework Directive, the water District is the Loire (*http://ec.europa.eu/environment/water/water-framework/facts_figures/index_en.htm*).

The Loire River is mostly located in the Atlantic European region but its upstream part lies within the continental region (Figure 2.2).

(a)

(b)

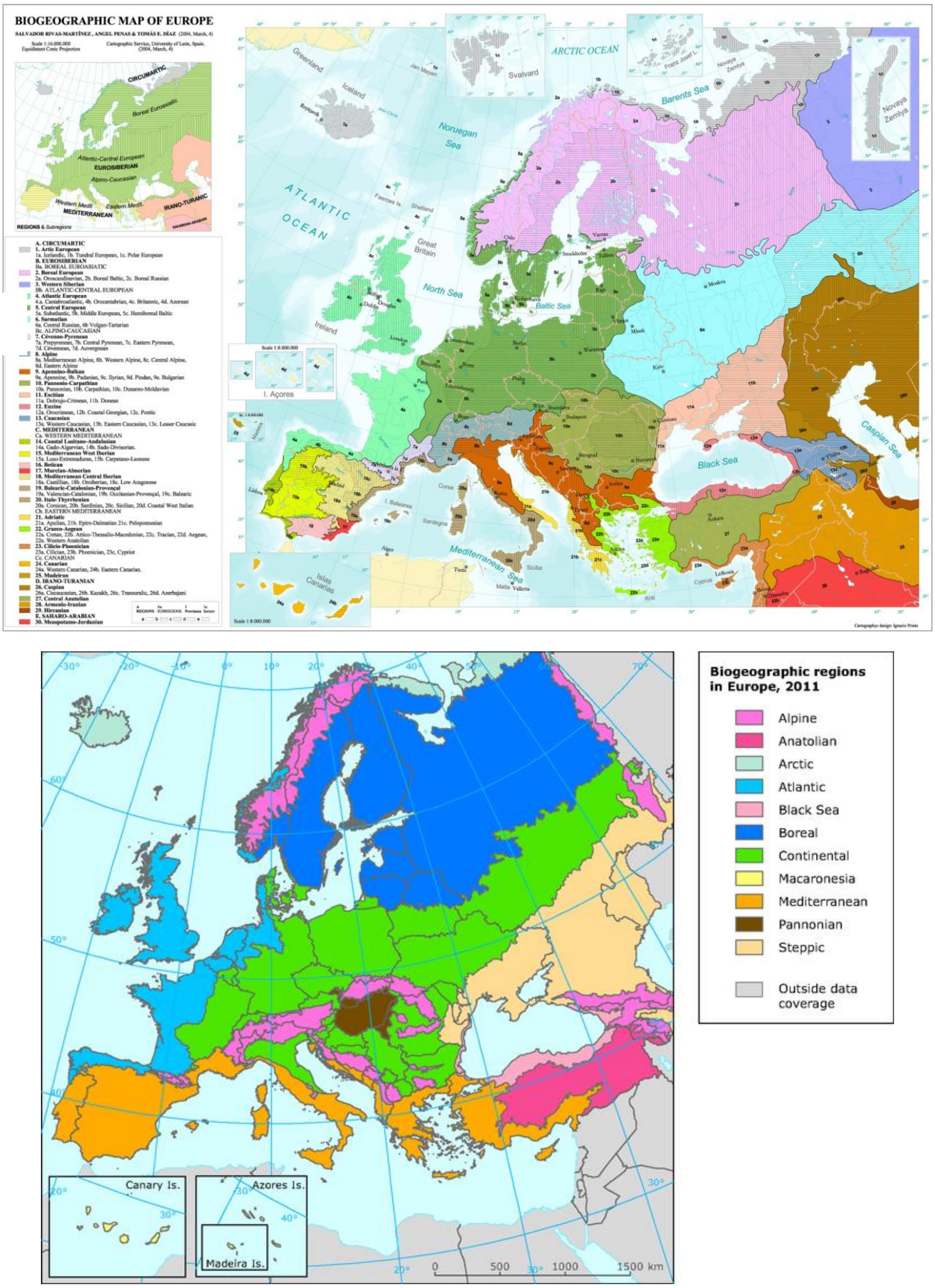


Figure 2.2 Biogeographic maps of Europe extracted from: *www.globalbioclimatics.org*; *http://www.eea.europa.eu/data-and-maps/figures/biogeographical-regions-in-europe-1*

2.2 Catchment

At the catchment scale, the aim is to give a broad overview of the topographic, geological and land cover controls on water and sediment delivery to the river network. The scales adopted comply with the recommendations from the Water Framework Directive (WFD).

The Loire river is the longest river in France with a length of 1 012 km. Its drainage area represents 117 000 km², that is one fifth of France's area (Figure 2.3). The characteristics of the River Loire catchment are summarized in Table 3.1.

2.3 Landscape unit

A landscape unit is a portion of a catchment with similar landscape morphological characteristics (elevation, relief,geology, land cover etc.). Three landscape units were delineated for the Loire using DTM, geological maps, Corine land cover and/or orthophotos (Figure 2.4): the Upper Loire (LU1), from its source to the confluence with the Allier River; the Middle Loire (LU2), from the confluence with the Allier to the confluence with the Maine; the lower Loire (LU3), from the confluence with the Maine to the ocean.

2.4 River segment

Delineation below the Landscape Unit scale is only carried out on landscape unit 2 (i.e., the Middle Loire).

River segments are sections of river subject to similar valley scales influences and energy conditions. Major tributaries confluences and valley confinement can be used to delineate the segments. Contribution from major tributaries and the valley confinement are presented in Figures 2.5 and 2.6, respectively.

Based on major confluences three river segments can be distinguished in Landscape Unit 2 (Figure 2.7): from the Allier confluence to the Cher (S1); from the Cher to the Vienne (S2); from the Vienne to the Maine (S3)

Figure 2.3 Location map of the Loire catchment

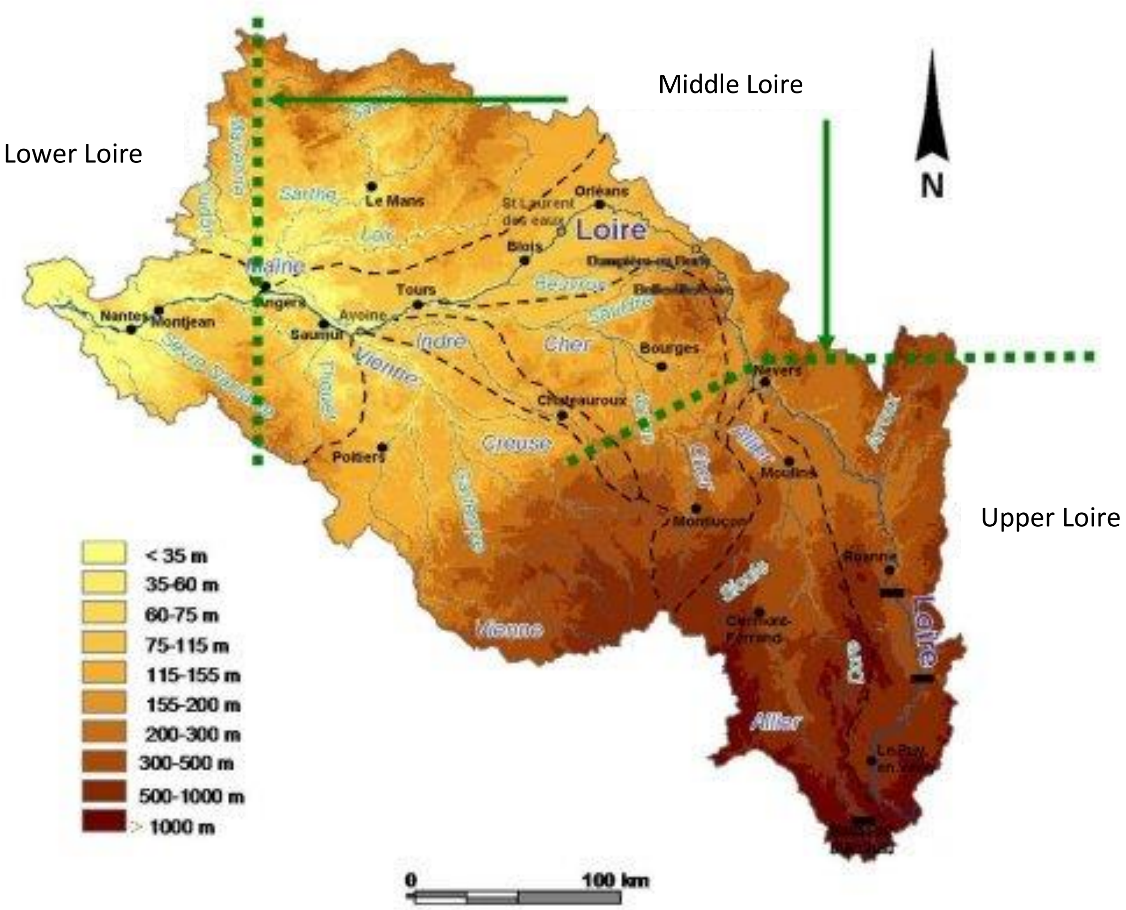


Figure 2.4 Relief of the river Loire and delineation of the three landscape units.

Upper Loire

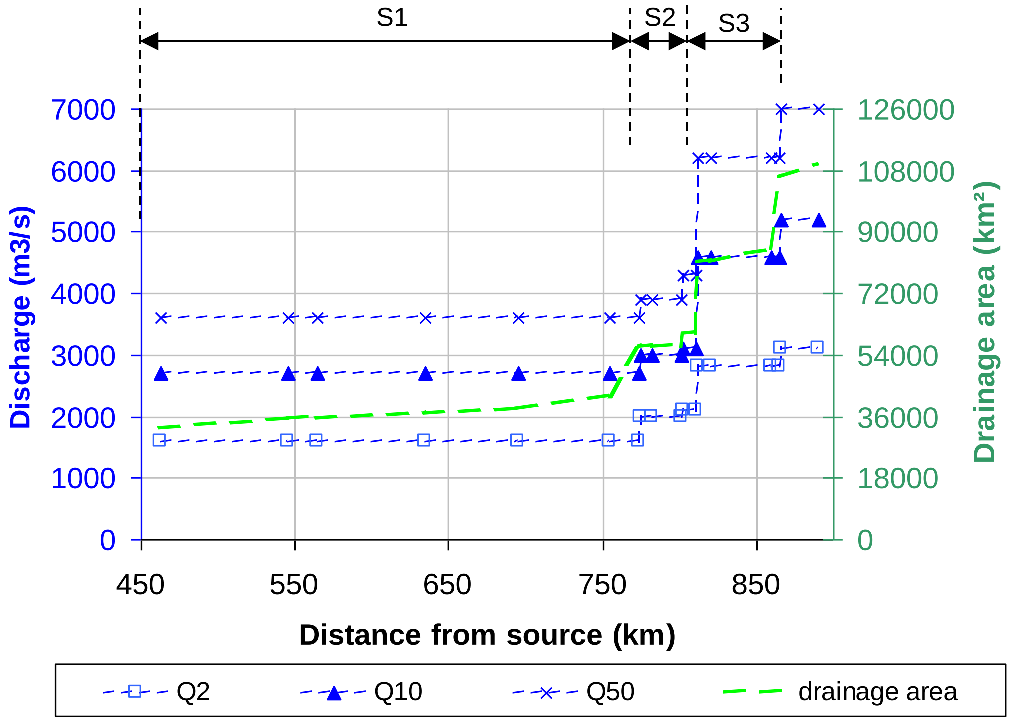


Figure 2.5 Contribution from the tributaries to the Loire's discharge for specific return period.

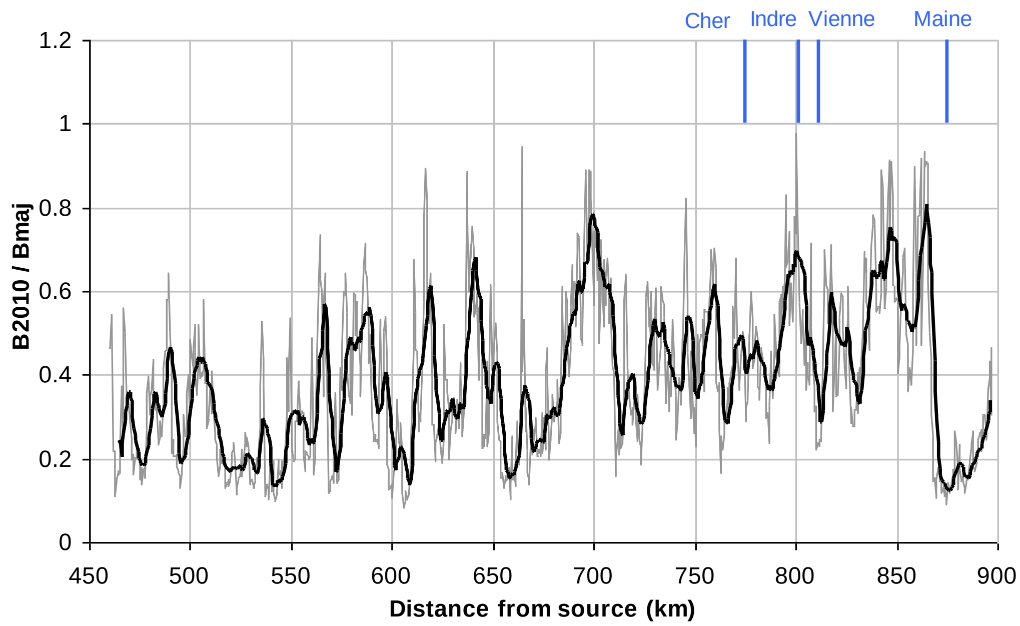


Figure 2.6 Confinement ratio (Active channel width measured on the 2010 aerial photographs *B2010* over floodplain width *Bmaj*)

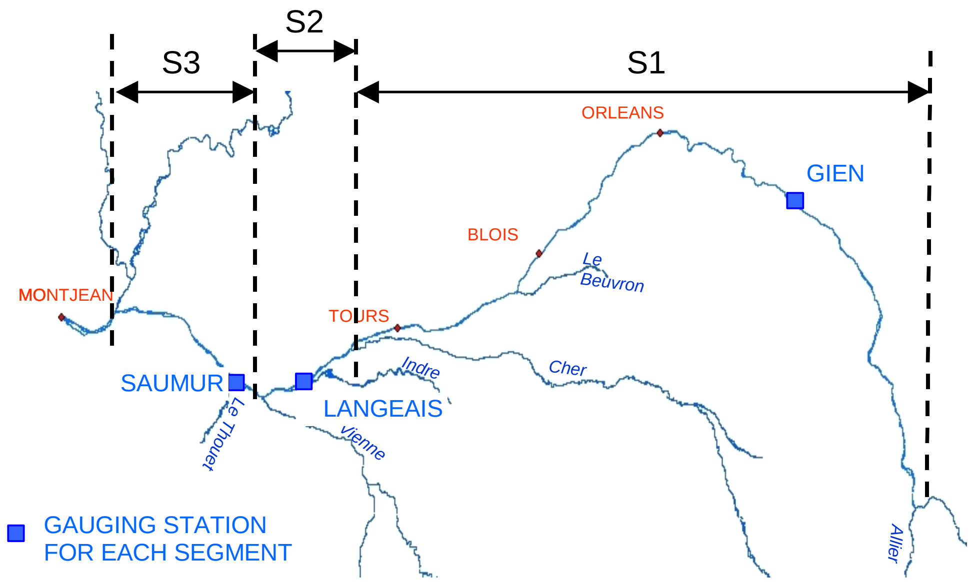


Figure 2.7 Delineation of the three segment considered in LU2 and location of the gauging stations considered in the flow data analysis.

2.5 River reaches

The reach corresponds to a section of river and floodplain along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions. As a general rule, the length of a reach should not be smaller than 20 times the mean channel width (although shorter reaches can be defined where local circumstances are particularly complex). The reach delineation is done using aerial photographs and identifying different channel configurations. Based on those characteristics, river types are assigned to each reach as defined by the simple (not extended) classification in section 7 of Deliverable 2.1 Part 1.

As delineating and describing all reaches identified on the second landscape unit of the Loire river is a large task, five reaches of different type are discussed in the following paragraphs. Their location and general description is provided in Figure 2.8 and Table 2.1.

2.6 Geomorphic unit

Geomorphic unit are areas containing a landform created by erosion and/or deposition inside or outside of the river channel. Criteria for delineation include form, sediment structure/calibre, water depth/velocity and sometimes large wood or plant stands. A preliminary analysis can be conducted using aerial photos but field surveys are necessary for more detail. Considering the five reaches described in the previous paragraph, a delineation of the geomorphic units based on the results of the application of a hydro-dynamic model is proposed in section 4.2.

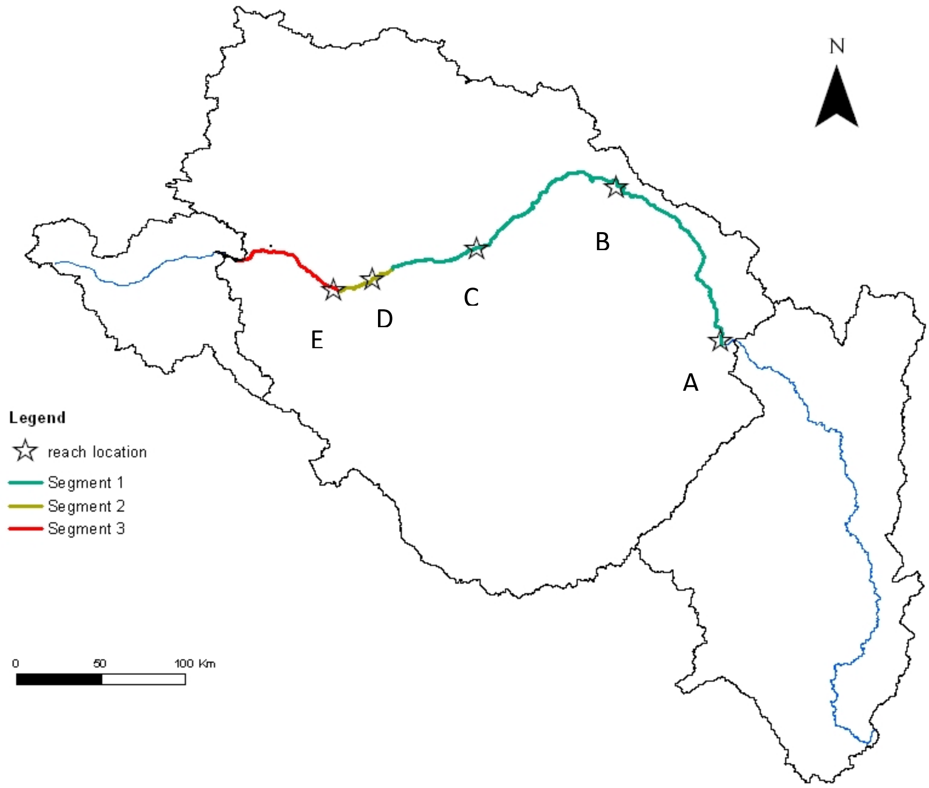


Figure 2.8 Location of the five reaches detailed in the characterization process.

Table 2.1 Description of the river reaches

Segment	Reach	Confinement	Threads	Planform	Si	Bi	Ai	Type
1	A	Partly confined	Transitional	Wandering	-	1.5	1.3	5
1	B	Unconfined	Single	Meandering	1.57	1	1.2	4
1	C	Partly confined	Single	Straight	1	1.02	1.01	2
2	D	Partly confined	Multi threads	Braided ?	1.07	1.1	1.9	6
3	E	Partly confined	Transitional	Wandering	-	1.4	1.4	5

Si is the sinuosity Index, *Bi* is the braiding index and *Ai* is the anabranching index.

3. Characterisation of the Spatial Units

3.1 Catchment

Table 3.1 lists the main characteristics of the Loire catchment. The average annual hydrologic balance has been estimated by Vernoux (2010) as: 813 mm/year of rain (about 95 billions m^3); 123 mm of runoff (about 14,4 billions m^3); 129 mm of seepage (about 15 billions m^3)

3.2 Landscape unit

The characterization of the landscape units is similar to the catchment but with a greater level of detail (Tables 3.2, 3.3, 3.4).

Table 3.1 Characteristics of the Loire's catchment

Characteristics	Value	WFD class
Catchment are (km²)	117 000	Very large
Maximum elevation (mNGF)	1 857	-
Average elevation (mNGF)	282	-
Minimum elevation (mNGF)	- 82	-
Elevation zones	7.2 %	High: > 800 m
	38.0 %	Mild: 200-800 m
	55.1 %	Lowland: < 200m
Relative relief[10] (m)	1 919	-
Stream length (km)	1 012	-
Overall gradient (m/m)	0.0019	-
Geology / soils http://infoterre.brgm.fr http://www.onegeology.org	54.5 %	Calcareous
	24.4 %	Siliceous
	21.2 %	Mixed
Soil permeability[11]	24.3 %	Permeable
	17.7 %	Low permeability
	58 %	Impermeable
Land cover[12] http://sd1878-2.sivit.org/	9.6 %	Artificial zone
	58.8 %	Agricultural zone
	26.3 %	Forest
	4.1 %	Grassland & shrubs
	0.12 %	Open space with sparse vegetation
	1.15 %	Water zone

Soil permeability is based on the classification derived by Zumstein (1989) and implemented by Wasson et al. (2002).

[10] The relative relief is the difference between the highest and the lowest points in the drainage area.

[11] The classes adopted for soil permeability are detailed in Table 3.

[12] The Corine Land cover database has been analysed using the typology detailed in Table

Table 3.2 Classes adopted for soil permeability.

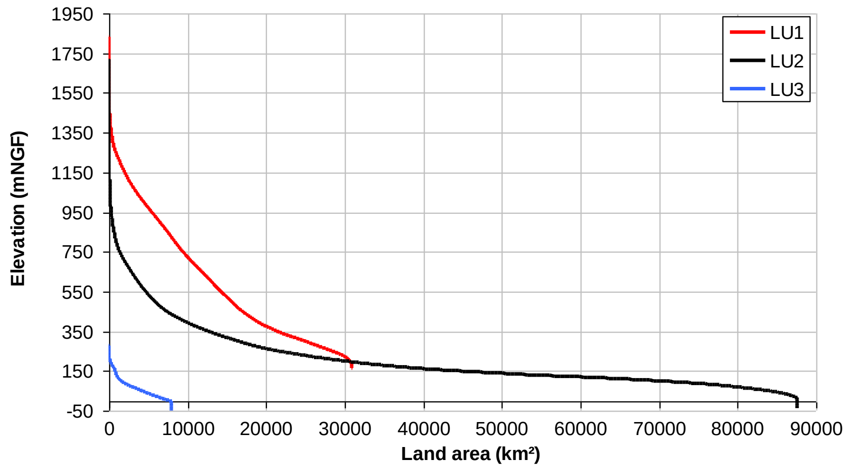
Class adopted	Rock type
Permeable	Sandstone, molasses, sand, dolomite
Low permeability	Schist
Impermeable	Metamorphic rock, granite

Table 3.3 Typology adopted for the Corine Land Cover database

Code provided in the database	Land cover type adopted
111 to 142	Artificial zone
211 to 244	Agricultural zone
311, 312, 313	Forest
321 to 324	Grassland and shrubs
331 to 335	Open space with no vegetation or sparse vegetation
411 to 523	Water zone

Figures 3.1, 3.2 and 3.3 show the distribution of the slope and elevation for the each of the three Landscape Units, and figure 3.4 presents the slope-elevation distribution for the three landscape units. Small slopes ($s<5°$) and low elevations ($H<500m$) prevail, especially for the landscape unit 2.

Table 3.4 Characteristics of the landscape units

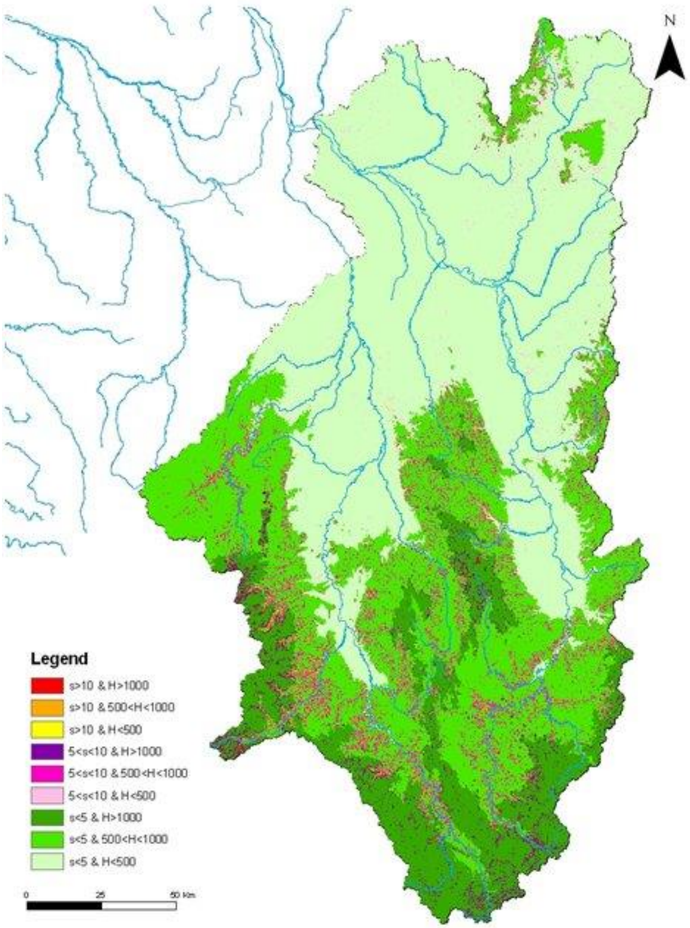
Characteristics		Landscape units		
		LU1	**LU2**	**LU3**
Rainfall	Number of rain gauges http://www.sandre.eaufrance.fr	582	1267	78
Relief / Topography	Network length (km)	459	416	137
	Area (km²)	30,625	79,415	7,900
	Drainage density[13] (km/km²)	0.015	0.005	0.017
	Hypsometric curve[14]			
Relief / Topography	Channel elevation U/S (mNGF) Channel elevation D/S (mNGF)	1,408 164.74	164.74 10.32	10.32 2

[13] The drainage density (river network length / landscape unit area in km/km²) indicates the degree of dissection of the landscape unit and is also an indicator of likely runoff intensity.

[14] The hypsometric curve (plot of the area of the landscape unit that exceeds different elevation thresholds) indicates the broad morphology and steepness of the landscape unit.

Characteristics			Landscape units								
			LU1			LU2			LU3		
	Gradient (m/m)		0.0027			0.0037			0.00007		
	Land surface slope[15] and elevation distribution (%).		Elevation LU1			Elevation LU2			Elevation LU3		
		Slope (°)	H<500	500<H<1000	H>1000	H<225	225<H<500	H>500	H<50	50<H<125	H>125
		S < 5	48.24	30.52	12.65	73.75	15.68	1.87	46.86	38.36	12.47
		5 < S < 10	1.37	4.71	1.53	3.06	2.96	1.50	0.83	0.87	0.44
		S > 10	0.13	0.69	0.16	0.25	0.45	0.49	0.09	0.06	0.02
Geology / Surface : groundwater	Calcareous underlain Siliceous underlain Mixed underlain		38.1 % 19.4 % 42.5 %			67.4 % 17.6 % 15.0 %			23.9 % 51.8 % 24.3 %		
	Permeable Low permeability Impermeable		9.1 % 33.1 % 57.8 %			24.3 % 17.7 % 58.0 %			20.3 % 10.6 % 69.1 %		
Land cover	Artificial zone		8.6 %			9.4 %			14.8 %		
	Agricultural zone		51 %			60.1 %			72.9 %		
	Forest		31.6 %			26.2 %			9.7 %		
	Grassland and shrubs		8 %			2.8 %			0.9 %		
	Sparse vegetation		0.08 %			0.1 %			0.2 %		
	Water zone		0.08 %			1.3 %			1.5 %		
Potential fine sediment availability	Average soil erosion rate ($t.ha^{-1}.yr^{-1}$)		1.25 (Pesera)			0.72 (Pesera)			1.35 (Pesera)		
Vegetation (dominant species)	Floodplain Riparian Aquatic		*Populus nigra* *Salicion albae* Few aquatic plants in active			*Populus nigra* *Salicion albae* channel - present in stagnant			*Populus nigra* *Salicion albae* water of secondary channels		

[15] The land surface slope has been derived using the following toolbox in Arc gis [Spatial Analyst Tools → Surface → Slope]; it identified the rate of maximum change in z value from each cell. The slope are expressed in degree. The distribution has been calculated using the raster calculator.



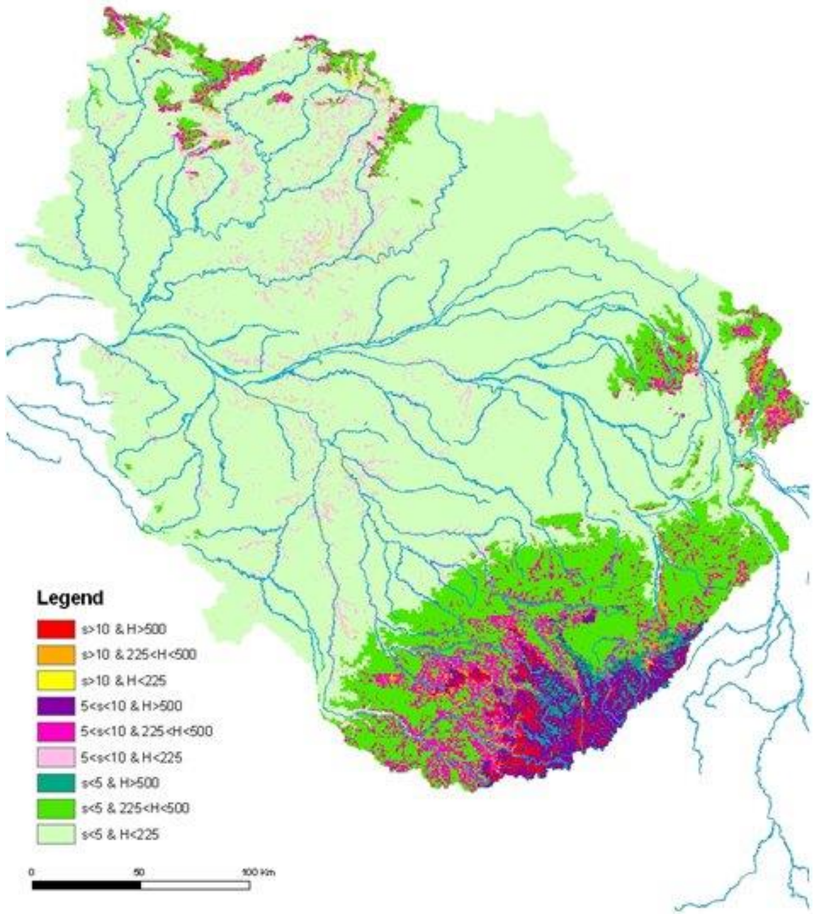


Figure 3.1 Landscape unit 1– Distribution of slope s and elevation H **Figure 3.2 Landscape unit 2 - Distribution of slope *s* and elevation *H***

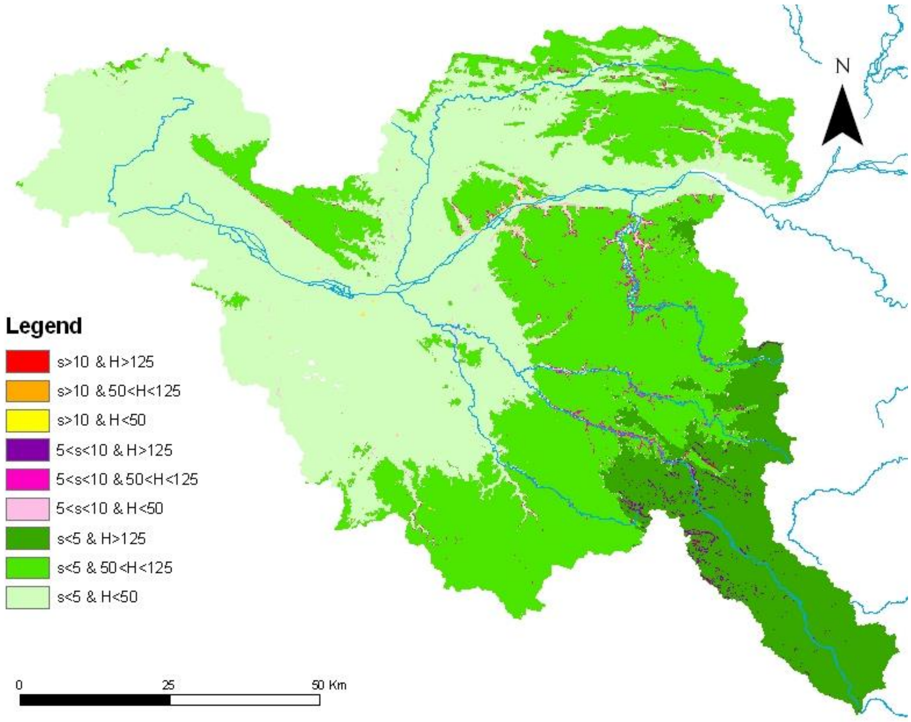


Figure 3.3 Landscape unit 3 - Distribution of slope *s* and elevation *H*

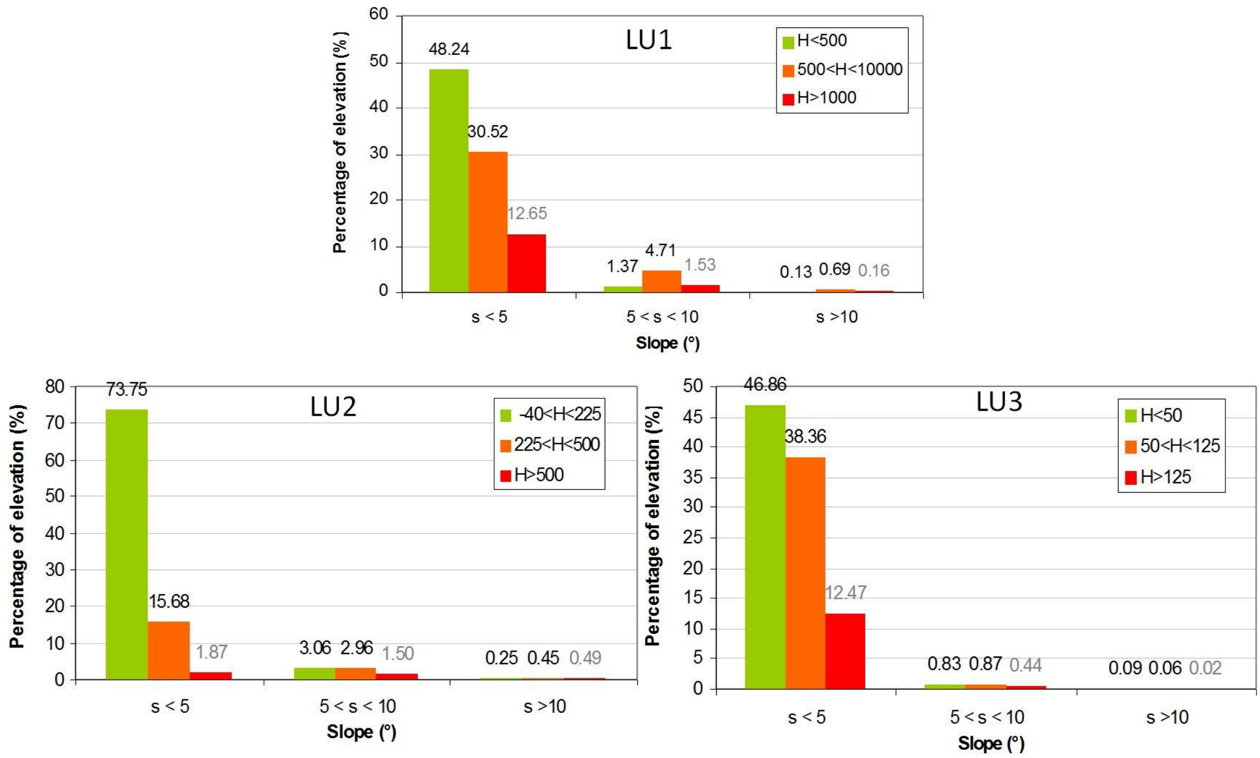


Figure 3.4 Land surface slope – elevation distribution for the 3 landscape units.

Figures 3.5 and 3.6 present the main hydrologic characteristics (precipitation) as a monthly average (Figure 3.5) or as a time-serie of the annual average (Figure 3.6).

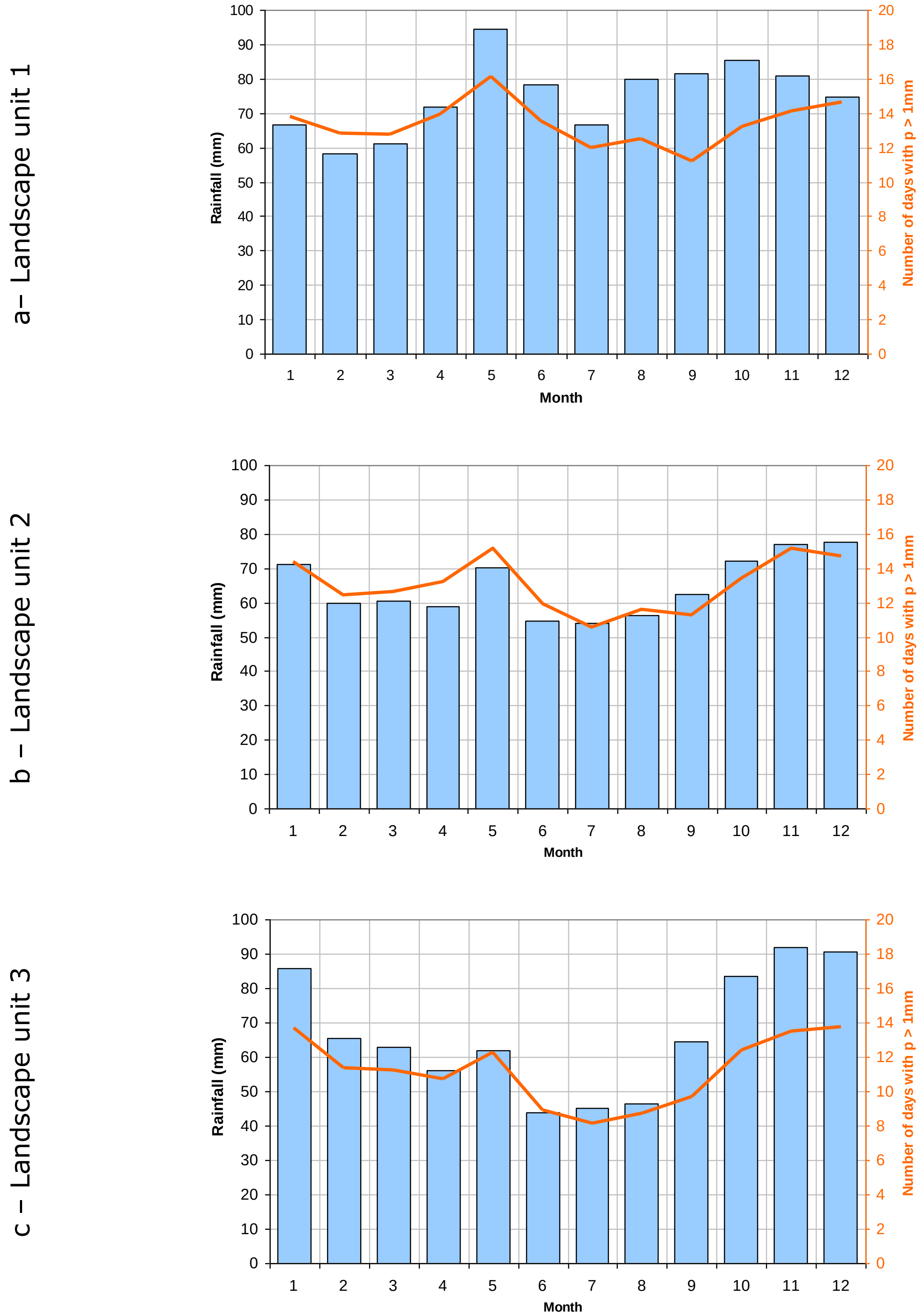


Figure 3.5 Average precipitation and number of rain days per month in the three landscape units (based on daily data available between 1958 and 2011).

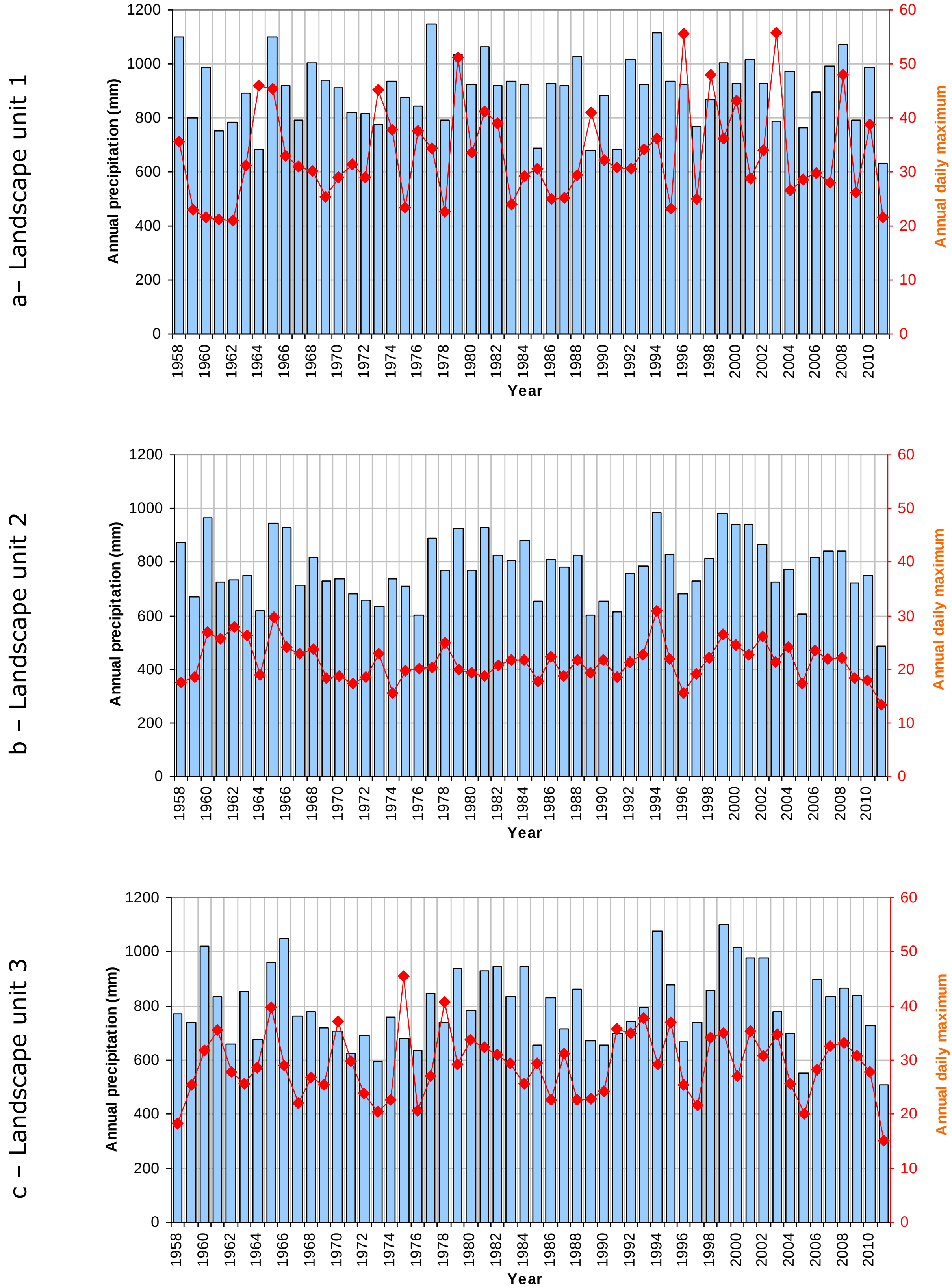
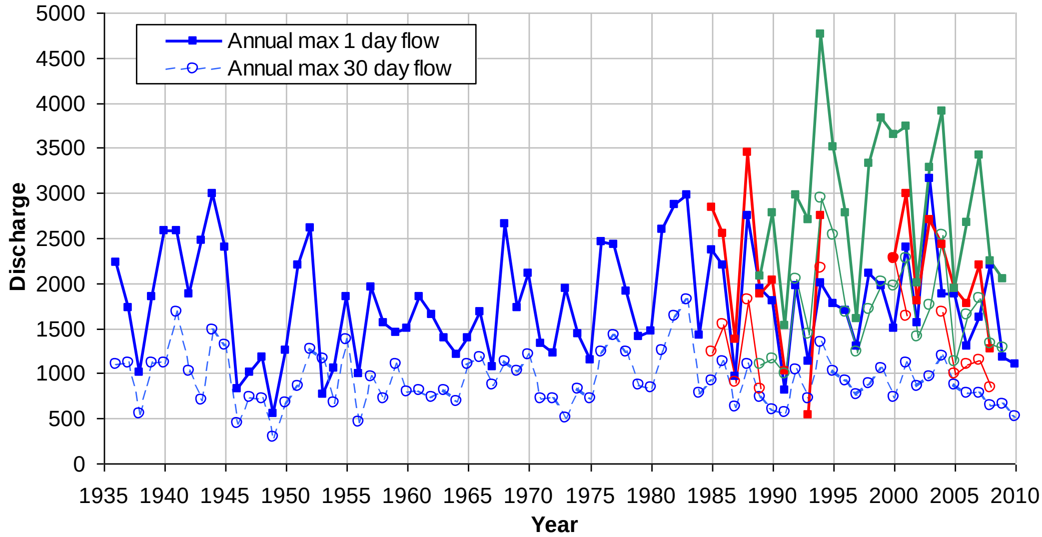


Figure 3.6 Average annual rainfall and maximum annual daily flow.

3.3 River segment

The characterisation of river segments has been carried out on Landscape Unit 2 only (i.e., the Middle Loire), where three river segments were delineated (see section 2.4). The characteristics of the three river segments are detailed in Table 3.5. The flow data (Figure 3.7) are compiled from Gien (1936-2012), Langeais (1985-2012), Saumur (1988-2012) for S1, S2 and S3 respectively. Daily flow data were used for the analysis. The maximum and minimum 30-day moving average were calculated for each year of the record. The moving average values indicate the continuity of flow.

(a)



(b)

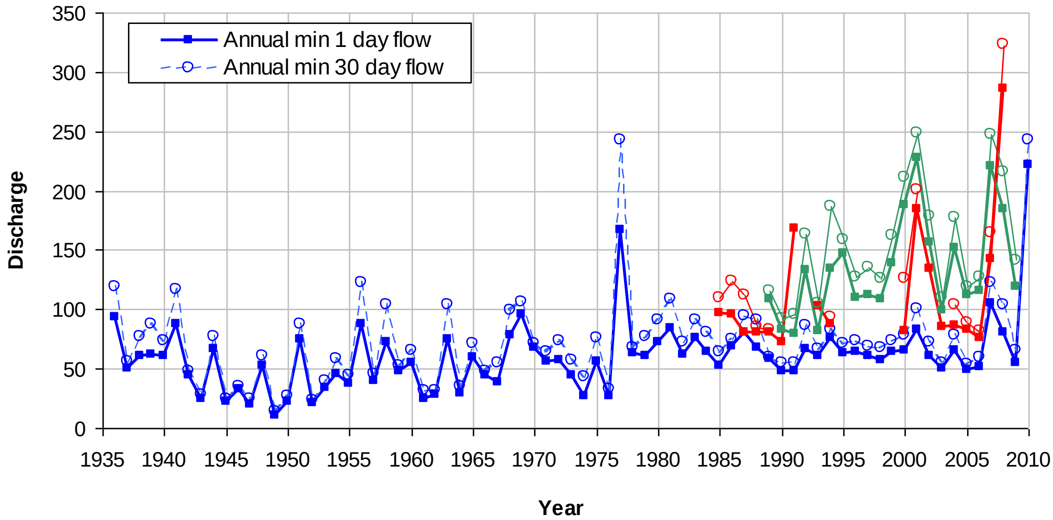


Figure 3.7 (a) Annual minima and maxima 1 day flow and (b) annual minima and maxima 30 day flow for S1 (blue line), S2 (red line) and S3 (green line).

Table 3.5 Characteristics of the river segments (LQ, MQ and UQ stand for Lower flow, Median flow and Upper flow respectively)

Characteristics		**Segments**								
		S1			**S2**			**S3**		
Flow regime	(i) Channel forming discharge:	**GIEN**			**LANGEAIS**			**SAUMUR**		
	Qp_{median}	330			423			708		
	Qp_2	1600			1900			2800		
	Qp_{10}	2700			2800			4600		
	(ii) Flow extremes:	LQ	MQ	UQ	LQ	MQ	UQ	LQ	MQ	UQ
	Annual max 1 day flow	556	1741	3160	540	2097	3450	1520	2890	4750
	Annual max 30 day flow	296	932	1820	819	1392	2275	987	1713	2935
	Annual min 1 day flow	11	59	167	72	112	285	80	134	228
	Annual min 30 day flow	14	73	243	81	130	323	92	154	248
	Timing of extreme flow conditions	max 1 day flow : February min 1 day flow : August			max 1 day flow : January min 1 day flow : August			max 1 day flow : January min 1 day flow : August		
	(iii) Annual pattern of monthly flows:	LQ	MQ	UQ	LQ	MQ	UQ	LQ	MQ	UQ
	Jan	69.5	527	2860	98	693	2750	144	1160	4750
	Feb	105	600	2390	168	732	2673	187	1210	3340
	Mar	97.5	482	2750	106	671	3450	202	1080	3420
	Apr	54	413	2570	103	616	2510	203	917	2280
	May	57	355	2980	147	583	2982	171	743	3740
	Jun	40	259	1700	103	363	1257	149	489	1730
	Jul	22	140	890	76	217	549	92.5	300	804
	Aug	11	102	1610	83	144	509	81.4	211	703
	Sep	18	118	1200	78	155	899	79.5	230	1170
	Oct	18	188	2470	72	221	1150	95	338	1690
	Nov	22	332	2460	91	371	2323	131	638	2970
	Dec	51	451	3160	90	483	2691	133	920	3820
Valley characteristics	Valley gradient (m/m)	0.00041			0.00027			0.00022		
	Valley confinement	Partly confined			Partly confined			Partly confined		

Characteristics		Segments S1	Segments S2	Segments S3
	Degree of valley confinement (B/Bf)	0.30	0.44	0.40
Sediment	Dominant bed material	Sand/gravel	Sand/gravel	Sand/gravel
Riparian corridor features	Average width (m)	588	629	830
	Area (km²)[16]	149.4	27.6	58.1
	Average width of riparian corridor (typical valley width - bankfull width)	675	421	717
	Structure - Proportion under: mature trees shrubs bare soils	 29.7 % 39 % 31.3 %	 58 % 2.2 % 39.9 %	 15 % 35 % 50 %
	Wood delivery potential[17]	9.45 %	29.3 %	7.4 %
Physical pressures	Blocking structures (dam, weir,…): High (interception > 90 %) Moderate (low impact on continuity) Low (minor structure with low impact)	 0 4 0	 0 0 0	 0 0 0
	Spanning structures (bridges): High (width reduction > 20 %) Moderate (5%<width reduction < 20% Low (width reduction < 5%)	 2 3 24	 0 0 3	 0 2 7

The riparian corridor corresponds to the area available for accommodating flood water, river channel dynamics and interactions between fluvial processes and vegetation. It is defined by the outer limit of naturally functioning riparian vegetation cover within any restricting embankments.

[16] Area calculated with Spatial Staistics Tools → Utilities → calculate areas

[17] The wood delivery potential is the proportion of the active river channel edge covered by mature (dead or living) tress

3.4 River reaches

The five reaches introduced in sectione 2.5 are characterised and discussed in the following paragraphs.

3.4.1 Reach A (Type 5)

Reach A is 6.5 km long and is located upstream of segment 1 (Figure 3.8). The upstream boundary corresponds to a confluence and the downstream boundary to a structure. The characterization of reach A is provided in Table 3.6.

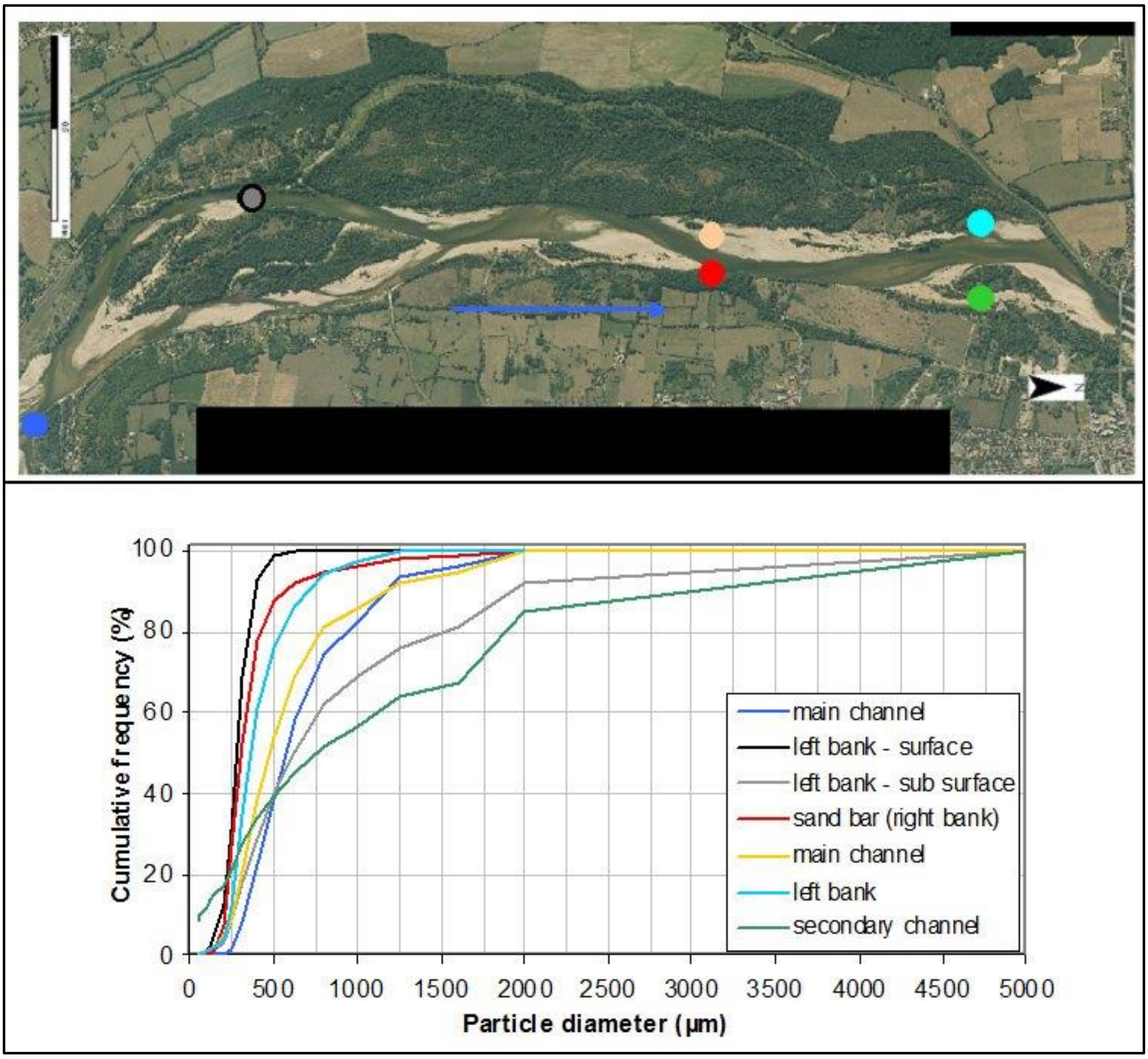


Figure 3.8 Reach A (photo 2005, DREAL Centre) with locations of grain size sampling (above) and grain size distributions (below)

Table 3.6 Characteristics of river reach A.

Characteristics		Value
Channel dimensions	Bankfull / active channel width	290
	Baseflow channel width	172.5
	Bankfull / active channel sinuosity	1.07
	Baseflow sinuosity	1.14
	Braiding index	1.5
	Anabranching index	1.3
	Average reach gradient (m/m)	0.00028
	Channel gradient	0.00055
	Width over depth ratio[18]	65
River energy	Total stream power (W/m) with Qp_{median}= 330 m^3/s	1771 (channel gradient) 912 (reach gradient)
	Specific stream power (W/m²)	3
	Average bed shear stress (h=2)	19
Bed and bank material	Dominant material calibre Sediment composition	Gravel – sand
Riparian and aquatic vegetation	Proportion of the corridor under : Bare sediment Low vegetation (grass) Medium vegetation (shrubs) High vegetation (trees)	 0.31 % 64.1 % 1.13 % 34.45 %
	Lateral gradient in vegetation	Subdued difference
	Patchiness in vegetation structure	Large area of similar vegetation structure
	Main riparian tree species : "Soft wood" "Hard wood"	 Salicion alba, Populus nigra Fraxinus
	Presence of large wood	None
Physical pressures	Bed armouring River bed artificially reinforced	Absent None
River bank condition	Set back levees	Yes

3.4.2 Reach B (Type 4)

Reach B is located in the meandering part of segment 1. The reach is delineated upstream by the presence of a vegetated island (and a secondary channel) and downstream by the presence of a bridge (Figure 3.9). The characterization of reach B is provided in Table 3.7.

[18] The width over depth ratio is estimated from topographic cross sections surveyed in 1995 and provided by the DREAL Centre. The values are extracted for "bankfull condition".

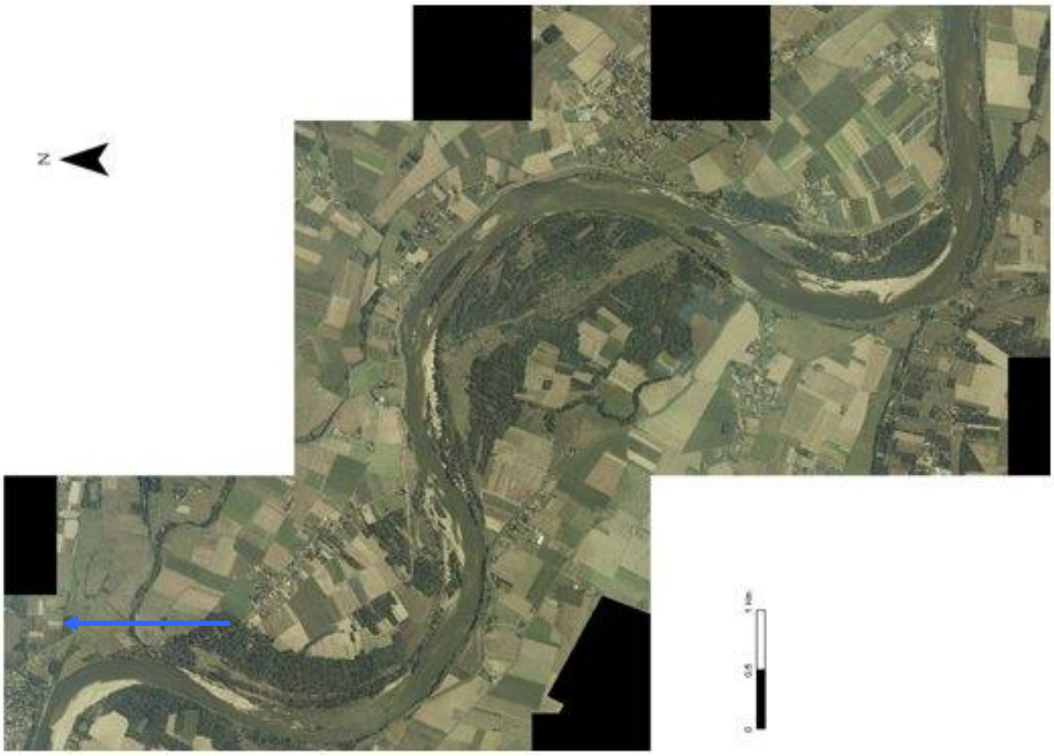


Figure 3.9 Delineation of reach B (photo 2005, DREAL Centre)

Table 3.7 Characteristics of river reach B.

Characteristics		**Value**
Channel dimensions	Bankfull / active channel width	175
	Baseflow channel width	265
	Bankfull / active channel sinuosity	1.47
	Baseflow sinuosity	1.57
	Braiding index	1
	Anabranching index	1.2
	Average reach gradient (m/m)	0.00054
	Channel gradient	0.00049
	Width over depth ratio[19]	54
River energy	Total stream power (W/m) with Qp_{median}= 330 m^3/s	1575 (channel gradient) 1749 (reach gradient)
	Specific stream power (W/m²)	6
	Average bed shear stress	19
Bed and bank material	Dominant material calibre	Gravel – sand
Riparian and aquatic vegetation	Proportion of the corridor under : Bare sediment Low vegetation (grass) Medium vegetation (shrubs) High vegetation (trees)	 0.92 % 73.3 % 2.90 % 21.87 %
	Lateral gradient in vegetation	Subdued difference
	Patchiness in vegetation structure	Large area of similar vegetation structure
	Main riparian tree species	S. alba, P.nigra, Fraxinus
	Presence of large wood	None
Physical pressures	River bed condition : Bed armouring River bed artificially reinforced	 Absent No
River bank condition	Set back levees	Yes

[19] The width over depth ratio is estimated from topographic cross sections surveyed in 1995 and provided by the DREAL Centre. The values are extracted for "bankfull condition".

3.4.3 Reach C (Type 2)

Reach C is located in the downstream part of segment 1. The reach is delineated upstream by a bridge and downstream by the presence of a bedrock outcrop (Figure 3.10). The characterization of reach C is provided in Table 3.8.

Figure 3.10 Delineation of reach C (photo 2005, DREAL Centre)

Table 3.8 Characteristics of river reach C.

Characteristics		**Value**
Channel dimensions	Bankfull / active channel width	305
	Baseflow channel width	252
	Bankfull / active channel sinuosity	1.03
	Baseflow sinuosity	1.03
	Braiding index	1.02
	Anabranching index	1.01
	Average reach gradient (m/m)	0.00050
	Channel gradient (m/m)	0.00037
	Width over depth ratio[20]	48.50
River energy	Total stream power (W/m) with Qp_{median}= 330 m^3/s	1201 (channel gradient) 1619 (reach gradient)
	Specific stream power (W/m^2)	6
	Average bed shear stress	18
Bed and bank material	Dominant material calibre	Gravel – sand
Pot. fine sediment avail. (T/year)	Evaluated from Pesera map	1092
Riparian and aquatic vegetation	Proportion of the corridor under : Bare sediment Low vegetation (grass) Medium vegetation (shrubs) High vegetation (trees)	 12.6 % 28.2 % 29.4 % 29.8 %
	Lateral gradient in vegetation	Subdued difference
	Patchiness in vegetation structure	Similar vegetation structure
	Main riparian tree species	S. alba, P.nigra, Fraxinus
	Presence of large wood	None
Physical pressures	River bed condition : Bed armouring River bed artificially reinforced	Absent No
River bank condition	Set back levees	Yes

[20] The width over depth ratio is estimated from topographic cross sections surveyed in 1995 and provided by the DREAL Centre. The values are extracted for "bankfull condition".

3.4.4 Reach D (Type 6)

Reach D is located in segment 2. Its boundaries correspond to a change in channel pattern from a single channel to a multiple channel configuration (Figure 3.11). Reach D is described in Table 3.9.

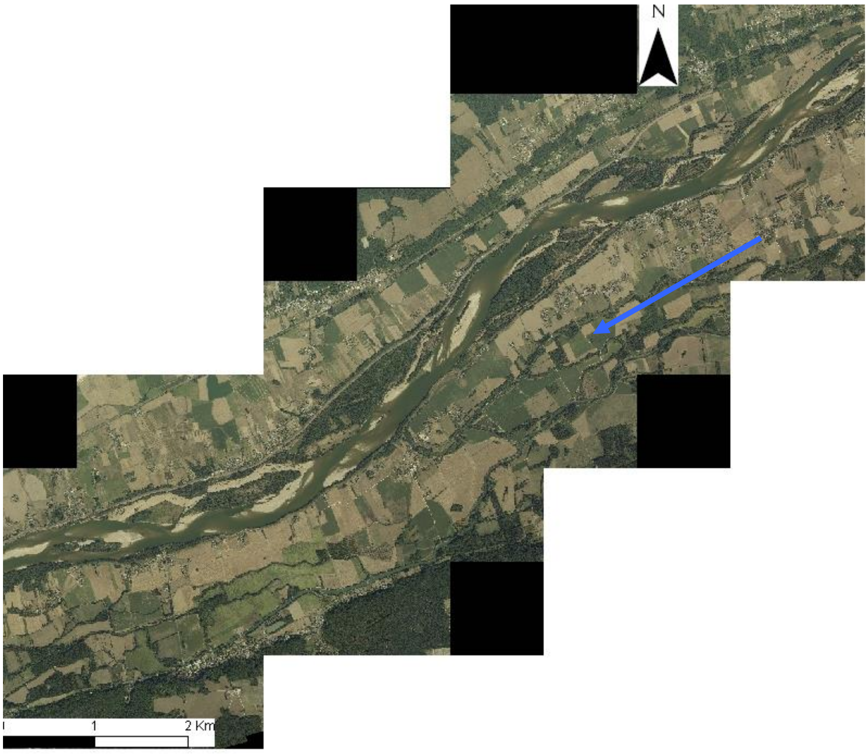


Figure 3.11 Delineation of reach D (photo 2005, DREAL Centre)

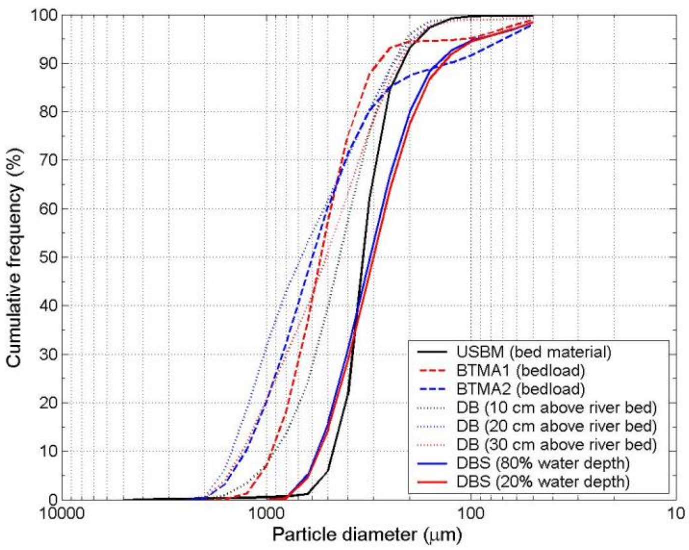


Figure 3.12 Evolution of the sediment size in one vertical (fraction less than 40 microns was eliminated). USBM-54 = bed material, BTMA = bedload, DB = Delft Bottle with indicative location of measure above river bed and DBS = Delft Bottle Surface with indicative location along the water column (data compiled by the University of Tours; Gautier, 2007).

Table 3.9 Characteristics of river reach D.

Characteristics		Value
Channel dimensions	Bankfull / active channel width	425
	Baseflow channel width	320
	Bankfull / active channel sinuosity	1.04
	Baseflow sinuosity	1.06
	Braiding index	1.1
	Anabranching index	1.9
	Average reach gradient (m/m)	0.00060
	Channel gradient (m/m)	0.00025
	Width over depth ratio[21]	74
River energy	Total stream power (W/m) with Qp_{median}= 423 m^3/s	1040 (channel gradient) 2490 (reach gradient)
	Specific stream power (W/m²)	3
	Average bed shear stress	14
Bed and bank material	Dominant material calibre Sediment composition	Gravel – sand Figure 3.12
Riparian and aquatic vegetation	Proportion of the corridor under : Bare sediment Low vegetation (grass) Medium vegetation (shrubs) High vegetation (trees)	 4.75 % 46.2 % 19.2 % 29.8 %
	Lateral gradient in vegetation	Subdued difference
	Patchiness in vegetation structure	Large area of similar vegetation structure
	Main riparian tree species	S. alba, P. nigra, Fraxinus
	Presence of large wood	None
Physical pressures	River bed condition : Bed armouring River bed artificially reinforced	 Absent No
River bank condition	Set back levees	Yes

3.4.5 Reach E (Type 5)

Reach E is located upstream of segment 3. Its upstream boundary is defined by the confluence with the Vienne River and its downstream boundary is a bridge located in Saumur (Figure 3.13). Reach E is characterised in Table 3.10.

[21] The width over depth ratio is estimated from topographic cross sections surveyed in 1995 and provided by the DREAL Centre. The values are extracted for "bankfull condition".

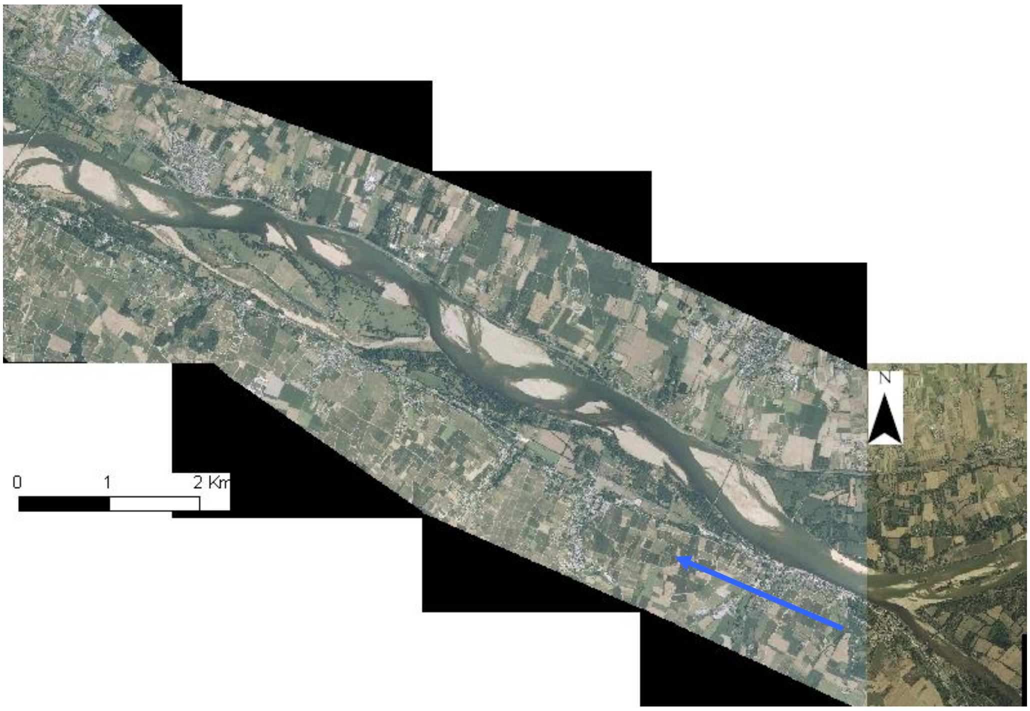


Figure 3.13 Delineation of reach E (photo 2005 and 2002, DREAL Centre).

Table 3.10 Characteristics of river reach E.

Characteristics		**Value**
Channel dimensions	Bankfull / active channel width	640
	Baseflow channel width	376
	Bankfull / active channel sinuosity	1.03
	Baseflow sinuosity	1.08
	Braiding index	1.4
	Anabranching index	1.4
	Average reach gradient (m/m)	0.00073
	Channel gradient (m/m)	0.00046
	Width over depth ratio[22]	119
River energy	Total stream power (W/m) with Qp_{median}= 708 m^3/s	3225 (channel gradient) 5082 (reach gradient)
	Specific stream power (W/m²)	6
	Average bed shear stress (h=2)	24
Bed and bank material	Dominant material calibre Sediment composition	Gravel – sand
Riparian and aquatic vegetation	Proportion of the corridor under : Bare sediment Low vegetation (grass) Medium vegetation (shrubs) High vegetation (trees)	 24.7 % 17.1 % 28.3 % 29.6 %
	Lateral gradient in vegetation	Subdued difference
	Patchiness in vegetation structure	Large area of similar vegetation structure
	Main riparian tree species:	Fraxinus
	Presence of large wood	None
Physical pressures	River bed condition: Bed armouring Bed clogging River bed artificially reinforced	 No No No
River bank condition	Set back levees	Yes

[22] The width over depth ratio is estimated from topographic cross sections surveyed in 1995 and provided by the DREAL Centre. The values are extracted for "bankfull condition".

4. Characterisation of the geomorphic units

4.1 Complementary hydraulic parameters

A 1D hydraulic model (RubarBE) was implemented on the Middle Loire (see Deliverable 2.1 Part 2 Annex I5). Results obtained on the reaches described in the previous section are provided below. The model geometry is derived from cross sections surveyed in 1995 complemented with Lidar data (2003) to include a description of the floodplain. Hydrologic data were extracted from the Gien gauging station for reaches A, B, C, Langeais for reach D and Saumur for reach E. The data were provided by the DREAL Centre unless stated otherwise. The model was calibrated on the 1996 flood event (Q_{max} = 1690 m^3/s at Gien) and validated on the 2003 event (Q_{max} = 2560 m^3/s at Gien). The roughness coefficient was adapted so as to reduce the difference between the measured and the modelled water levels. The relative errors obtained are +/- 10%. Once calibrated and validated the model was run for different flow conditions. The following discharges are considered as channel forming discharge is often not associated with a single value of Q but rather to a range of values: baseflow (Q_{base}); approximately 50% of bank full ($Q_{0.5bf}$); approximately bank full (Q_{bf}); an overbank event (Q_5 or Q_{10})

4.2 Modelling applications on the five reaches

The delineation of the reach units into geomorphic units and their characterization were achieved on the five reaches introduced in section 0 and characterised in section 0.

4.2.1 Reach A (type 5)

Figure 4.1a illustrates the width over depth ratio *W/H* and velocity obtained for the different discharges considered. Based on the results, four geomorphic units can be distinguished: a first geomorphic unit GU1 is characterized by a W/H of 100 and is detected between PK 460 and PK 463; a second unit GU2 presenting a lower W/H ratio and higher velocity is located between PK 463 and PK 464; a third geomorphic unit GU3 with a higher W/H ratio and a lower velocity is located between PK 464 and PK 465.5; and finally a fourth unit GU4 is located between PK 465.5 and 466.5. The calculated specific stream power and average bed shear stress are presented in Figure 4.1b. The distinction between geomorphic units GU1 and GU2 is confirmed; the boundary between GU3 and GU4 is not as clear. Geomorphic units GU1 and GU3 presents low values of bed shear stress and stream power, indicating reaches where aggradation is most likely. The values calculated with the model outputs can be compared with the average values estimated during the characterisation phase presented in Table 3.6. The average width over depth ratio was estimated at 65 for reach A which is coherent with the results of the model for a median discharge. Similarly, the specific stream power and average bed shear stress, estimated at 3 W/m² and 19 N/m², respectively, are coherent with the model outputs. Nevertheless, the model allows calculation of the parameters along the whole reach length and confirms the visual distinction of geomorphic units.

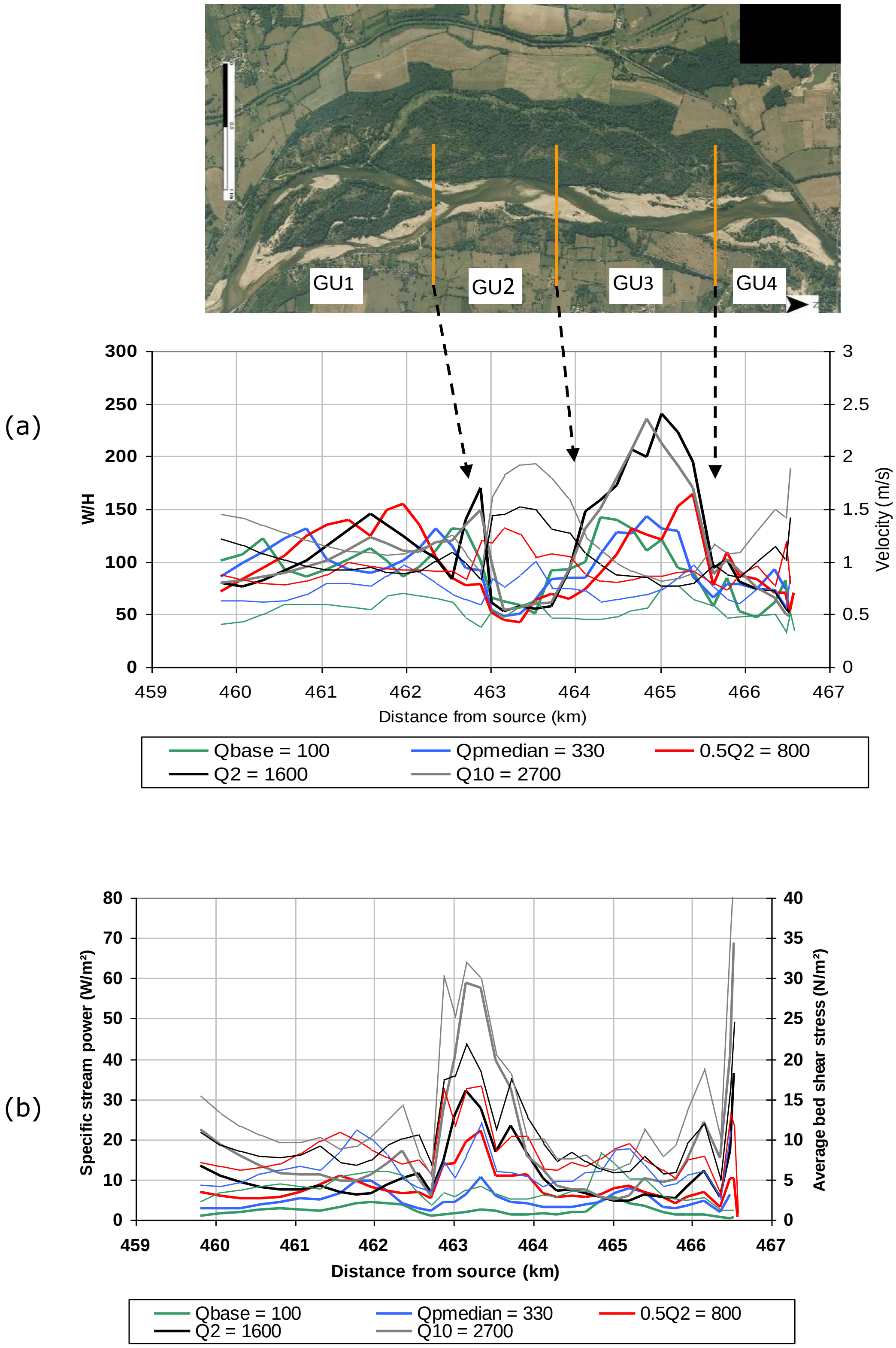


Figure 4.1 Reach A – (a) Width over depth ratio (W/H, thick lines) and velocity (thin lines) and (b) specific stream power (thick lines) and average bed shear stress (thin lines) for the different discharges considered. The location of the discontinuities identified are reported on aerial photograph (scale differs).

Using the aerial photographs, model results and the descriptions of geomorphic units provided in Deliverable 2.1 Part1 section 5, a more detailed characterisation of the geomorphic units is suggested: emergent units within the channel, channel margin and floodplain features are distinguished (Table 4.1).

Table 4.1 : Detailed description of the four geomorphic units defined in reach A.

	Features within the bankfull channel			Bank features	Floodplain features
	River bed	**Emergent sediment**	**Wood and vegetation**		
GU1	Dune ?	Islands	?	Complex bank profile	Terrace
GU2	Dune ?	Lateral bar with vegetation development	?	Complex bank profile	Abandonned channel on left bank (activated during flood events)
GU3	Dune ?	Lateral bar	?	Complex bank profile	Abandonned channel on left bank (activated during flood events)
GU4	Dune ?	Lateral bar with vegetation development	?	Complex bank profile	Terrace

4.2.2 Reach B (type 4)

Figure 4.2 illustrates the width over depth ratio (W/H), velocity, specific stream power and average bed shear stress for the range of discharges considered. Based on the hydraulic parameters, the boundaries of four geomorphic units can be identified: GU1 (PK 592 – PK 596) is characterized by a uniform width over depth ratio (W/H); GU2 (PK 596 – PK 597) is defined by an increase in W/H; GU3 (PK 597 – PK 603) has relatively constant values of W/H (except for Qbase); GU4 (PK 603 – PK 607) shows lower values of W/H and higher velocity. The values calculated with the model outputs are compared with the average values estimated for a medium discharge during the characterisation phase presented in Table 3.7. The width over depth ratio obtained with the model is higher than the previous estimation (W/H_{model}= 99 and W/H = 54). The values of specific stream power are similar with both approaches and the average bed shear stress calculated with the model outputs is lower than the estimated bed shear stress.

Table 4.2 Reach B - detailed description of the four geomorphic units defined.

	Features within the bankfull channel			Bank features	Floodplain features
	River bed	**Emergent sediment**	**Wood and vegetation**		
GU1	Dune ?	Lateral island	?	Complex bank profile	Terrace
GU2	Dune ?	Middle bar with vegetation development	?	Complex bank profile	Terrace
GU3	Dune ?	Lateral bars with vegetation development	?	Complex bank profile	Abandoned channel
GU4	Dune ?	Point bar	?	Complex bank profile	Terrace

(a)

(b)

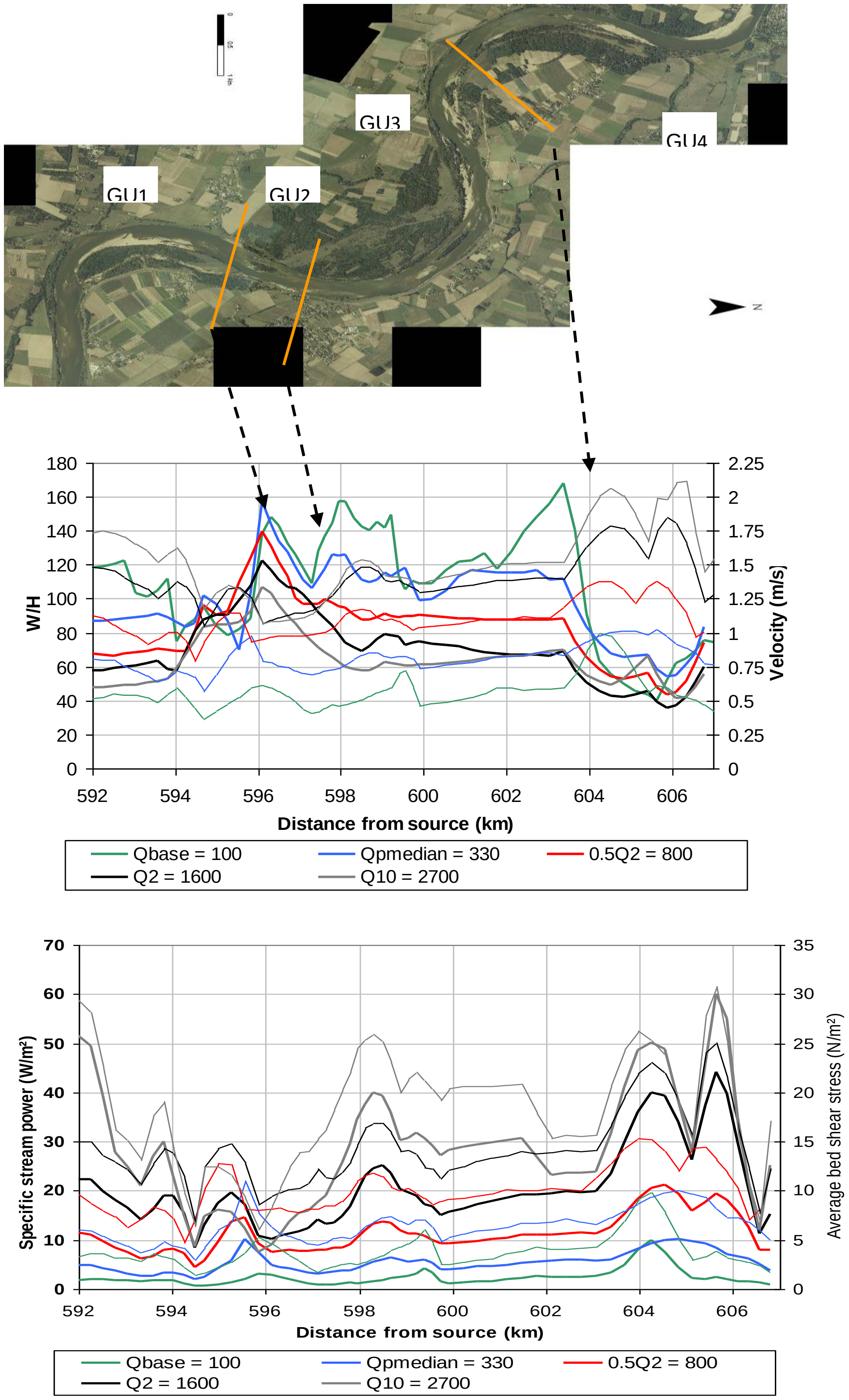


Figure 4.2 Reach B – Hydraulic parameters

4.2.3 Reach C (type 2)

Figure 4.3 illustrates the width over depth ratio, velocity, specific stream power and average bed shear stress for the range of discharges considered. At low discharges (Q_{base}, and $Q_{pmedian}$) high variations in width over depth ratios and velocity are observed. Results obtained for higher discharge values are smoother; based on those results, two geomorphic units are distinguished: GU1 (PK 718.7 – PK 719.2) is characterized by uniform velocity; GU2 (PK 719.2 – PK720) is defined by an increase in velocity.

The values calculated with the model outputs are compared with the average values estimated for a medium discharge during the characterisation phase are presented in Table 3.8. The width over depth ratio obtained with the model is higher than the previous estimation (W/H_{model} = 100 and W/H = 48.5).

The values of specific stream power are similar with both approaches ($\omega_{model} \approx \omega \approx 6$ W/m²) whereas the average bed shear stress calculated with the model outputs is lower than the estimated bed shear stress.

4.2.4 Reach D (type 6)

Figure 4.4a illustrates the width over depth ratio (W/H) and velocity obtained for the different discharges considered. Based on the results, five geomorphic units can be distinguished: GU1 (PK783 – PK 785.5) characterized by a stable width over depth ratio; GU2 (PK 785.5 – PK 787.1) delineated by two peaks in W/H; GU3 (PK 787.1 – PK 788.8) is charaterized by the presence of a vegetated island delineated by two peaks in width over depth ratio; GU4 (788.8 – PK 794) presents a stable W/H ratio; GU5 is characterized by an increase in W/H.

The calculated specific stream power and average bed shear stress are presented in Figure 4.4b. The results corroborate the distinction of GU1 and GU5. The delineation of the other geomorphic units is less distinct.

The values calculated with the model outputs are compared with the reach averaged values estimated during the characterisation phase presented in Table 3.9. The average width over depth ratio for the reach was estimated at 74 which is slightly lower than the average calculated W/H (W/H = 95). The specific stream power and bed shear stress calculated with the model outputs present similar values of around 3 whereas the estimated τ_b was found equal to 14 N/m² and the specific stream power equals 3 W/m².

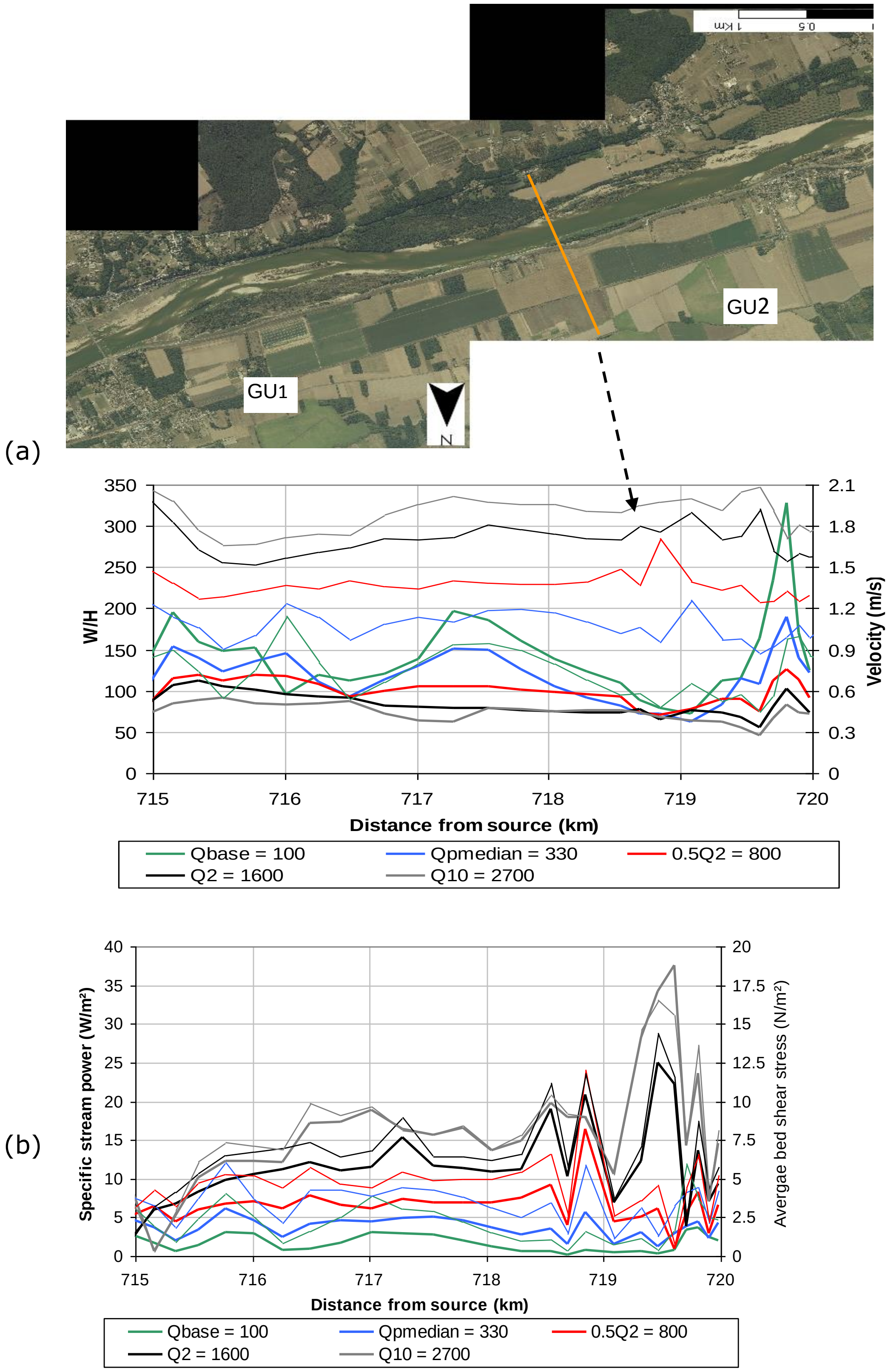


Figure 4.3 Reach C - Hydraulic parameters

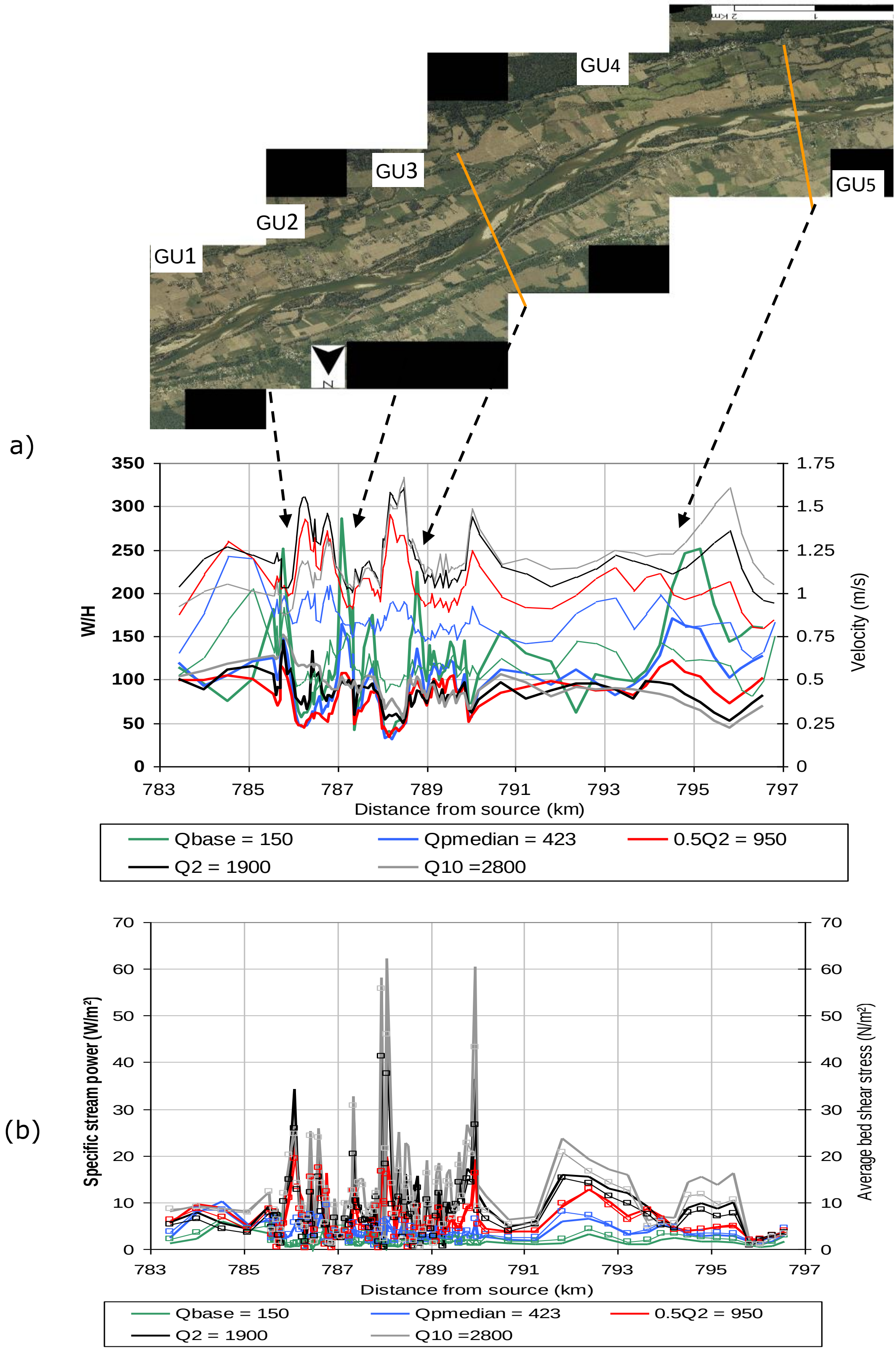


Figure 4.4 Reach D – Hydraulic parameters

4.2.5 Reach E (type 5)

Figure 4.5a illustrates the width over depth ratio (W/H) and velocity obtained for the different discharges considered. The W/H ratio results obtained with the baseflow discharge (*i.e.* Q_{base}) present high discontinuities due to the presence of numerous sand bars; those results have been ignored when delineating the geomorphic units. 3 geomorphic units have been distinguished: GU1 (PK811 – PK 816.1) is characterized by a width over depth ratio equals to 75 in average for Q_2; GU2 (PK 816.1 – PK 821.8) shows higher values of *W/H* ratio (about 140 in average); GU3 (PK 821.8 – PK 824) is charaterized by the a decresase in *W/H* (with a value of about 100).

The calculated specific stream power and average bed shear stress are presented in Figure 4.5b. The distinction of the geomorphic units is not as clear considering ω and τ_b .

The values calculated with the model outputs are compared with the reach averaged values estimated during the characterisation phase presented in Table 3.10. The average width over depth ratio for the reach was estimated at 119 which is similar to the average calculated *W/H* (*W/H* = 106). The specific stream power and bed shear stress calculated with the model outputs present values of 3 and 4 respectively whereas the estimated specific stream power and the estimated bed shear stress attain much higher values with 6 W/m² and 24 N/m² respectively.

(a)

(b)

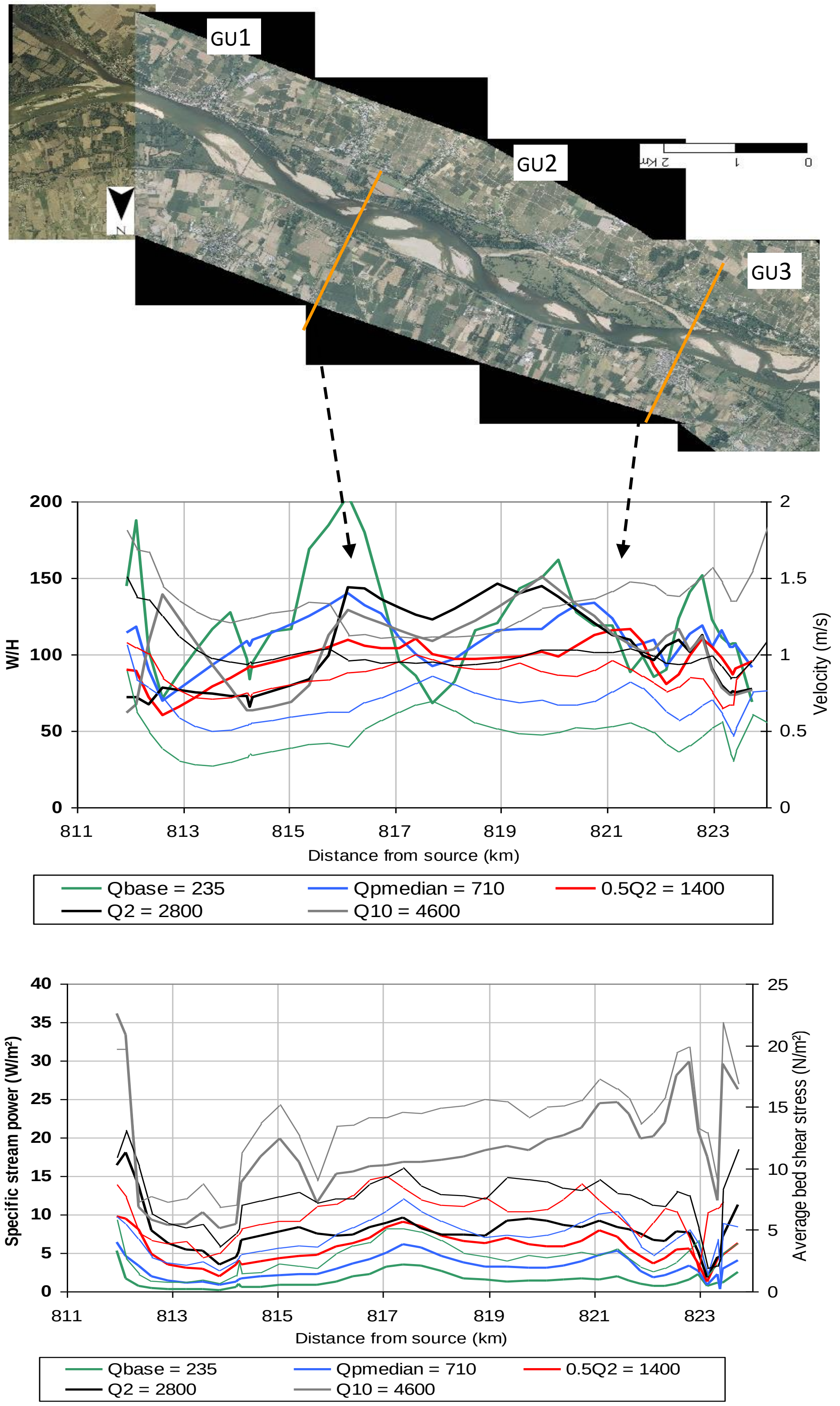


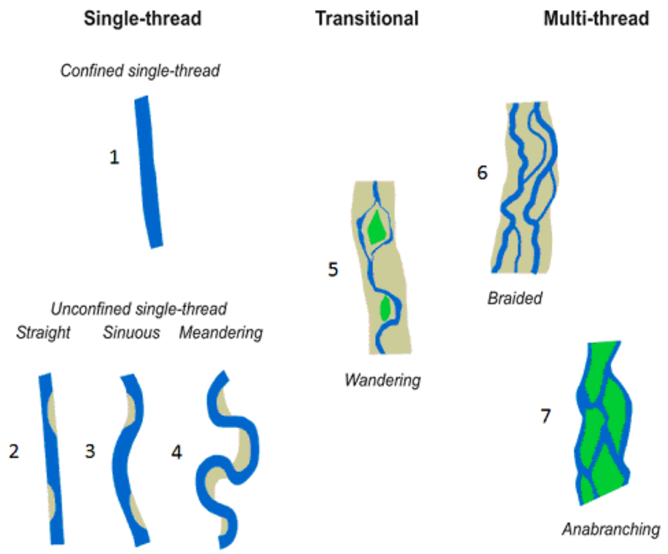
Figure 4.5 Reach E – Hydraulic parameters

4.3 Comparison of the different types of reaches

The parameters obtained for the different types of reaches are compared so as to assess whether a reach type can be discriminated based on its hydraulic characteristics. Figure 4.6a provides a reminder of the simple river typology describe in section 6 of Deliverable 2.1 Part 1, and Figure 4.7 compares the calculated hydraulic parameters for these reaches.

Reach A and reach E are of type 5 and present a similar trend when considering the relationship between specific discharge and width over depth ratio (Figure 4.6b). Reaches B and C are defined as type 4 and type 2, respectively, and their width over depth ratio follow the same trend. The trend of W/H presented for reach C (type 6) differs from the other types.

(a)



(b)

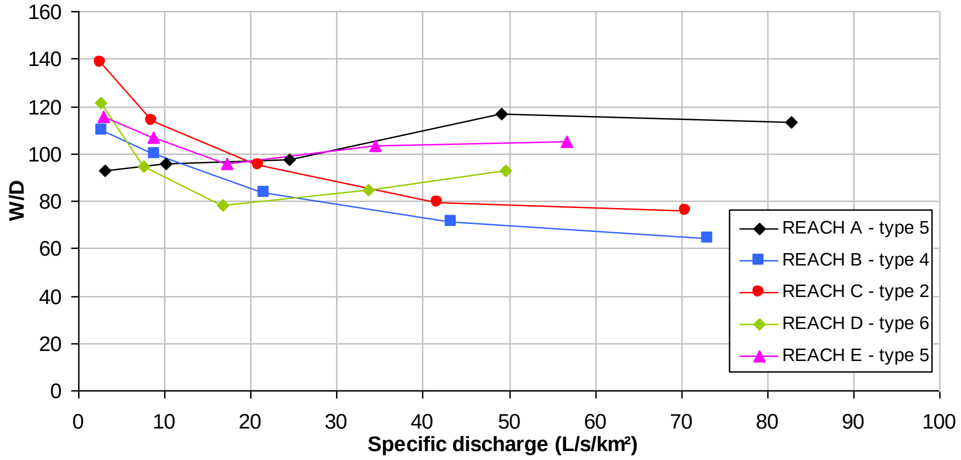
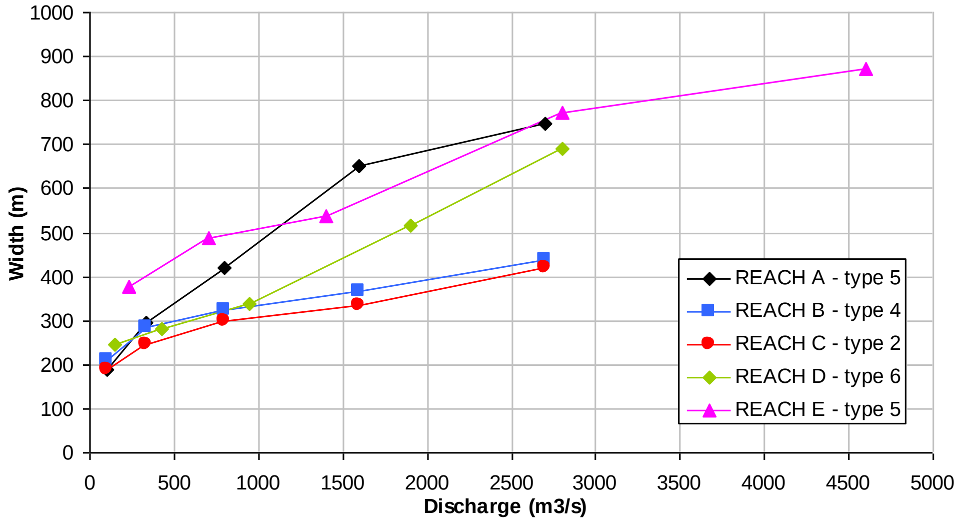
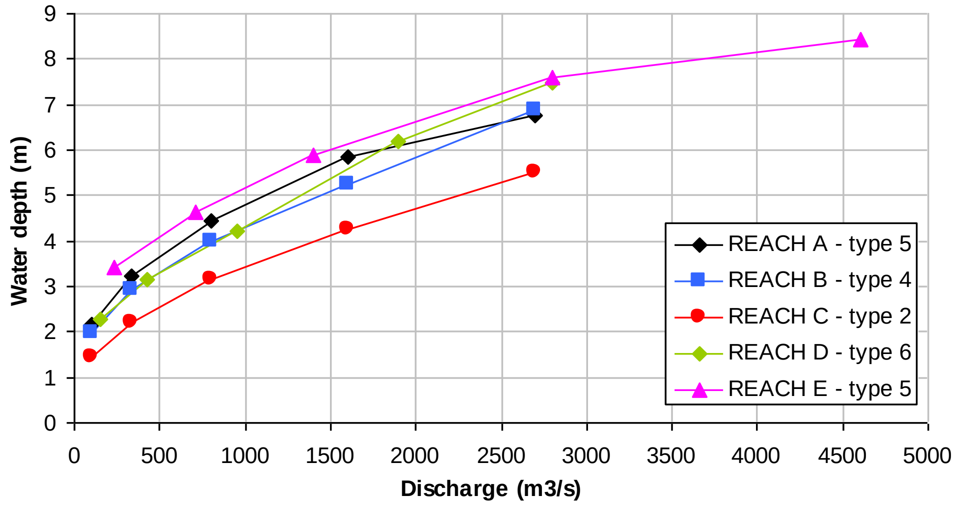


Figure 4.6 Comparison of river reach types: (a) reminder of the simple river typology (extracted from section 6), (b) Specific discharge and width over depth ratio for the five types of reaches described in the previous paragraphs.

(a)



(b)



(c)

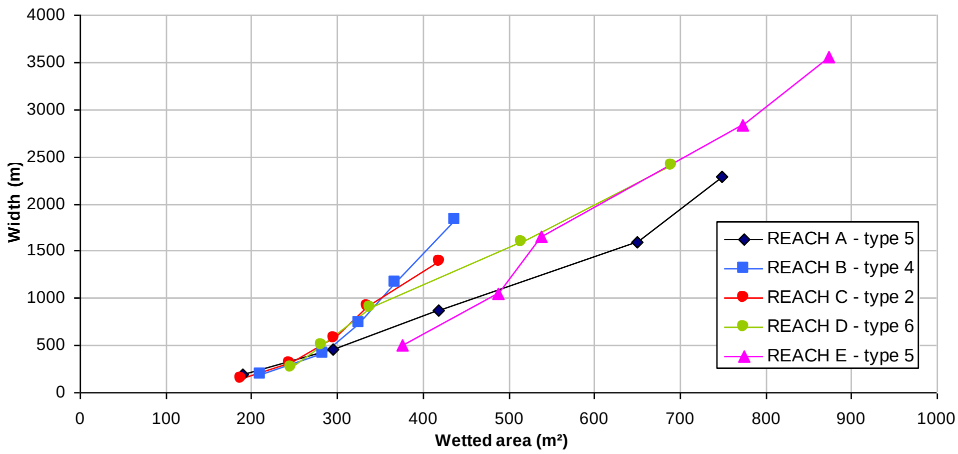


Figure 4.7 Comparison of hydraulic parameters.

The effective bed shear stress over the critical shear stress is plotted against the width over depth ratio for the five reaches considered in Figure 4.8. The two type 5 reaches (reach A and reach E) present a small range of width over depth ratio but a high variability in τ_{eff} / τ_{cr}. In reach B, τ_{eff} / τ_{cr} do not vary much and is independent from W/H. In reach D, τ_{eff} / τ_{cr} decreases as the W/H ratio increases. The average specific stream power calculated for each reach with the hydraulic model outputs is presented in Figure 4.9. For Q_{base} and Q_{median}, the specific stream power is similar for the different reaches. For half bankfull and bankfull discharges, the two type 5 reaches (reach A and reach E) present similar values. No specific trend is observed for reaches B and C. The estimates of specific stream power evaluated during the characterisation phase for the median discharge (diamond shaped on the graph) are close to the value calculated with the model output.

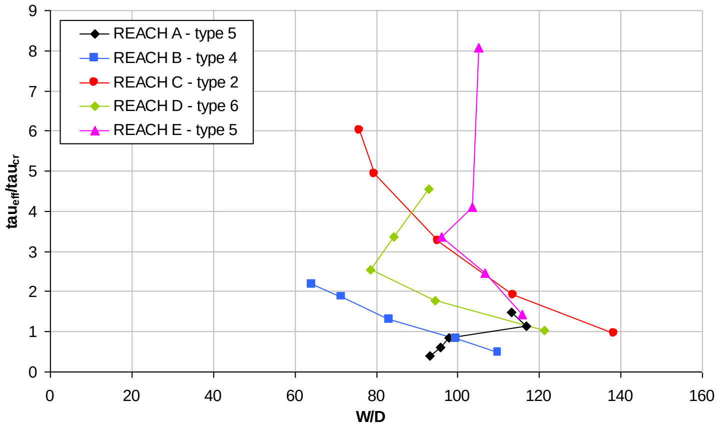


Figure 4.8 Effective shear stress over critical shear stress and width over depth ratio.

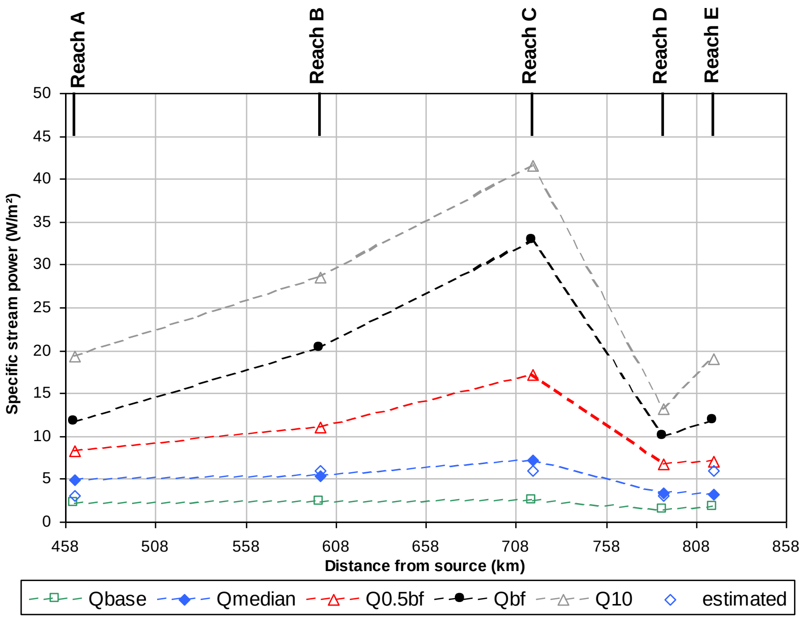


Figure 4.9 Reaches' average specific stream power for the different discharges considered (blue diamonds represent the values estimated during the characterisation phase).

4.4 Estimation of sediment transport

Based on the model results, empirical estimations of sediment transport are provided for reach A and reach C. As more data are available for reach C, a detailed analysis and a complete 1D morpho-dynamic model are undertaken.

4.4.1 Reach A (type 5)

Using the model results obtained for various discharges and the Meyer-Peter and Müller formula, a sediment rating curve *Qs(Q)* is derived (Figure 4.10). The median grain size is adjusteded by ±15 % so as to illustrate the sensitivity of the empirical formula to grain size.

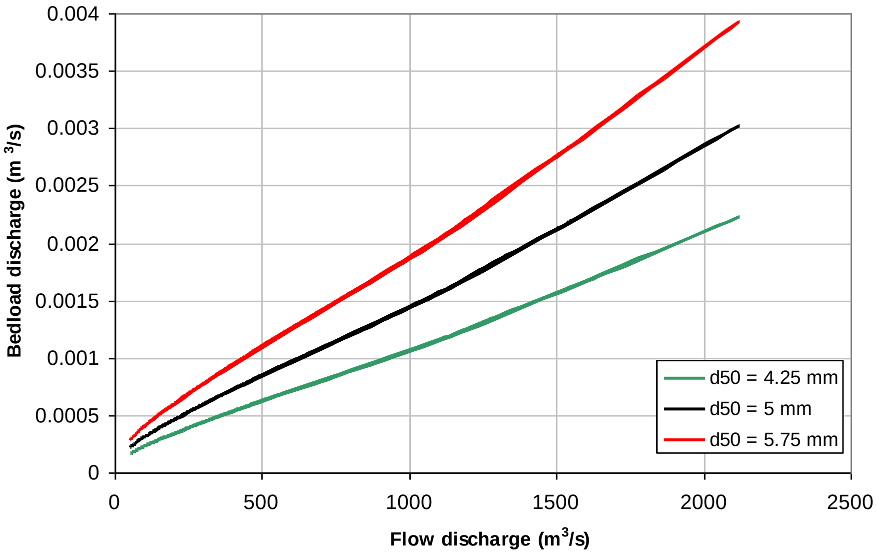


Figure 4.10 Sediment rating curve for reach A.

Using the daily discharge data available at the nearest gauging station, the bedload (Qb) can be estimated for different periods: between 1996-1998, Qb = 785 439 T; 2010 Qb = 355 120 T; 2011 Qb = 346 555 T

4.4.2 Reach C (type 2)

Reach C is analyzed slightly differently as detailed topographic data were surveyed in 2000 and 2002 and sediment sampling was undertaken in 2012. The topographic and sediment sampling data have been used to build the hydrodynamic model.

A longitudinal plot of the river bed evolution between 2000 and 2002 is illustrated inFigure 4.11. The calculated bed levels computed with different options are compared to the measured values. At first glance, the results do not appear to be conclusive; however, when considering a 1D morpho-dynamic model of complex cross section, it appears illusive to attempt to reproduce exactly the cross section deformation (Figure 4.12). The surface areas eroded or deposited are more relevant.

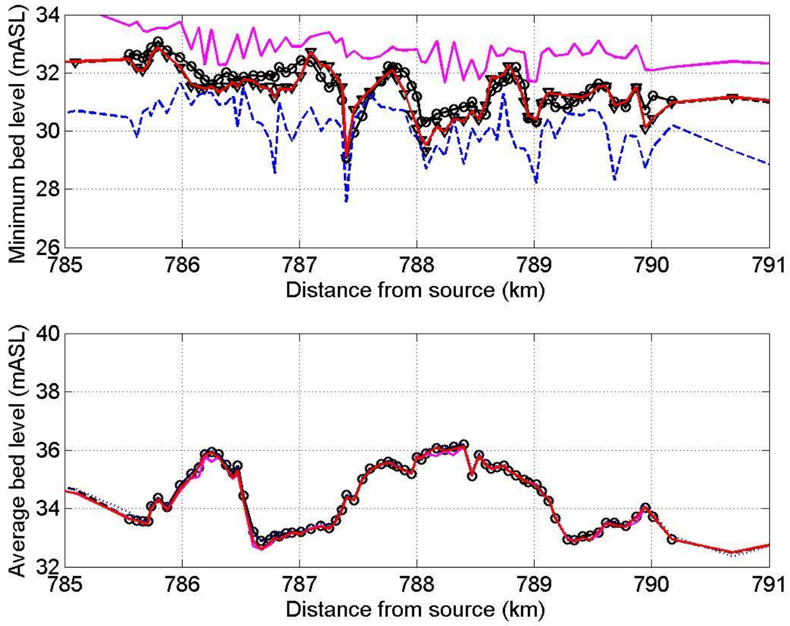


Figure 4.11 Comparison of the measured bed level (triangle for 2000 and circles for 2002) and calculated levels for the period 2000 – 2002 considering : (a) the minimum bed level (i.e. lowest point in the cross section) and (b) the average bed level (i.e. average bed level between the river banks).

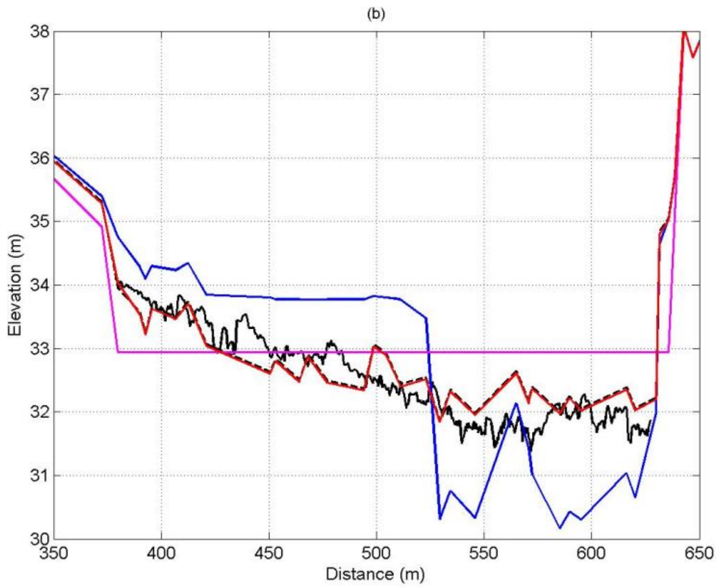


Figure 4.12 Example of cross section obtained at the end of the calculation (dotted black line : initial bed level and plain black line : measured bed level in 2002).

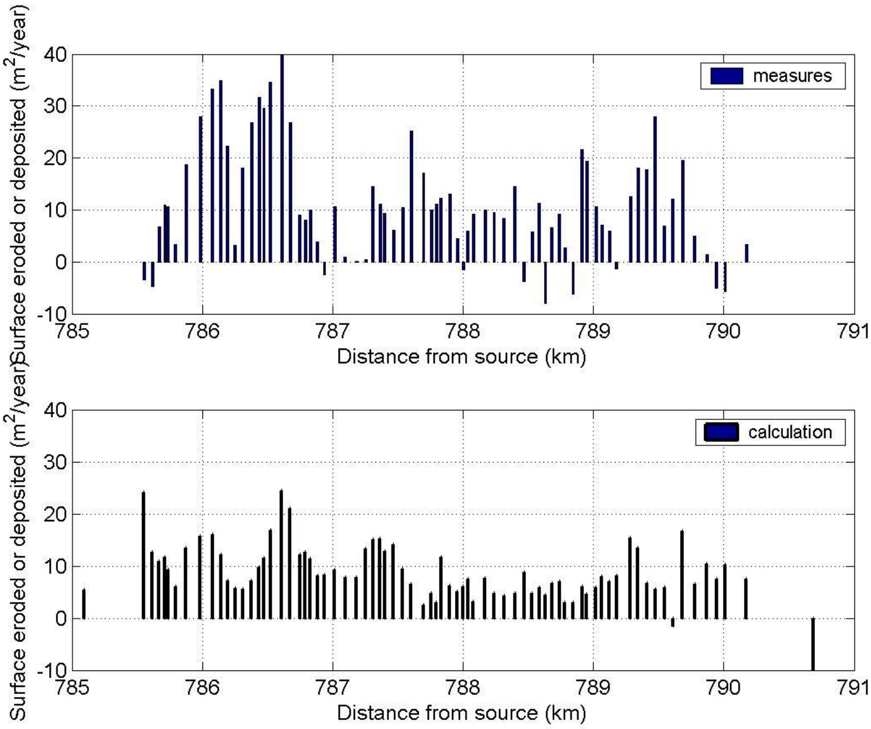


Figure 4.13 Example of representation of the measured and modelled surfaces eroded or deposited.

The 1D morpho-dynamic modelling correctly reproduces the general trend of deposition observed on reach C (Figure 4.13). Using the results of the sediment sampling undertaken by Claude et al. (2012), bedload transport is estimated. The authors compare estimates obtained from direct sampling, dune tracking and empirical formulae derived by Van Rijn (1993) and Meyer-Peter Muller (1948) (for details on formulae, refer to Deliverable 2.1 Part 2, Annex H). Using the data available in the article by Claude et al. (2012) and latest version of the Van Rijn formulae, the total bedload transport is computed (Figure 4.14). Apart from result obtained with the Van Rijn formula from 1984, the calculated total bedload discharges are comparable especially for water discharges lower than 800 m^3/s.

The calculated unit bedload discharges were then compared to the measured bedload discharges. Results are presented in Figure 4.15. The dune tracking approach appears to underestimate the bedload discharge.

The results illustrate the variability in bedload discharges obtained by various approaches. This should be kept in mind when estimating annual transport volumes as considerable spatial and temporal variability occur.

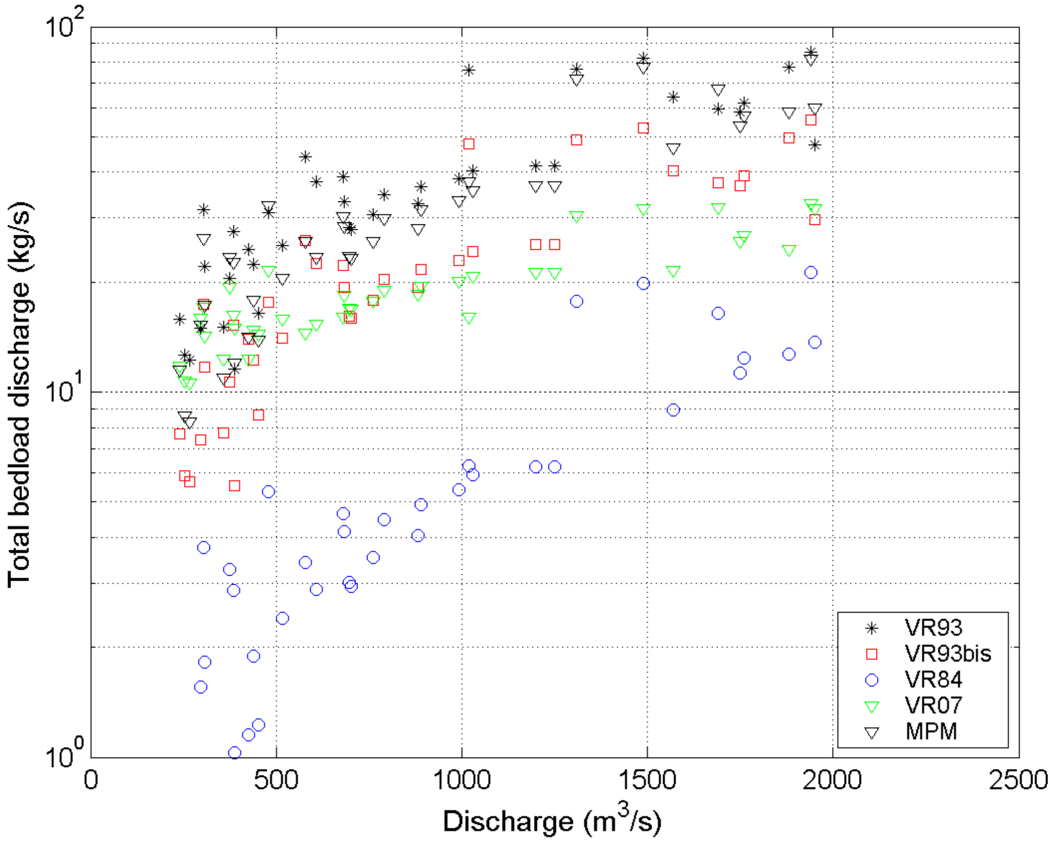
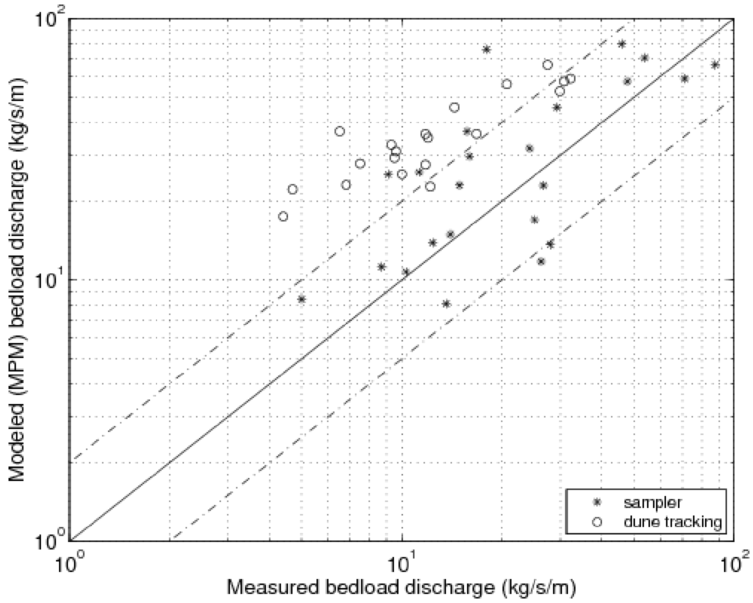


Figure 4.14 Total bedload discharges estimated by Van Rijn formulas (1984, 1993, 2007) and Meyer-Peter and Müller formulas.

(a)



(b)

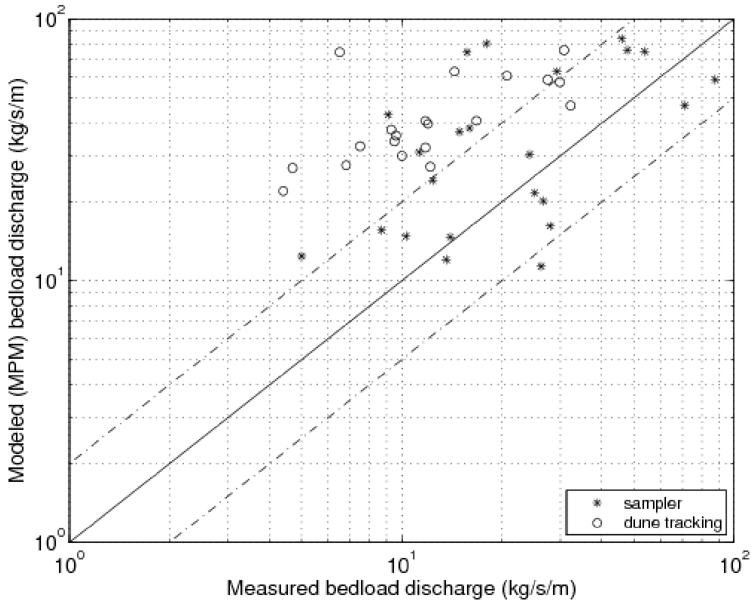
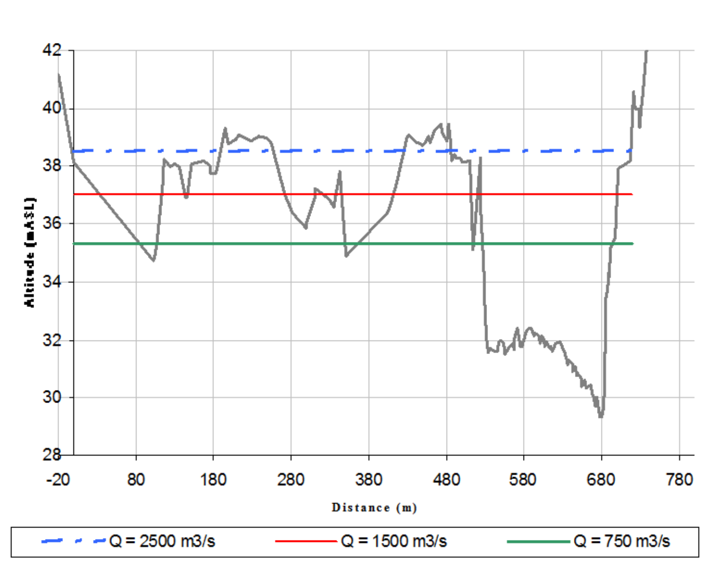


Figure 4.15 Modelled and measured unit bedload discharges for (a) calculation with Meyer-Peter and Müller formula (1948) and (b) Van Rijn (1993) formula.

4.4 *Relating model results to vegetation*

Based on the model results, daily discharge data and changes in vegetation observed between 1999 and 2005, we attempted to relate vegetation to inundation duration (Auble et al., 1994) for reach C. Vegetation maps have been compiled by the DREAL Centre in 1999 and 2005 and the gauging station of Langeais is used for flow data. The hydraulic model is used to define stage-discharge relationship at specific cross sections. Then, using the daily flow record, inundation duration of different points can be determined. Figure 4.16 illustrates calculated water surface elevation for several discharges at one of the hydraulic cross sections and the corresponding inundation duration.



Classes of discharges	Inundation duration
Q > 2500 m^3/s	0.42 %
2000<Q<2500 m^3/s	1.10 %
1500<Q<2000 m^3/s	2.20 %
1000<Q<1500 m^3/s	5.72 %
750<Q<1000 m^3/s	8.92 %
500<Q<750 m^3/s	17.48 %
250<Q<500 m^3/s	25.62 %
Q<250 m^3/s	38.53 %

Figure 4.16 Water surface elevation at cross section 43, classes of discharges and inundation duration identified for the period 1999 – 2005.

The changes in vegetation observed between 1999 and 2005 with the location of cross section 43 are presented in Figure 4.17. Forest has developed on the right bank which has been inundated less than 0.42% of the time.

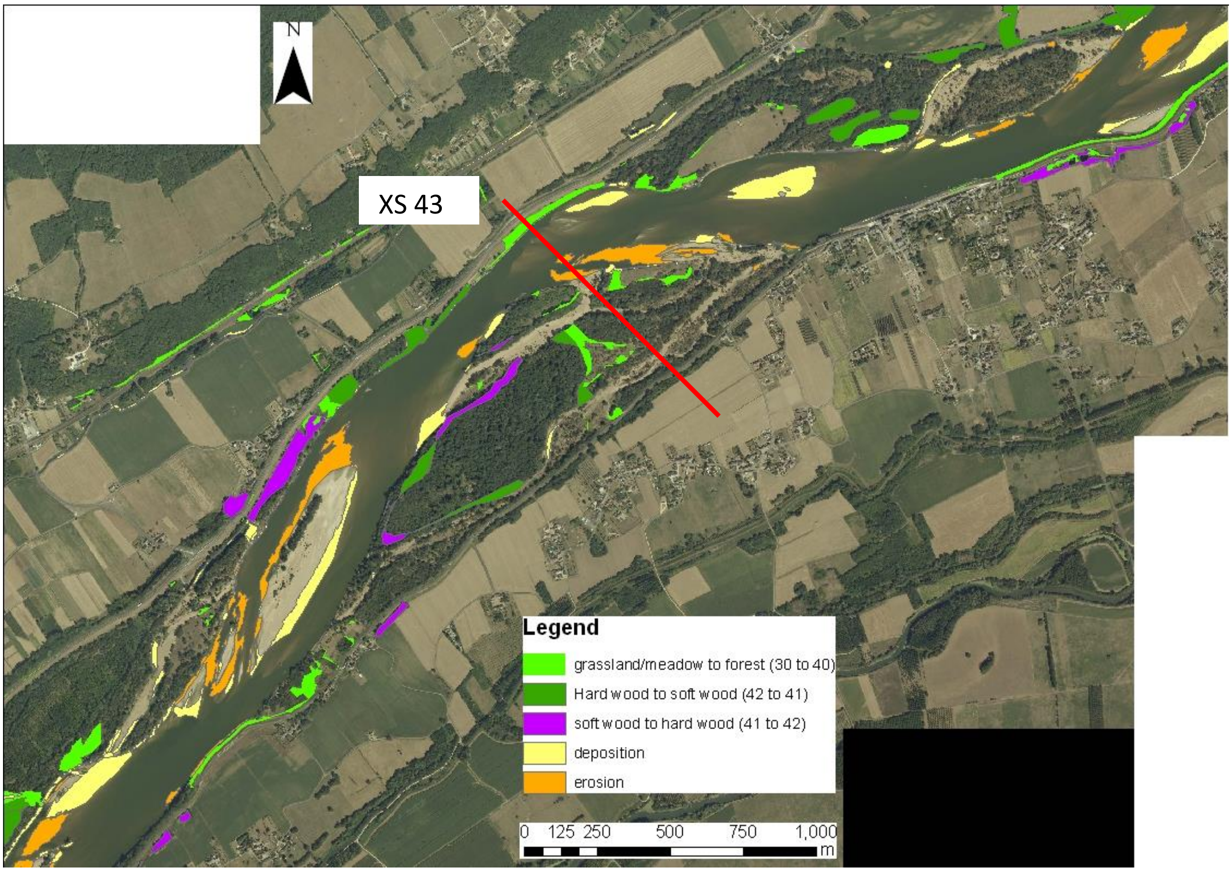


Figure 4.17 Changes in vegetation observed between 1999 and 2005.

5. References

Auble, G. T.; Friedman, J. M. & Scott, M. L., 1994. Relating riparian vegetation to present and future streamflows. Ecological Applications, 4(3), 544-554.

Claude, N., Rodrigues, S., Bustillo, V., Bréhéret, J.G., Macaire, J.J., Jugé, P., 2012. Estimating bedload transport in a large sand gravel river from direct sampling, dune tracking and empirical formulas. Geomorphology, 179, pp. 40-57.

Gautier, J.; Rodrigues, S.; Peters, J.; Peeters, P. & Jugé, P., 2008. Transport solide en Loire moyenne lors des crues. Justification des mesures in situ et quantification. La Houille Blanche, SHF : Transport solides et gestion des sédiments en milieu naturels et urbains, 5, 71-78

Kirkby, M.J., Jones, R.J.A., Irvine, B., Gobin, A, Govers, G., Cerdan, O., Van Rompaey, A.J.J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S., Van Lynden, G.J. and Huting, J. 2004. Pan-European Soil Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. Explanation of Special Publication Ispra 2004 No.73 (S.P.I.04.73). European Soil Bureau Research Report No.16, EUR 21176, 18pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities, Luxembourg.

Meyer Peter, E., Müller, R., 1948. Formulas for bed-load transport. Proceedings of the 2nd IAHR congress, Stockholm, 39-64.

Panagos P., Van Liedekerke M., Jones A., Montanarella L., 2012. European Soil Data Centre: Response to European policy support and public data requirements. Land Use Policy, 29 (2), pp. 329-338. doi:10.1016/j.landusepol.2011.07.003

Quintana-Seguí P., Le Moigne P., Durand Y., Martin E., Habets F., Baillon M., Canellas C., Franchisteguy L. & Morel S. 2008. Analysis of Near Surface Atmospheric Variables: Validation of the SAFRAN analysis over France. Journal of Applied Meteorology and Climatology, 47, 92-107. doi:10.1175/2007JAMC1636.1

S.P.I.04.73., 2004. The PESERA Map: Pan-European Soil Erosion Risk Assessment. Special Publication Ispra 2004 No.73, map in ISO B1 format. Office for Official Publications of the European Communities

Vernoux, J. F., Billault, P., Pennequin, P. 2010. Bilan hydrologique et usage de l’eau dans le basin de la Loire. Géosciences, 2, 81.

Vidal J.-P., Martin E., Franchistéguy L., Baillon M. & Soubeyroux J.-M. 2010. A 50-year high-resolution atmospheric reanalysis over France with the Safran system. International Journal of Climatology, 30 (11), 1627–1644. doi: 10.1002/joc.2003

Wasson, J.G., Chandesris, A., Pella, H. and Blanc, L., 2002. Les hydro-écorégions de France métropolitaine. Approche régionale de la typologie des eaux courantes et éléments pour la définition des peuplements de référence d'invertébrés. Ministère de l'Ecologie et du Développement Durable, Cemagref BEA/LHQ. 190 p.

Zumstein, J.F., 1989. Atlas de la lithologie et de la perméabilité du bassin Rhin Meuse. Agence de l’eau Rhin Meuse.

Catchment Case Study 8

Application of the multi-scale framework to the Tagliamento River (Italy)

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1. Introduction

In this report the multi-scale framework illustrated in the D2.1 main report is applied to the Tagliamento River, a large gravel-bed river in northeastern Italy. Differently from the River Frome case study, which shows all the stages of the methodology, this case study focuses only on some stages. Specifically the following aspects of the methodology are illustrated for the Tagliamento River:

- delineation of the spatial units within the catchment;

- temporal changes of channel morphology;

- trajectory of changes and controlling factors;

- assessing future channel changes.

Reconstruction of evolutionary trajectory of channel morphology, identification of controlling factors, and assessing future channel evolution are key aspects to guide management strategies. e.g. assessment of restoration options.

2. Delineation of spatial units

The Tagliamento River is located in northeastern Italy, in the Friuli Venezia Giulia Region. It drains a 2580 km^2 catchment and has a length of 178 km (Figure 1.1). From its source at 1194 m a.s.l., the river flows first within the eastern Southern Alps and Prealps, then across the Venetian-Friulian plain and enters the Adriatic Sea. The catchment features a total relief of 2696 m (Figure 1.2).

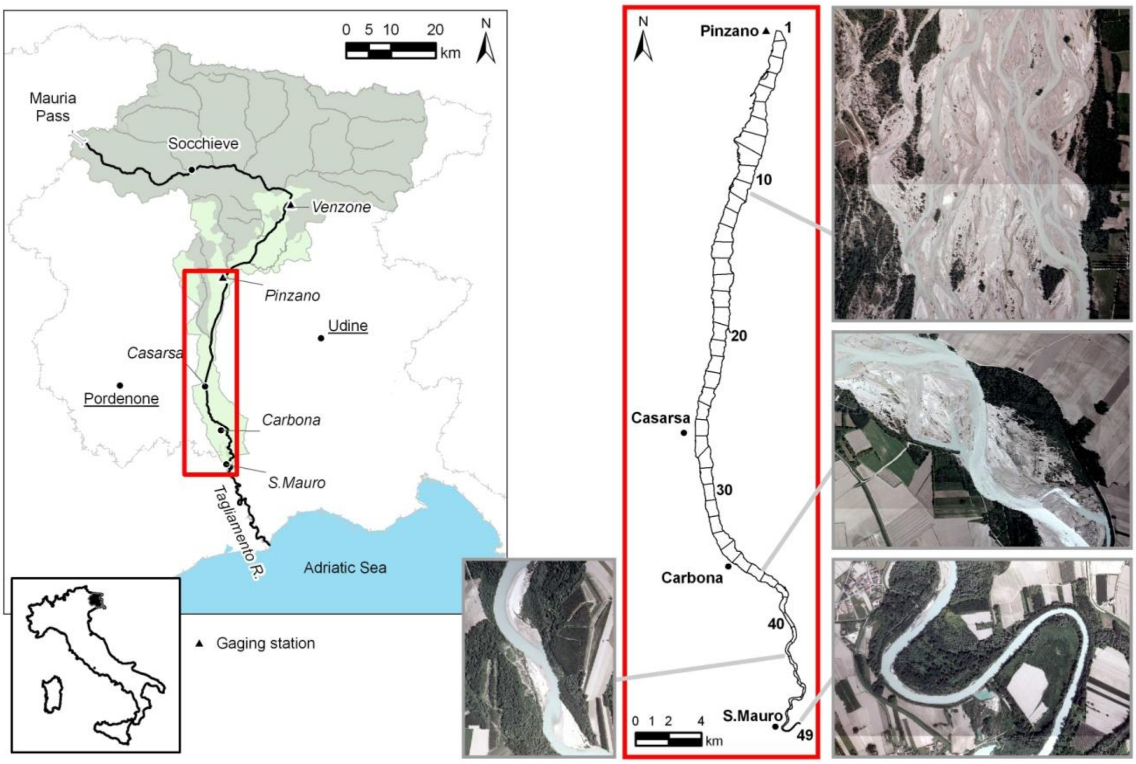

Figure 1.1 Location map of the Tagliamento River and the reaches, from Pinzano to S. Mauro, where channel changes were analyzed. The aerial photos show the different channel morphologies, from braided to meandering, that characterized those reaches. (from Ziliani and Surian, 2012).

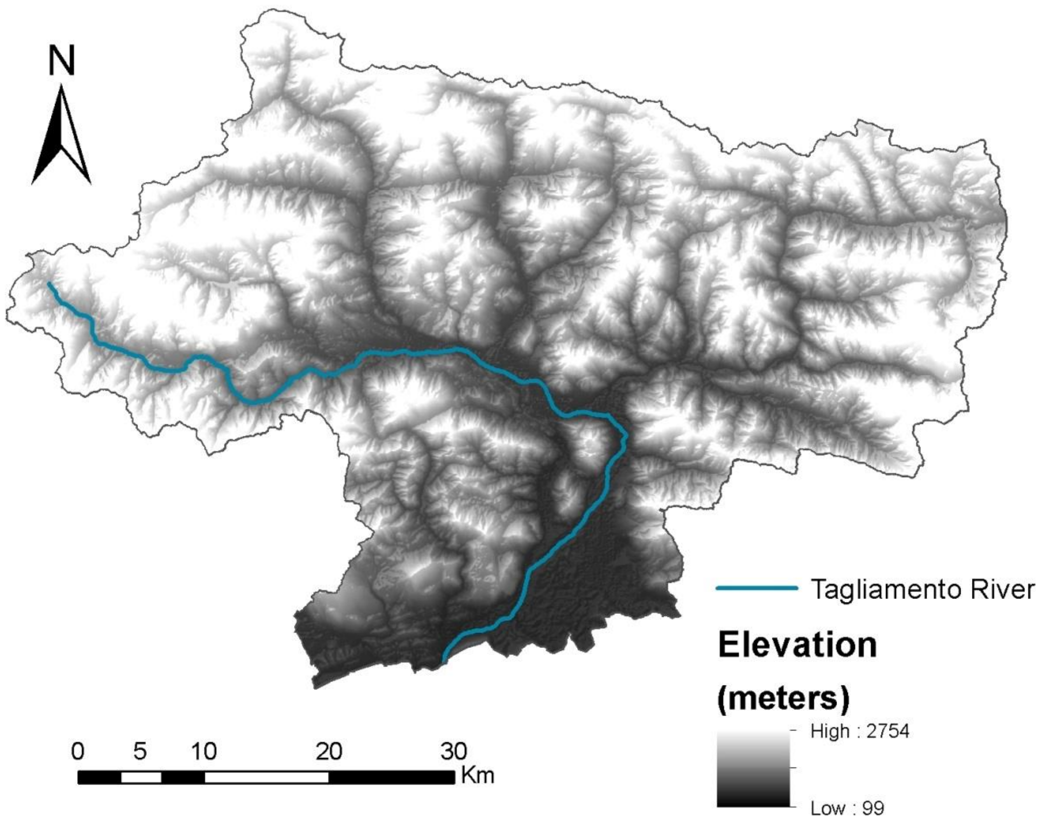

Figure 1.2 Digital Elevation Model of the Tagliamento River catchment.

2.1 Landscape units

Landscape units are portions of the catchment with similar morphological characteristics. The catchment is divided into landscape units that are broadly consistent in terms of their topography, geology and land cover.

The Tagliamento catchment was delineated into 5 landscape units (Figure 2.1). The first unit ("Alpine") is characterized by the highest elevations and corresponds to the Alpine region; it is relatively low populated, with large areas covered by forest. In the second units ("Pre-Alpine") there are both mountain and hilly areas and elevations are lower than in the first unit. The land cover in this unit does not differ much from that of the first unit. The third unit, called "Intermontane Plain", is a plain within the Pre-Alpine unit: in its southern sector this plain is bordered by the end moraine systems that was formed by the Tagliamento glacier during the Last Glacial Maximum. The fourth and the fifth landscape units correspond to the Friulian alluvial plain. The fourth unit is the "High Alluvial Plain" which is characterized by a moderate gradient, coarse sediments (i.e. gravel) and a thick unconfined aquifer. In the fifth unit ("Low Alluvial Plain") the gradient is low, sediments are fine (sand, silt and clay) and the aquifer is artesian.

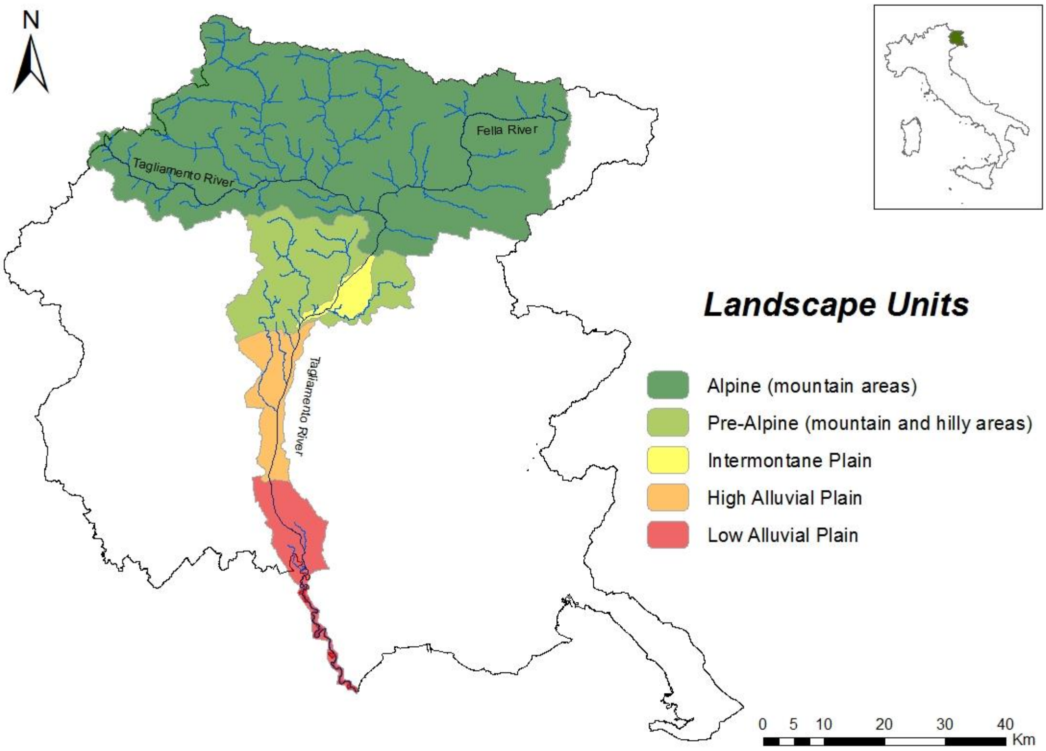

Figure 2.1 The Tagliamento catchment was delineated into 5 landscape units based on elevation, geology and land cover.

2.2 River segments

River segments are sections of the river network that are subjected to similar valley-scale influences and energy conditions. Delineation is based on major changes in valley confinement and valley or channel gradient.

The Tagliamento River is delineated into 6 segments (Figure 2.2). Segments 1 and 2 are in the "Alpine Landscape Unit" and differ both in terms of valley confinement (significantly higher in Segment 1) and valley gradient (higher in Segment 1). Segment 3 is still within the mountain area, but it is characterized by a low degree of confinement being the channel partly-confined or unconfined. Segments 4, 5 and 6 belong to the "High Alluvial Plain Landscape Unit", i.e. segment 4, and to the "Low Alluvial Plain Landscape Unit", i.e. segments 5 and 6. The two latter segments differ in terms of channel gradient, being the gradient very low in segment 6.

2.3 River Reaches

The reach is a section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent set of process-form interactions. Delineation was based primarily on channel planform but also on the presence of tributary confluences and changes in channel slope and/or width.

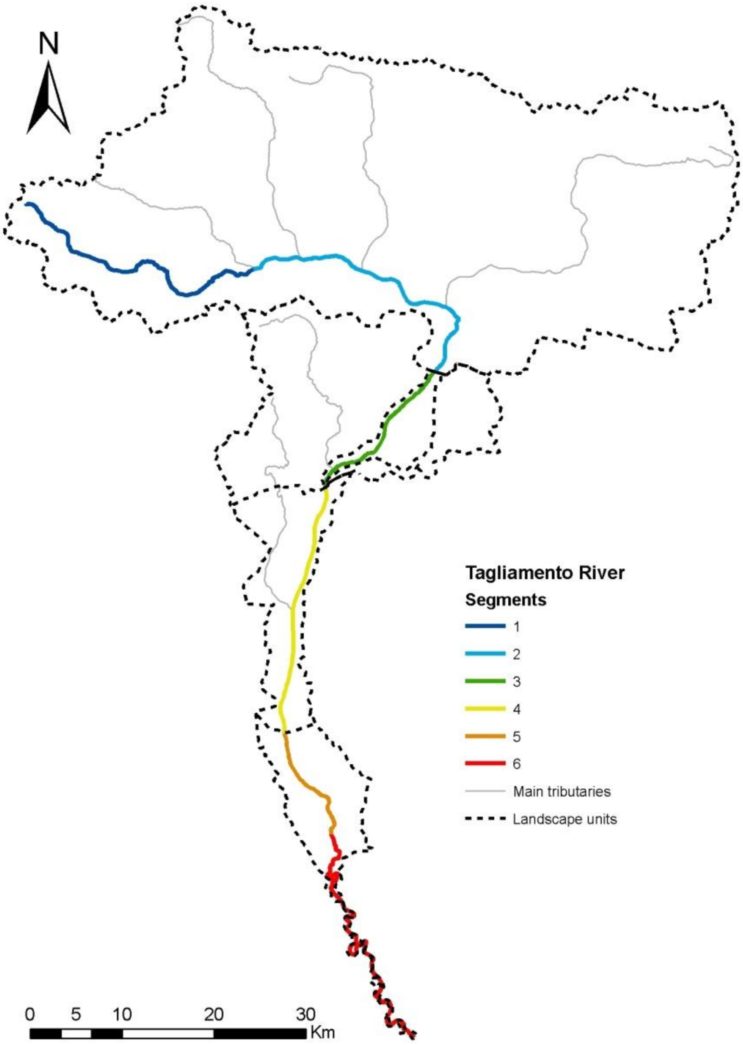

Figure 2.2 The Tagliamento River is delineated into 6 segments based on major changes in valley confinement and valley or channel gradient.

The Tagliamento River was delineated into 57 river reaches (Figure 2.3; Table 2.1). The channel morphology varies from single-thread to braided in the first segment, where the channel is confined or partly-confined. Reaches are predominantly braided in the segments 2, 3, 4, and 5. Sinuous and meandering reaches characterized the lowest section of the river where channel slope is low (segment 6).

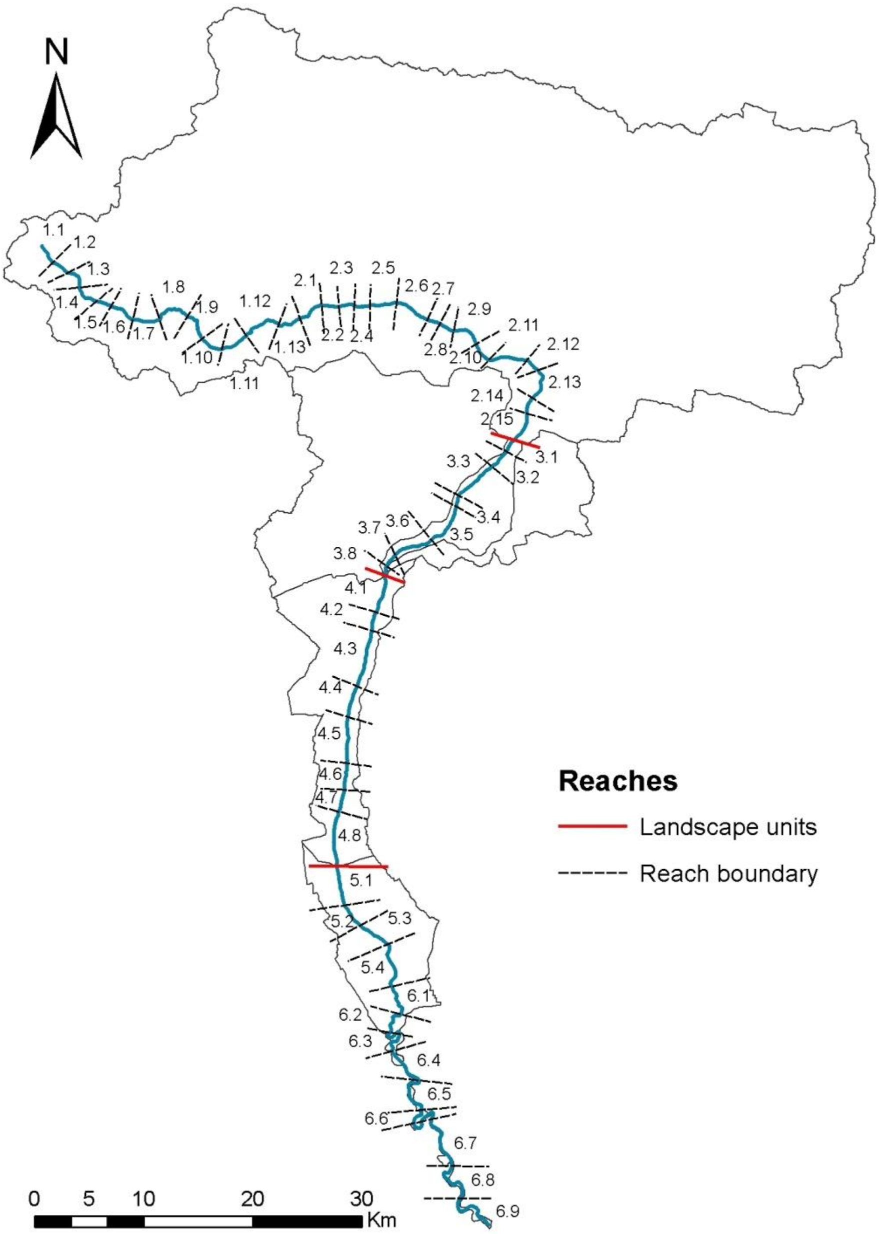

Figure 2.3 The Tagliamento River was delineated into 57 reaches. Reach divisions align first with the landscape unit and segment divisions, and are then delineated based on channel planform, presence of tributary confluences, changes in channel slope and/or width.

Table 2.1 Characteristics used in the reach delineation process.

Landscape Unit	Segment	Reach	Confinement	Planform	Other Discontinuities
1. Alpine	1	1.1	Confined	Single-thread	
		1.2	Partly confined	Single-thread	
		1.3	Partly confined	Wandering	
		1.4	Partly confined	Sinuous	
		1.5	Confined	Single-thread	
		1.6	Confined	Braided	
		1.7	Partly confined	Braided	
		1.8	Confined	Single-thread	
		1.9	Confined	Single-thread	
		1.1	Confined	Braided	Downstream width change
		1.11	Confined	Braided	Upstream width change
		1.12	Confined	Single-thread	
		1.13	Partly confined	Sinuous	
	2	2.1	Partly confined	Braided	
		2.2	Unconfined	Braided	
		2.3	Partly confined	Braided	Downstream tributary
		2.4	Partly confined	Braided	Upstream tributary, downstream width change
		2.5	Partly confined	Braided	Downstream and upstream width change
		2.6	Partly confined	Braided	Downstream and upstream tributary
		2.7	Partly confined	Braided	Upstream tributary
		2.8	Unconfined	Braided	
		2.9	Partly confined	Braided	
		2.1	Unconfined	Braided	
		2.11	Partly confined	Braided	Downstream tributary
		2.12	Partly confined	Braided	Upstream tributary
		2.13	Unconfined	Braided	
		2.14	Partly confined	Straight	
		2.15	Unconfined	Braided	
2. Pre-Alpine	3	3.1	Partly confined	Braided	
3. Intermontane Plain		3.2	Unconfined	Braided	Downstream width change
		3.3	Unconfined	Braided	Downstream tributary, upstream width change
		3.4	Partly confined	Braided	
		3.5	Unconfined	Braided	
		3.6	Partly confined	Braided	Downstream tributary
		3.7	Partly confined	Braided	Upstream tributary
		3.8	Confined	Braided	
4. High Alluvial Plain	4	4.1	Partly confined	Braided	
		4.2	Unconfined	Braided	Downstream width change
		4.3	Unconfined	Braided	Upstream and downstream width change
		4.4	Unconfined	Braided	Downstream tributary, upstream width change
		4.5	Unconfined	Braided	Upstream tributary
		4.6	Unconfined	Braided	Downstream tributary
		4.7	Unconfined	Braided	Downstream and upstream width change
		4.8	Unconfined	Braided	Downstream and upstream width change
5. Low Alluvial Plain	5	5.1	Unconfined	Braided	Downstream and upstream width change
		5.2	Unconfined	Wandering	Downstream and upstream width change
		5.3	Unconfined	Braided	Upstream width change
		5.4	Unconfined	Sinuous	Downstream change in slope
	6	6.1	Unconfined	Sinuous	Upstream change in slope
		6.2	Unconfined	Sinuous	
		6.3	Unconfined	Meandering	
		6.4	Unconfined	Straight	
		6.5	Unconfined	Meandering	
		6.6	Unconfined	Meandering	
		6.7	Unconfined	Sinuous	
		6.8	Unconfined	Meandering	
		6.9	Unconfined	Sinuous	

3. Characterization of temporal changes in channel morphology

The geomorphological character of river reaches depends not only upon interventions and processes within the reach but also within the upstream (and sometimes the downstream) catchment. In addition, the character of river reaches responds in a delayed way to processes and interventions within the catchment. As a result, understanding geomorphology at the reach scale requires an understanding of current and past processes and interventions at larger spatial scales. Without such a multi-scale understanding, management strategies are not fully informed and may not provide sustainable solutions.

The Tagliamento river system is considered the last large natural Alpine river in Europe (Gurnell *et al.*, 2000; Tockner *et al.*, 2003). Despite its overall good eco-morphological quality, human activities, including channelization, gravel mining, torrent control works in the drainage basin, have led to sediment flux modifications and notable morphological changes, in particular in the lower river sections (segments 4, 5 and 6; see Figure 3.1). Channel changes in the Tagliamento River were analyzed at the segment and reach scales, taking into account also larger scale (i.e. catchment) to understand controls of such changes (Ziliani and Surian, 2012). Specifically a river section 49 km long, from Pinzano gorge to S. Mauro, was analyzed (Figure 1.1). Referring to the spatial delineation previously illustrated (Figure 2.3, Table 2.1), 15 reaches were analyzed, from reach 4.1 to reach 6.3. The aim of this analysis was to reconstruct a detailed evolutionary trajectory of channel morphology and to understand controlling factors. A better explanation of phases of adjustment is crucial for making predictions on future channel evolution. As for controlling factors, the aim is to assess the role of those acting at catchment and at reach scales and to assess the relevance of the single factors on channel adjustments.

3.1 Methods and data sources

Channel width, islands, braiding intensity, bank protection structures, and mining areas were analysed using maps and aerial photos. The historical analysis, covering a period of about 200 years (from 1805 to 2009), was carried out with a GIS using 32 maps and 320 aerial photos. Map scales range between 1:5000 (1986-1988) and 1:86,400 (1833), while aerial photo scales between 1:12,270 (1966) and 1:34,480 (1993). The 49 km long river section was analyzed considering "subreaches" 1 km in length. This explains why in the following parts we will also refer to subreaches, that is to a smaller scale of that defined in the spatial delineation.

Available cross sections and new cross-section field surveys were used to analyze bed-level changes. Overall, 168 cross-section surveys, carried out in seven periods from 1970 to 2010, were used in our analyses. Spatial resolution is good as distance between cross sections is 1 km or less, while some problems are associated with temporal resolution. In fact, only a few cross sections were surveyed 4 or 5 times, thus allowing a detailed temporal analysis of changes. Bed elevation changes were analysed through calculation and comparison of mean bed elevation for each cross section.

Field surveys were carried out using standardized forms specifically designed to assess channel changes (Rinaldi, 2008). Surveys require observation and measurement of several morphological and sedimentological features (e.g., differences in elevation between higher bars and gravel in floodplains/recent terraces, lack/abundance of sediment lobes, or widespread presence/complete absence of bed armouring). Data collected through such surveys integrate data coming from the other methods (GIS analysis of planform changes and topographic surveys), in particular data regarding bed-level changes. The geomorphological surveys allowed us to infer direction (aggradation vs. incision) and magnitude of long- and short-term channel changes.

3.2 Changes in channel morphology

Changes in channel width (average width of the whole river section) over the period 1805-2009 are shown in Figure 3.1A. For clarity, temporal resolution of measurements from the 1980s to 2009 was reduced, using three average values respectively for the 1980s, the 1990s, and the last ten years. On the whole, a remarkable reduction of channel width is evident: from 1355 m in 1833 to 545 m in the 1990s, that is a narrowing of 60%. The narrowing process was not constant over the period. The first period, from 1805 to 1891, shows small width variations: specifically a widening of 4% (1805-1833) followed by a narrowing of 7% (1833-1891). Then, from the end of the nineteenth century, channel narrowing started to take place with increasing magnitude. The average rate of narrowing was low at the beginning of the twentieth century (2 m/y in the period 1891-1927) and reached a maximum value of 18 m/y in the period from 1970 to the 1980s. As identified in other Italian rivers (Surian et al., 2009), two phases of narrowing of different intensity can be defined in the Tagliamento River. In the first phase ("phase 1" in Figure 3.1A), from the end of the nineteenth century to the 1950s, 33% of the total narrowing took place; while in the second phase, from the 1950s to the 1990s, 56% with rate of narrowing varying from 6 to 18 m/y. The most recent period, from the 1990s to 2009, was characterized by a moderate widening process (4 m/y) (Figure 3.1B).

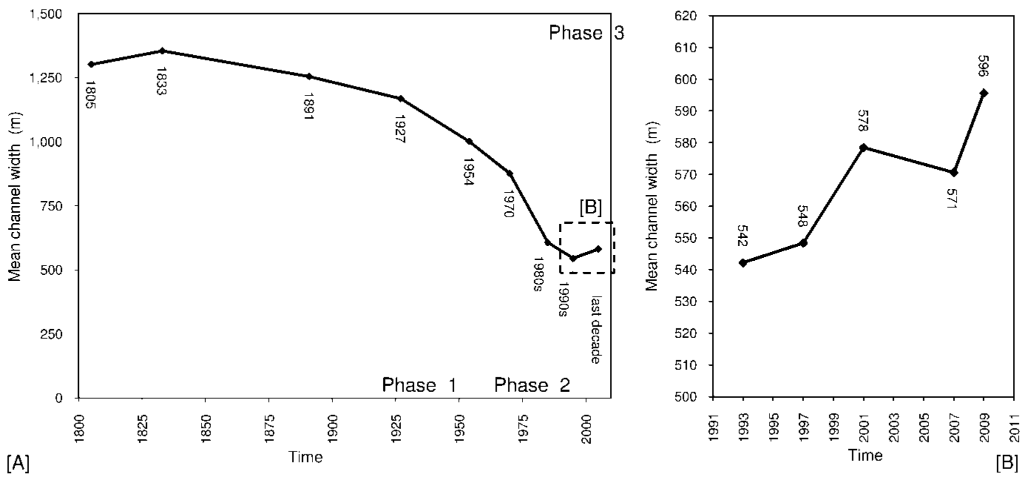

Figure 3.1 (A) Changes in channel width over the period 1805-2009; main phases of adjustment are shown ("Phase" 1, 2, and 3); (B) changes in channel width over the period 1993-2009 ("Phase 3") (from Ziliani and Surian, 2012).

Bed-level changes were analyzed combining data coming from cross-section comparisons and geomorphological surveys. Such a mixed approach was dictated by the fact that the cross-section data set covers a limited period (1970-2010) and it has some spatial gaps. Figure 3.2 shows bed-level changes over the period 1970-2001/2003. An average incision of 1 m was calculated for the whole river section, but the process was not homogeneous along the river. In the upstream part of the river section (from subreach 1 to subreach 14), incision was very low (0.15 m on average); while in the downstream part, it is 1.5 m on average. In the braided and wandering reaches (from subreach 15 to subreach 37) incision is between 1.0 and 1.5 m commonly and was up to 2.0 m. Incision in the single-thread reaches (from subreach 38 to subreach 49), is 2.0 m commonly and up to 3.0 m. Besides confirming data from cross sections, geomorphological surveys allowed estimates of changes that had occurred before 1970. Incision of 0.3-0.4 m was assessed for the period 1950s-1970 by field measurements of terrace elevations. In conclusion, except for the upstream subreaches (from 1 to 14), incision was 1.8-1.9 m on average in the period 1950s-2001/2003.

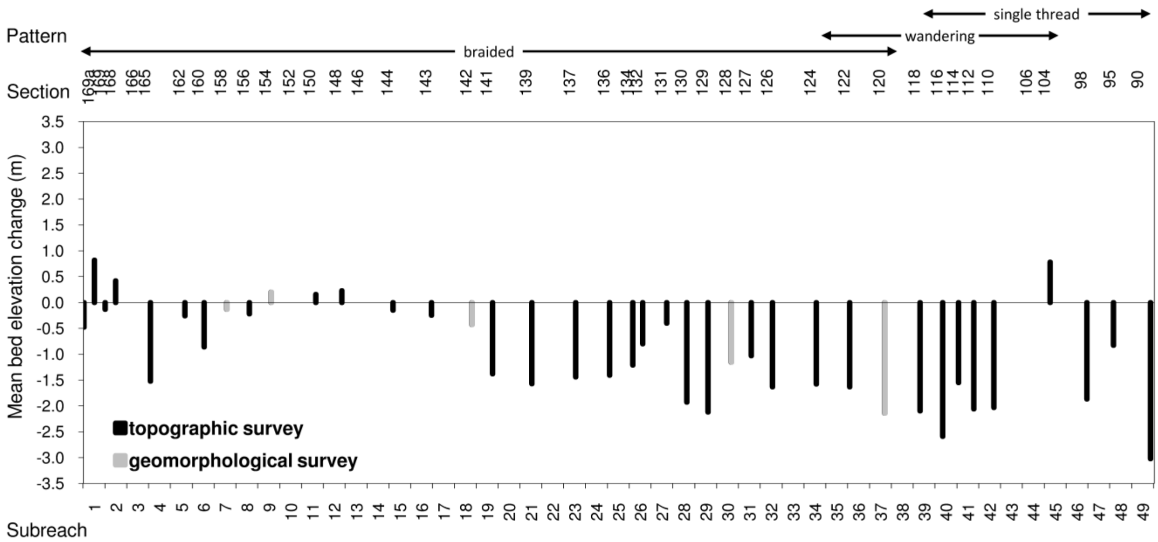

Figure 3.2 Bed-level changes in the period 1970-2003. Changes were derived from comparison of cross sections and from geomorphological surveys (from Ziliani and Surian, 2012).

As with the long-term bed elevation changes, recent changes in bed elevation were analyzed using data from cross-sections and geomorphological surveys. Though the combined data set (cross sections plus geomorphological surveys) still had some spatial gaps (i.e., several subreaches without data), an overall picture of bed-level variation in the period 2001/2003 to 2006/2010 was obtained (Figure 3.3). There was no clear dominant process in this time period because aggradation up to 1.0 m and incision up to 0.5 m occurred. Overall, an average aggradation of 0.2 m was estimated for the entire study section. Figure 3.3 suggests that aggradation was dominant and more intense in the upper reaches (e.g. subreaches 7 and 9) and in the single-thread reaches (e.g., subreaches 42 and 44), while the middle sector underwent smaller or no variations (e.g., slight incision between subreaches 28 and 37). These latter considerations are affected by uncertainty owing to lack of data for some subreaches.

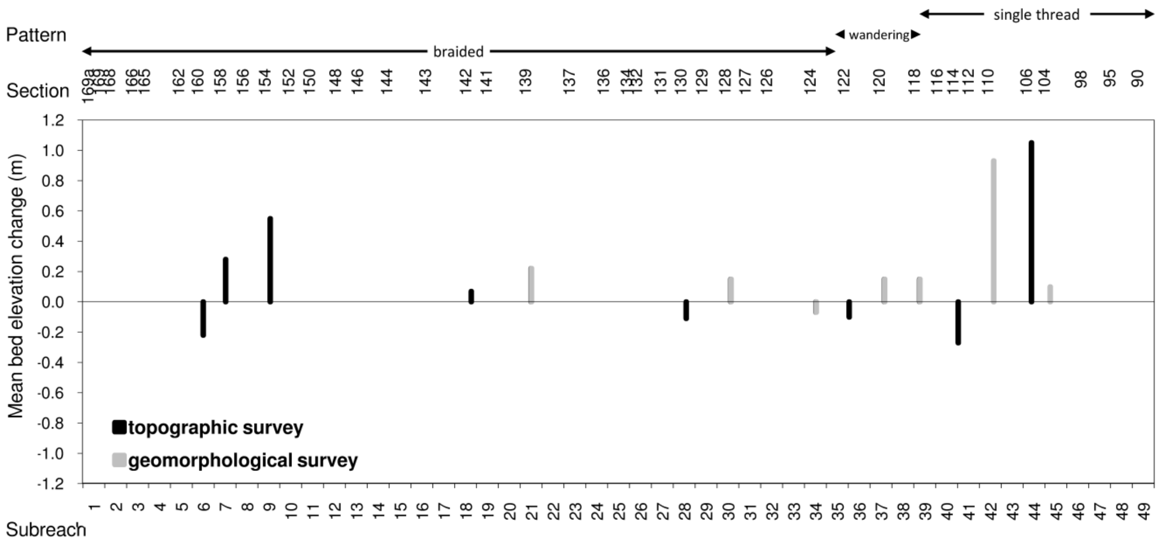

Figure 3.3. Bed-level changes in the short period (2001-2010). Changes were derived from comparison of cross sections and from geomorphological surveys (from Ziliani and Surian, 2012).

3.3 Controlling factors of channel evolution in the Tagliamento River

In order to explain the morphological changes observed in the Tagliamento River we started linking the evolutionary trajectory with several factors acting at reach and catchment scale (Figure 3.4). As for controlling factors, it was shown that the long-term channel evolution of the Tagliamento River was driven primarily by human intervention at reach scale (i.e., sediment mining and channelization) (Ziliani and Surian, 2012). The main reasons for excluding factors at catchment scale (i.e., increase in forest cover and torrent-control works) are (i) availability of sediment supply from the braided reaches that are upstream of the study section (i.e. reaches located in "Segment 3", see Table 1) and (ii) outcomes from numerical modelling that shows that changes in upstream sediment input have small effects on channel dynamics in the study section (see next chapter for details about numerical modelling). Referring to the existing interpretation of channel adjustments in Italian rivers (e.g., Surian and Rinaldi, 2003; Surian et al., 2009), this case study shows that, under specific conditions, human intervention at catchment scale can have no, or minor, consequences on downstream reaches. Though sediment connectivity is very high in the Tagliamento system, changes in sediment supply in the catchment area have no effect on downstream reaches over relatively short time periods (i.e., decades).

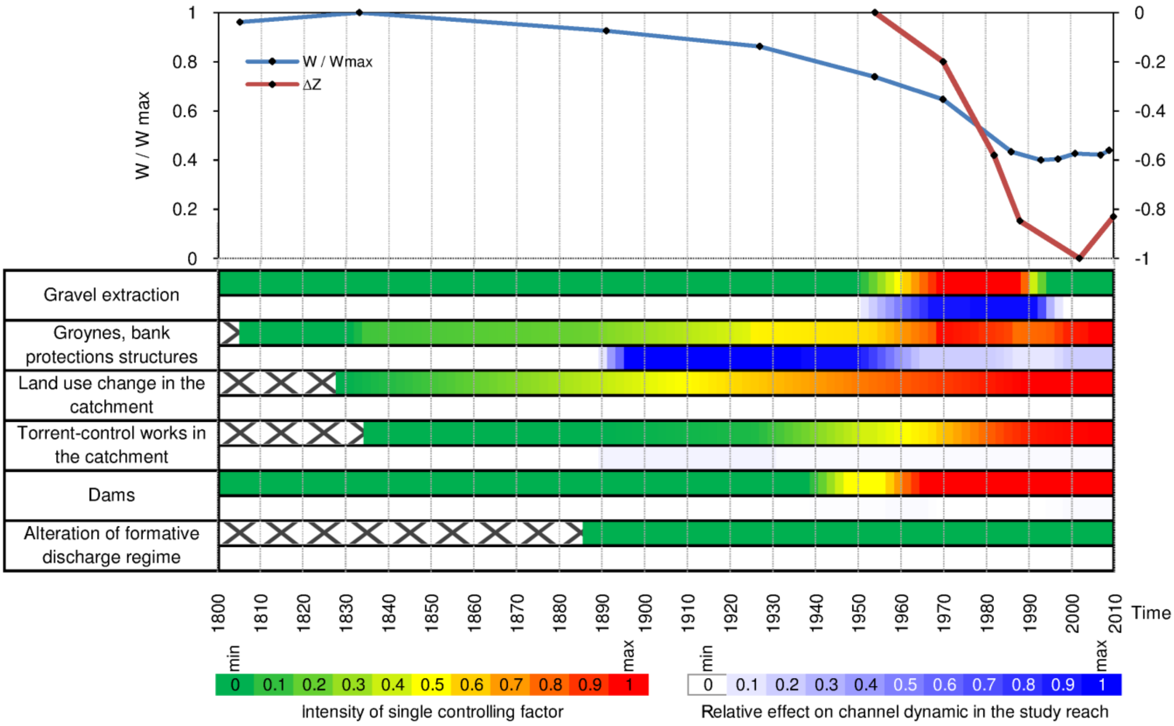

Figure 3.4 Evolutionary trajectory of channel morphology and controlling factors over the last 200 years. W/Wmax and ΔZ represents, respectively, a dimensionless width and bed elevation change referring to elevation in the 1950s. Different colours are used to show the intensity of single controlling factors and the relative effect of each factor on channel dynamics. Periods with no data are shown with a cross (from Ziliani and Surian, 2012).

4. Assessing future channel changes

Prediction of future channel evolution has several practical implications because it may represent a key tool to guide management strategies. Prediction requires use of models (e.g. conceptual, physical, analytical or numerical models) (Wilcock and Iverson, 2003). Uncertainty associated with any kind of model and complexity of fluvial systems, specifically of braided rivers, are major issues to be taken into account. This means that we should be aware that prediction of channel morphology has inherent limitations since results of any model are affected by a degree of uncertainty and braided rivers are very complex systems that exhibit self-organized critical behaviour.

Modelling was carried out in the Tagliamento River along 11 reaches (from reach 4.1 to reach 5.3, see Table 1) having a braided morphology and a total length of 33 km. The aim of modelling was to explore future channel evolution taking into account different scenarios of sediment supply at catchment and reach scale (Surian and Ziliani, 2012; Ziliani et al., 2013). Two different modelling approaches were combined to predict channel morphology: (i) a conceptual model based on a historical analysis of channel changes and controlling factors and (ii) numerical modelling, using a reduced complexity model (CAESAR; Coulthard et al., 2007).

4.1 CAESAR application to the Tagliamento River

A cellular model (CAESAR) was used to predict channel morphology over the period 2001-2081. The approach used included the following steps: sensitivity analysis, calibration, validation, and, finally, long-term simulations. This approach allowed us to analyze 12 input factors initially and then to focus calibration only on 2 factors of the model identified as most important. Sensitivity analysis and calibration were performed on a 7.5 km reach, using a hydrological time series of 20 months. Validation and long-term simulations on the whole 33 km study reaches, respectively over a period of 8 years (2001 - 2009) and 80 years (2001 - 2081).

The model was applied using constant conditions for flow regime and different conditions (i.e. scenarios) for sediment supply. Flow regime in the period 2000-2010 was replicated several times, thus assuming no changes in flow regime in the next years. As for sediments, we explored different possible scenarios of management: in two scenarios bed load supply was increased (for instance assuming removal of bank protection structures), in one scenario upstream bed load input was reduced, in the fourth scenario no change in sediment supply was assumed, referring to present condition.

4.2 Prediction of channel morphology

The numerical modelling showed that channel widening will continue in the future (up to 2080), independently from sediment management strategies (Figure 4.1). As expected, channel width (w) was larger in the scenario (SC) where bank protections were removed (w = 1230 m in SC2) and smaller in the scenario where upstream sediment input was reduced (w = 1130 m in SC4). It is worth noting that SC1 (scenario with no interventions) and SC3 (scenario with an increase of upstream sediment input) produced very similar results in terms of channel width (Figure 4.1), confirming a low influence of upstream sediment input on channel dynamics in the study reaches.

There are clearly some differences between the results of the numerical model and those of the conceptual model, but overall the results can be considered satisfactory. Both models predict that channel widening will continue in the future and magnitude of widening in the five scenarios is comparable. Besides inherent errors associated to both models (e.g. it is possible that the cellular model underestimated the effect of vegetation growth on channel dynamics), some differences are also due to input data. Specifically, the flow regime of the periods 1993-2009 and 2000-2010 were used as input data for the conceptual and the numerical model respectively.

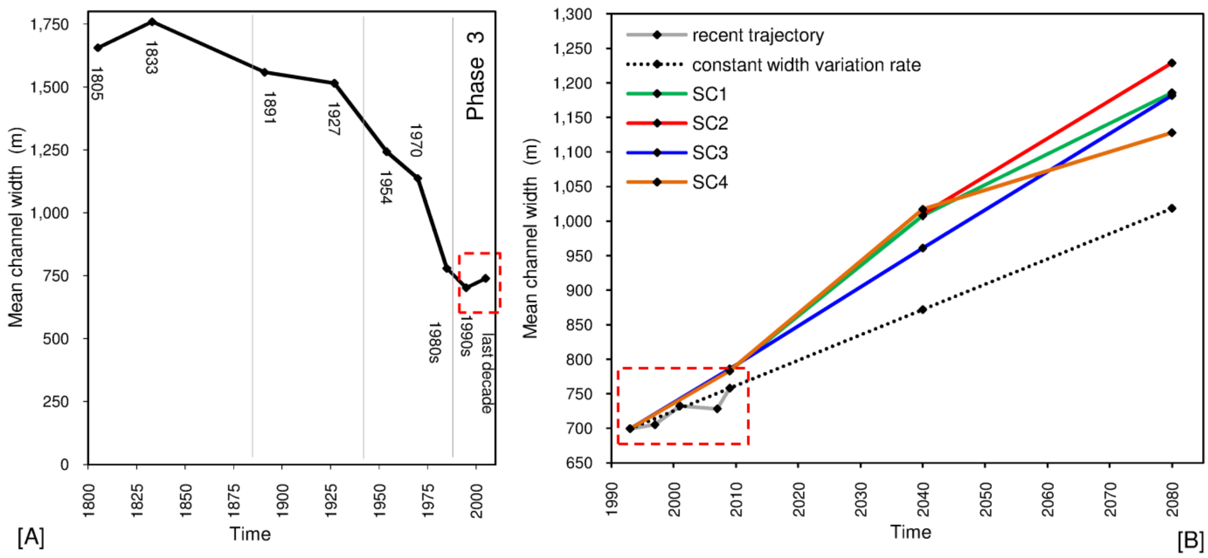

Figure 4.1 (A) Changes in channel width over the period 1805-2009; (B) Prediction of channel width for the period 2009-2080; recent trajectory: channel width measured from aerial photos; constant width variation rate: derived from the conceptual model; SC1, SC2, SC3, SC4: simulations of different scenarios of sediment management using a numerical model (CAESAR), assuming no intervention (SC1), removal of bank protections (SC2), increase of upstream sediment input (SC3), and decrease of upstream sediment input (SC4) (from Surian and Ziliani, 2012).

5. References

Coulthard, T.J., Hicks, D.M. and Van De Wiel M.J. (2007). *Cellular modelling of river catchments and reaches: advantages, limitations and prospects*. Geomorphology, 90, 192-207.

Gurnell A.G., E. Petts, N. Harris, J. V. Ward, K. Tockner P. J. Edwards, J. Kollmann (2000). Large wood retention in river channels: The case of the Fiume Tagliamento, Italy, Earth Surf. Processes Landf*., 25*(3), 255-275, doi:10.1002/(SICI)1096-9837(200003).

Rinaldi M. (2008). Schede di rilevamento geomorfologico di alvei fluviali. Il Quaternario, 21(1B), 353-366.

Surian N., Rinaldi M. (2003). Morphological response to river engineering and management in alluvial channels in Italy. Geomorphology, 50(4), 307-326.

Surian N., Rinaldi M., Pellegrini L., Audisio C., Maraga F., Teruggi L., Turitto O., Ziliani L., (2009). Channel adjustments in northern and central Italy over the last 200 years. In: James L.A., Rathburn S.L., Whittecar G.R. (Eds.), Management and Restoration of Fluvial Systems with Broad Historical Changes and Human Impacts. Special Paper 451, Geological Society of America, Boulder, U.S.A., pp. 83-95.

Surian N., Ziliani L. (2012). Prediction of channel morphology in a large braided river. In: Proceedings of the 1st International Conference on Integrative Sciences and Sustainable Development of Rivers (ISRivers 2012), 26-28 June 2012, Lyon, France, pp. 1-3, published on-line (http://www.graie.org/ISRivers/actes/a_index.htm).

Tockner K., J. V. Ward, D. B. Arscott, P. J. Edwards, J. Kollmann, A. M. Gurnell, G. E. Petts, B. Maiolini (2003). The Tagliamento River: A model ecosystem of European importance. Aquatic Sci*., 65*(3), 239-253, doi:10.1007/s00027-003-0699-9.

Wilcock, P.R. and Iverson, R.M. (2003). *Prediction in geomorphology*. In: Prediction in geomorphology, Wilcock, P.R. and Iverson, R.M. (Eds.), Geophysical Monograph 135, American Geophysical Union, 3-11.

Ziliani L., Surian N. (2012). Evolutionary trajectory of channel morphology and controlling factors in a large gravel-bed river. Geomorphology, 173-174, 104-117. DOI: 10.1016/j.geomorph.2012.06.001.

Ziliani L., Surian N., Coulthard T.J., Tarantola S. (2013). Reduced-complexity modeling of braided rivers: Assessing model performance by sensitivity analysis, calibration, and validation. Journal of Geophysical Research: Earth Surface, 118, 2243-2262. doi:10.1002/jgrf.20154.

Catchment Case Study 9
Application of the multi-scale framework to the Rivers Lech and River Lafnitz, Austria

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1. Introduction and objectives

In this case study the multi-scale framework is applied to two Austrian catchments: the Lech River and the Lafnitz River (Figure 1.1). The aims of this case study are to provide examples of the application of the multi-scale framework (delineation and characterisation) to two Austrian catchments with different characteristicsin order to exemplify the application of the framework and to illustrate interpretation of the results. Both rivers where selected because i) they represent two more or less naturally functioning rivers, with minor anthropogenic influences; ii) they are located in two different environments (e.g. different climate, geology, topography, etc), and their morphologies are thus driven by different process domains and processes; and iii) different data sets are available for each catchment. The Lech is an alpine catchment with high precipitation rates, a hydrological regime which is moderate nival (main influence: snow melt) and a mean flow of about 44 m^3s^{-1} (at Lechaschau). The Lafnitz in contrast is located in the Ilyrian biogeographic region, with lower precipitation rates, a pluvio nival to summer pluvial hydrological regime (main influence: rain) and a mean flow of about 14 m^3s^{-1} (at Eltendorf).

Figure 1.1 The Danube River Basin with the Lech River (left circle) and the Lafnitz River (right circle).

2. The catchments

2.1. River Lech

The river Lech is a right bank tributary to the Danube River and is located in the western part of the Danube River Basin (Figure 2.1). The Lech originates from the confluence of several small brooks, close to the lake Formarinsee (1880 m a.s.l.) in Vorarlberg. It flows in a north-east direction through Tyrol and leaves Austria at Weißhaus. In Germany, it flows northwards and enters the Danube at Marxheim.

The investigated section of the Upper Lech River is about 82 km long and the catchment area is about 1415 km². The entire catchment is located in the Northern Calcareous Alps and lies within the temperate oceanic climate, with a mean annual precipitation of about 1760 mm. The topography is mountainous and characterised by steep slopes and elevations above 750 m a.s.l. The land cover is dominated by forests, scrubs and other herbaceous vegetation, and open spaces with little or no vegetation.

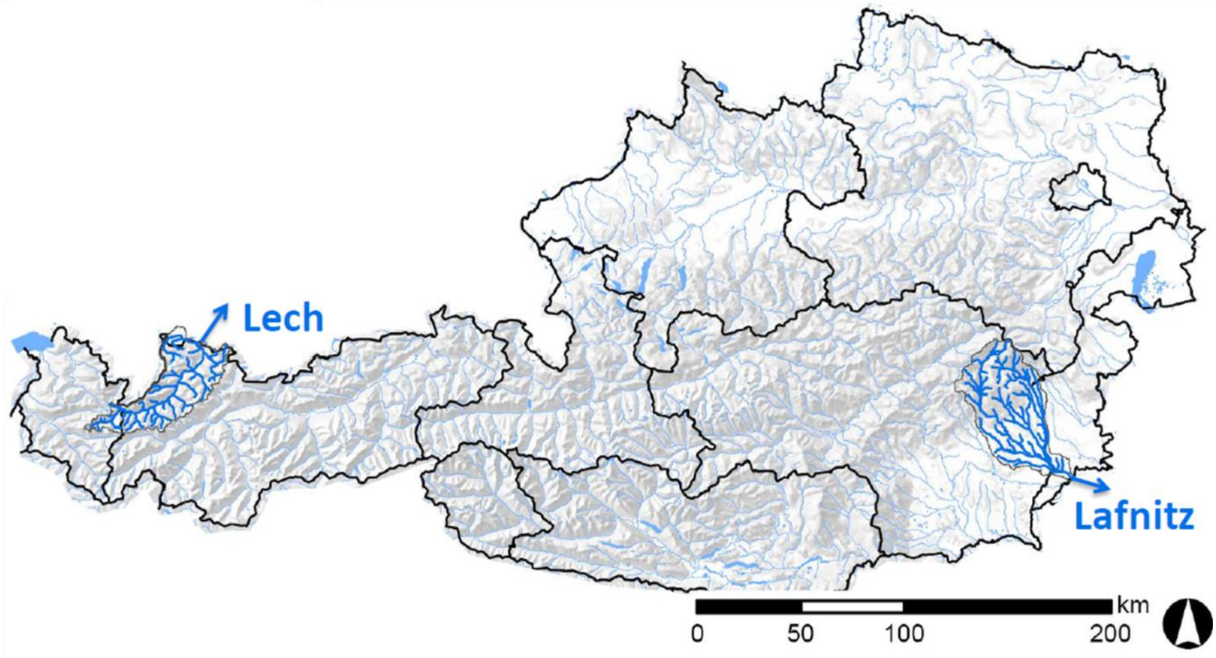

Figure 2.1 Location of the catchments of the Lech and the Lafnitz River (data source: HAÖ, 2007)..

2.2. River Lafnitz

The river Lafnitz is a left bank tributary of the Raab River, which enters the Danube shortly after Győr on the right bank. The catchment of the Lafnitz is located in the mid-western part of the Danube River Basin (Figure 2.1). The Lafnitz originates at “Lafnitzeck” between the Wechsel- and the Masenberg mountain massif in Styria. It starts with a north eastern course, follows a semi-circle and flows than southwards. In this middle section of the Lafnitz River, from Lafnitz to Fürstenfeld, it represents the border between Styria and Burgenland. It then crosses the Burgenland and leaves Austria at Neuheiligenkreuz. In Hungary, shortly after the border with Austria, it enters the Raab River which follows again a semi-circle and flows in a north-eastern direction until it drains into the Danube.

The Lafnitz River, has a length of about 83 km and a catchment area of about 1990 km². It has a temperate continental climate with a mean annual precipitation of about 840 mm. The upstream part of the Lafnitz (till Rohrbach) runs through Austroalpine Crysalline Complexes, whereas the middle and downstream sections flow through clastic sediments of an intramontaneous basin. The upstream section is characterised by a mountainous to hilly topography with medium to steep slopes and elevations above 500 m a.s.l. Forests, pastures and heterogeneous agricultural areas are the dominant land cover classes in this area.

The downstream section of the catchment has a hilly topography and an altitudinal range of 200 to 500 m a.s.l. The main land cover types of this area are arable land and forests.

3.Materials and Methods

The delineation and characterisation method is based on the multi-scale framework developed in Deliverable 2.1 Part 1 and is described briefly here.

3.1 Delineation

Delineation is applied as a top down process from the region scale downwards to the smallest spatial units (Figure 3.1). The boundaries of the higher spatial scale units have to be congruent with boundaries at lower levels.

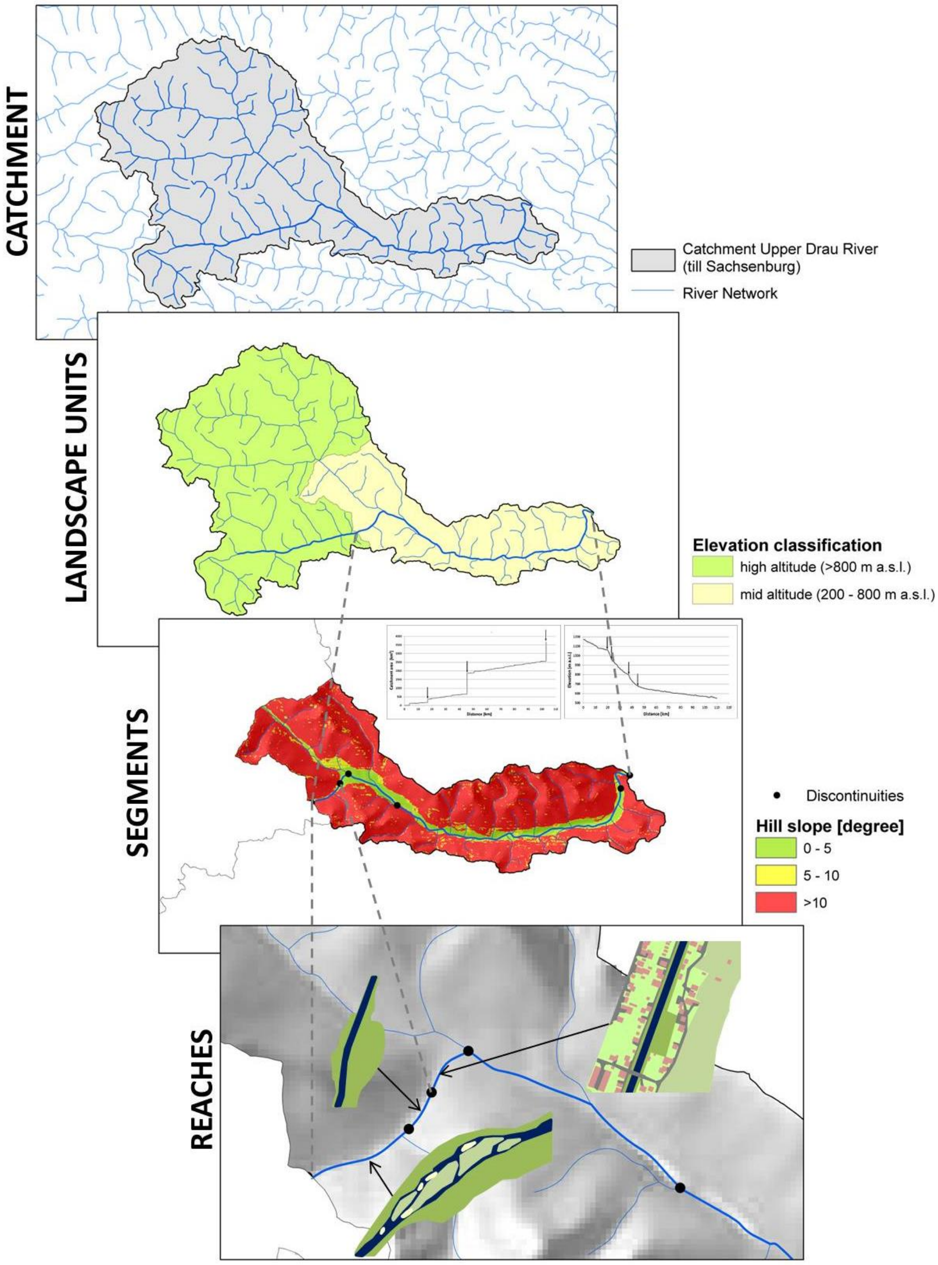

Figure 3.1 Delineation as a top down process from catchment scale to reach scale.

3.1.1 Region

In the most cases, at this scale delineation is not necessary as most catchments (except very large ones) lie within one region. As basis for the delineation and later on the characterisation of the region, the bioclimatic and biogeographic maps of Europe (see Rivas-Martínez et al., 2004a; Rivas-Martínez et al., 2004b) were used.

3.1.2 Catchment

To delineate the catchment and the sub-catchments, topographic and river network information is necessary. However, in Austria the digital hydrological atlas (HAÖ, 2007), from here on referred to as digHAO, provides the river network, the catchments and sub-catchments covering the entire national territory of Austria.

3.1.3 Landscape Unit

Landscape units represent physiographically similar areas and are delineated based on geology, elevation and relief. For the delineation of the Austrian catchments, the geological map of Austria (Egger et al., 1999) and a digital elevation model (based on data from Jarvis et al., 2008) with a raster width of 80 m were used. Data with better resolution (smaller raster widths) of the entire catchments were not available. The delineation due to elevation (Table 3.1) is based on values given in the Water Framework Directive (EC, 2000).

Table 3.1 Elevation classification used for the delineation of landscape units.

Elevation range in m a.s.l	Class name
< 200	Low altitude areas
200-800	Mid altitude areas
> 800	High altitude areas

3.1.4 Segment

Segments present sub-divisions of landscape units and have thus to be defined with respect to the given boundaries. The number of segments per landscape unit should be kept small, e.g. from one to three, and their length should be larger than 10 km.

The main factors by which segments are delineated are major discontinuities in valley gradients, major changes in catchment area and the degree to which the river is laterally confined.

Discontinuities in valley gradients were determined visually by the interpretation of the longitudinal valley profiles (Figure 3.2).

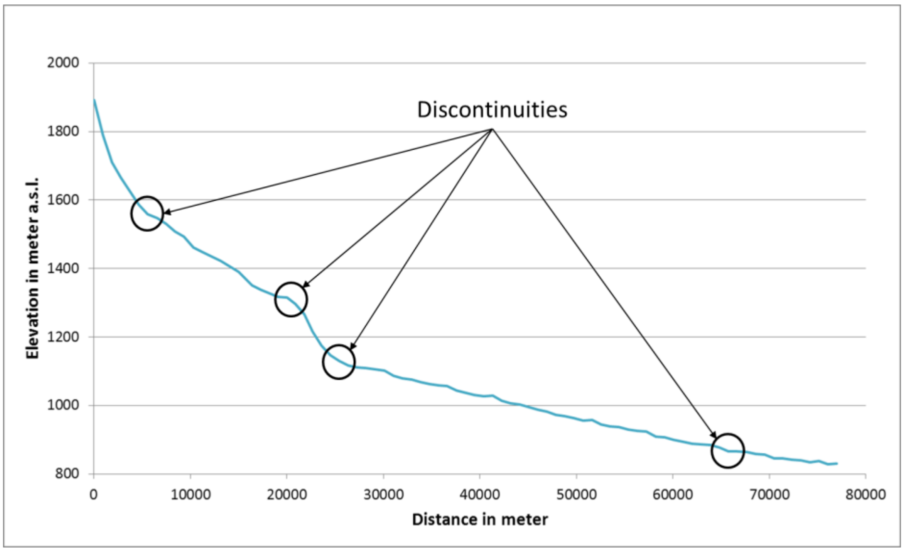

Figure 3.2 Visual interpretation of discontinuities in valley gradient.

Changes in catchment area are mainly caused by tributaries. We used the relative increase in area in combination with the absolute value of the additional catchment area as criteria for segment boundaries. The areas of the sub-catchments were derived from the digHAO (HAÖ, 2007). Based on the upstream area A_u [km^2] and the catchment area of the tributary A_{ti} [km^2] (Figure 3.3) the relative increase in area A_{in} [%] was calculated in the following way (Equation 1):

$$A_{in} = \frac{A_{ti} * 100}{A_u} \qquad \textbf{Equation 1}$$

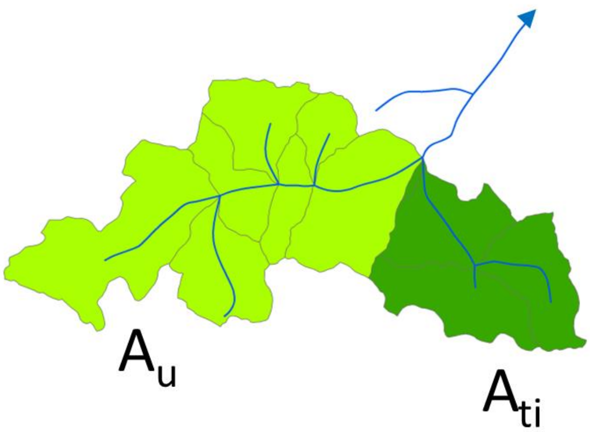

Figure 3.3 Definition of upstream area A_u and area of the tributary A_{ti}.

In Table 3.2, the criteria which cause the delineation based on major changes in catchment area, are reported. The criteria thresholds are based on visual interpretation of discontinuities in the catchment area development graphs for both rivers.

Changes in hydrological regime, which are available for each gauging station in the catchment area, may also cause a segment boundary. However, these changes are generally due to tributaries entering the river and may thus be already recorded by the increase in catchment area.

Table 3.2 Delineation criteria based on major changes in catchment area. If the upstream catchment area A_u is >50 km² and one or both limits, given below, are exceeded, a segment boundary has been drawn.

Absolute increase in catchment area A_{ti}	**Relative increase in catchment area A_{in}**
> 85 km²	> 25 %

The assessment of confinement of rivers is based upon approaches of Rinaldi et al. (2012) and Brierley and Fryirs (2005). Rivers are defined as confined, partialy confined and unconfined. For the Lech and the Lafnitz, Google Earth (2013) and a digital elevation model (Jarvis et al., 2008) were used to assess the degree of confinement.

3.1.5 Reach

As the segments are a sub-division of the landscape units, the reaches are sub-divisions of segments and have thus to be defined according to the segment boundaries. A reach is a river entity which is sufficiently uniform in respect to processes, channel and floodplain morphology, sediment regime and calibre, discharge and so on.

For delineating the Austrian rivers Lech and Lafnitz, we used channel planform, characterized by sinuosity, braiding and anabranching indices. For further information concerning the attributes see "Simple Classification of River Types based on Confinement and planform" in Deliverable 2.1 Part 1 Chapter 4.

Delineation was also applied where artificial structures like dams or weirs interrupt the water and sediment continuity.

3.2 Characterisation

The aim of the characterization is to describe the delineated units and thereby support understanding of the condition and functioning of the fluvial system. The characterization approach is open ended and can thus be adapted to the present river system and optimized concerning available information and data sets.

3.2.1 Region

The characteristics of the region were defined by using the biogeographic and bioclimatic maps presented by Rivas-Martínez et al. (2004a; 2004b). Additionally, the main river basin (Figure 3.4), corresponding to the Water Framework Directive WFD (EC, 2000), is given to provide some geographical reference.

Figure 3.4 Overview of European river basins. Austria has a share on three international river basins, the Danube, the Rhine and the Elbe respectively.

3.2.2 Catchment

At the catchment scale, an overview of the topographic, geological and land cover controls on hydrology and sediment delivery is assembled. Table 3.3 presents an overview concerning the evaluated characteristics and the data sources that were used.

Geology was not characterised within this section as it was used for delineation of landscape units and is therefore discussed in that section. However, hydrogeology and soil type, which are evaluated here, are based on the geology.

3.2.3 Landscape Unit

At the landscape unit scale, parameters to investigate water and sediment delivery potential, natural vegetation and the impact of important physical pressures are evaluated. The data sources that were used for characterisation of the landscape units are given in Table 3.4.

Table 3.3 Overview of evaluated characteristics and used data sources at the catchment scale.

Characteristic	Used data source	Notes
Geology	Geological map of Austria (Egger et al., 1999)	Geology was used for the delineation and is thus not characterized here.
Altitude typology	digital elevation model (Jarvis et al., 2008)	Data with higher resolution/smaller cell widths (e.g. LIDAR data) should be used if available. The classification of the WFD was refined and used to give a general overview.
Catchmen size	DigHAO (HAÖ, 2007)	The classification sheme of the WFD was used.
Soil type	DigHAO (HAÖ, 2007)	
Hydrogeology	DigHAO (HAÖ, 2007)	
Land cover	Corine Land Cover 2000 (www.umweltbundesamt.at)	The spatial distribution of land cover classes is evaluated and the proportion of each land cover class is given.

Table 3.4 Overview of evaluated characteristics and used data sources at the landscape unit scale.

Characteristic	Used data source	Notes
River network and drainage density	DigHAO (HAÖ, 2007)	
Mean annual precipitation	DigHAO (HAÖ, 2007)	The mean annual precipitation for the entire catchment and the spatial distribution based on sub-catchments is evaluated.
Heavey precipitation	DigHAO (HAÖ, 2007)	The spatial distribution of precipitation intensities (2-years reoccurance intervall) is analyzed for the entire catchment
Mean annual actual evapotranspiration	DigHAO (HAÖ, 2007)	Similar to mean annual precipitation, the spatial distribution and the mean over the entire catchment is analysed.
Mean annual runoff	DigHAO (HAÖ, 2007)	The mean annual runoff is based on water balance calculations and is given for the entire catchment.
Relief/ hill slope	digital elevation model (Jarvis et al., 2008) and elevation classes from DigHAO (HAÖ, 2007)	Data with higher resolution/smaller cell widths (e.g. LIDAR data) should be used if available. The aerial coverage and the mean slope for each height class are evaluated.
Soil erodibility class	Soil data base (http://eusoils.jrc.ec.europa.eu)	
Estimated annual soil erosion	Soil data base (http://eusoils.jrc.ec.europa.eu)	
Floodplain and Riparian Vegetation	Potential floodplain vegetation map (Muhar et al., 2004)	
Physical pressures	Impacts on hydrology and on river morphology (Lebensministerium, 2010)	Transverse structures which have impacts on longitudinal sediment continuity are identified. On a sub-catchment level, alterations and continuity interruptions of sediment transport are evaluated.

3.2.4 Segment

For each segment, parameters of the flow regime, valley characteristics and properties of riparian vegetation are evaluated. The data sources that were used are presented in Table 3.5.

Additional physical parameters to those of the landscape unit (impacts on the longitudinal connectivity of sediment and water) were not evaluated here.

Table 3.5 Overview of evaluated characteristics and used data sources at the segment scale

Characteristic	Used data source	Notes
Hydrological parameters	Hydrological regime (Mader et al., 1996); characteristic values (BMLFUW, 2009); eHYD (Lebensministerium, 2013)	For both study sites, several gauging stations are available. For each of them, the hydrological regime and characteristic values are identified.
Season / month of annual floods	DigHAO (HAÖ, 2007)	
Trends of mean annual discharge	DigHAO (HAÖ, 2007)	
Valley gradient	digital elevation model (Jarvis et al., 2008)	Data with higher resolution/smaller cell widths (e.g. LIDAR data) should be used if available.
Valley confinement (mean valley bottom extent, mean bankfull width)	digital elevation model (Jarvis et al., 2008) and GoogleEarth (2013)	Data with higher resolution/smaller cell widths (e.g. LIDAR data) should be used if available.
Outer limits and structure of riparian corridor	Orthophotos in tiris (TirisMaps, 2013), Gis Vorarlberg (VoGIS, 2013) and Gis Steiermark (DigitalerAtlasSteiermark, 2013); Actual riparian vegetation types and lateral extent are taken from Muhar et al. (2004). Additional information concerning vegetation types were derived from Kilian et al. (1993).	Vegetation was characterised based on the following properties: longitudinal and lateral extent, vegetation density and vegetation structure (Figure 3.5). Vegetation types are given based on altitudinal zones and the so called "growing region".

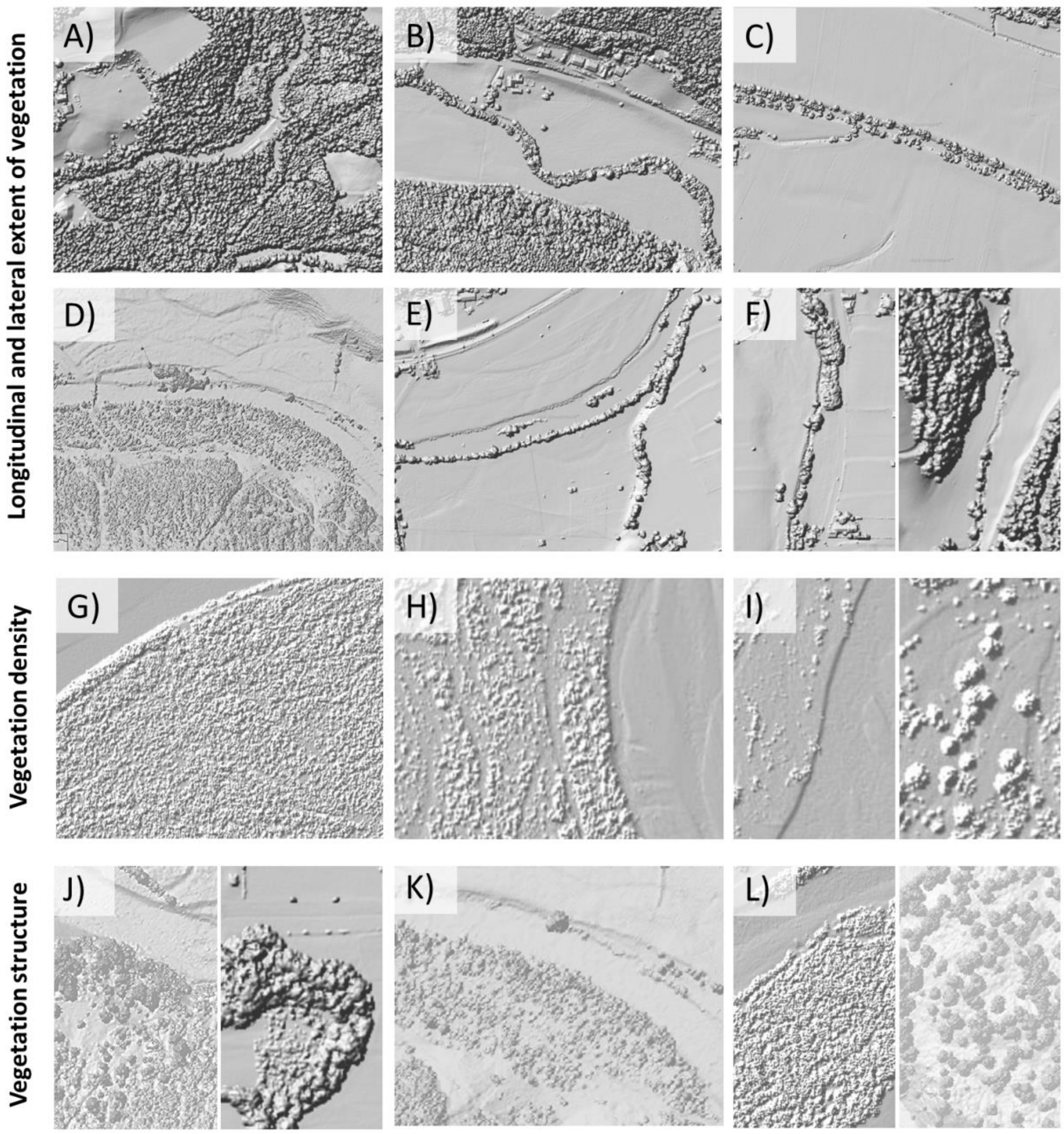

Figure 3.5 Examples for different vegetation characteristics (longitudinal and lateral gradient A-F, density G-I; and structure J-L). A) continuous vegetation on both river sides, large lateral extent; B) continuous vegetataion on both river sides, small lateral extent; C) scattered vegetation on both river sides, small lateral extent; D) continuous vegetataion on one river side, large lateral extent; E) continuous vegetation on one river side, small lateral extent; F) scattered vegetation, small lateral extent;G) dense vegetation; H) medium vegetation density, patchy; I) sparse vegetation; J) heterogeneous vegetation structure, different heigth, age and morphological types; K) different vegetation forms are allocated on a gradient.; L) homogeneous vegetation structure (data source: TirisMaps, 2013; VoGIS, 2013; DigitalerAtlasSteiermark, 2013 and GoogleEarth, 2013).

3.2.5 Reach

Some parameters proposed in the multi-scale framework were not evaluated (e.g. channel gradient, bank sediment calibre, and aquatic and riparian vegetation), due to a lack of detailed data. Other parameters where only derived for certain reaches. The different characteristics are shown in Table 3.6.

Table 3.6 Overview of evaluated characteristics and used data sources at the reach scale.

Characteristic	Used data source	Notes
Bed calibre	Line counts (Auer, 2012)	The data is only available for a small section of the Lech River upstream of Johannesbrücke
Channel width	1D model (HEC-RAS) results – several discharges were modeled	The data is only available for a small section of the Lech River upstream of Johannesbrücke
Flow parameters	1D model (HEC-RAS) results – several discharges were modeled	The data is only available for a small section of the Lech River upstream of Johannesbrücke
River bed and bank condition – physical pressures	Impacts on river morphology (Lebensministerium, 2010)	Here only physical pressures concerning lateral and vertical continuity of sediment, e.g. bank protection, bed reinforcements and so on, are treated. Longitudinal discontinuities were already evaluated at higher spatial scales. The data is available for both study cases.

3.2.6 Geomorphic Units

Geomorphic Units were not evaluated for the Austrian case studies.

4. Results

In the following sections the results of delineation and characterisation are presented for the Lech and Lafnitz catchments.

4.1 Delineation of the Lech river and catchment

4.1.1 Region

The entire catchment of the Lech River is located in the Eastern Alpine biogeographic region (Figure 4.1) and the bio-climate can be classified as temperate oceanic (Figure 4.2).

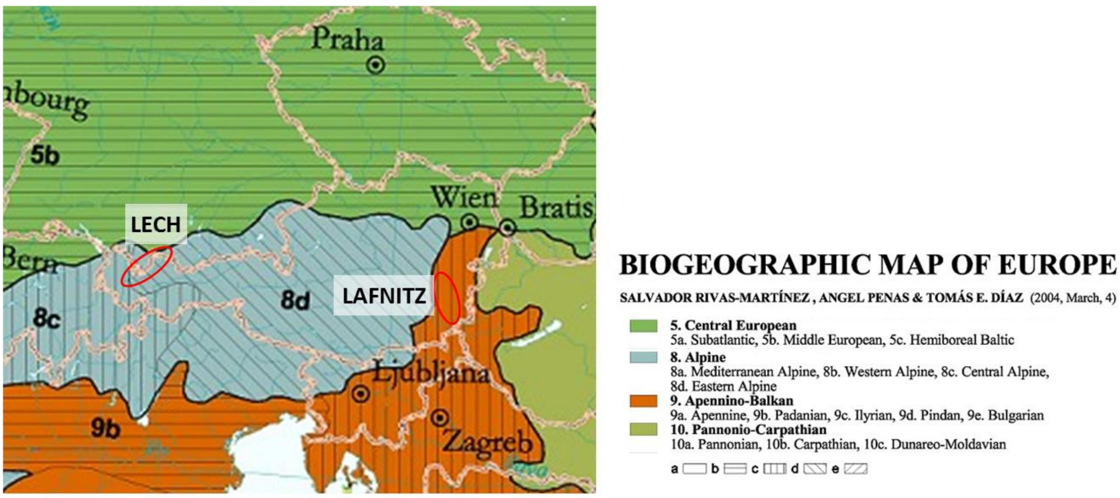

Figure 4.1: Biogeographic regions of Austria (Rivas-Martínez et al., 2004b).

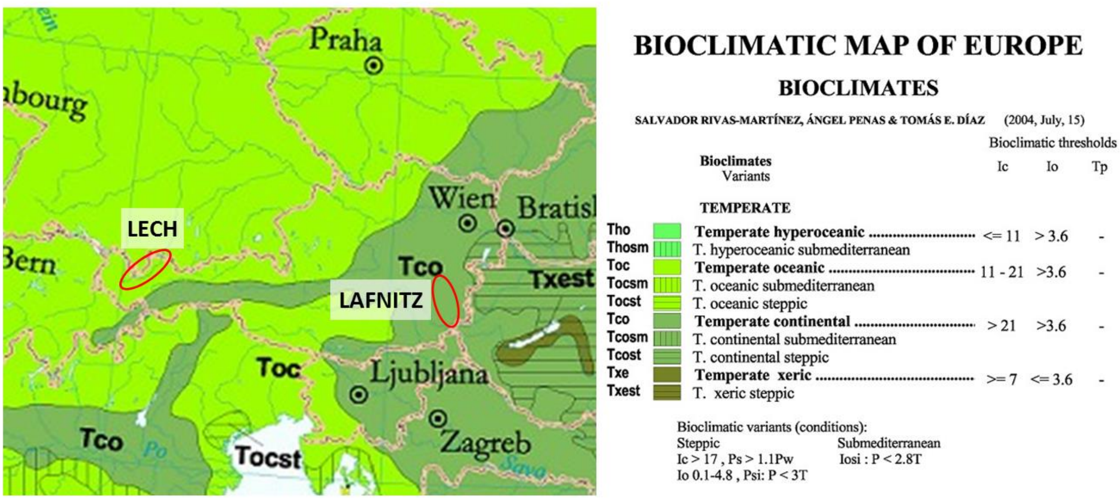

Figure 4.2 Bioclimatic regions of Austria (Rivas-Martínez et al., 2004a).

4.1.2 Catchment

The watershed and topography of the Lech catchment are presented in Figure 4.3.

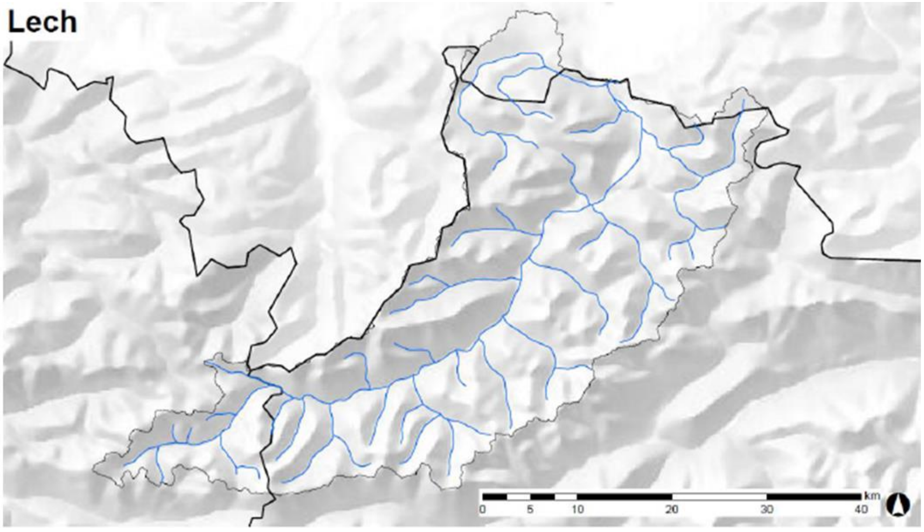

Figure 4.3 Delineation of the Lech catchment (data source: HAÖ, 2007).

4.1.3 Landscape Unit

The bases for delineation of landscape units are geology (Figure 4.4), topography (Figure 4.5) and the elevation classes based on the Water Framework Directive. The entire catchment exhibits similar properties – calcareous geology, mountainous topography and surface elevations above 750 m a.s.l. - and thus only one landscape unit is derived.

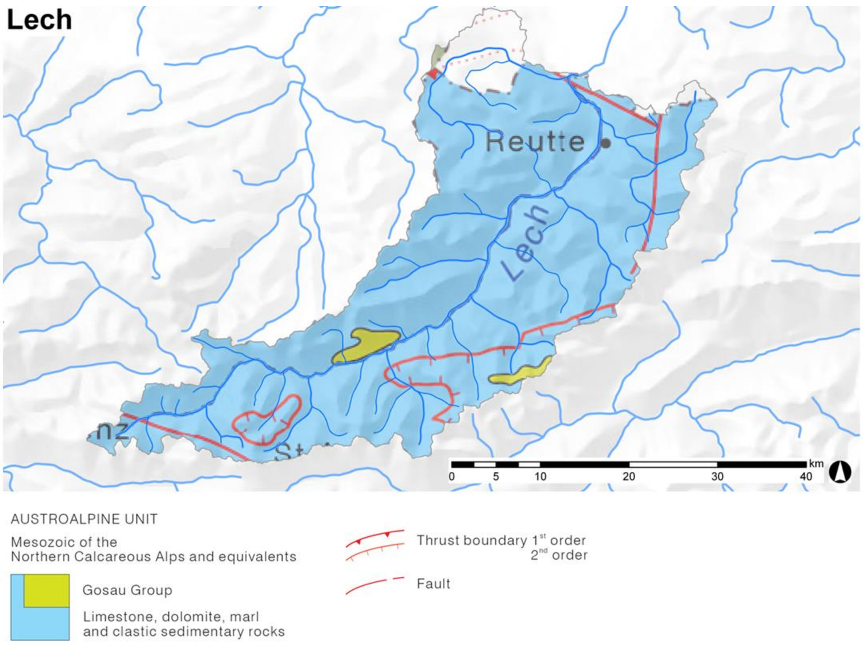

Figure 4.4 Geology of the Lech catchment (data source: Egger et al., 1999 and HAÖ, 2007).

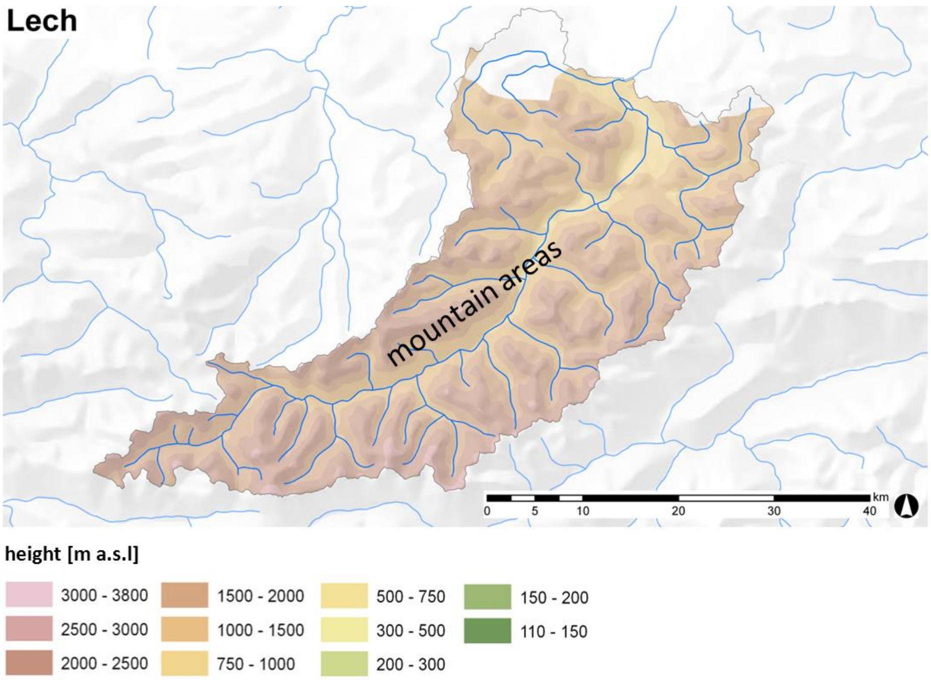

Figure 4.5 Topography of the Lech catchment (data source: HAÖ, 2007).

4.1.4 Segment

Segments are delineated based on discontinuities of valley gradient, changes in confinement and by major tributary confluences.

At the Lech River four discontinuities in valley gradient were observed (Figure 4.6):

- ⇨ at Johannestal (transition from a steeper to a medium slope)
- ⇨ Krumbach (a rapid change from a medium to a steep slope)
- ⇨ downstream of Krabach (again a rapid change from a steep to a more gentle slope) and
- ⇨ at Rothlech/Weißenbach (slight change to a smaller slope).

The locations of the discontinuities are shown in Figure 4.7. Additional to those discontinuities, the following major tributaries were identified (Figure 4.8):

- the Zürsbach at Lech
- the Kaiserbach at Steeg
- the Alperschonbach at Bach
- the Rothlech at Weißenbach
- the Archbach at Pflach and
- the Vilsfluss downstream of Vils.

Confinement was also evaluated and used for the delineation of segments. In Figure 4.9 the valley width and the contact of the river with the hill slopes are illustrated for several locations along the river. The stretches with similar confinement are shown in Figure 4.10.

Based on these three parameters the Lech River was divided into twelve segments (Figure 4.11). The characteristics of each segment that were used as delineation criteria are given in Table 4.1.

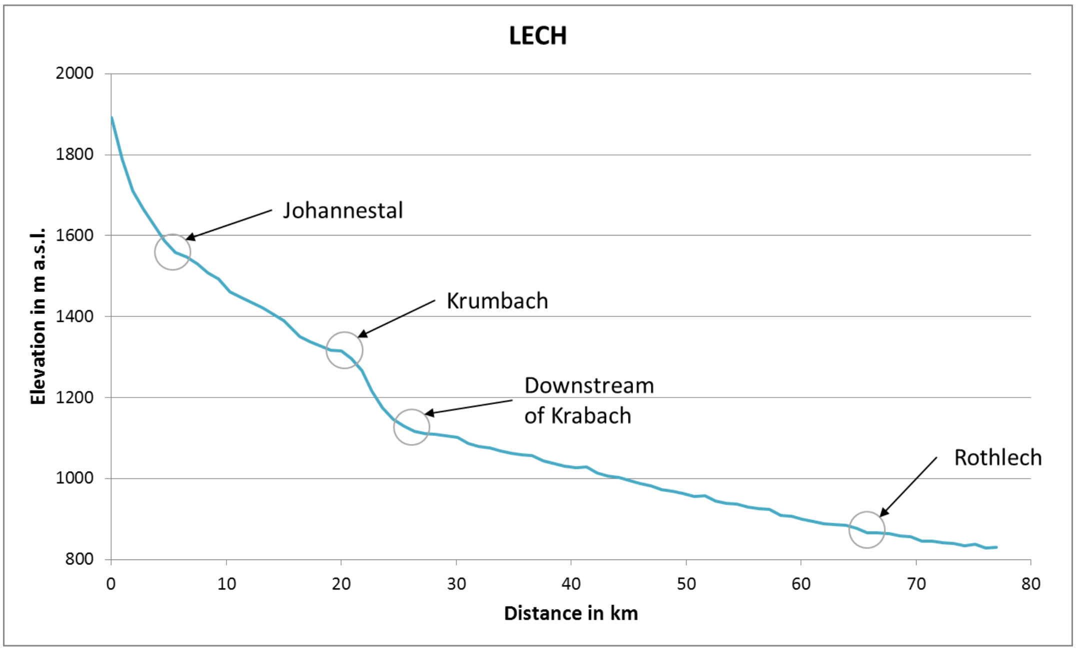

Figure 4.6 Longitudinal profile of the Lech vally with discontinuities in valley gradient.

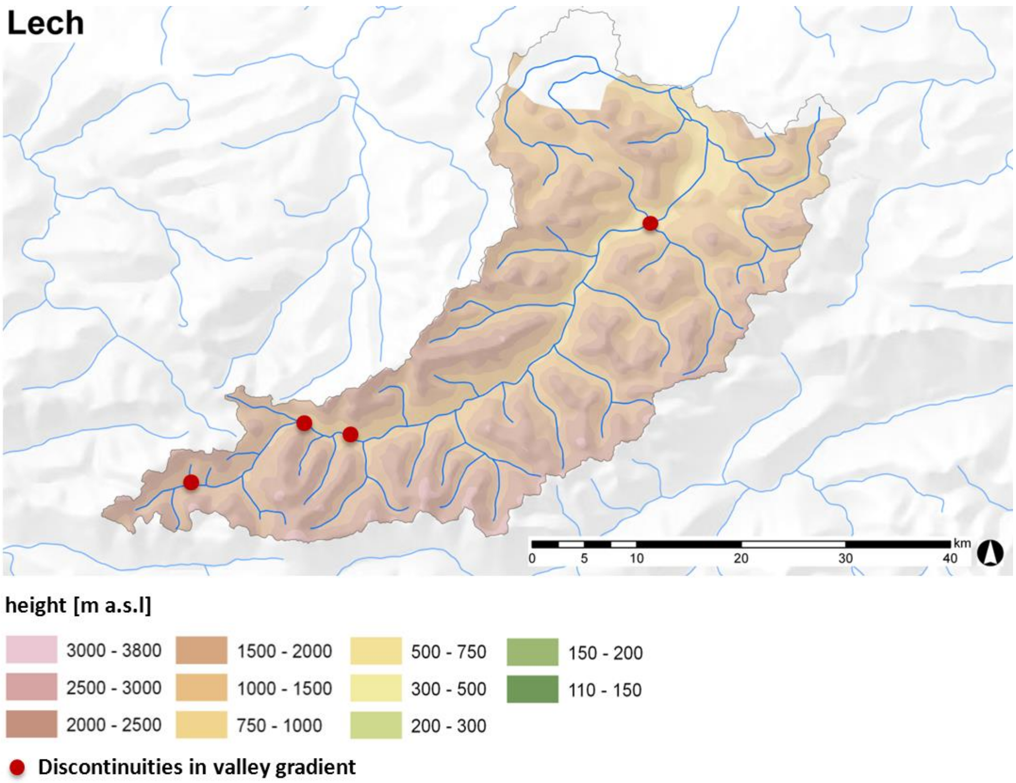

Figure 4.7 Plan view which shows the locations of discontinuities in valley gradient (data source: HAÖ, 2007).

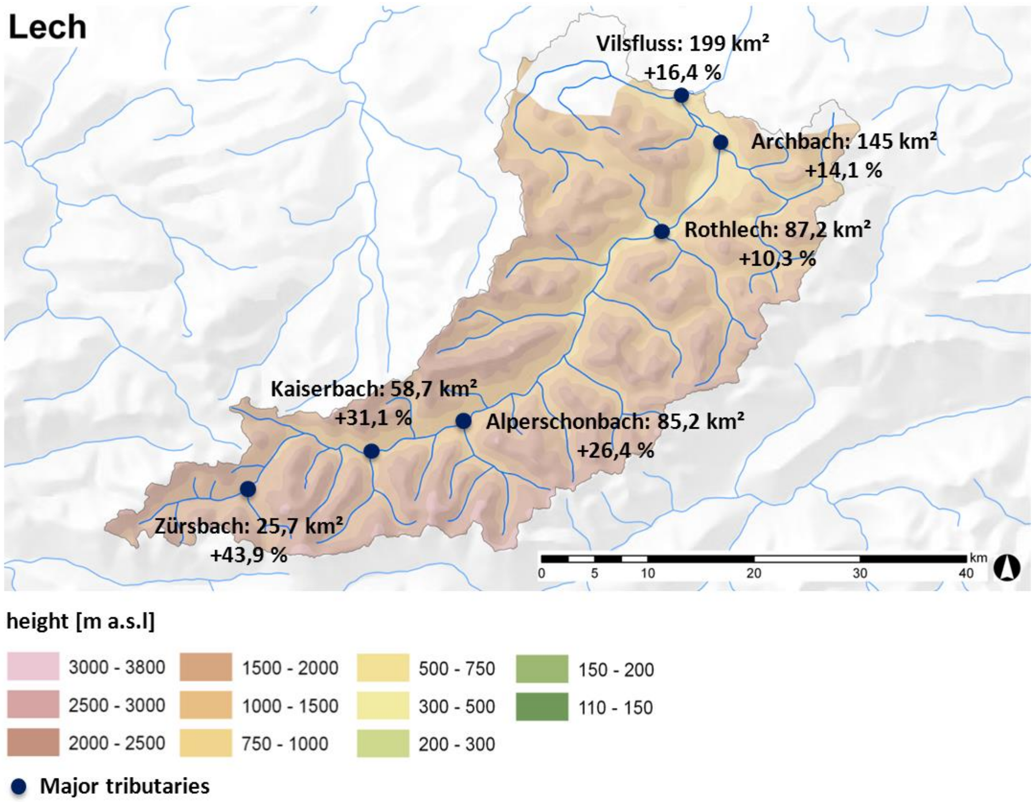

Figure 4.8 Overview of major tributaries to the Lech river. The values indicate the absolute [km²] and relative [%] increase in catchment area (data source: HAÖ, 2007).

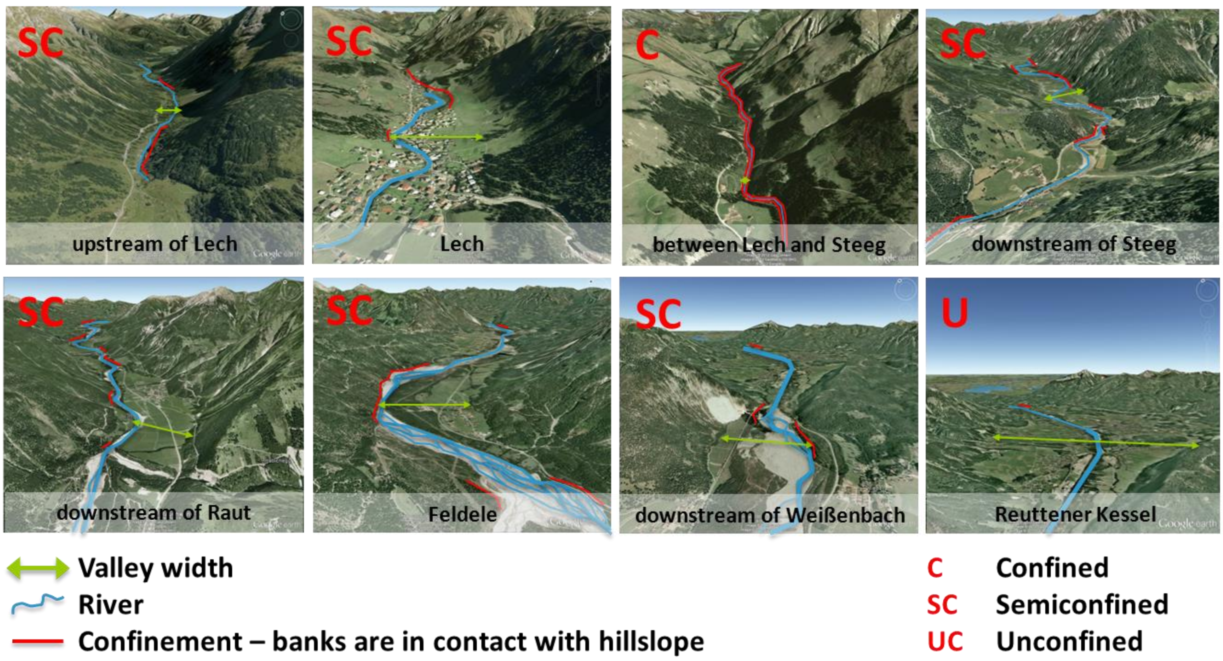

Figure 4.9 Illustration of the confinement at several locations along the Lech River. Views are in flow direction (data source: GoogleEarth, 2013).

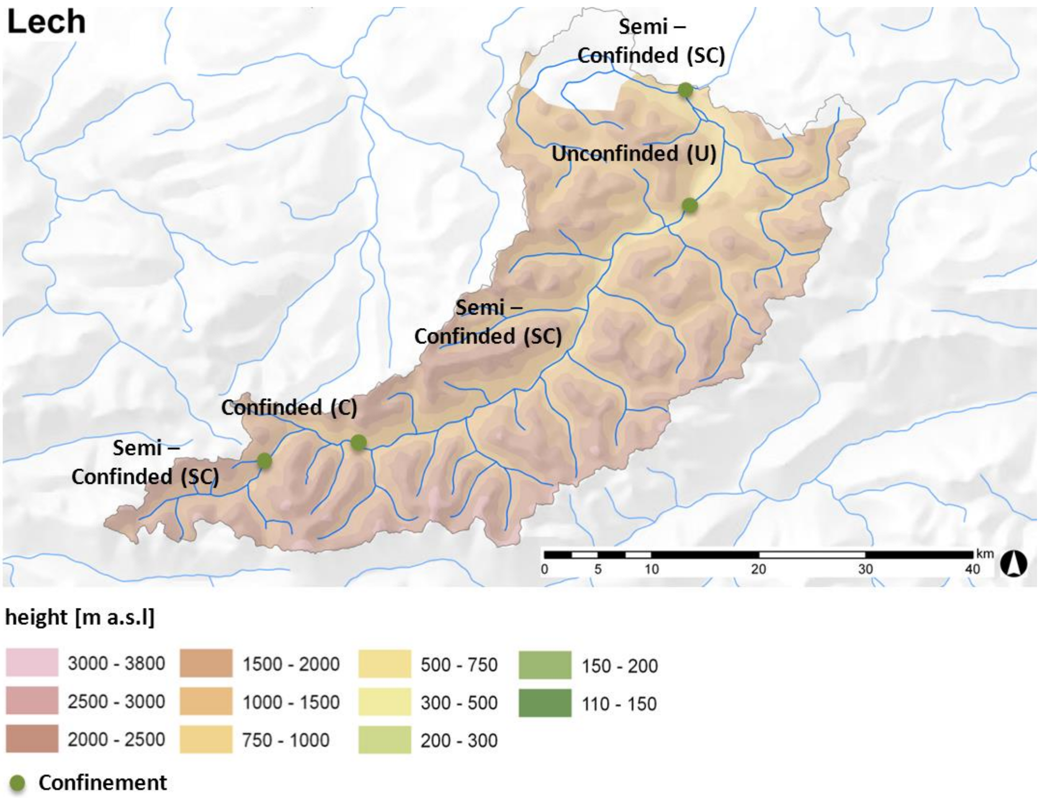

Figure 4.10 Plan view of changes in valley confinement at the Lech River (data source: HAÖ, 2007).

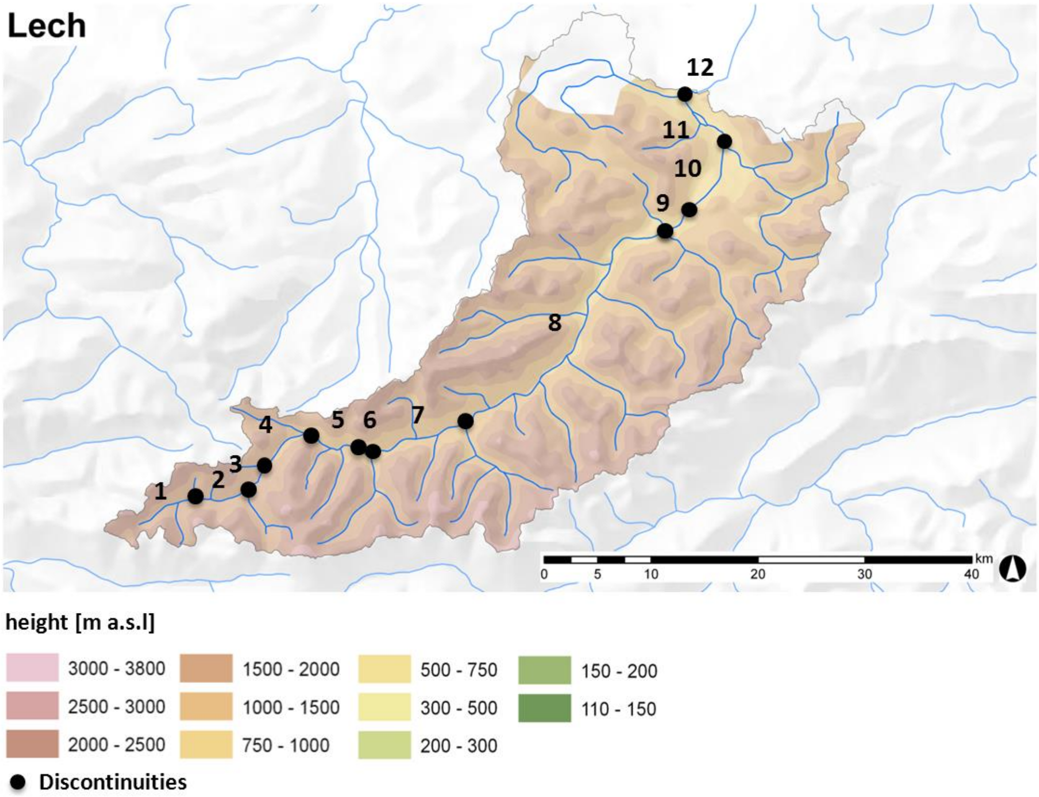

Figure 4.11 Overview of all discontinuities and thus resulting segments of the Lech River (data source: HAÖ, 2007).

Table 4.1 Overview of discontinuities in valley slope, confinement and hydrology (major tributaries)

Segment	Valley Slope [%]	Major Tributary at the beginning of the Segment	Confinement
1	>5		Semi-confined
2	1-3		
3		Zürsbach	
4			Confined
5	3-5		
6	0,5-1		Semi-confined
7		Kaiserbach	
8		Alperschonbach	
9	0-0,5	Weißenbach	
10			
11		Archbach	Unconfined
12		Vilsfluss	Semi-confined

4.1.5 Reach

The delineation of reaches is based on the channel and floodplain morphology, and artificial discontinuities that affect the longitudinal continuity of water and sediment.

In total 19 reaches were identified for the Lech River. Their location and planform type are illustrated in Figure 4.12. Reach numbers are given in Figure 4.13 and some additional information is provided in Table 4.2.

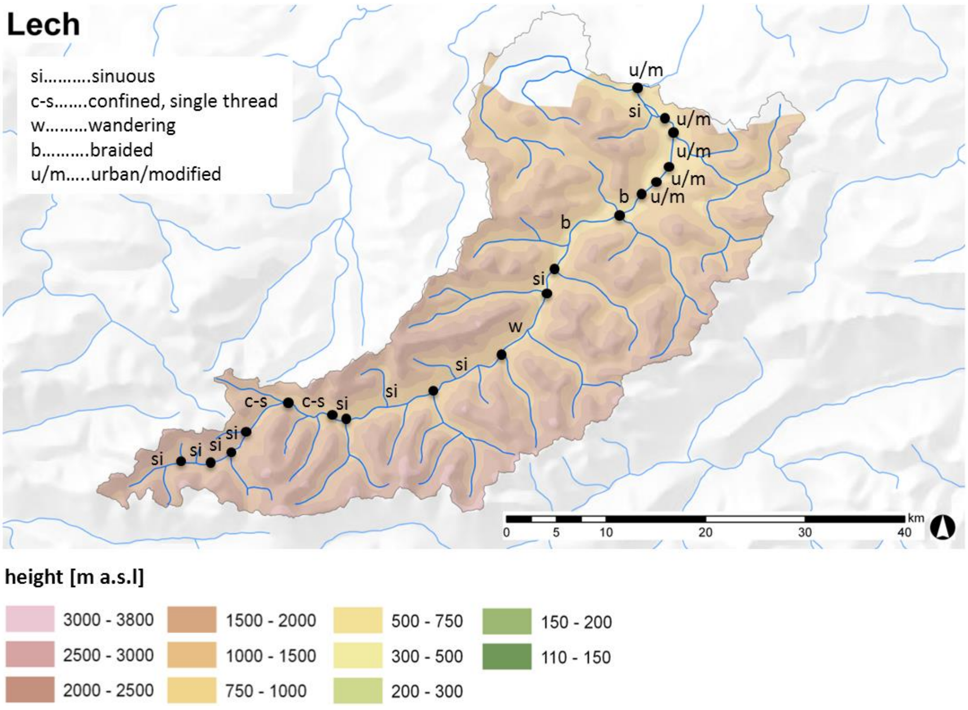

Figure 4.12 Location of reaches and indication of their planform morphology (data source: HAÖ, 2007).

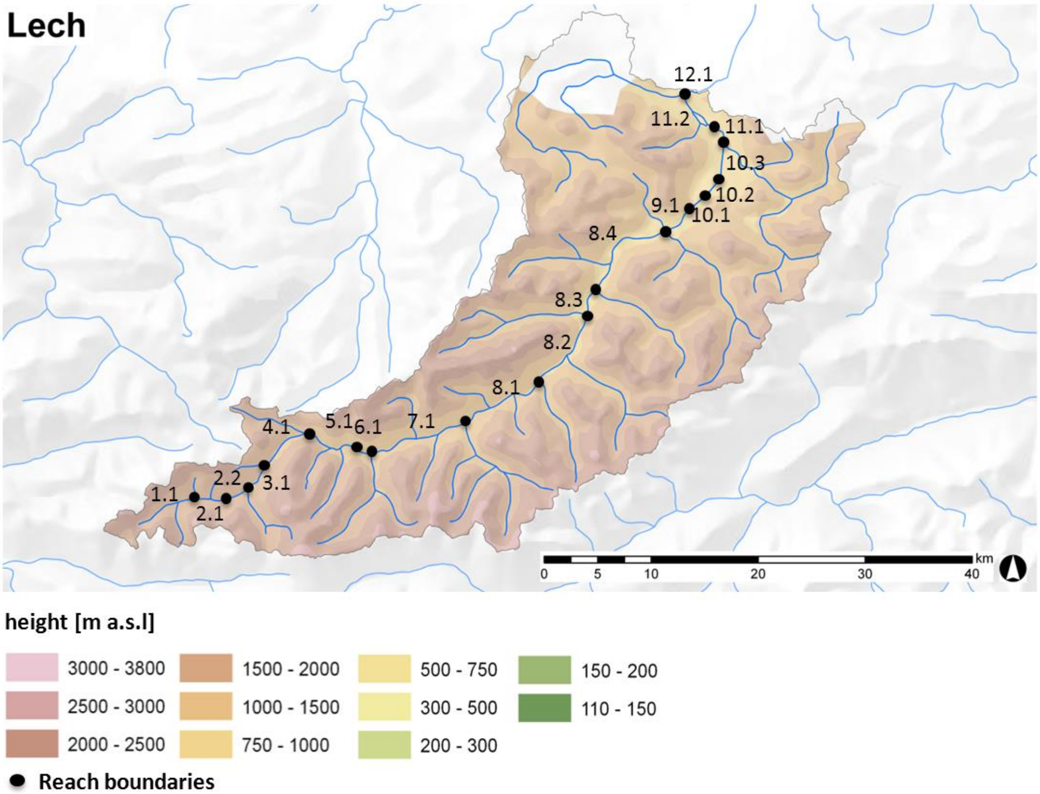

Figure 4.13 Assignation of reach numbers which are based on the segment numbers (data source: HAÖ, 2007).

Table 4.2 Overview of some reach properties.

Segment	Confinement	Reach	Reach length [km]	Planform morphology	Artificial discontinuities
1	Semi-confined	1.1	5,6	Sinuous	-
2	Semi-confined	2.1	2,4	Sinuous	
		2.2	3,2	Sinuous	Upstream dam
3	Semi-confined	3.1	2,7	Sinuous	Upstream dam
4	Confined	4.1	5,1	Single thread	-
5	Confined	5.1	5,5	Single thread	-
6	Semi-confined	6.1	1,6	Sinuous	-
7	Semi-confined	7.1	9,6	Sinuous	-
8	Semi-confined	8.1	8,5	Sinuous	-
		8.2	7,9	Wandering	-
		8.3	2,6	Sinuous	-
		8.4	9,8	Braiding	-
9	Semi-confined	9.1	3,4	Braiding	-
10	Semi-confined	10.1	1,7	Urban/modified	Upstream dam
		10.2	1,8	Urban/modified	-
		10.3	3,2	Urban/modified	-
11	Unconfined	11.1	1,8	Urban/modified	-
		11.2	5,0	Sinuous	Upstream dam
12	Semi-confined	12.1	1,0	Urban/modified	-

4.2 Characterisation of the Lech river and catchment

4.2.1 Region

The investigated section of the Lech River is located in the Eastern Alpine biogeographic region and it has a temperate oceanic climate. The Alps are characterized by a backbone of crystalline formations and external fringes of limestone - where the catchment is located - and schist formation (EEA, 2002). In this alpine region, sufficient rainfall is available to support the establishment of forests. The rainfall exhibits a highly variable spatial and annual distribution, and the mountain peaks may protect valleys from high levels of rain. Due to their geomorphology and the varying exposure to wind, sun, rain and other variables, the Alps represent a complex set of microclimates (EEA, 2002). The low temperatures cause a slow degradation of litter-fall and thus humus accumulation. The development of stratified soil characteristics is also low due to continuous erosion.

4.2.2 Catchment

The catchment area is 1415 km² large and more than 65% of the catchment area is located at altitudes higher than 1400 m a.s.l. The entire catchment can be classified as high altitude areas (>800 m a.s.l.) corresponding to the Water Framework Directive classification (Figure 4.14).

The catchment has an elongated shape and several tributaries enter the Lech River from the left and right sides. The upstream part of the river can be characterized as a torrent.

The main soil types present in the catchment area are Rendzinas, Fluvisols and Lithosols (Figure 4.15). Rendzina is a shallow soil with calcareous bed material and an A-horizon with high amounts of humus. Lithosols are present in the higher regions of the catchment and are weakly developed soils. Fluviosols are the result of fluvial deposition and exist along the Lech River mainly downstream of Grießau. All soil types are developed on calcareous bed material (calcaric). Figure 4.16 presents the main aquifer materials of the Lech catchment. As the catchment is located in the Northern Calcareous Alps, calcareous rock and dolomite are prevalent, but marl and sandstone are also common as aquifers. Similar to the Fluvisol soil type, tertiary sediments like gravel and sand can be found in the valley bottom. However, they extend further upstream than the Fluvisol.

The land cover of the Lech catchment is dominated by coniferous forest (25,5 %) and natural grassland (23,4 %); 15,5 % of the catchment is occupied by moors and heathland, about 13 % is sparsely vegetated and around 9 % is bare rock (Figures 4.17 and 4.18). About 2% of the entire catchment is under an urban land cover.

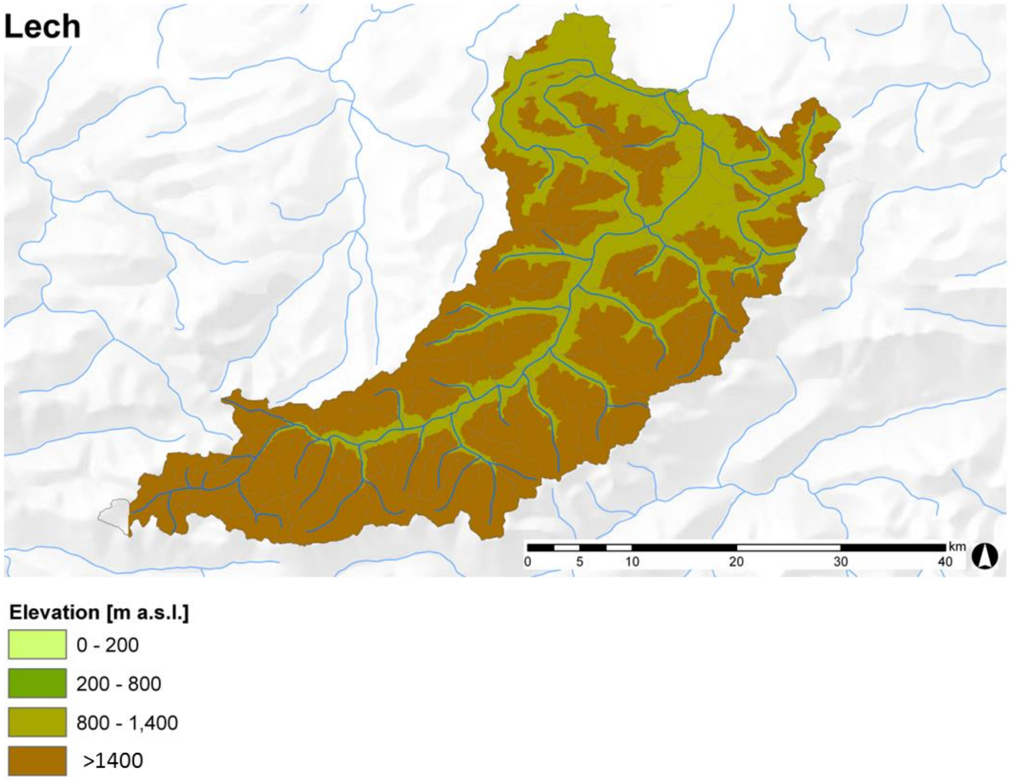

Figure 4.14 Altitudinal zones of the Lech catchment (data source: HAÖ, 2007 and Jarvis et al., 2008).

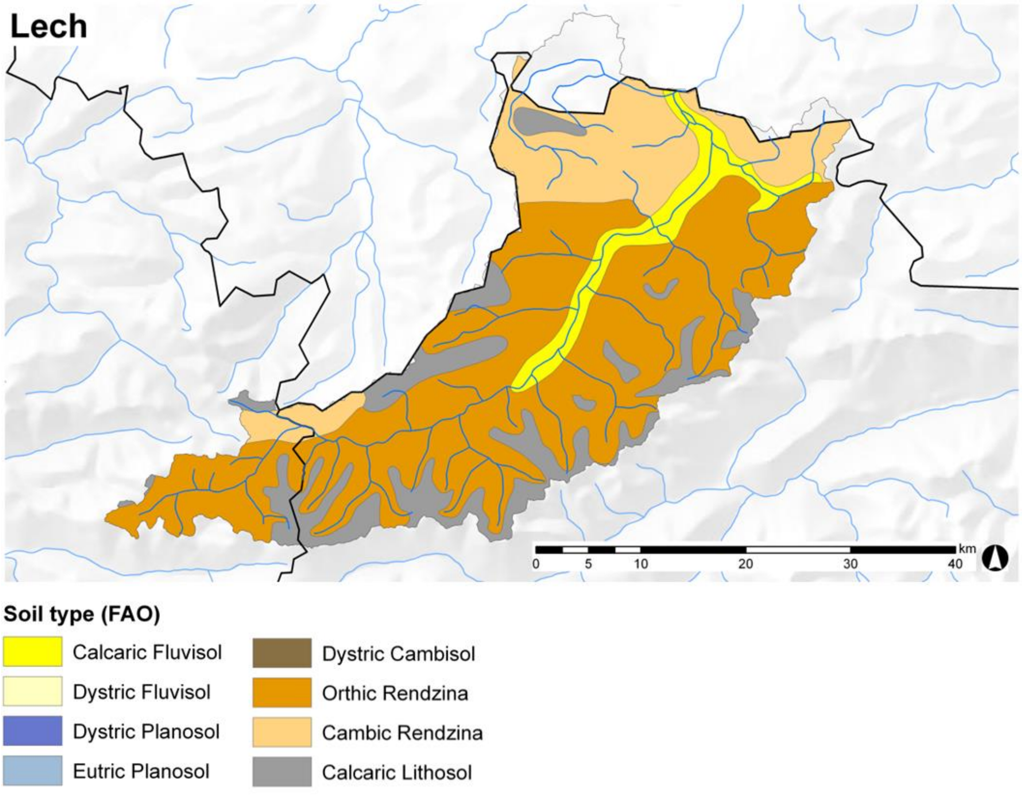

Figure 4.15 FAO soil types of the Lech catchment (data source: HAÖ, 2007).

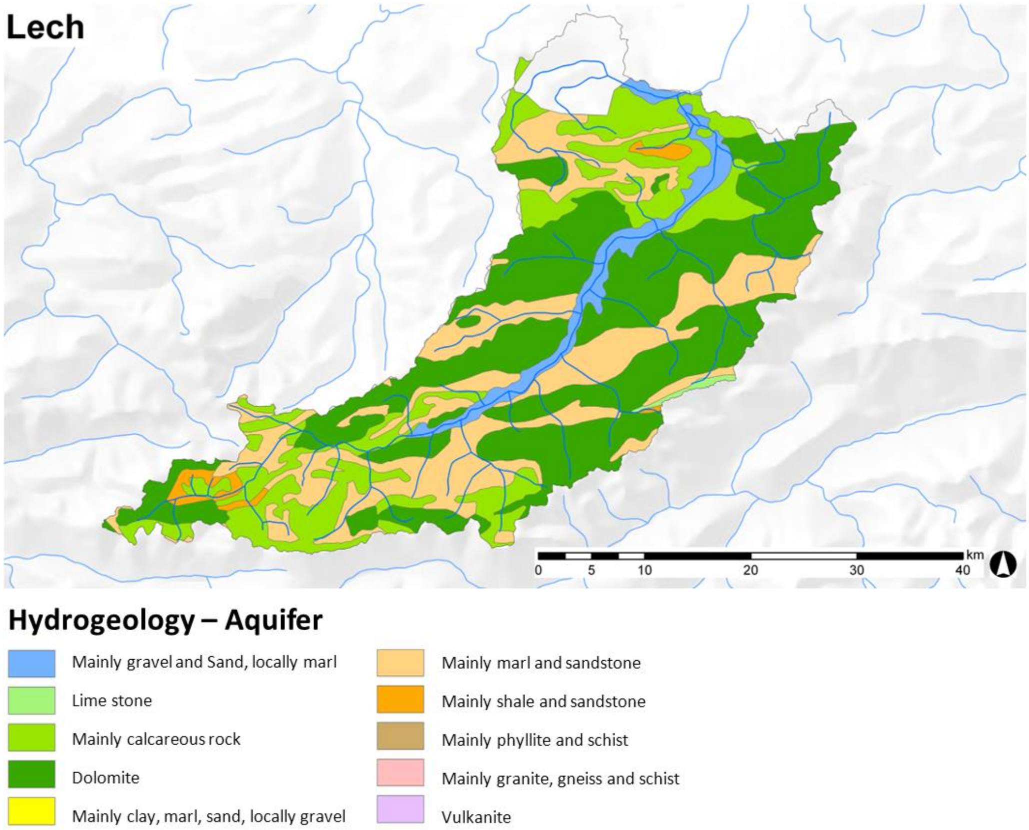

Figure 4.16 Hydrogeological classification of the Lech catchment (data source: HAÖ, 2007).

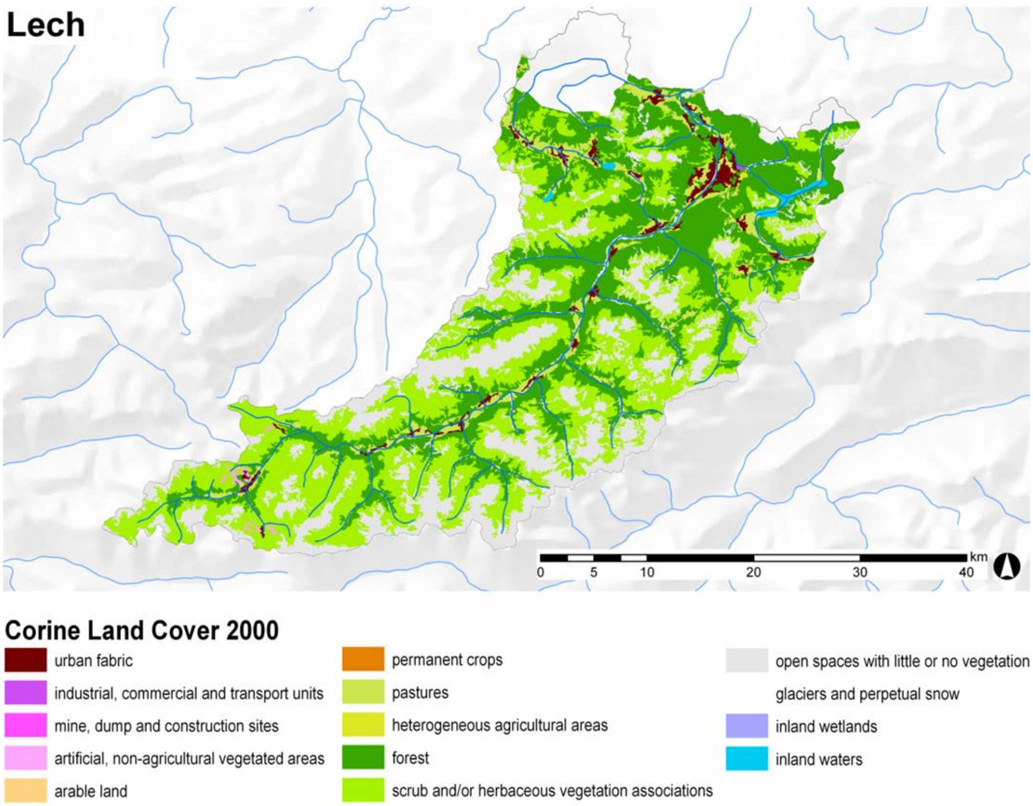

Figure 4.17 Land cover based on Corine Land Cover 2000 - Level 2 classification (data source: HAÖ, 2007 and Umweltbundesamt, 2006).

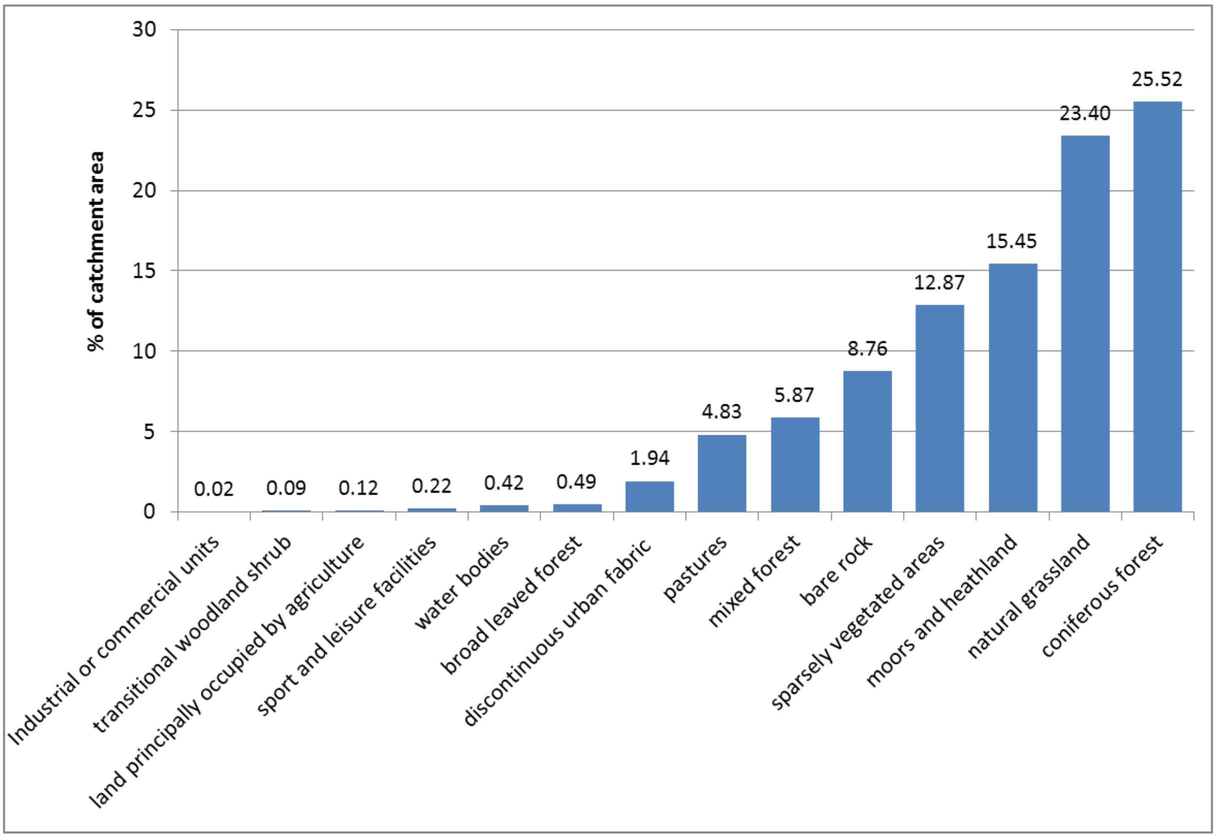

Figure 4.18 Land cover distribution in percent for the Lech catchment - Level 3 classification (data source: HAÖ, 2007 and Umweltbundesamt, 2006).

4.2.3 Landscape Unit

Landscape units are characterised by properties which describe water and sediment delivery potential, by vegetation characteristics and by a broad assessment of physical pressures on the sediment regime.

The Lech River has a dendritic drainage pattern (develops in areas with homogeneous terrain, with no distinctive geological control (Brierley and Fryirs, 2005)). The resulting drainage density and its variability are shown in Figure 4.19.

The mean annual precipitation of the Lech catchment is 1756 mm, ranging from 1305 mm close to the German border, to 1997 mm in the western (upstream) part of the catchment (Figure 4.20). The gradient of decreasing mean annual precipitation, from the south-west to the north east, is not represented in the distribution of heavy precipitation intensities (at a 2-year return period). The intensities decrease from the north-east to the south-west, and with increasing altitude (4.21).

The mean annual actual evapotranspiration is about 400 mm for the catchment. The mean annual precipitation and transpiration result in a mean annual runoff of 1350 mm. The precipitation, evapotranspiration and runoff data were derived from the HAÖ (2007).

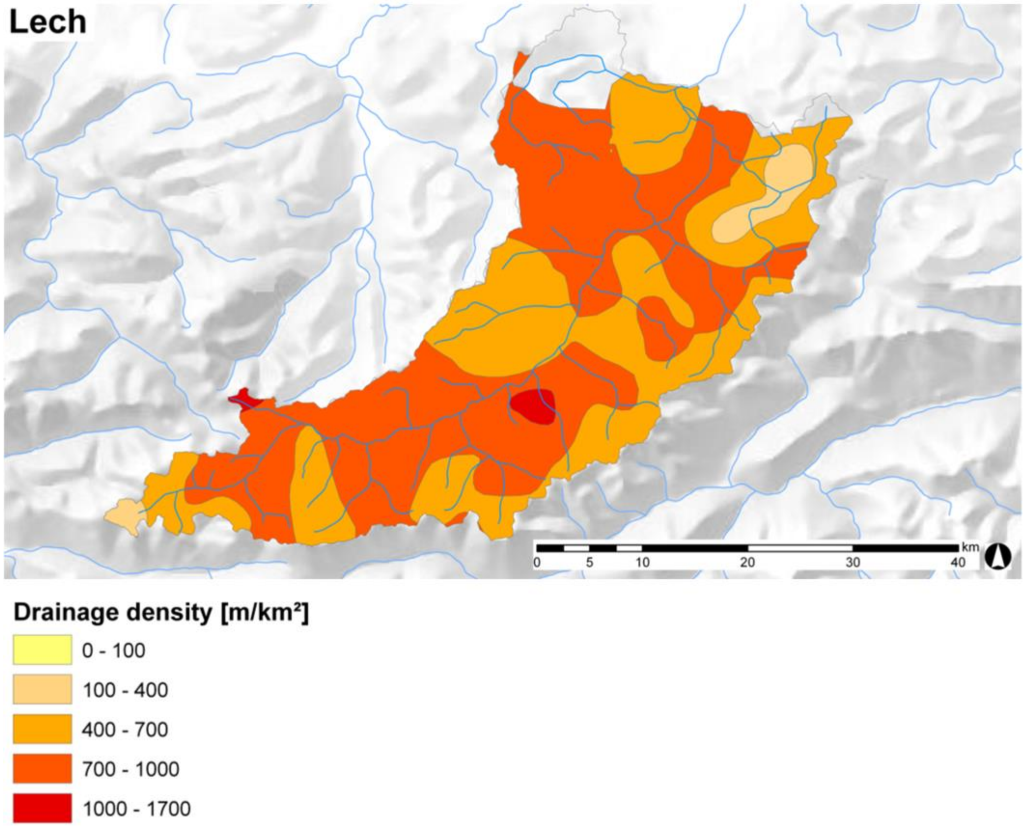

Figure 4.19 Variability of the drainage density at the Lech catchment (data source: HAÖ, 2007).

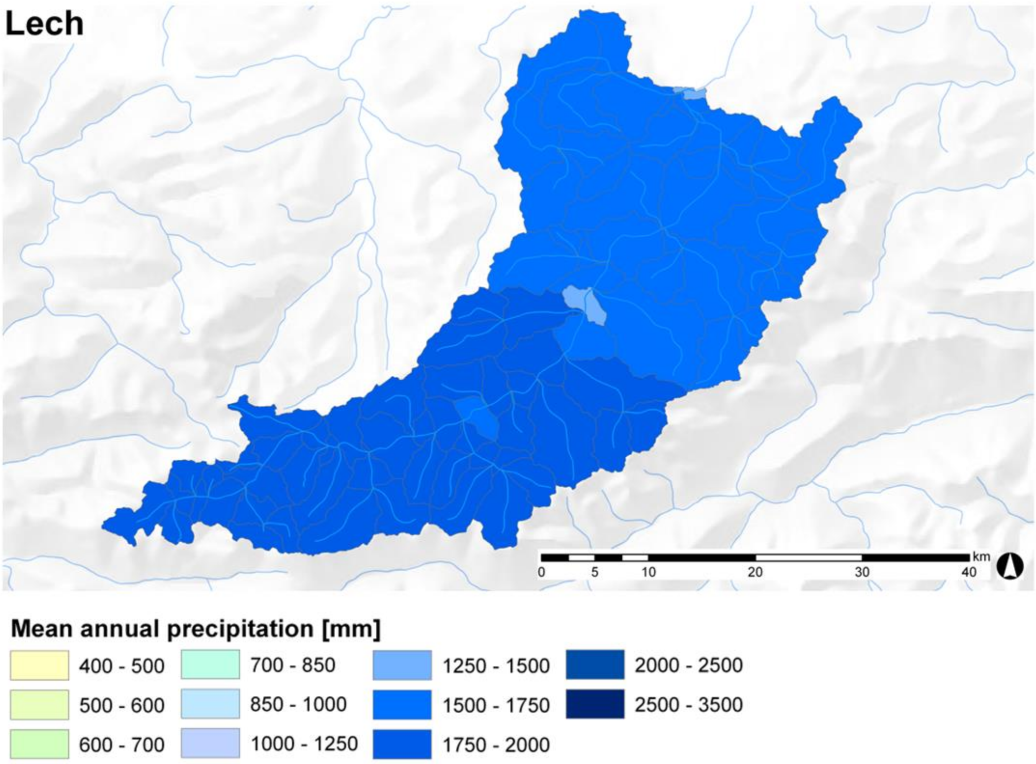

Figure 4.20 Mean annual precipitation for each subcatchment of the Lech catchment (data source: HAÖ, 2007).

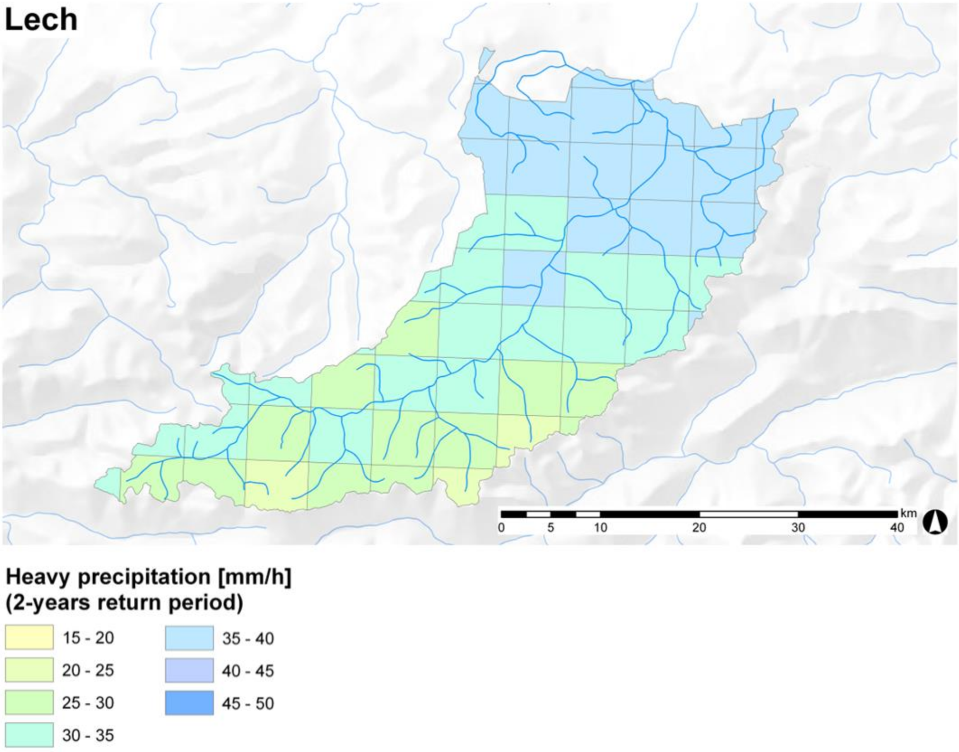

Figure 4.21 Distribution of heavy precipitation intensity with a reoccurance intervall of 2 years (data source: HAÖ, 2007).

As stated before, the topography of the Lech catchment is mountainous. The slopes of the hills increase with increasing elevation and the highest percentage of the catchment area, 38,6%, lies within the altitudinal zone 1500 to 2000 m a.s.l. (Figure 4.22). In Figure 4.23, the spatial distribution of the hillslope gradients is presented. The valley bottom, with smaller gradients, is clearly visible. Nevertheless, these slopes are based on a digital elevation model with a raster width of 80 m, which may affect the accuracy of this assessment.

The combination of land cover, precipitation, relief, and soil/rock material determines amongst others the availability of fine and coarse material. The soil erodibility for the catchment is presented in (Figure 4.24). The highest erodibility is along the valley bottom and in unvegetated areas (cf. Figure 4.23).

In Figure 4.25, the mean annual soil erosion is presented. It has been calculated by the PESERA model which is a physically based and spatial distributed model, and integrates topography, climate an soil properties to forecast run-off and soil erosion (Kirkby et al., 2004). Large parts of the catchment are classified as "no erosion", along the valley bottom small erosion rates, 0 to 0,05 t ha^{-1} yr^{-1} respectively, are present and higher erosion rates occur in a scattered pattern over the entire catchment.

However, it has to be kept in mind that the spatial resolution is quite coarse, the model has some limitations (see Kirkby et al., 2004), and the results of the model should be used with caution. Further, the availability of sediment based on mass movements is not considered in the erosion maps, which is an important source of coarse and also fine sediments within an alpine catchment.

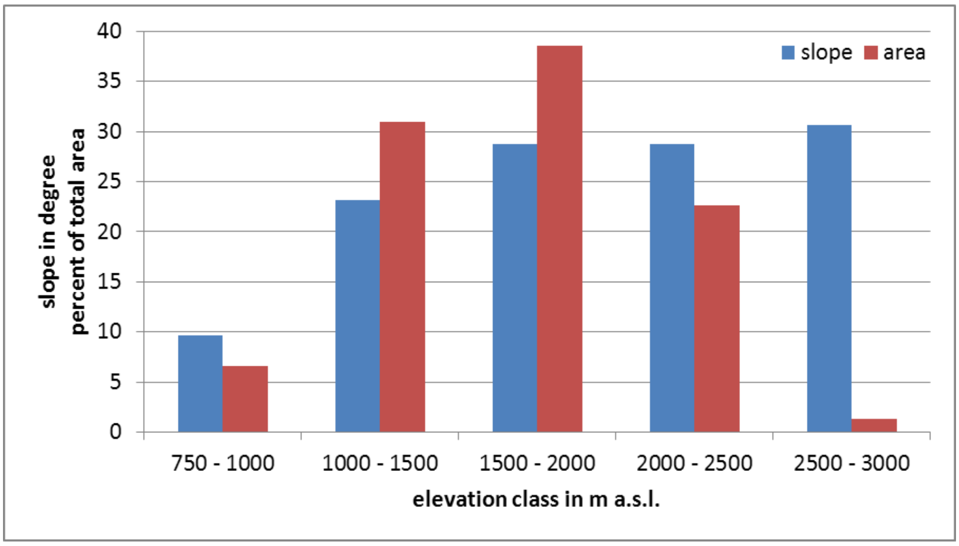

Figure 4.22 Mean slopes of the elevation classes and percentage of altitudianal class on total catchment area (data source: HAÖ, 2007 and Jarvis et al., 2008).

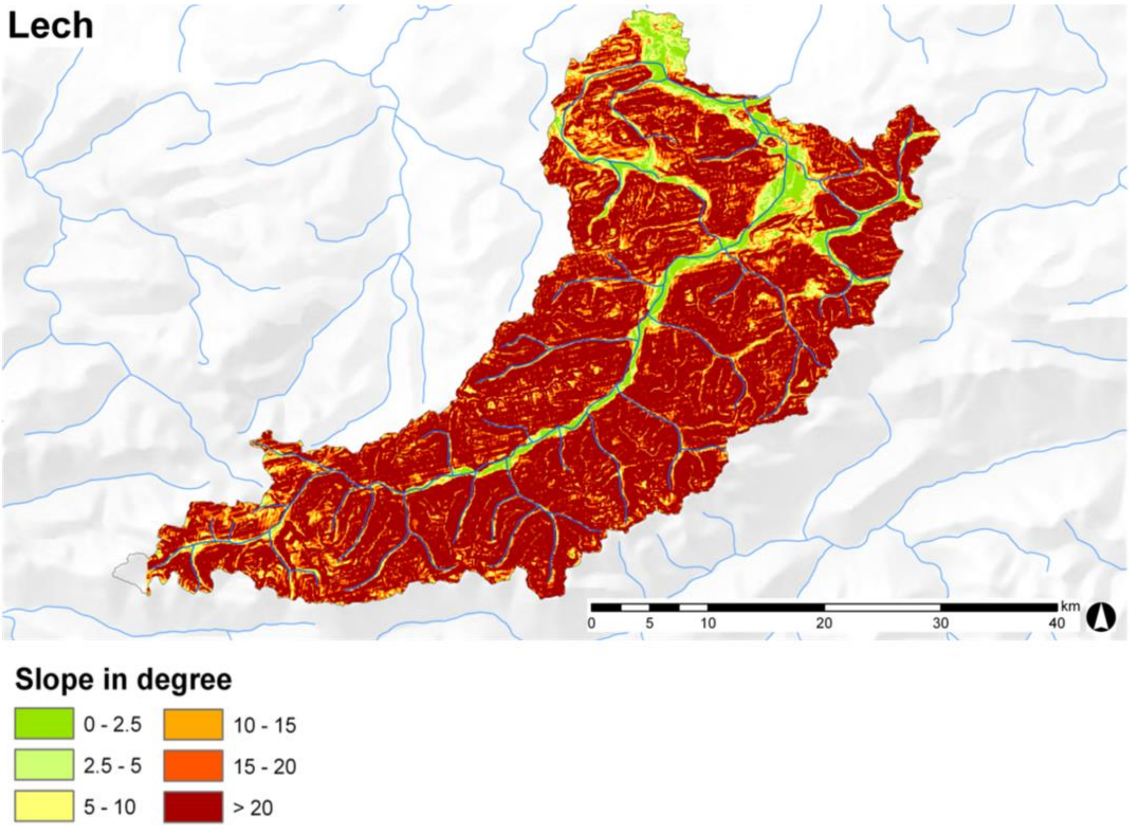

Figure 4.23 Illustration of hillslope angle of the Lech catchment (data source: HAÖ, 2007 and Jarvis et al., 2008).

The types and the widths of potential riparian vegetation along the Lech River are presented in Figure 4.26. In the upstream part of the river (upstream of the Prenten), the width of the potential natural vegetation is up to 100 m, in the downstream section widths of up to 500 m are reached. The dominant riparian vegetation complexes are pioneer shrubs (willows and green alder) in the upstream part, grey alder and willows in the section from Prenten to Vorderhornbach and downstream of Höfen, and Scots pine and willows in the braiding section between Vorderhornbach and Höfen. The actual vegetation is characterized in detail at the segment scale.

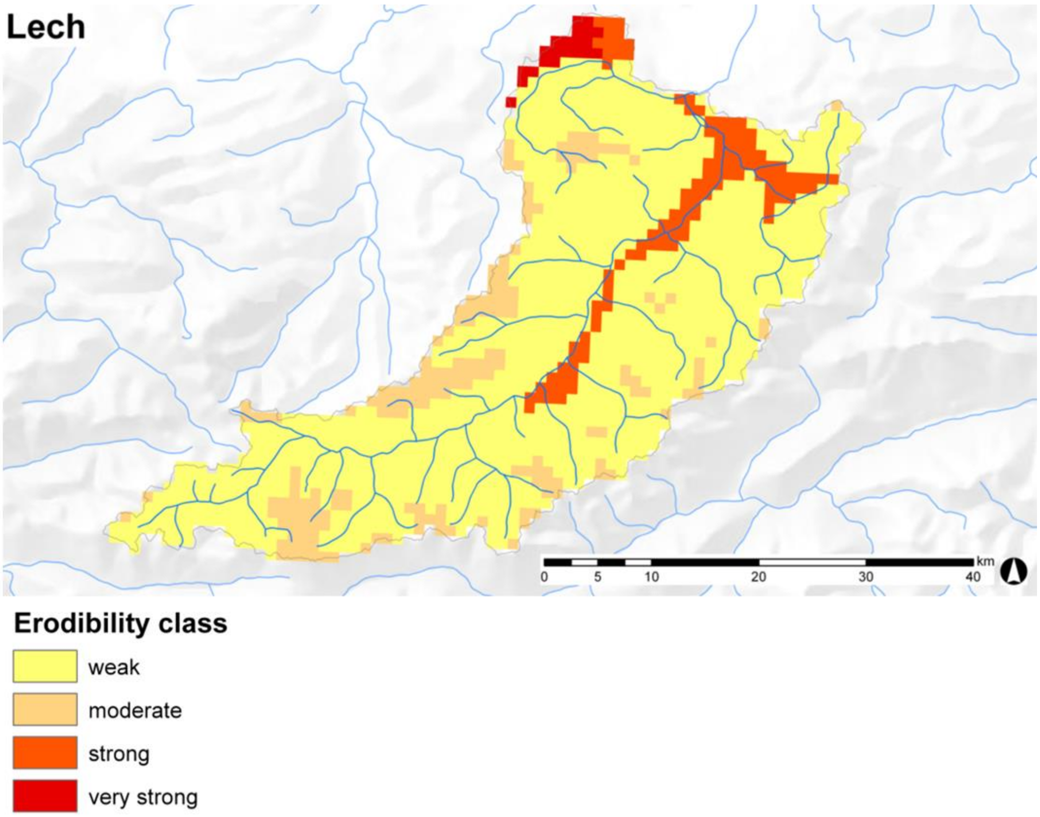

Figure 4.24 Variation of soil erodibility within the catchment area of the Lech River (data source: HAÖ, 2007 and Kirkby et al., 2004)

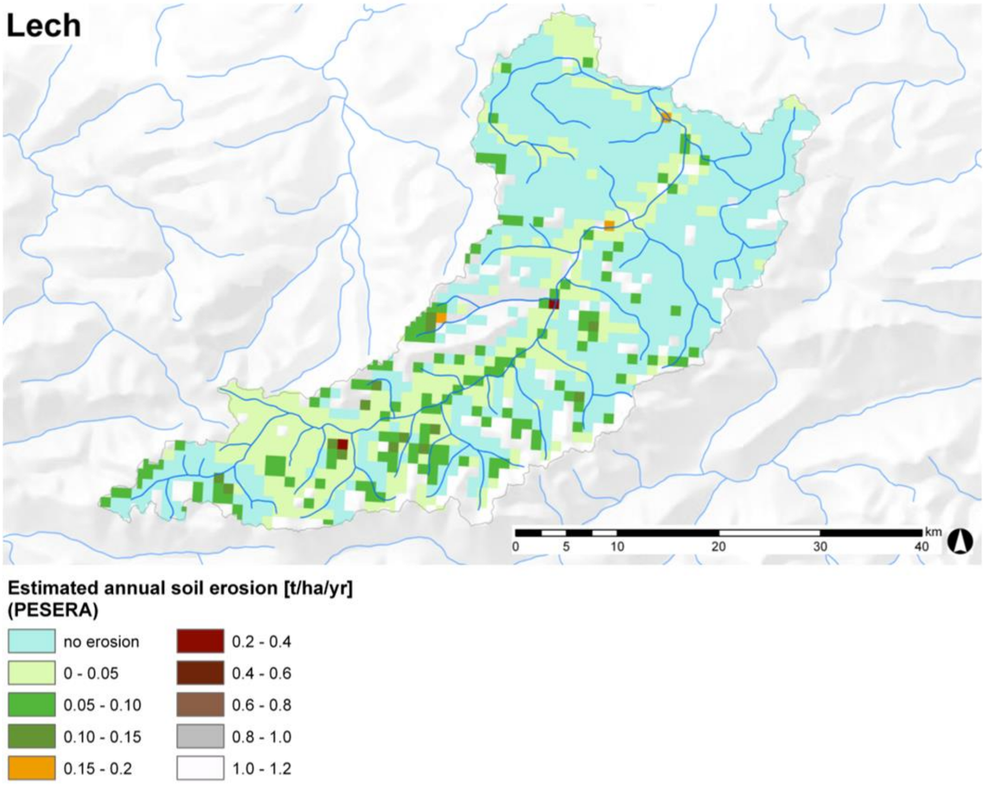

Figure 4.25 Estimated annual soil erosion based on PESERA (data source: HAÖ, 2007 and Kirkby et al., 2004).

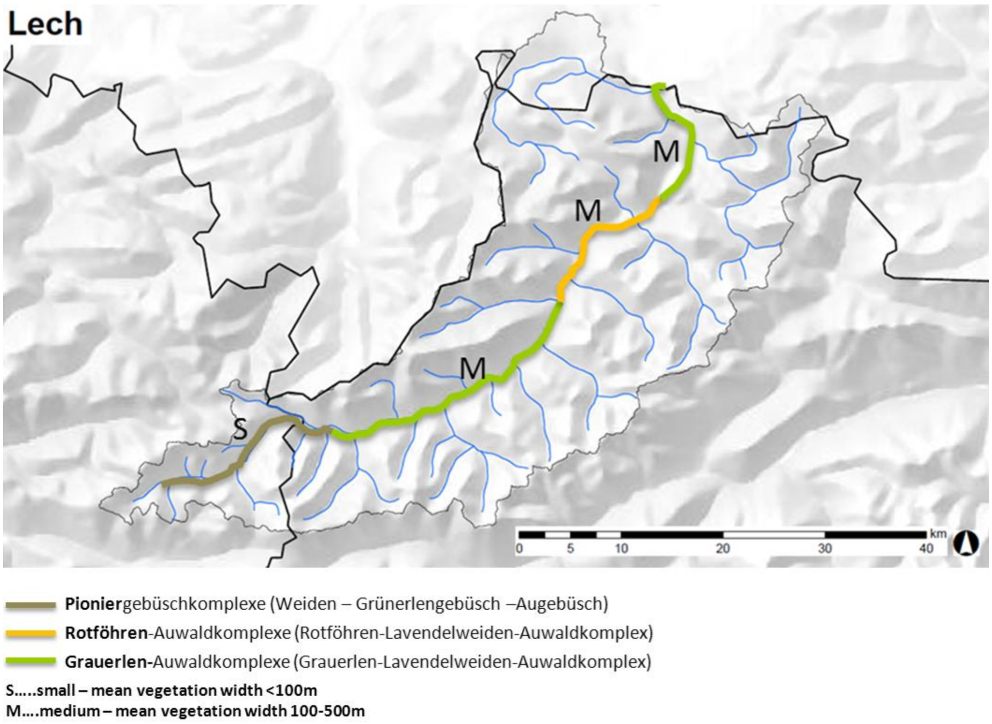

Figure 4.26 Distribution of potential riparian vegetation types and widths along the Lech River (Muhar et al., 2004).

Physical pressures like hydropower plants, torrent controls and other retention structures are roughly identified in the landscape unit scale as not all delineated elements of smaller scales might be investigated and thus impacts on water and sediment transport might not be identified.

The physical pressures within the Lech catchment are indicated in Figure 4.27 and 4.28. It can be seen, that the first transverse structure on the Lech River is located upstream of the village of Lech, and the second one is within the village. Therefore, it can be assumed that the sediment contribution of the upstream catchment area is, at least temporally, altered. The next structure influencing the longitudinal water and sediment continuum of the Lech is located in Reutte, and this is followed by several other structures.

Many structures are located within the tributaries, but most of them are only likely to slightly influence the sediment and water continuum (e.g. sills, ramps, cascades,…). If we suppose that the "undefined structures" are not retention structures, which we do not know (a map with the locations of torrent controls was not available), we could assume that the sediment and water continuum shows a small alteration downstream of Lech, which might be negligible downstream of some larger tributaries (e.g. Krumbach, Krabach, Kaiserbach). Between Steeg and Reutte the continuum and the sediment transport from the tributaries to the Lech River is not influenced.

However, in Figure 4.28 several residual water stretches are indicated and thus at least temporal alterations in sediment and water transport are present. Figure 4.29 illustrates continuity interruptions and other alterations at the sub-catchment level.

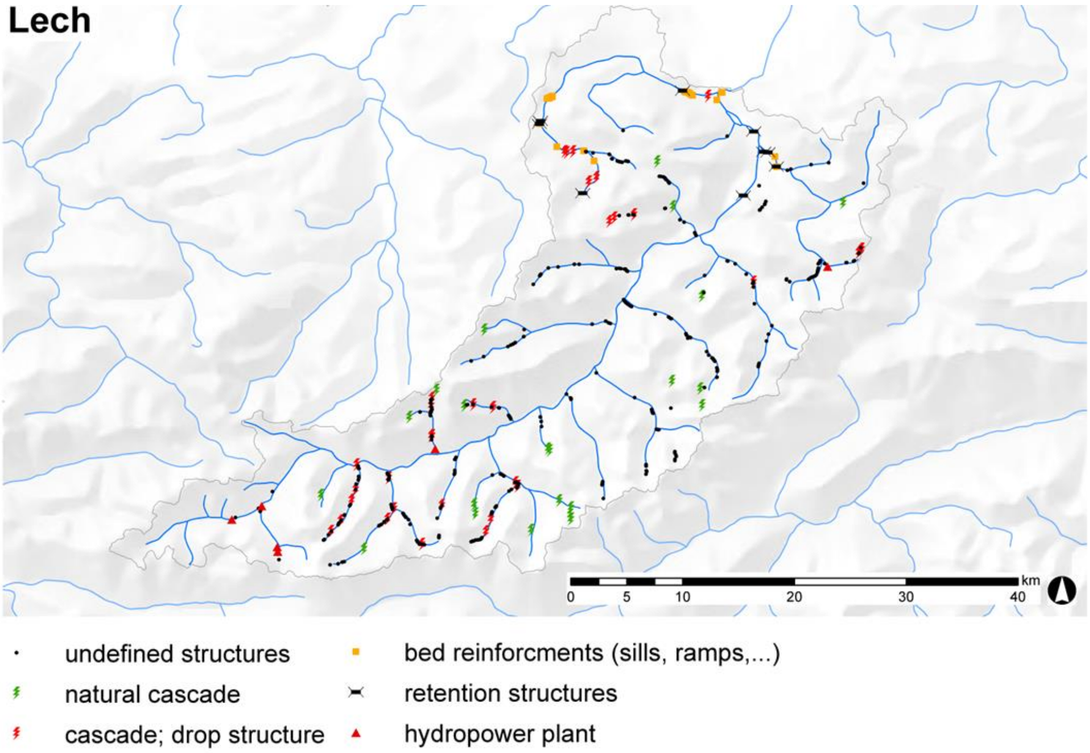

Figure 4.27 Physical pressures at the Lech catchment (based on HAÖ, 2007 and Lebensministerium, 2010).

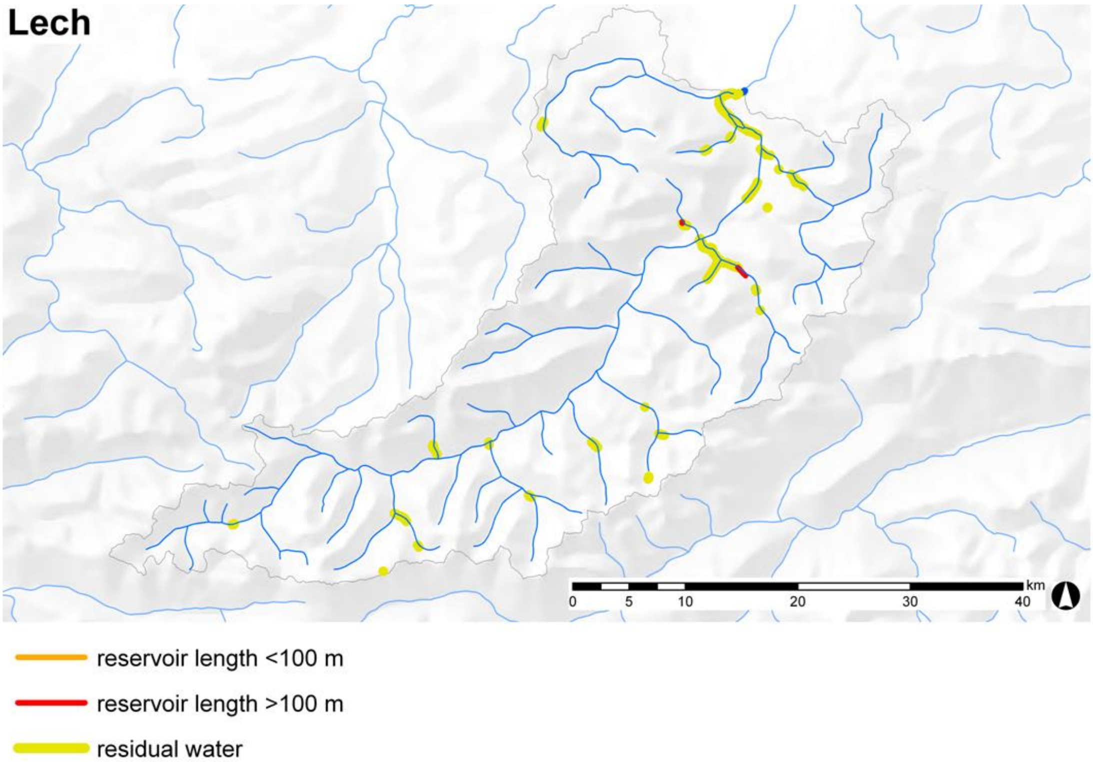

Figure 4.28 Physical pressures - reservoirs and residual water (based on HAÖ, 2007 and Lebensministerium, 2010).

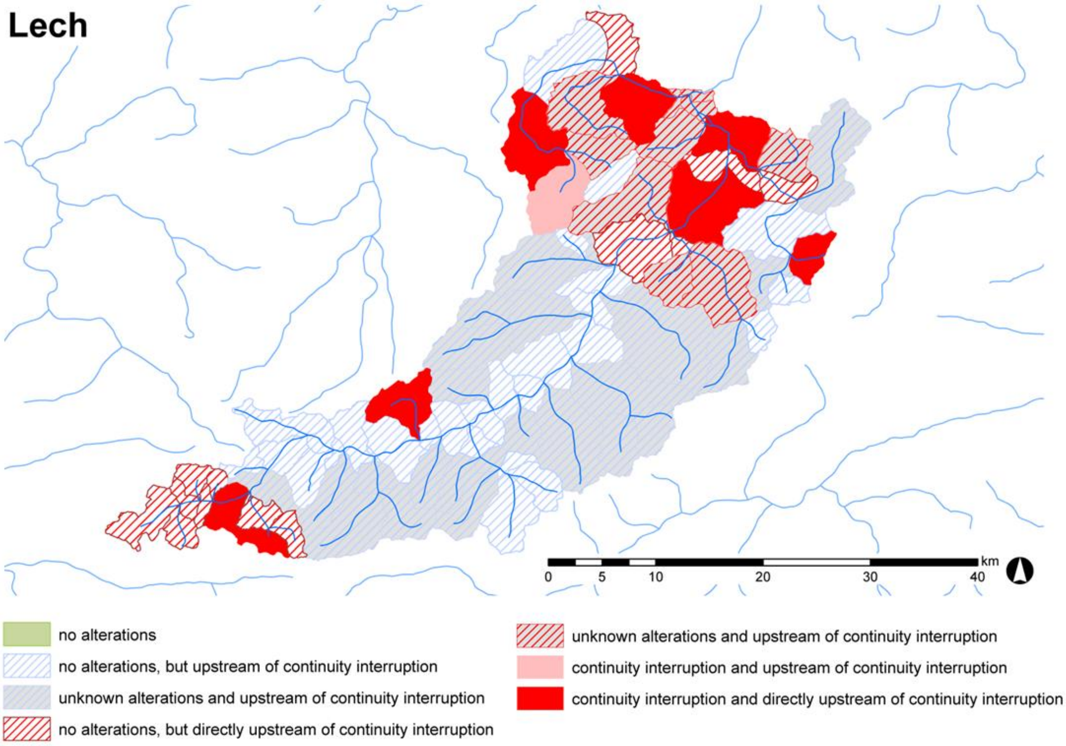

Figure 4.29 Illustration of alterations and continuity interruptions in sub-catchments (based on HAÖ, 2007 and Lebensministerium, 2010). Unknown alterations indicate that structures are present but their impact on the downstream water and sediment continuity is unknown.

4.2.4 Segment

Twelve segments have been delineated based on slope, confinement and major tributaries (for details see Table 3.1). Each segment is characterized in terms of its flow regime, valley characteristics, sediment and riparian vegetation. Physical pressures have already been described at a higher (Landscape Unit) scale, thus no additional information is given here.

(i) Hydrological properties

For the evaluation of hydrological properties, three gauging stations were used. They are located at the village of Lech (Tannbergbrücke), at Steeg and at Lechaschau. Several hydrological characteristic values are provided in Table 4.3.

The temporal distributions of monthly discharge values (minimum, mean and maximum), based on time periods of at least 37 years, are illustrated in Figures 4.30, 4.31 and 4.32. The hydrological regime is moderate nival and the highest monthly mean discharge occurs in June. The low flow period starts in autumn and ends with the beginning of spring. During colder seasons, a high percentage of precipitation is stored as snow and with increasing temperatures in spring, the snow melts and causes an increase in discharge.

During the spring snowmelt, there is a typical diurnal variation in discharge (Figure 4.33), which depends, amongst other factors, on solar radiation and the distance between the areas with snow cover and the location of the gauging station.

Hydrographs for 2008 for the three gauging stations are presented in Figure 4.34. The annual flood occurred in July, which is the month with the highest probability for it. It can be seen, that the discharge at the different gauging stations shows very similar characteristics.

Table 4.3 Hydrological regime and characteristic values for three gauging stations on the River Lech.

	Lech (Tannbergbrücke)	Steeg	Lechaschau	References
Regime	moderate nival			Mader et al., 1996
NQ MQ	0.34 m^3/s 5.13 m^3/s	0.54 m^3/s 12.7 m^3/s	1.96 m^3/s 44.1 m^3/s	BMLFUW, 2009
HQ_1 HQ_2 HQ_5 HQ_{30} HQ_{100}	45 m^3/s - 74 m^3/s 105 m^3/s 135 m^3/s	86 m^3/s 114 m^3/s 151 m^3/s 225 m^3/s 307 m^3/s	299 m^3/s 394 m^3/s 515 m^3/s 570 m^3/s 762 m^3/s	Lebensministerium, 2013

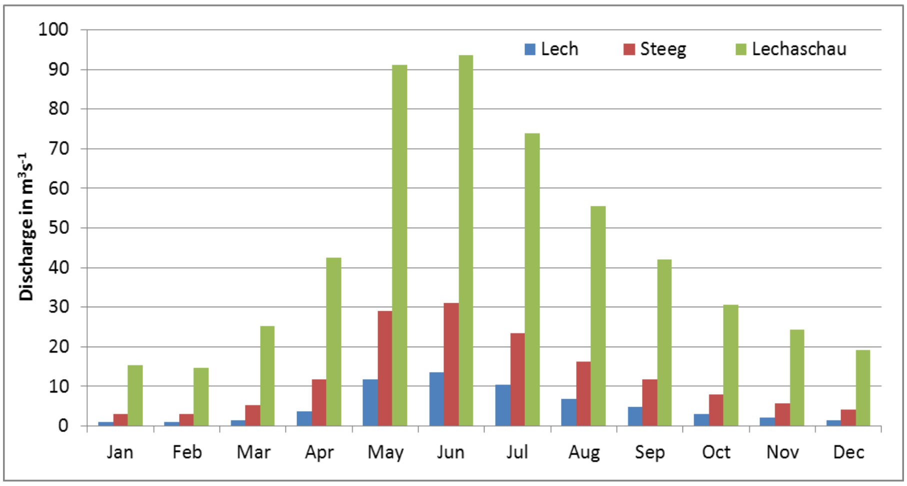

Figure 4.30 Mean monthly discharges for the three gauging stations at the Lech. The time period for Lechaschau was 1971 to 2008, and for the Steeg and Lech it was 1951-2008 (based on BMLFUW, 2009).

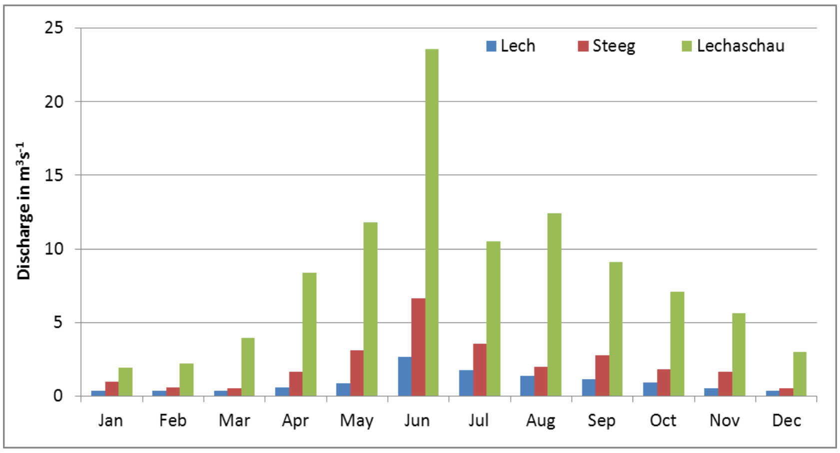

Figure 4.31 Minimum discharge for each moth over the period 1971 to 2008 for Lechaschau and the period 1951-2008 for Steeg and Lech (based on BMLFUW, 2009).

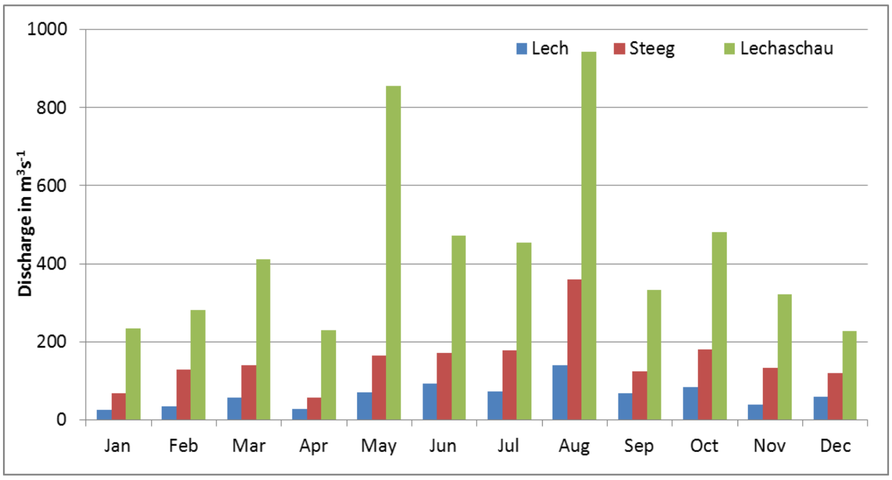

Figure 4.32 Maximum discharge for each moth over the period 1971 to 2008 for Lechaschau and the period 1951-2008 for Steeg and Lech (based on BMLFUW, 2009).

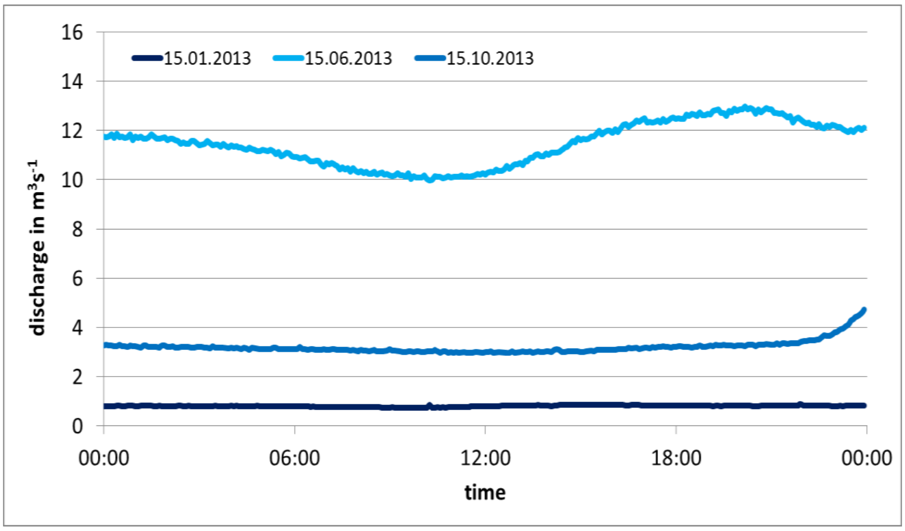

Figure 4.33 Hydrographs for a day in January, June and October to show seasonal differences and diurnal variations. The data is shown for the gauging station Tannbergbrücke at Lech (based on Lebensministerium, 2013).

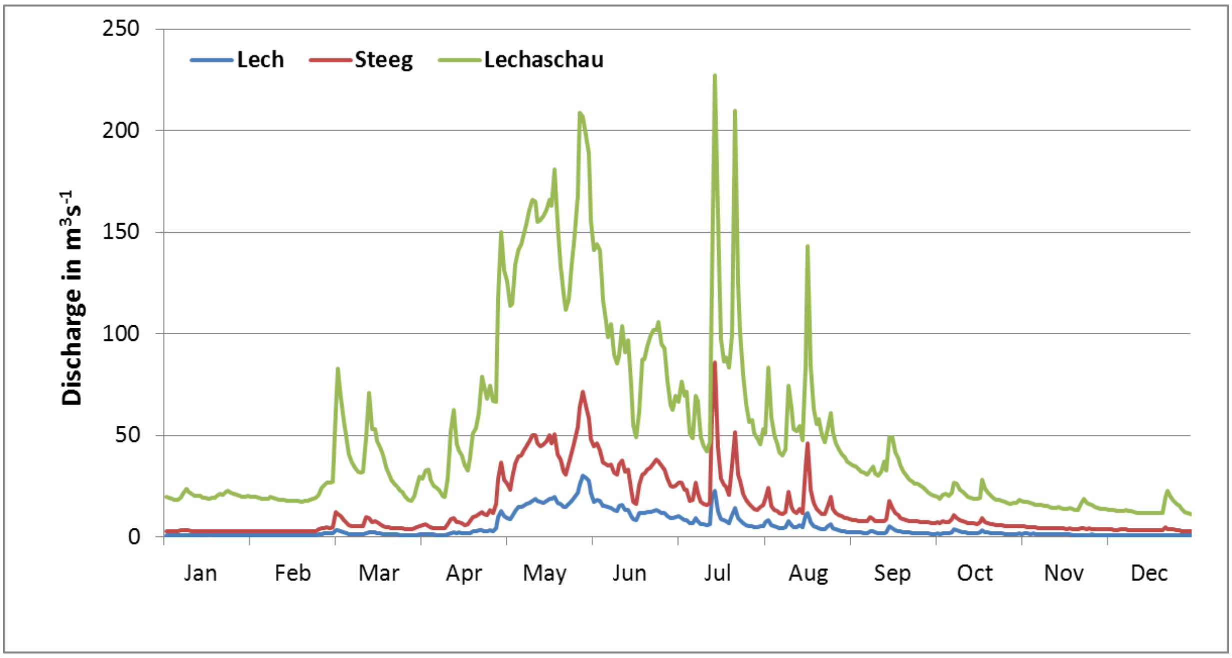

Figure 4.34 Hydrographs for the year 2008 for several gauging stations at the Lech River (based on BMLFUW, 2009).

In Figure 4.35, changes of the mean annual discharge over the time period 1951 to 2000 are illustrated. In the downstream section, a significant increase of mean annual run-off by 0,005 to 0,025 % per year is present. In the Upstream section neither an increasing nor decreasing trend could be identified.

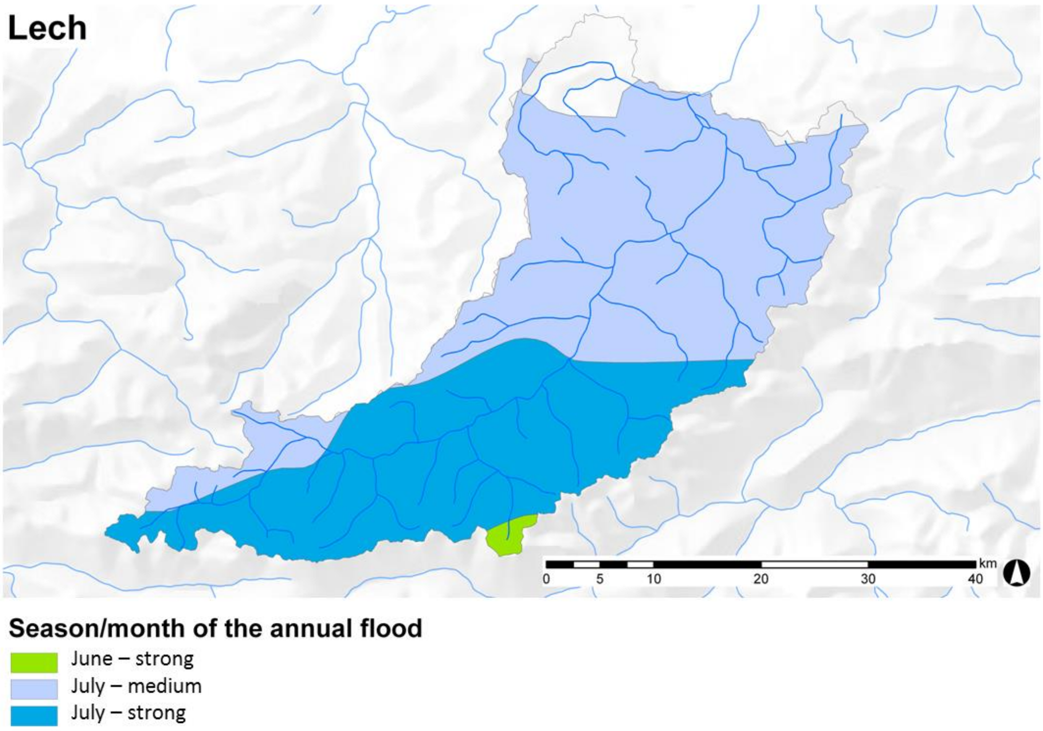

Figure 4.35 Season/month of the annual flood; strong and medium indicate the likelihood that the annual flood occurs in a certain month/season (based on HAÖ, 2007).

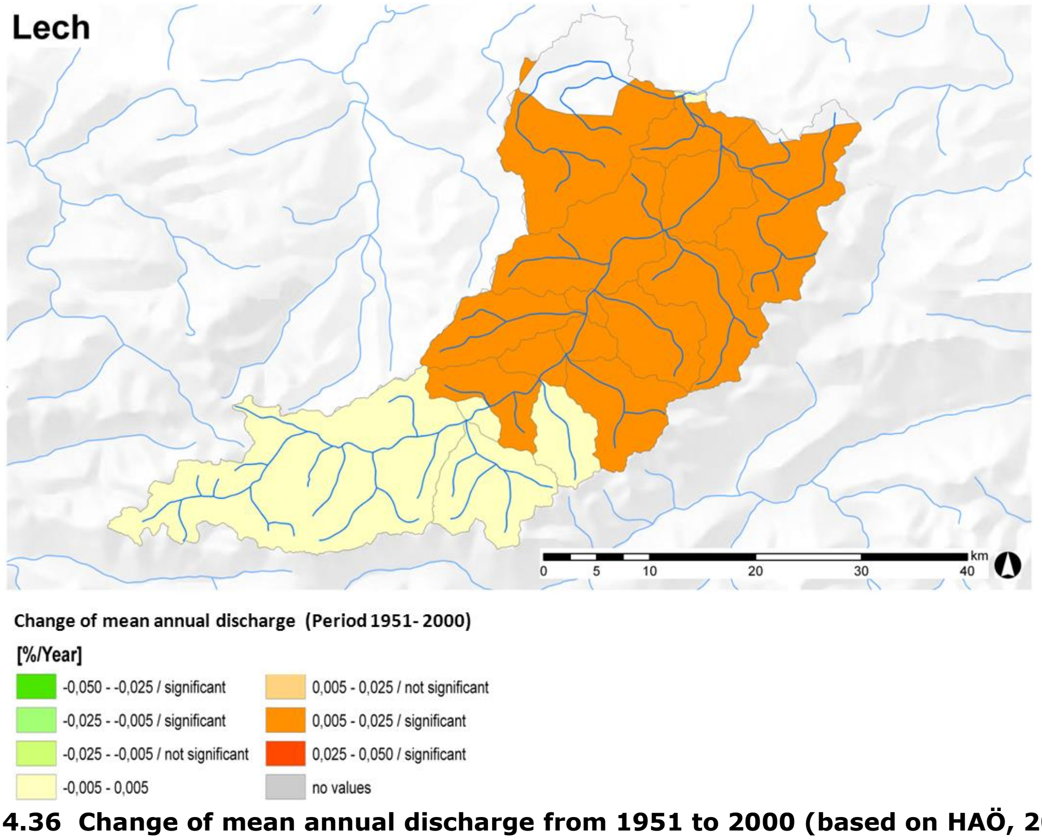

Figure 4.36 Change of mean annual discharge from 1951 to 2000 (based on HAÖ, 2007).

(ii) Topography

For each segment, properties of the valley, such as gradient and valley bottom extent, were identified, and the mean bankfull widths were measured. An overview is given in Table 4.4, where the lateral extent of riparian vegetation is also stated.

Table 4.4 Characterisation of segments in terms of valley gradient, valley bottom extent, mean bankfull width and precense (lateral extent) of riparian vegetation

Segment	Valley gradient [%]	valley bottom extent [m]	Mean bankfull width [m]	Lateral extent of riparian vegetation*
1	>5	100-200	12	Not defined (n.d)
2	1-3	100-200	25	Small
3	1-3	200-300	20	Small
4	1-3	<100	40	Small
5	1-5	<100	20	Small
6	0,5-1	100-200	40	Medium
7	0,5-1	200-500	35	Medium
8	0,5-1	>500	125	Medium-large
9	0-0,5	200-500	225	Medium
10	0-0,5	>500	85	Medium
11	0-0,5	>500	105	Medium
12	0-0,5	200-500	130	Medium

* lateral extent of riparian vegetation based on Muhar et al. (2004)

(iii) Vegetation

Based on the classification of growing regions (Kilian et al., 1993), segments 1 to 9 can be assigned to the "Nördliche Zwischenalpen – Westteil", whilst segments 10 to 12 are in the "Nördliche Randalpen – Westteil". The plant associations for the regions are presented in Tables 4.5 and 4.6.

Table 4.5 Plant associations of altitudinal zones in the western part of the "Nördlichen Zwischenalpen" (Kilian et al., 1993). A. mixed oak forest; B. spruce-fir forest; C. fir free spruce forest (edaphic or based on local climate); D. scots pine forests; E. Grey alder (riparian forest and wet hillslopes); F spruce forest; G. Latschengebüsch (*pinus mugo supsp.*); H. larch-Swiss Stone pine forest; I. green alder (at wet and snowy areas); Spirkenwald (pinus mugo supsp. uncinata) as pioneer vegetation and at steep and shady hillslopes.

Altitudinal zone	Elevation [m]	Growing regions and plant associations								
		Nördlichen Zwischenalpen – Westteil								
Submontane	500-750	A	(B)		D	E				
Montane	750-1000		B	C	D	E				
Midmontane	1000-1300				D	E				
Altimontane	1300-1600					E				
Subalpine (low)	1600-1800						F	(G)		I
Subalpine (high)	1800-2050							G	H	I

Table 4.6 Plant associations of altitudinal zones in the western part of the "Nördlichen Randalpen" (Kilian et al., 1993). A. English oak-European hornbeam forest; B. European beech forest; C. spruce-fir-beech forest; D. spruce-fir forest (edaphic); E. alpine heath-Scots pine forest; F. mixed lime forest (drier areas); G. spruce forest; H. larch forest; I. Latschengebüsch (*pinus mugo supsp.)*; J. green alder (at wet and snowy areas); Spirkenwald (pinus mugo supsp. uncinata) as pioneer vegetation and at steep and shady hillslopes; grey alder (riparian forest).

Altitudinal zone	Elevation [m]	Growing regions and plant associations									
		Nördlichen Randalpen – Westteil									
Submontane	400-600	A	B		D	E	F				
Montane	600-800		B		D	E	F				
Midmontane	800-1200			C		E				(I)	
Altimontane	1200-1450			C						(I)	
Subalpine (low)	1450-1650							G		I	J
Subalpine (high)	1650-1950								H	I	J

The potential vegetation of segments 1 to 4 is characterized as *Piceeto montanum* (Pitschmann et al., 1973).

Segment 1: The vegetation along this river segment consists of herbs and grasses. Within the floodplain, only a few shrubs and trees are present. In the surrounding area, *pinus mugo supsp. mugo* ("Latsche"), *pinus mugo supsp. uncinata* ("Spirke") and *picea abies* (spruce) can be found. For further details see Amann et al. (2010).

Segment 2: This segment is characterised by discontinuous patches of vegetation along the floodplain. Open and vegetated bars are present in transitional river sections. The dominant species are spruce and dwarf pine. The patches exhibit low to medium vegetation (stand) densities and the structure is, for most areas, quite homogeneous. However, on bars the vegetated structure is more heterogeneous (different heights, species and densities).

Segment 3: Within the urban area of the village Lech, no vegetation is present along the banks. In the downstream part of segment 3, scattered to continuous vegetation exists, with a small lateral extent. The vegetation consists mainly of shrubs and spruce trees.

Segment 4: As this segment is characterised as confined, the river is in direct contact with the hill slopes and floodplains exist only in some small stretches. The hill slopes are partially covered with spruce forest and grey alder can occur on the floodplain, but mostly bare material is present (Figure 4.37). The vegetated areas on the hill slopes and the bars have different structures and densities.

The potential vegetation of segment 5 and 6 is characterized as *Piceto abietum* (Pitschmann et al., 1973).

Segment 5: Like segment 4, segment 5 is located in a confined section of the Upper Lech, and the vegetation patches are quite similar to the previous segment.

Figure 4.37 Small braiding sections with (left) and without (right) vegetation on the bars (VoGIS, 2013).

<u>Segment 6</u>: This segment is characterised by discontinuous, scattered vegetation patches along the banks, with minor lateral extent. Due to the patchy structure and the small lateral and longitudinal extent, the existing vegetation is not a naturally functioning riparian forest. The surrounding floodplain is mainly used as meadows and pasture.

The potential riparian vegetation of segments 7 and 8 is characterized as *Salicetum albae* (Pitschmann et al., 1973).

<u>Segment 7</u>: Continuous vegetation is present along both banks, with different lateral extents. Within stretches where the river banks are not in contact with the hill slopes and at tributaries, the lateral extent is larger. But for the rest of the river the mean lateral extent is about 10 m to 30 m. The vegetation has an homogeneous structure and a medium to high density. Within the active channel some bare bars are present.

<u>Segment 8</u>: The upstream part of segment 8 is similar to segment 7, but the downstream section is characterized by larger lateral extents of the floodplain (Figure 4.38). The structure is less homogeneous and the densities vary. On some bars vegetation patches are present.

Figure 4.38 Upstream (left) and downstream (right) section of segment 8 with different extents and structure of floodplain vegetation (TirisMaps, 2013).

Segments 9 to 12 are classified as the growing region "Nördliche Randalpen – Westteil" (Kilian et al., 1993).

Segment 9: In this segment the lateral extent of the vegetation is large. However,many bare bars and some bars with pioneer species are present within the active channel.

Segment 10: This segment can be divided into three parts the upstream, the middle and the downstream sections. On both sides of the upstream river section, continuous vegetation is present. On the right side the lateral extent is larger (up to 220 m) than on the left side (around 30 m). Further, the vegetation on the left side is more homogeneous than on the right side, where the structure, the density and the lateral extent varies greatly.

The middle part of the segment is located within the urban area of the villages of Reutte and Lechaschau. There, the vegetation is present continuously on both sides, but with a smaller lateral extent on the left side (minimum 10 m) and a larger extent on the right side (up to 170 m). The downstream part of the segment is characterised by larger extents of riparian vegetation on both sides of the river. In the middle and the downstream part of the segment, bare bars are present.

Segment 11: Continuous vegetation is present on both sides of this river segment. The structure and the stand densities of the plants are heterogeneous. The lateral extent of the riparian vegetation is generally large but with a high variability in width.

Segment 12: This segment is characterised by a continuous vegetation belt on the left side of the river, extending laterally to the foot of the hill slopes. On the right side of the river, the lateral extent of the vegetation varies. In the upstream part a gravel mine reduces the extent of the vegetated floodplain to a few meters, whereas in the downstream part the lateral extent is larger, but still confined by a water return circuit from a hydro power plant.

4.2.5 Reach

At the reach scale bed sediment calibre, channel width, some flow parameters, and physical pressures concerning lateral and vertical continuity of sediment are evaluated. Most of these properties are only evaluated for the downstream part of reach 8.4.

(i) Bed sediment calibre

The mean grain size of the surface layer at reach 8.4 is about 21 mm and the most frequent fraction is medium to coarse gravel. The grain size distribution of the available samples and some characteristic values are given in Figure 4.39 and Table 4.7, respectively.

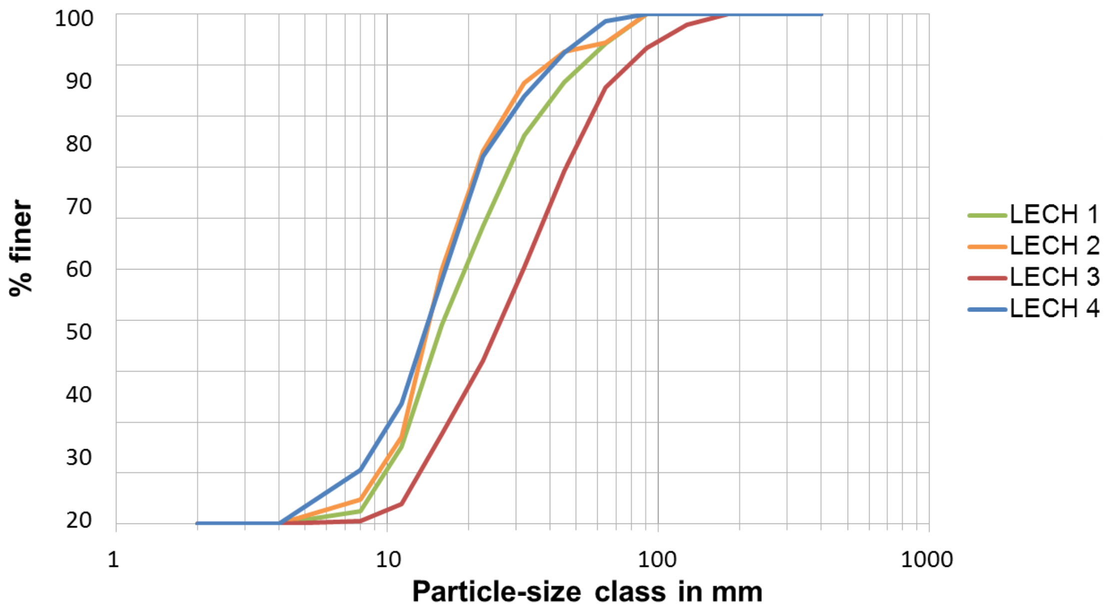

Figure 4.39 Cumulative grain size distributions of four samples taken at the Lech upstream of Johannestalbrücke (Auer, 2012).

Table 4.7 Characteristic grain diameters for the line samples taken in the Lech River (Auer, 2012)

Sample	d_{90} in mm	d_{50} in mm	d_{10} in mm
Lech 1	53	20	10
Lech 2	39	16	9
Lech 3	79	32	14
Lech 4	41	17	7
Mean values	53	21	10

(ii) Channel width and flow parameters

The channel width is only derived for the downstream section of reach 8.4. As stated before, a 1D model (HEC-RAS 4.1, for further information see http://www.hec.usace.army.mil/software/hec-ras/) was used for the analysis of the maximum water surface extent (Figure 4.40), mean flow velocities, maximum water depth and the width/depth ratio. The developments of these parameters as functions of increasing discharge are visualized in Figure 4.41. The results of the six modelled discharges are presented in Table 4.8.

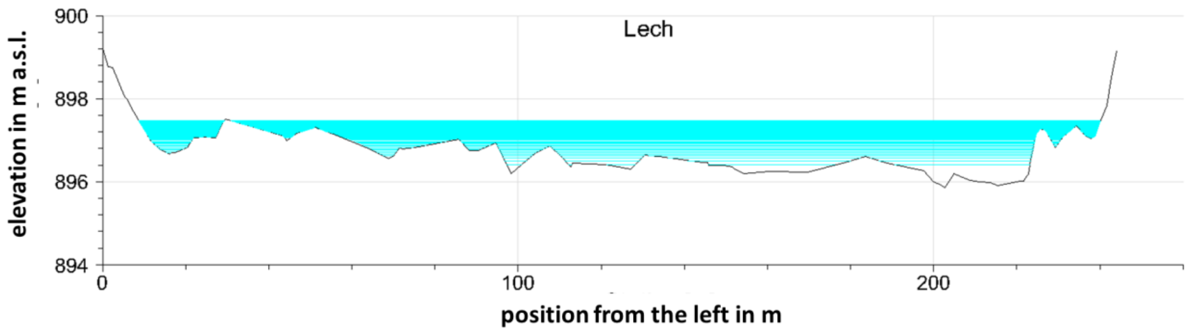

Figure 4.40 One of the cross sections at the Lech River. The blue lines indicate the modelled water surface elevation at different discharges (Auer, 2012).

Table 4.8 Simulation results for the downstream section of reach 8.4. MNQ_T stands for mean low flow based on daily discharge values, MQ is mean flow and HQ_1 is a one-year flood (Auer, 2012).

Discharge [m^3s^{-1}]	6,0 MNQ_T	18,0	30,0	32,5 MQ	59,9	193,4 HQ_1
Maximum water depth [m]	0.52	0.71	0.83	0.85	1.01	1.47
Mean flow velocity in [ms^{-1}]	0.5	0.63	0.72	0.73	0.87	1.23
Maximum water table extent in [m]	66.5	109.1	133.5	137.3	168.9	235
Width/depth ratio [-]	128	154	161	162	167	160

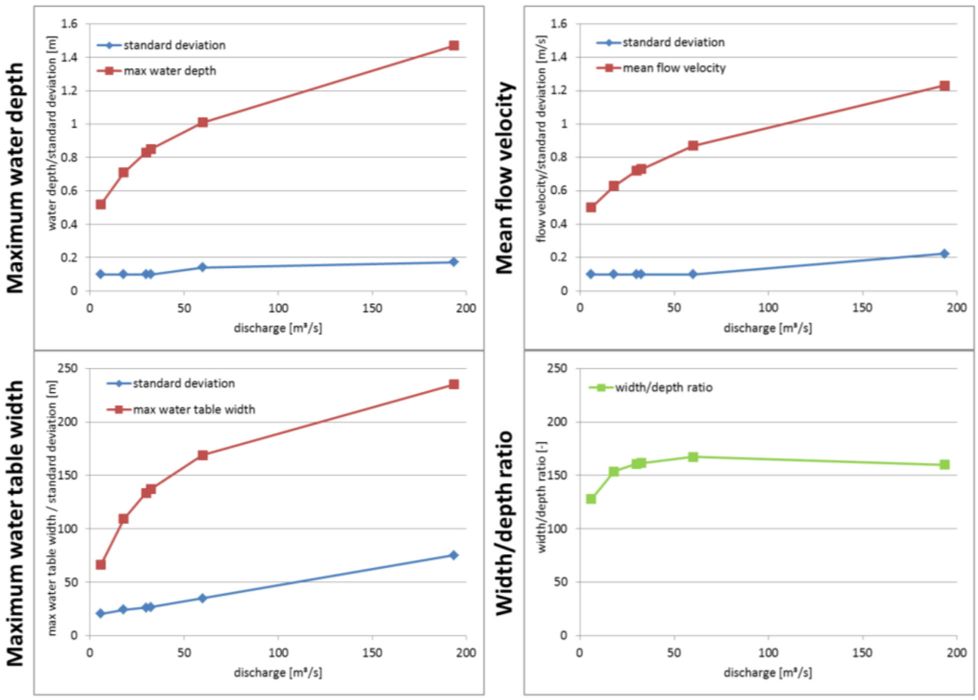

Figure 4.41 Development of different parameters as a functions of the discharge (Auer, 2012).

(iii) Physical pressures

In Figures 4.42. and 4.43, alterations of the bed and banks along the Lech River are indicated and an overview for all reaches is given in Table 4.9. In the following, the categories of bed and bank alterations are explained according to Mühlmann (2010).

<u>Bed alterations</u>

- ⇨ no to negligible alterations – bed dynamics are unlimited; none or only minor meassures like groundsill are present; no sediment retetion strucutres are located upstream or within the section
- ⇨ locally reinforced bed – bed dynamics are locally limited; repeated meassures of bed stabilisation (e.g. groundsills) are present, but between them bed dynamics can occur; or sediment retention structures are located within or upstream of this section
- ⇨ locally reinforced bed and altered substrate – bed dynamics are locally limited by repeated stabilisation measures, but between them bed dynamics are possible; however, the grain size distribution is altered due to deposits of fine material
- ⇨ widely reinforced bed – bed dynamics are prevented over the entire section (e.g. revetments), only some isolated areas with natural substrate exist; the river bed is characterised by total rearrangement
- ⇨ entirely reinforced bed – the river runs through a pipe or in a closed box section

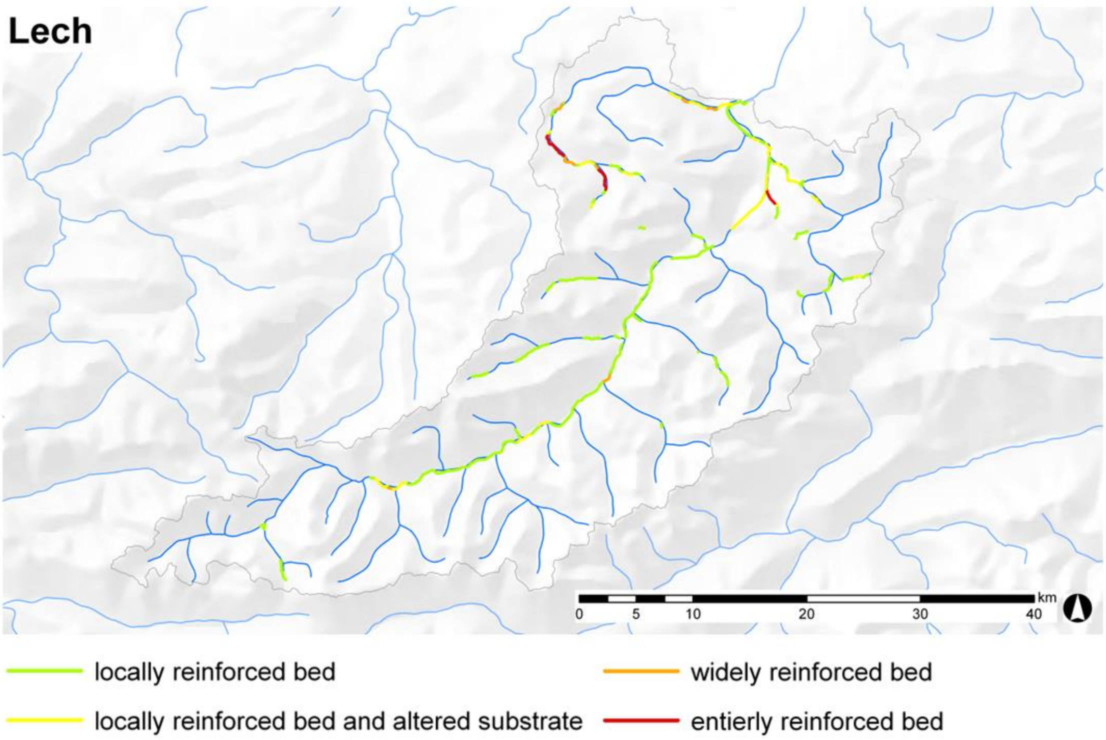

Figure 4.42 River stretches with anthropogenic impacts on the bed (based on HAÖ, 2007 and Lebensministerium, 2010).

Bank alterations

- ⇨ no to negligible alterations – bank dynamics are unlimited; none or only minor local reinforcement measures, for example at the outer bank or sites with bank erosion, are present
- ⇨ locally reinforced banks – banks are again and again locally reinforced, causing limited bank dynamics in these sections; between the reinforced areas, unlimited bank dynamics are possible
- ⇨ widely reinforced banks – dynamics can only occur at some locations; almost the entire river is systematically regulated, but small interruptions occur
- ⇨ entirely reinforced banks – the river banks are reinforced over the entire section without interruptions
- ⇨ entirely reinforced banks and bed – the river runs through a pipe or in a closed box section

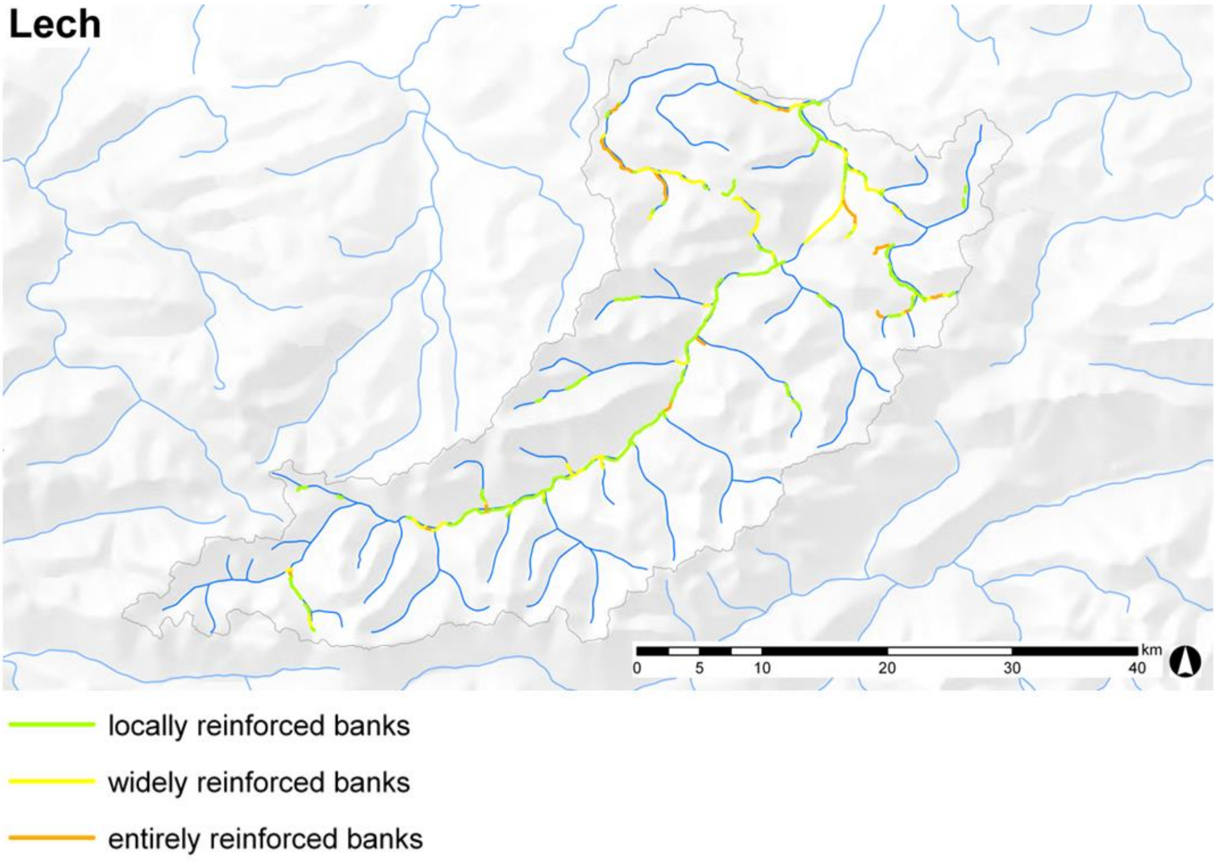

Figure 4.43 River stretches with reinforced banks (based on HAÖ, 2007 and Lebensministerium, 2010).

Table 4.8 Overview of bed and bank alterations (data based on Lebensministerium, 2010).

Reach	Bank reinforcement	Bed reinforcement and alteration of sediments
5.1	no to negligible alterations	no to negligible alterations
6.1	widely, at some sections entirely, reinforced banks	locally reinforced bed and altered substrate
7.1	locally reinforced banks, only at a very small section entirely reinforced	locally reinforced bed, only at small sections the substrate is altered
8.1	about two thirds of the reach are locally reinforced, the rest is widely reinforced	locally reinforced bed, at small sections presence of altered substrate
8.2	locally reinforced banks, only at a very small section entirely reinforced	Mainly locally reinforced bed and at some small sections with no to negligible alterations, but at some areas widely reinforced bed occurs
8.3	locally reinforced banks	locally reinforced bed
8.4	locally reinforced banks	Mainly locally reinforced bed and at some small sections with no to negligible alterations
9.1	no to negligible alterations	no to negligible alterations
10.1	widely reinforced banks	locally reinforced bed and altered substrate
10.2	widely reinforced banks	locally reinforced bed and altered substrate, at a very small sections entirely reinforced bed
10.3	widely reinforced banks, at some small stretches only locally reinforced	locally reinforced bed and at some sections altered substrate
11.1	widely reinforced banks	locally reinforced bed and altered substrate
11.2	locally reinforced banks	locally reinforced bed, only at small sections the substrate is altered
12.1	locally reinforced banks	locally reinforced bed

4.3 Summary

An overview of most of the characterisation and delineation properties is given in Table 4.9. The entire investigated catchment of the Lech is located within one biogeographical region and one landscape unit. The main river was delineated into twelve segments (mean length: 7 km) and nineteen reaches (mean length 4,3 km).

The investigated section of the Lech River is located in the Northern Calcareous Alps and exhibits a homogeneous geology (limestone, dolomite, marl and clastic sedimentary rock). The terrain is mountainous and more than 65 % of the catchment area is located at altitudes above 1400 m a.s.l. The mean slope only falls below 20 degree in the valley bottoms,. The entire catchment is affected by high precipitation, resulting in a mean annual runoff of 1350 mm.

Most of the catchment is covered with shrub and/or herbaceous vegetation associations (38,9%), forests (31,9%) and no or little vegetation (21,6%).

The upstream part of the river can be classified as a torrent. The valley slopes are steep and sediment inputs from tributaries is probably large (cf. Figure 4.44). Based on the available data, the sediment and water continuum is only negligibly interrupted (if at all) until the village of Lech, where a hydropower plant exists.

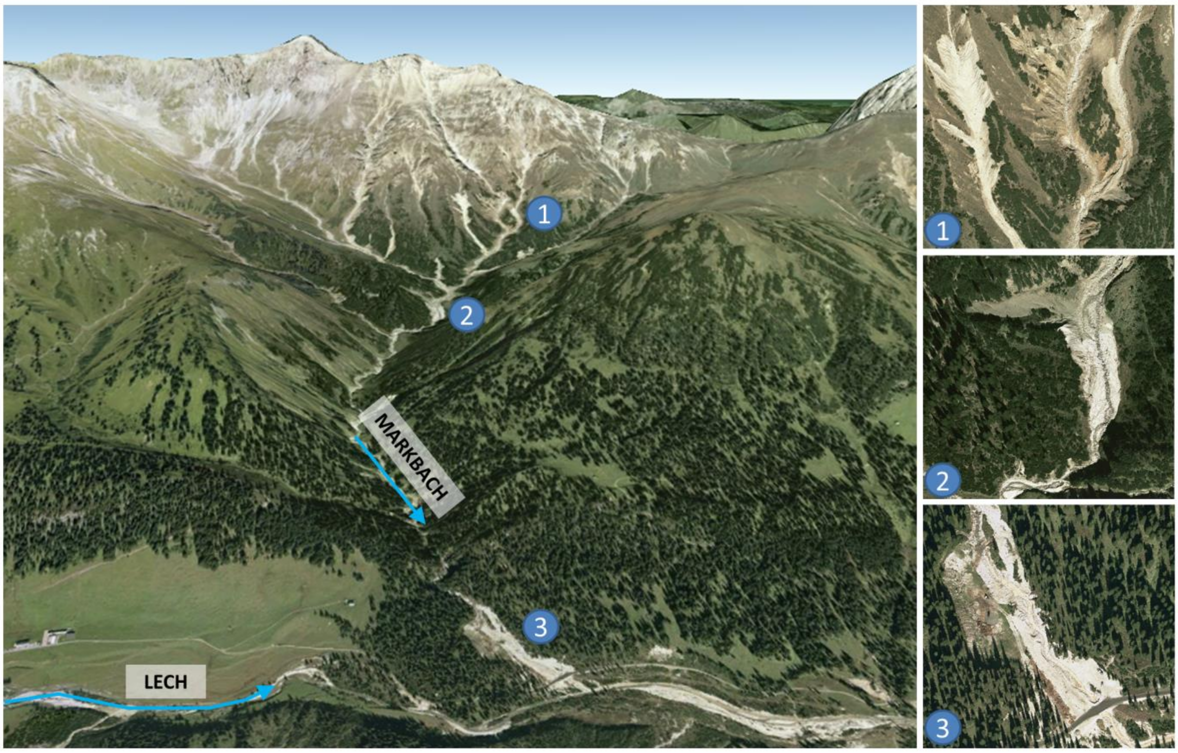

Figure 4.44 Example for an tributary at the upstream section of the Lech River. The pictures in the left indicate sources of bed load within the Markbach torrent (data source: GoogleEarth, 2013).

Downstream of the village there is a confined section in which the highest valley gradients within the investigated section of the Lech River occur. From the village of Steeg downstream, the valley becomes wider, the valley slope decreases and the river starts to oscillate from one side to the other side of the valley. The river course in this section is only slightly modified (Figure 4.45). Bed and bank reinforcements are locally present but there are no major structures that would interrupt the water or sediment transport until the Lech reaches the village of Reutte.

Torrents enter the Lech from both sides and have a high potential to transport large amounts of sediment. Several structures are present in these torrents, but their impact on the continuity of water and sediment cannot be evaluated based on the available data sets.

Just upstream of the village of Reutte, the valley width reduces over a short section. After this gorge-like stretch, the valley widens again and the valley gradient decreases. At Reutte there is a hydropower plant where water is diverted from the Lech. The residual flow section is about 1,8 km long.

Downstream of Reutte there is another hydropower plant with a water diversion leading to a residual flow section of about 6.3 km. Both hydropower plants cause major interruptions to the downstream transport of sediment.

The plan form of the River Lech is mostly sinuous, but braiding occursin some stretches.

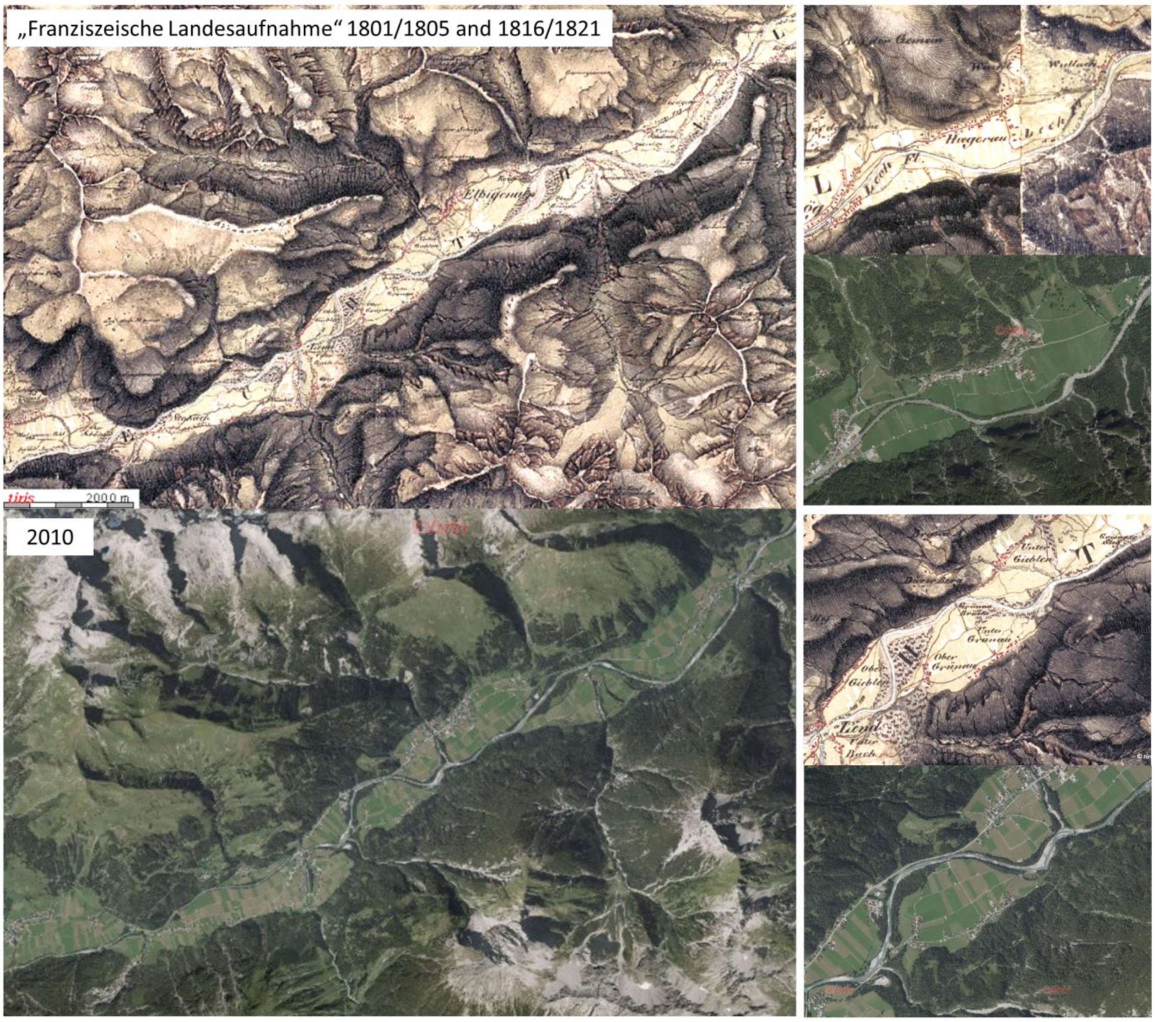

Figure 4.45 Examples of the almost unchanged river course (data source: TirisMaps, 2013). The topographic map was recorded around 1800 and the aerial images were taken in 2010.

Table 4.9 Overview of delineation and characterisation results for the Lech River.

Reach			Segment						
Reach number	Reach length [km]	River planform	Segment number	Segment length [km]	Confinement	flow regime	valley gradient [%]	mean valley bottom extent [m]	mean bankfull width [m]
1.1	5.6	Sinuous	1	-	Semi-confined	moderate nival	>5	100-200	12
2.1	2.4	Sinuous	2	5.6	Semi-confined	moderate nival	1-3	100-200	25
2.2	3.2	Sinuous							
3.1	2.7	Sinuous	3	2.7	Semi-confined	moderate nival	1-3	200-300	20
4.1	5.1	Single thread	4	5.1	Confined	moderate nival	1-3	<100	40
5.1	5.5	Single thread	5	5.5	Confined	moderate nival	3-5	<100	20
6.1	1.6	Sinuous	6	1.6	Semi-confined	moderate nival	0.5-1	100-200	40
7.1	9.6	Sinuous	7	9.6	Semi-confined	moderate nival	0.5-1	200-500	35
8.1	8.5	Sinuous	8	28.8	Semi-confined	moderate nival	0.5-1	>500	125
8.2	7.9	Wandering							
8.3	2.6	Sinuous							
8.4	9.8	Braiding							
9.1	3.4	Braiding	9	3.4	Semi-confined	moderate nival	0-0.5	200-500	225
10.1	1.7	Modified	10	6.7	Semi-confined	moderate nival	0-0.5	>500	85
10.2	1.8	Modified							
10.3	3.2	Modified							
11.1	1.8	Modified	11	6.8	Unconfined	moderate nival	0-0.5	>500	105
11.2	5.0	Sinuous							
12.1	1.0	Modified	12	1.0	Semi-confined	moderate nival	0-0.5	200-500	130

Landscape Unit									Catchment					Region	
	Landscape Unit / Catchment / Region length	Riparian complex	estimated annual soil erosion	hillslope	geology, elevation, relief	mean annual runoff	mean actual evapotranspiration	mean annual precipitation		Land cover / land use	soil types	topography/elevation	catchment area		Biolimatic and Bio-geographic Region
I.	82.4 km	Pioneer shrubs (willows and green alder) in the upstream part, gray alder and scots pine alternate as dominat species in the downstream part	higly variable within the catchment, highest values occur at the valley bottom and are lower than 0.4 t/ha/yr	the mean hillslope for the most parts of the catchment is >20 degree	Northern Calcareous Alps - Limestone, dolomite, marl and clastic sedimentary rock; mountain areas, elevations above 800 m a.s.l. - 65% of the catchment are located above 1400 m a.s.l.	1350 mm	400 mm	1756 mm - mean annual precipitations based on sub-catchments lie betwee 1305 mm and 1997 mm	A	shrub and/or herbaceous vegetation association 38.94%, forest 31.88%, open spaces with no or little vegetation 21.63%, pastured 4.83%, about 2% are used for urban fabric	Rendzinas, Fluvisold and Lithosols, all are developed on calcareous bed material	high altitude areas (>800m a.s.l.), 65% are located above 1400m a.s.l.	1415 km²	A	Eastern alpine biogeographic region, temperate oceanic climate

4.4 Delineation of the Lafnitz river and catchments

4.4.1 Region

The entire catchment of the Lafnitz River is located in the Illyrian biogeographic region (Figure 4.1) and the bioclimate can be classified as temperate continental (Figure 4.2).

4.4.2 Catchment

The delineation of the Lafnitz Catchment is presented in Figure 4.46.

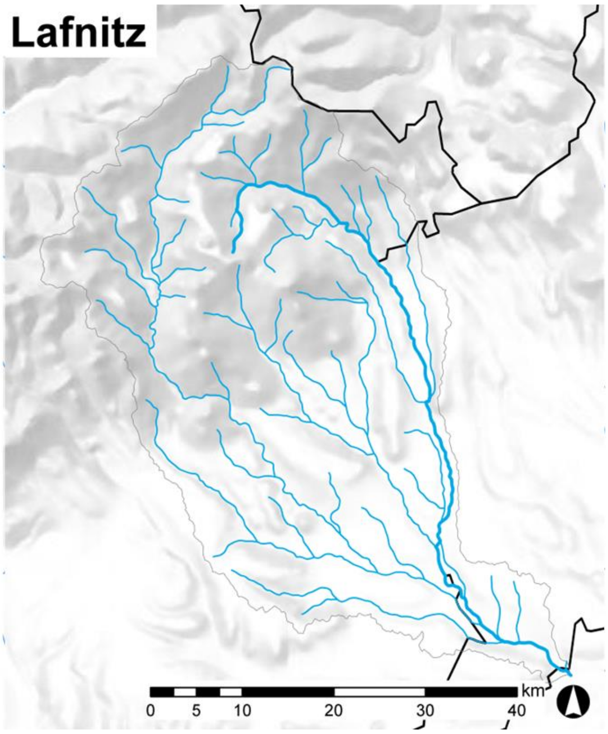

Figure 4.46 Delineation of the Lafnitz catchment – the Lafnitz River is indicated as a bold line (data source: HAÖ, 2007).

4.4.3 Landscape Unit

The basis for the delineation of the landscape units are the geology (Figure 4.47), the topography (Figure 4.48) and the elevation classes based on the Water Framework directive. Based on those properties, the Lafnitz catchment can be divided into a northern and a southern landscape unit, NLU and SLU respectively. The northern area is characterized by a mountainous to hilly topography and crystalline geology. Whereas the southern part is located in a hilly terrain and the bed materials are tertiary sediments.

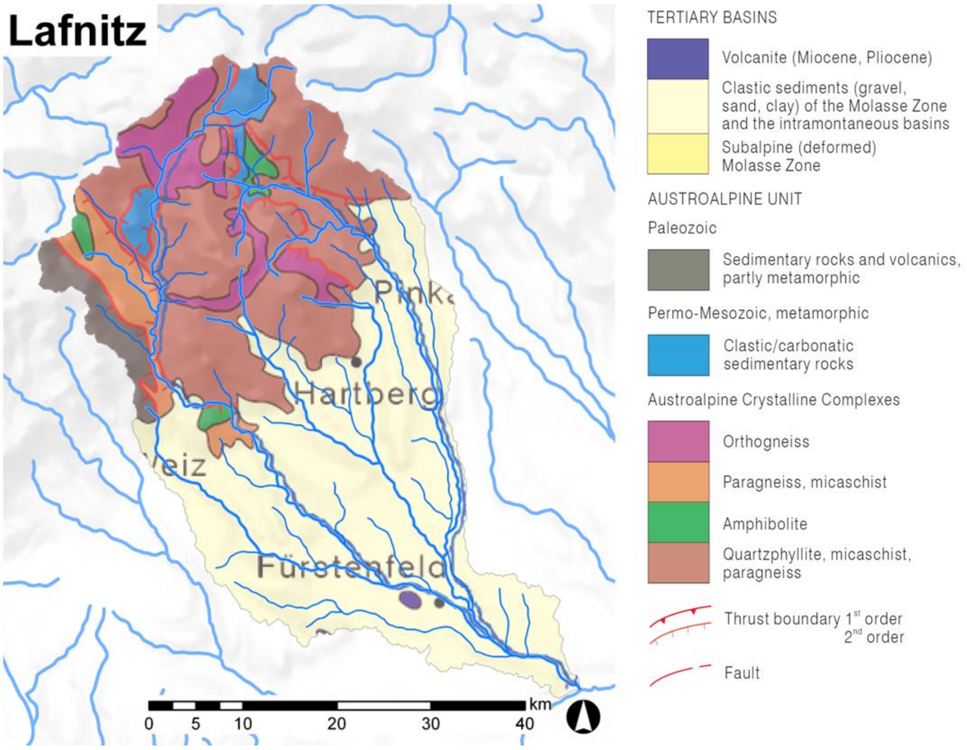

Figure 4.47 Geology of the Lafnitz catchment (data source: Egger et al., 1999 and HAÖ, 2007).

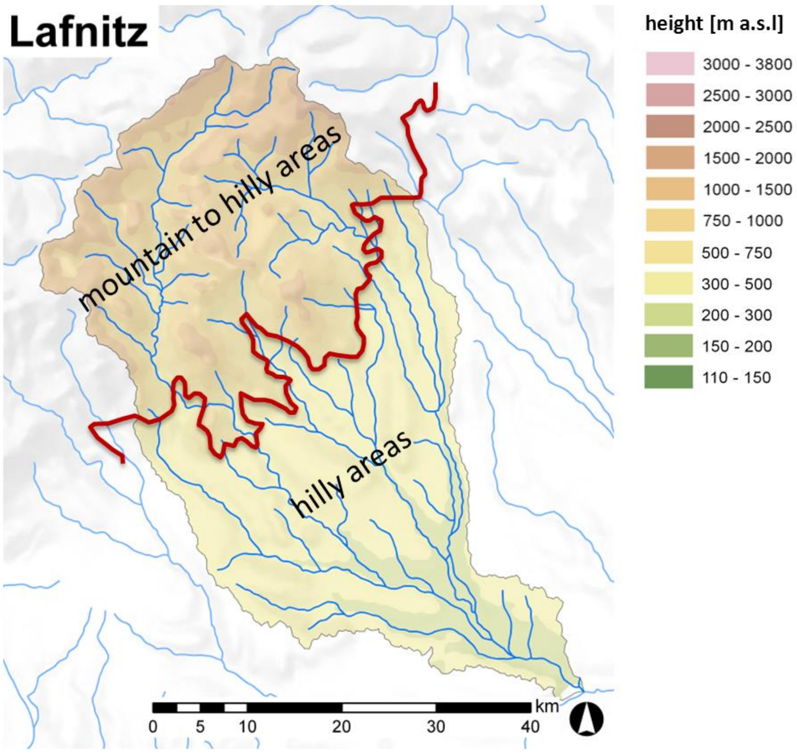

Figure 4.48 Delineation of the landscape units in a mountaineous to hilly area and a hilly area (data source: HAÖ, 2007).

4.4.4 Segment

At the Lafnitz River segments were delineated based on major tributaries and changes in confinement; discontinuities in valley gradient were not observed (Figure 4.49).

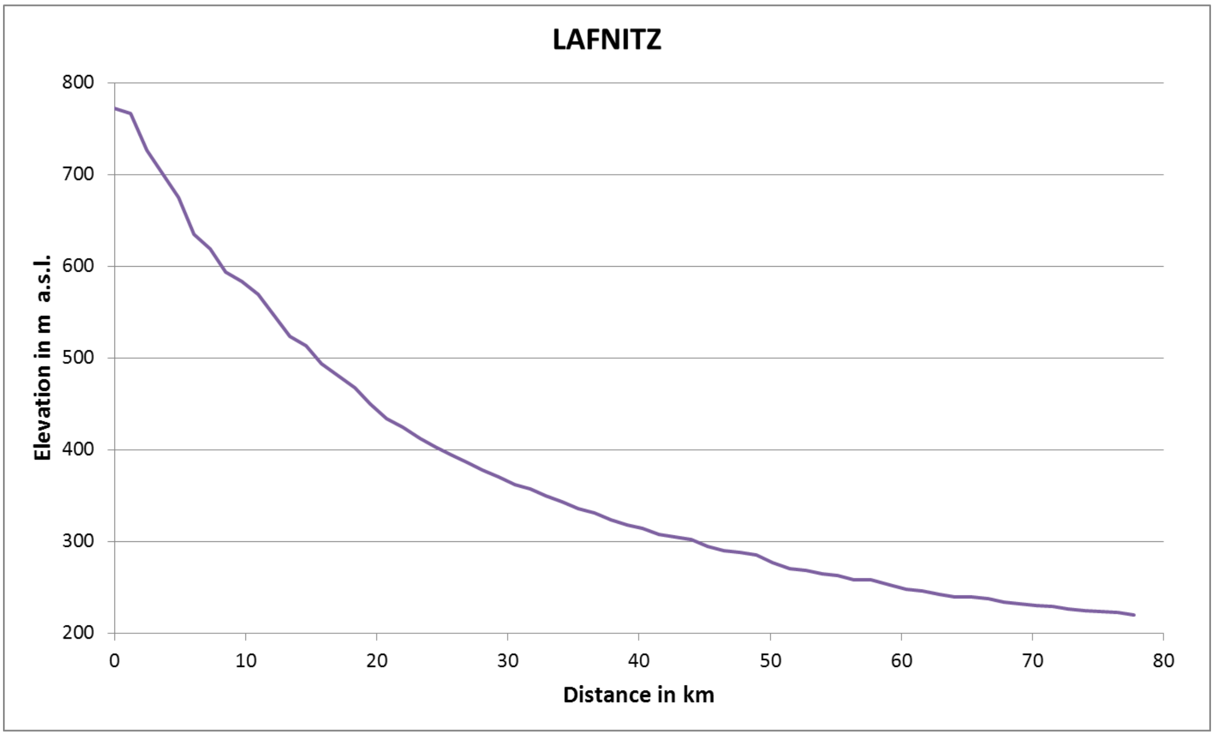

Figure 4.49 Longitudinal profile of the Lafnitz valley.

The following major tributaries were identified and their locations are illustrated in (Figure 4.50):

- the Weißenbach downstream of Waldbach
- the Schwarze Lafnitz at Bruck
- the Voraubach at Beigütl
- the Stögersbach upstream of Wörth
- the Safenbach at Deutsch Kaltenbrunn and
- the Feistritz at Königsdorf.

The confinement changes at three locations (see Figures 4.51 and 4.52). The location of the third and thus last change, from semi-confined to unconfined, equals the border between the northern and the southern landscape unit.

Figure 4.53 represents an overview of the location of all segments. Nine segments were delineated for the Lafnitz, where the first five segments belong to the northern landscape unit and the other ones to the southern landscape unit.

In Table 4.10 the delineation criteria for each segment are given.

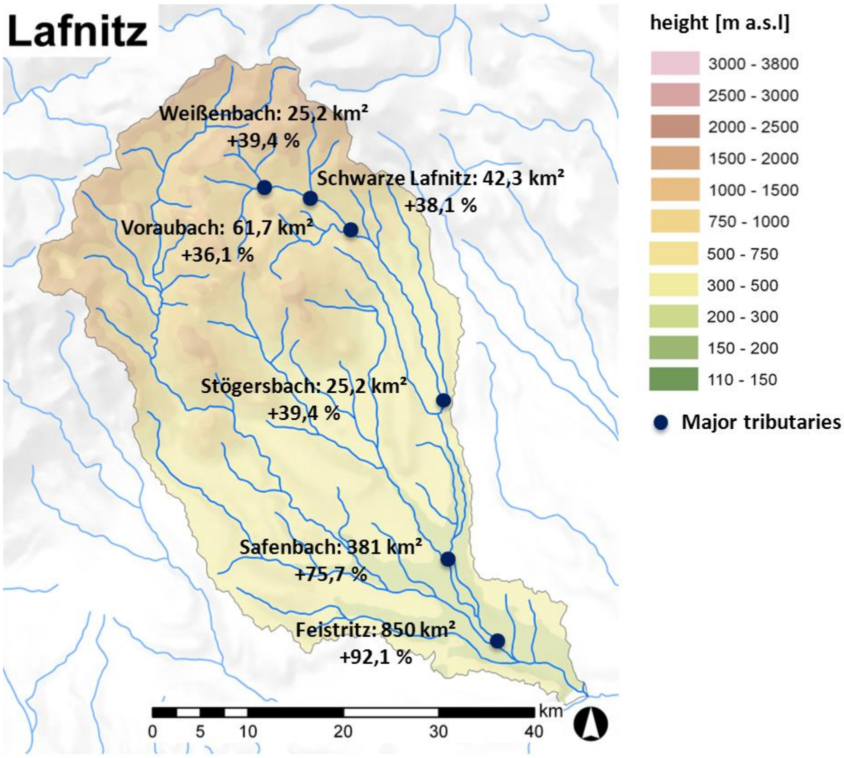

Figure 4.50 Overview of major tributaries to the Lafnitz River. The values indicate the absolute [km²] and the relative [%] increase in catchment area (data source: HAÖ, 2007).

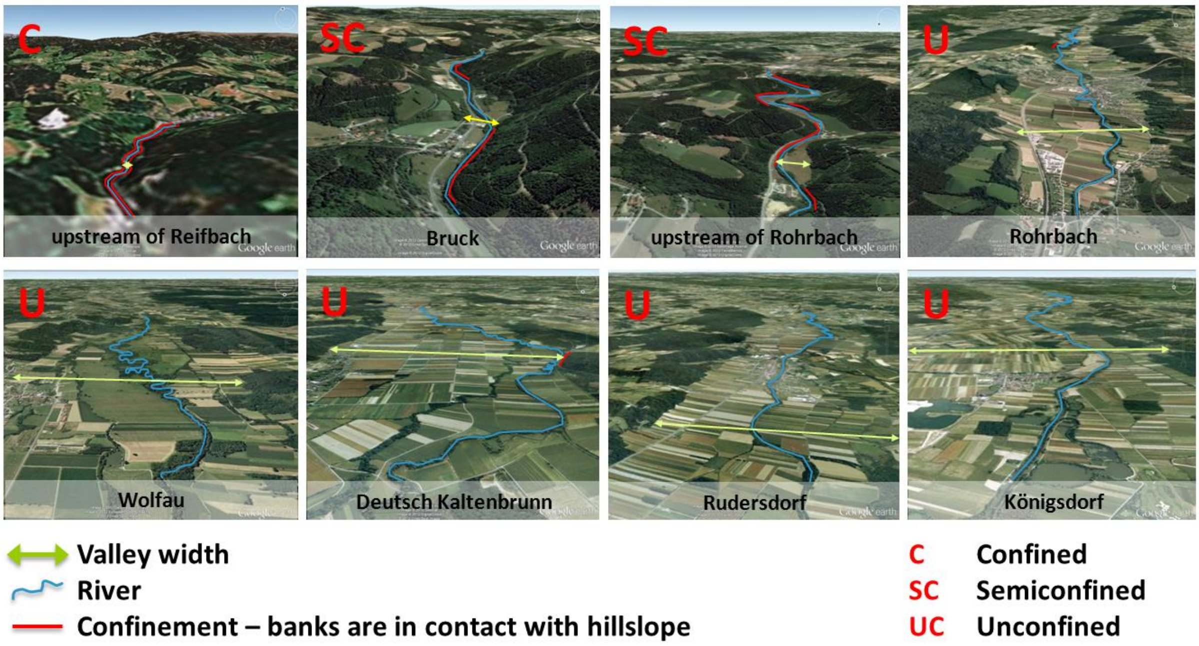

Figure 4.51 Illustration of the confinement at several locations along the Lafnitz River. Views are in flow direction (data source: GoogleEarth, 2013).

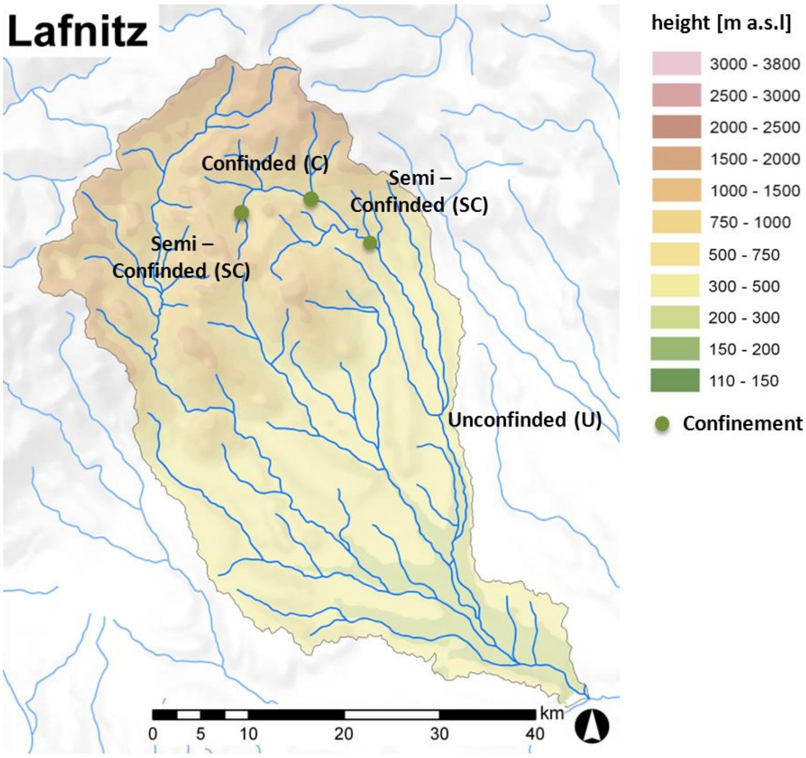

Figure 4.52 Plan view of changes in valley vonfinement at the Lafnitz River (data source: HAÖ, 2007).

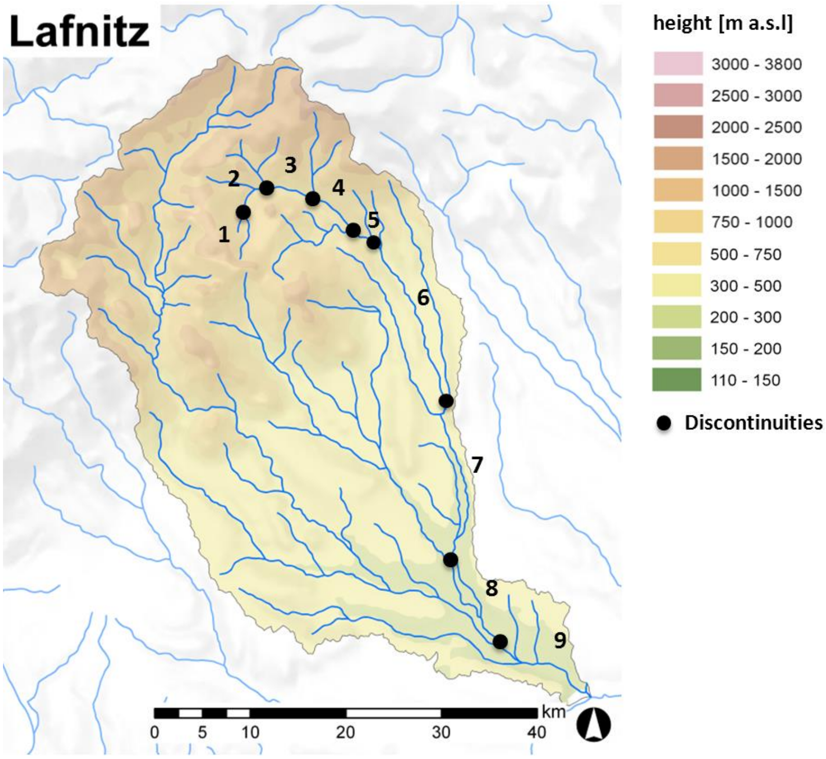

Figure 4.53 Overview of all discontinuities and thus resulting segments of the Lafnitz River (data source: HAÖ, 2007).

Table 4.10 Overview of discontinuities in valley slope, confinement and hydrology (major tributaries)

<table>
<tr><th>Segment</th><th>Valley Slope [%]</th><th>Major Tributary at the beginning of the Segment</th><th>Confinement</th></tr>
<tr><td>1</td><td rowspan="9">No discontinuities</td><td></td><td>Semi-confined</td></tr>
<tr><td>2</td><td></td><td rowspan="2">Confined</td></tr>
<tr><td>3</td><td>Weißenbach</td></tr>
<tr><td>4</td><td>Schwarze Lafnitz</td><td rowspan="2">Semi-confined</td></tr>
<tr><td>5</td><td>Voraubach</td></tr>
<tr><td>6</td><td></td><td rowspan="4">Unconfined</td></tr>
<tr><td>7</td><td>Stögersbach</td></tr>
<tr><td>8</td><td>Safenbach</td></tr>
<tr><td>9</td><td>Feistritz</td></tr>
</table>

4.4.5 Reach

The delineation of reaches is based on the channel and floodplain morphology, and artificial discontinuities that affect longitudinal continuity of sediment and water.

In total 16 reaches were delineated for the Lafnitz River. Their location and plan form type is illustrated in Figure 4.54. Reach numbers are given inFigure 4.55 and some additional information is shown in Table 4.11.

In the reaches 6.2, 7.3, 7.4 and 8.1, retention basins are located with their connection in parallel.

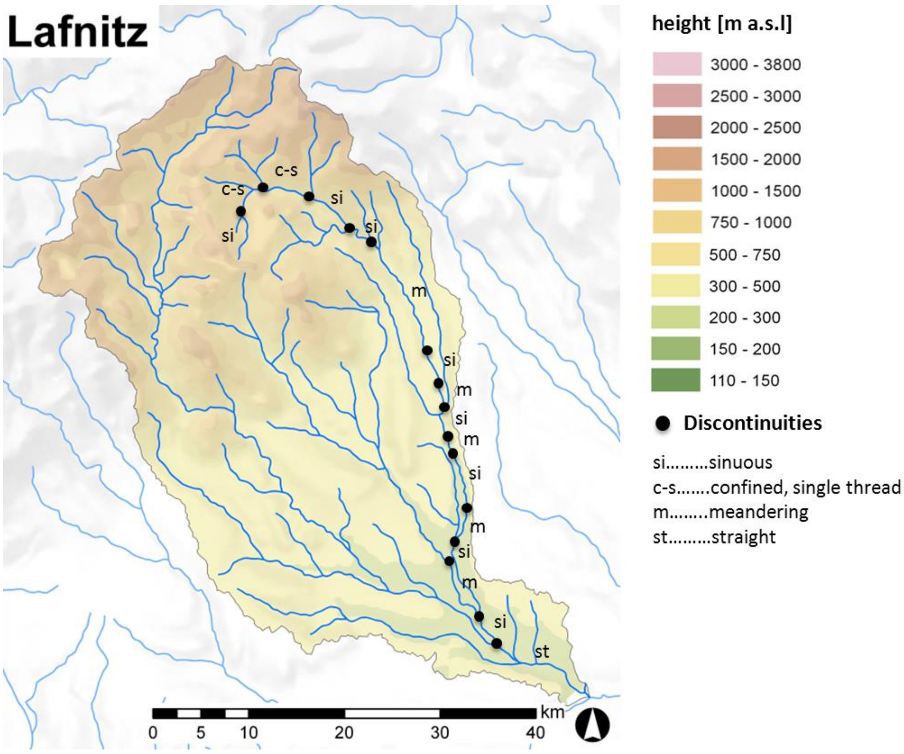

Figure 4.54 Location of reaches and indication of their planform morphology (data source: HAÖ, 2007).

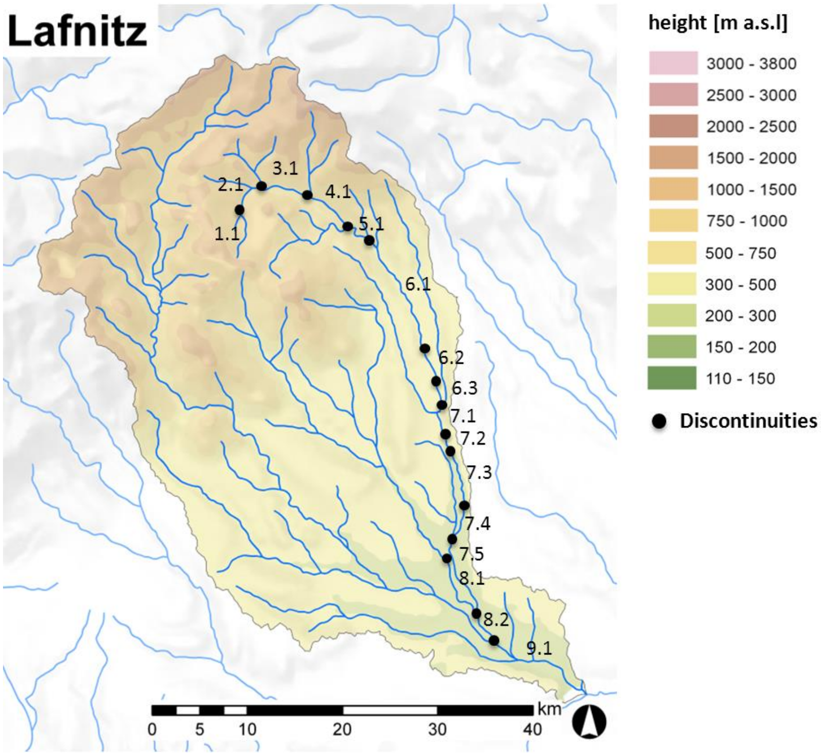

Figure 4.55 Assignation of reach numbers which are based on the segment numbers (data source: HAÖ, 2007).

Table 4.11 Overview of some reach properties.

Segment	Confinement	Reach	Reach length [km]	Planform morphology	Artificial discontinuities
1	Semi-confined	1.1	5,1	Sinuous	
2	Confined	2.1	4,0	Single thread	
3	Confined	3.1	5,8	Single thread	
4	Semi-confined	4.1	5,4	Sinuous	A retention structure is located in the middle of the reach; under mean flow conditions the discharge is not affected.
5	Semi-confined	5.1	2,9	Sinuous	
6	Unconfined	6.1	13,9	Meandering	
		6.2	4,4	Sinuous	
		6.3	2,3	Meandering	
7	Unconfined	7.1	3,7	Sinuous	
		7.2	1,5	Meandering	
		7.3	6,6	Sinuous	
		7.4	4,1	Meandering	
		7.5	2,2	Sinuous	
8	Unconfined	8.1	7,3	Meandering	
		8.2	3,6	Sinuous	
9	Unconfined	9.1	10,4	Straight	

4.5 Characterization of the Lafnitz river and catchments

4.5.1 Region

The entire Lafnitz River is located in the Illyrian biogeographic region whithin a temperate continental climate.

Based on EEA (2002), the region can also be classified as continenta. In the case of the Lafnitz River, the continental region is situated between the alpine region to the west and the Pannonian region to the east. The landscape in this area is generally hilly and the climate shows strong seasonal contrasts, e.g. warm summers and cold winters (EEA, 2002).

The soils within the continental biogeographic region are highly variable, depending on the climatic condition and the geology.

4.5.2 Catchment

The catchment area of the Lafnitz is about 1990 km² and most of it is located at altitudes between 200 and 800 m a.s.l. (72,1%). The residual area is located between 800 and 1400 m a.s.l. (26,5%) and a very small proportion can be found above 1400 m a.s.l. (1,4%). According to the Water Framework Directive the southern part of the catchment belongs to mid altitude areas (200-800 m a.s.l.) and the northern part to the high altitude areas (above 800 m a.s.l.) (Figure 4.56).

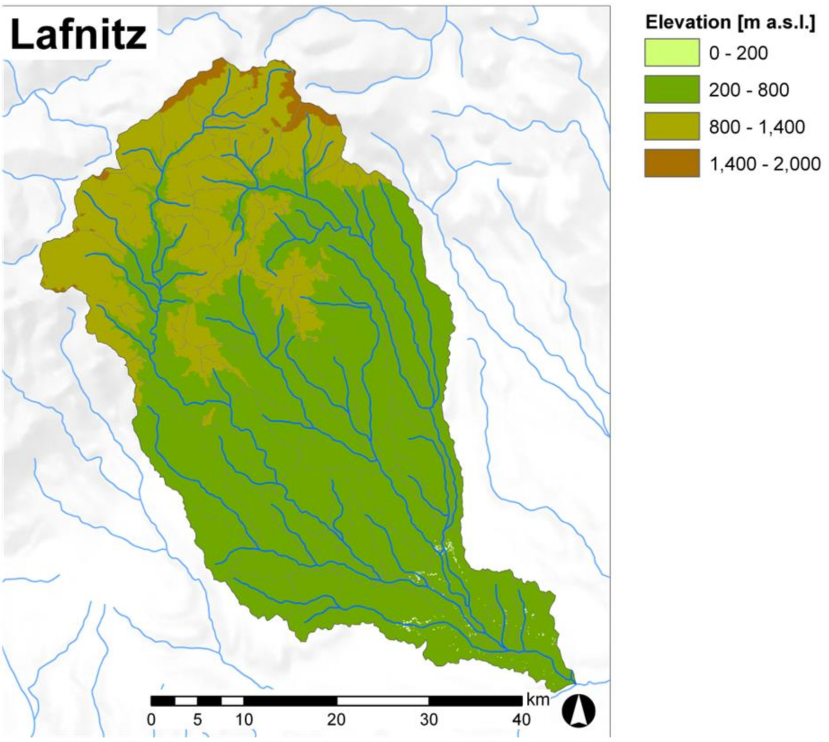

Figure 4.56 Altitudinal zones of the Lafnitz catchment (data source: HAÖ, 2007 and Jarvis et al., 2008).

The catchment has an elongated shape and several tributaries enter the Lafnitz River on both banks. Typical soil types are Cambisols, Planosols and Fluviosols. Rendzinas are present only locally in a small part of the Feistritz catchment – a sub-catchment of the Lafnitz (Figure 4.57).

Dystric Cambisols are present in the northern part of the catchment and are characterized by the absence of a layer with humus and/or clay accumulations. Cambisols further show only a weak horizontal classification and the prefix dystric indicates that the soil has a low fertility. Planosols are present in the south of the catchment, with exception of the larger valley bottoms for example the middle and downstream section of the Lafnitz and the downstream sections of the Feistritz and the Rittscheinbach, where Fluviosols are present. Planosol typically occur in wet low-lying areas and contain a subsurface layer of clay accumulation, which can lead to both seasonal waterlogging and drought stress. Within the catchment, two forms of Planosol occur, a dystric and an eutric one. Dystric indicates a low fertility of the soil whereas eutric implies a moderate to high fertility.

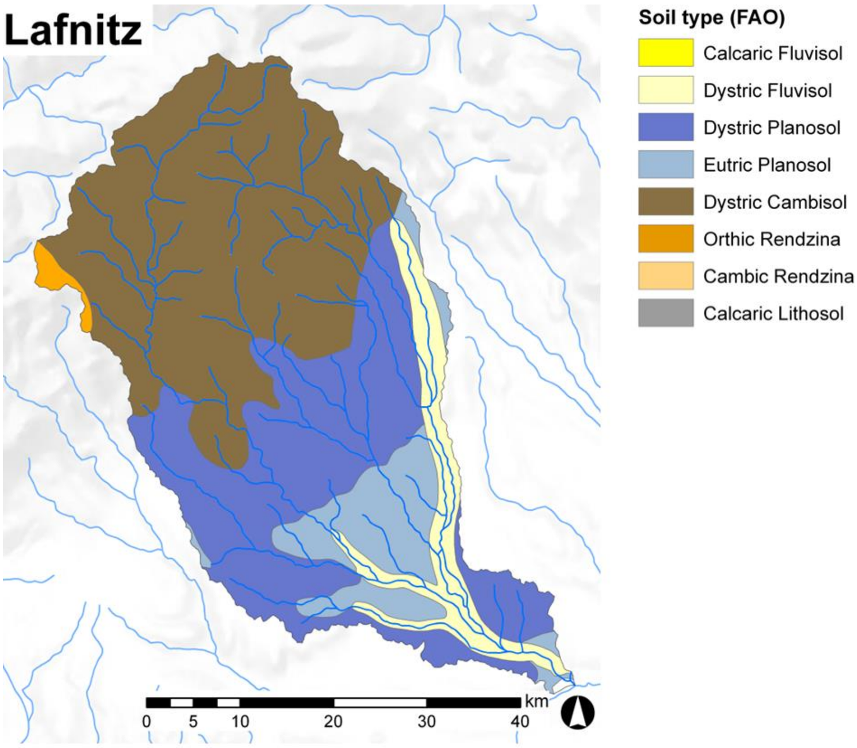

Figure 4.57 FAO soil types of the Lafnitz catchment (data source: HAÖ, 2007).

In Figure 4.58, the main aquifers are presented. The northern part, which consists of different types of rock, can easily be distinguished from the southern part of the catchment, which is represented by materials like gravel, sand, silt and clay. The pattern of the material distribution is similar to the soil types, and reflects more or less the geology of the region (Figure 4.57).

The dominant land cover classes of the Lafnitz catchment are different types of forest (in total 54,9%), arable land (36,5%) and pasture (5,9%). The spatial distribution and areal proportion of all land cover classes are shown in Figures 4.59 and 4.60. Again the northern and southern parts of the catchment are different. Almost the entire non irrigated arable land is located in the southern part, whereas pasture can be found only in the northern part. Complex cultivation (heterogeneous agricultural areas) and the different forest types are represented in the north and the south.

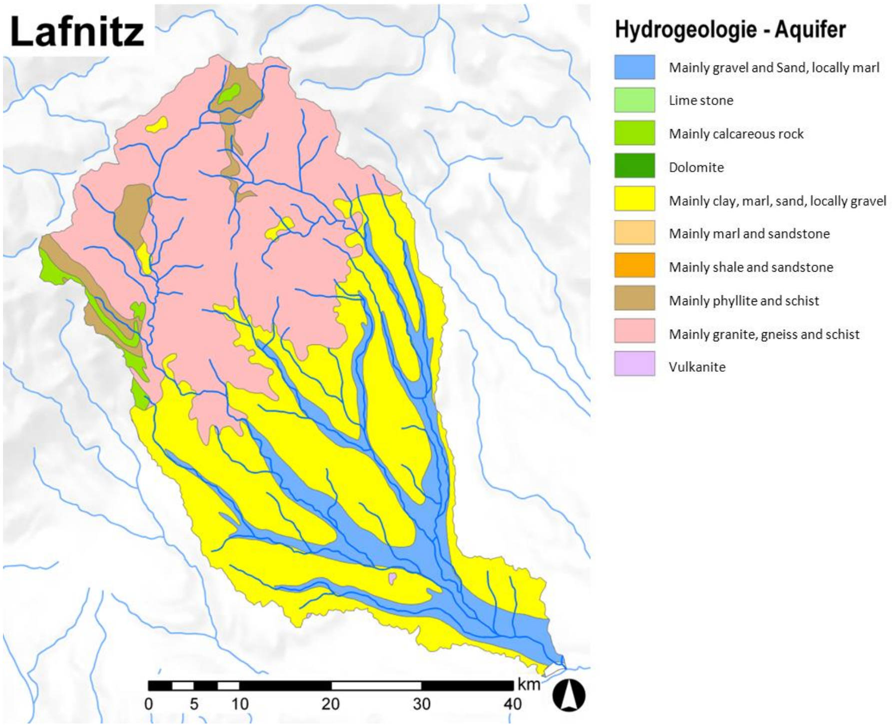

Figure 4.58 Hydrogeological classification of the Lafnitz catchment (data source: HAÖ, 2007).

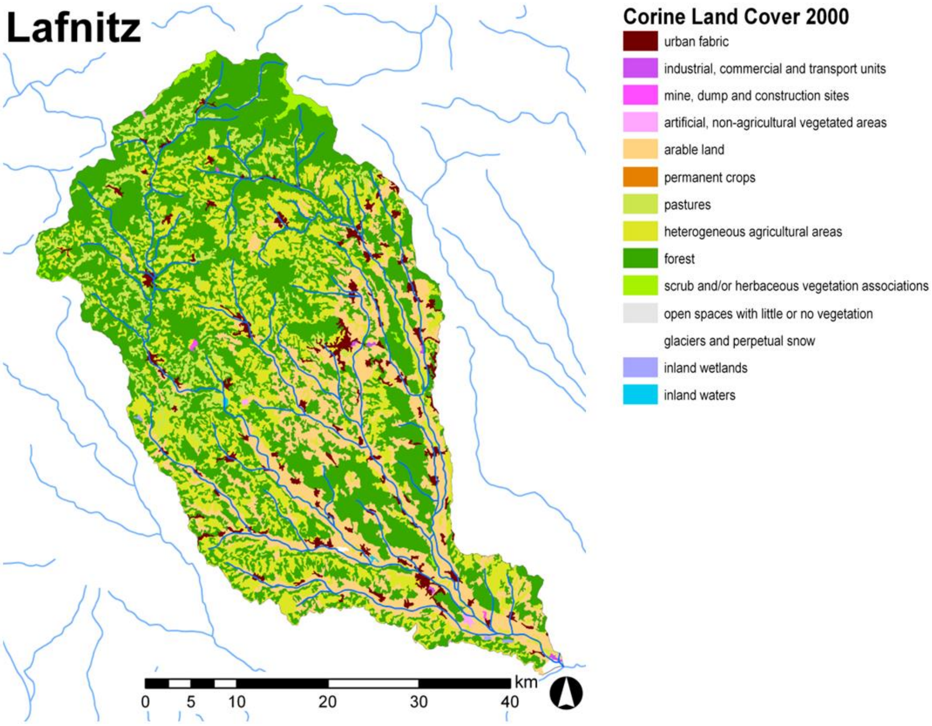

Figure 4.59 Land cover based on Corine Land Cover 2000 – Level 2 classification (data source: HAÖ, 2007 and Umweltbundesamt, 2006).

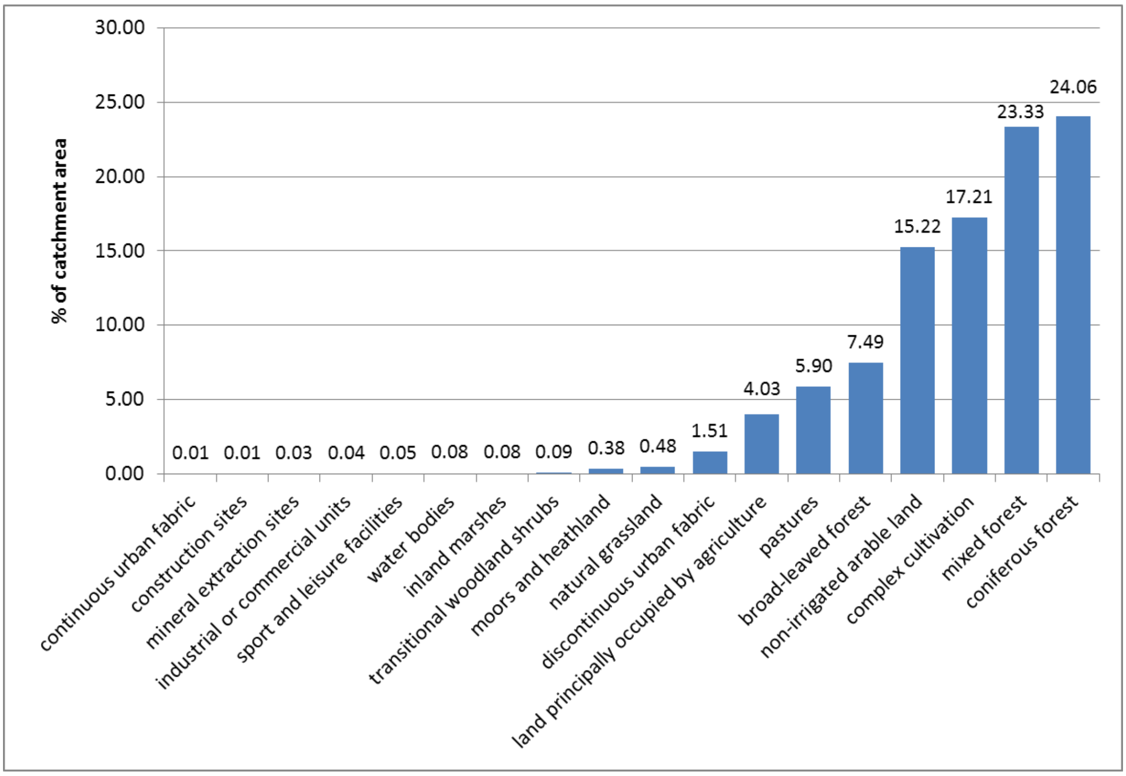

Figure 4.60 Land cover distribution in percent for the Lafnitz catchment - Level 3 classification (data source: HAÖ, 2007 and Umweltbundesamt, 2006).

4.5.3 Landscape Unit

Two landscape units have been delineated for the Lafnitz; the northern and the southern landscape unit. The characteristics (properties of water and sediment delivery potential, vegetation characteristics and some physical pressures) are evaluated for each of the landscape units individually.

The northern landscape unit (NLU) shows a dendritic drainage pattern, which represents an homogeneous terrain with no distinctive geological controls. The drainage pattern in the southern landscape unit (SLU) exhibits a more parallel pattern, suggesting a preferred drainage direction (Brierley and Fryirs, 2005). The resulting drainage density is more or less similar for the NLU and the SLU (Figure 4.61).

The mean annual precipitation for the entire Lafnitz catchment is about 842 mm. However, there is a precipitation gradient from the north to the south (Figure 4.62). The mean annual precipitation for the NLU is 915 mm, ranging from 742 to 1031 mm, and for the SLU it is 776 mm, ranging from 707 to 915 mm respectively. Similar patterns exist for the distribution of heavy precipitation intensities (Figure 4.63), the actual evapotranspiration and the mean annual runoff. They are generally higher in the NLU. than in the SLU (Table 4.12).

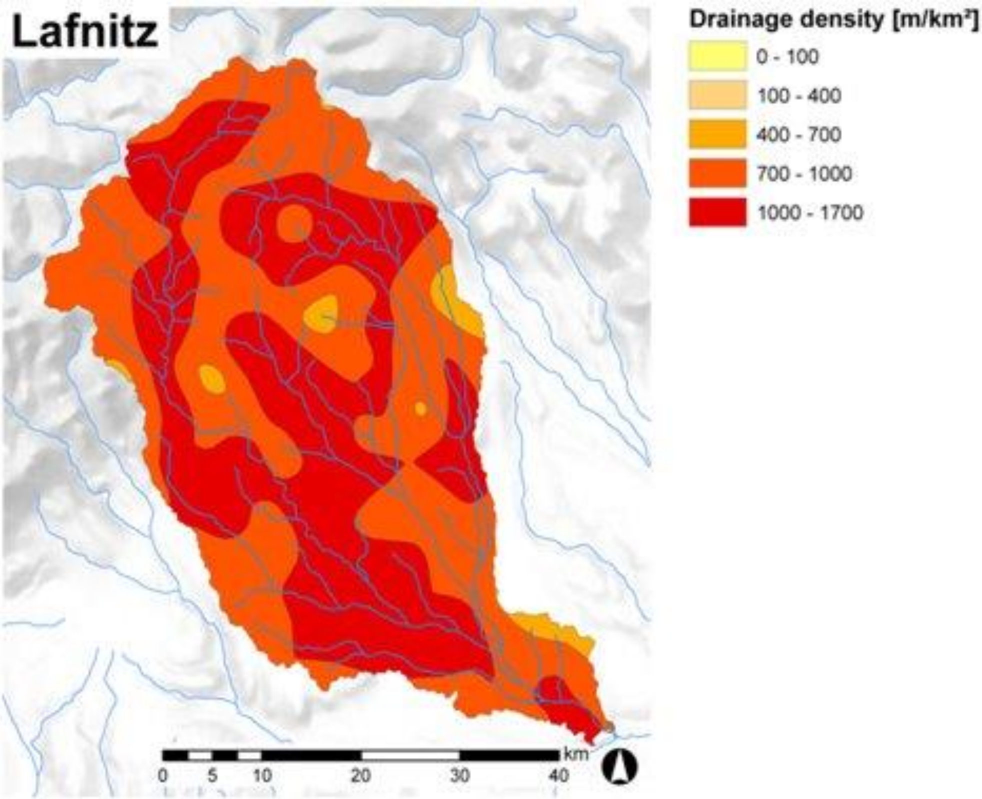

Figure 4.61 Variability in drainage density at the Lafnitz catchment (data source: HAÖ, 2007).

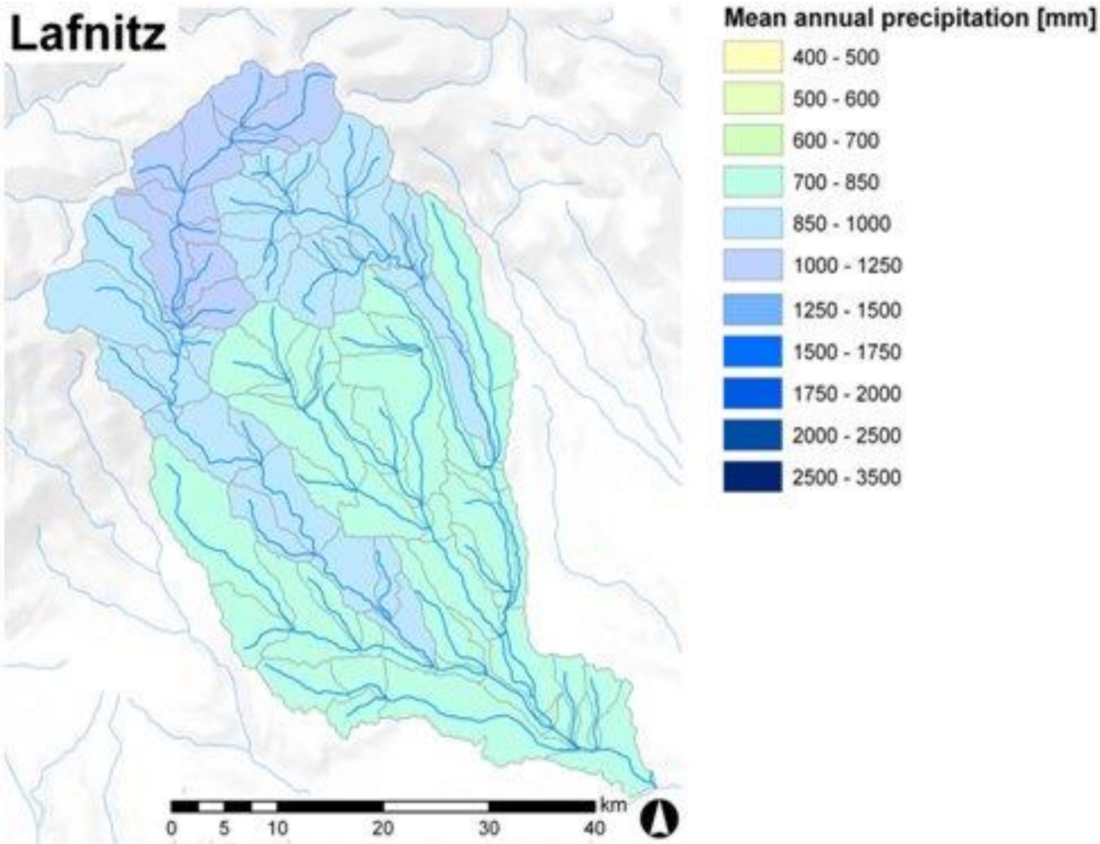

Figure 4.62 Mean annual precipitation for each subcatchment of the Lafnitz catchment (data source: HAÖ, 2007).

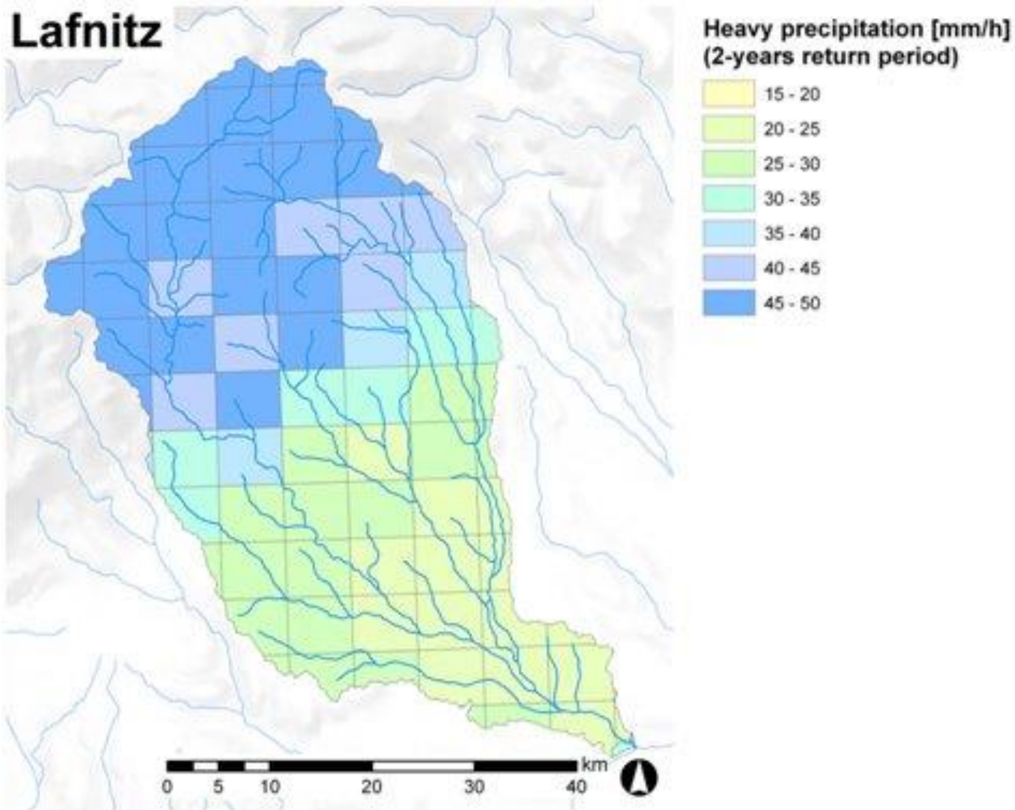

Figure 4.63 Distribution of heavy precipitation intensity with a reoccurance intervall of 2 years (data source: HAÖ, 2007).

Table 4.12 Overview of hydrological properties for both landscape units

Hydrological property	**NLU**	**SLU**
Heavy precipitation intensity* [mmh^{-1}] - mean	44,4	27,3
Heavy precipitation intensity* [mmh^{-1}] – max	48,8	45,5
Heavy precipitation intensity* [mmh^{-1}] – min	27,4	21,8
Actual evapotranspiration [mm] - mean	590,5	587,4
Actual evapotranspiration [mm] - max	582,6	563,3
Actual evapotranspiration [mm] - min	606,9	606,9
Runoff** [mm] – mean	309,7	146,1
Runoff** [mm] – max	445,6	309,4
Runoff** [mm] – min	108,3	69,1

*recurrence interval of 2 years; **based on the climatic water balance

Another difference between the two landscape units is the topography. As stated before, the NLU is located within the hilly to mountainous part of the catchment. More than two thirds of its area can be found at elevations higher than 750 m a.s.l., and the mean hill slope is 12.3 degrees. The SLU in contrast is located in a hilly terrain and almost 80% of the area lies within the elevation class of 300 to 500 m a.s.l. The mean slope is 6.1 degrees.

Additional information concerning the altitudinal zones and the hill slopes are given in Figure 4.64 and the spatial distribution of the hill slopes is shown in Figure 4.65.

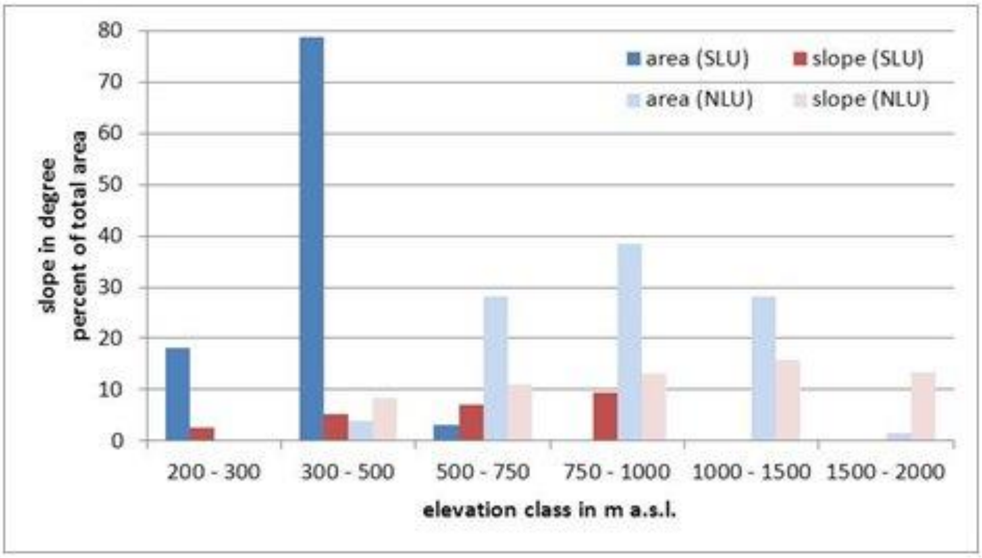

Figure 4.64 Mean slopes of the elevation classes and percentage of altitudianal class on total catchment area.

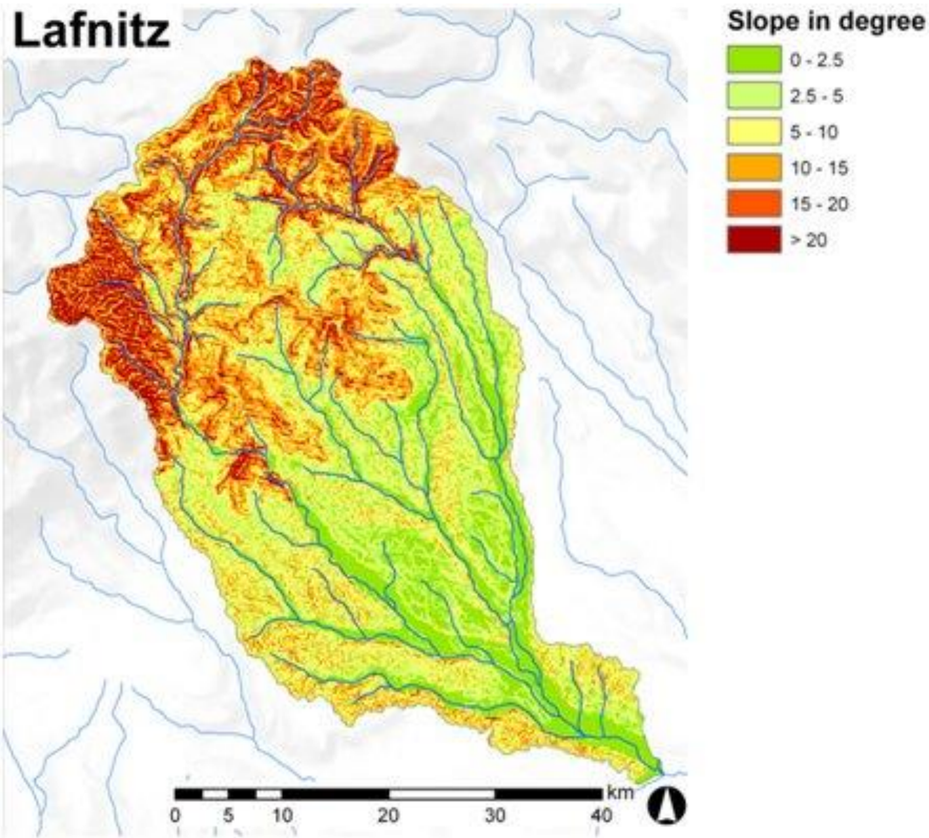

Figure 4.65 Illustration of hillslope angle of the Lafnitz catchment (data source: HAÖ, 2007 and Jarvis et al., 2008).

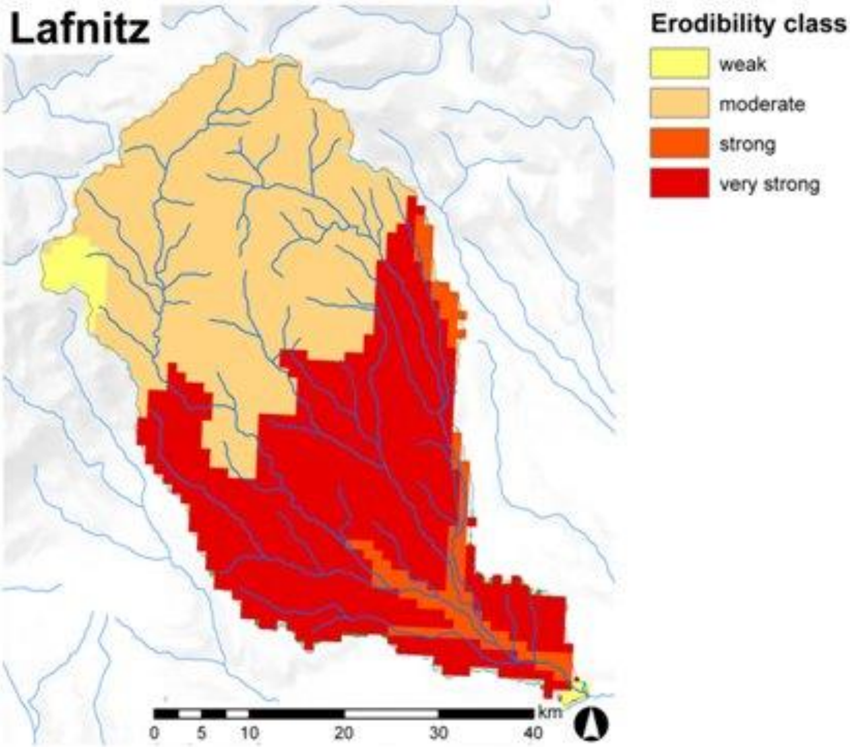

Figure 4.66 Variation of soil erodibility within the Lafnitz catchment (data source: HAÖ, 2007 and Kirkby et al., 2004).

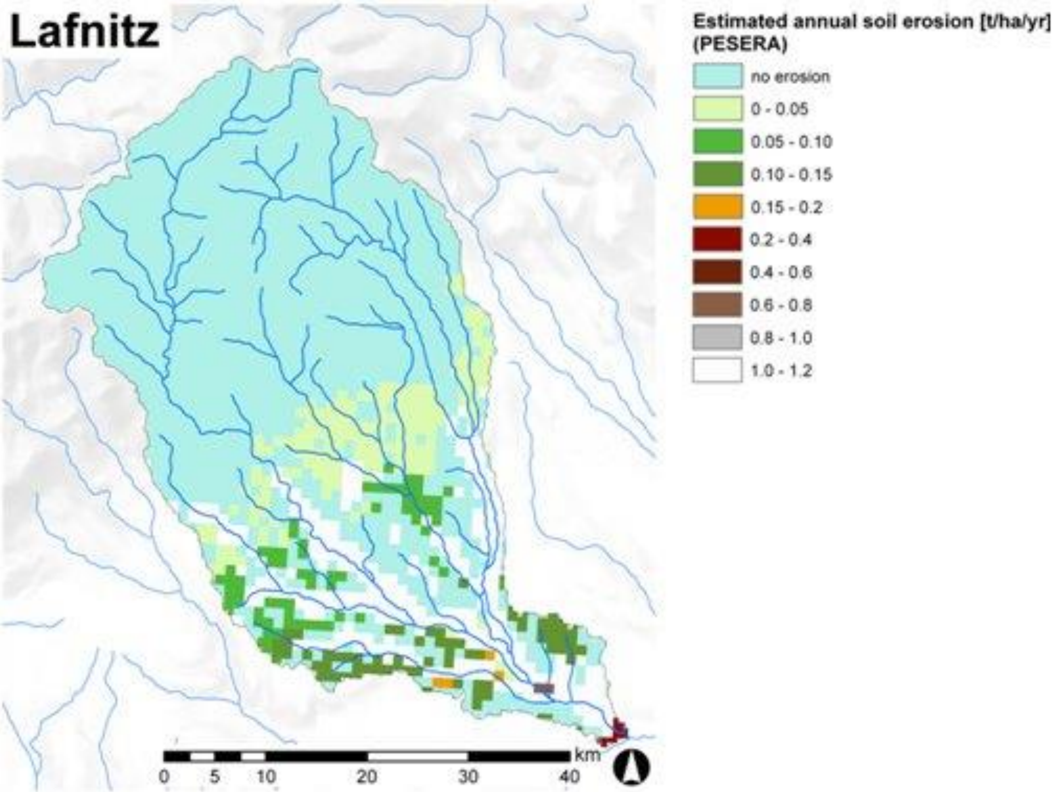

Figure 4.67 Estimated annual soil erosion based on PESERA (data source: HAÖ, 2007 and Kirkby et al., 2004).

As stated at the characterisation of the Lech River, the land cover, precipitation, relief, and soil/rock material determines amongst other properties the availability of fine and coarse material.

When looking at the spatial distribution of the erodibility classes (Figure 4.66), the dependency of the different soil/rock material can easily be assumed (c.f. Figure 4.57 and 4.58). In the NLU, where crystalline rock is the predominate material, the erodibility is lower than in the southern part, where clastic sediments (e.g. gravel, sand and clay) occur.

This is reflected in the mean annual soil erosion, presented in (Figure 4.67). Very high erosion rates occur in the valley bottoms, where arable land is the dominant land cover class. However, it has to be kept in mind that the model used for the derivation of the map has some limitations (see Kirkby et al., 2004).

The potential vegetation types and widths of the riparian vegetation along the Lafnitz River are presented in Figure 4.68. Black alder (Alnus glutinosa) is the dominant species of all the different riparian vegetation types along the Lafnitz River. In the upstream section or the NLU, black alder and green alder (Alnus viridis) occur at a very small lateral extent at both river sides. In the middle section of the Lafnitz River, from Lafnitz to Deutsch Kaltenbrunn, the riparian vegetation width increases and one of the dominant species - the green alder - is substituted by crack willow (Salix fragilis).

At the third section, the potential vegetation width exhibits a medium extent and the crack willow is gradually substituted by another willow species, the white willow (Salix alba).

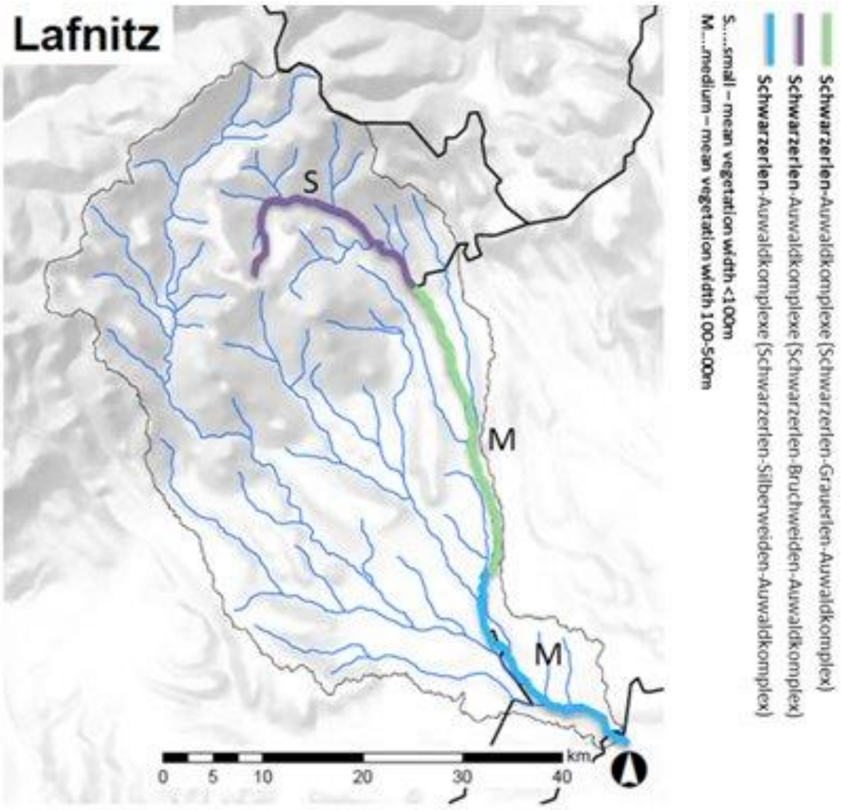

Figure 4.68 Distribution of potential riparian vegetation types and widths along the Lafnitz River (Muhar et al., 2004).

Several physical pressures with an impact on the longitudinal water and sediment transport and continuity are present. Figure 4.69 and 4.70 give an overview of the locations of these pressures. Measures of bed reinforcement are present over the entire catchment. These structures might not directly influence the downstream transport of sediment and water, but they may cause alterations in bed slope and bed material composition.

Retention structures like retention basins or torrent control structures have a higher impact on the water and sediment regime. On the Lafnitz River, six of these structures can be found: two are located upstream of Waldbach, one is between Bruck and Beigütl (Figure 4.71), one is located downstream of Wolfau, one upstream of Burgau, and the last one is located close to Dobersdorf. The purpose of these retention structures is flood protection.

Several hydropower plants are located in the catchment of the Lafnitz and on most tributaries, influencing the longitudinal continuity of water and sediments. However, only one hydropower plant is located directly on the Lafnitz River, close to the village Wörth.

A generalised map, showing the alterations and continuity interruption for each sub-catchment, is presented in Figure 4.72. It illustrates that almost the entire catchment is located upstream of a continuity interruption, and that lots of sub-catchments are affected by different kind of structures.

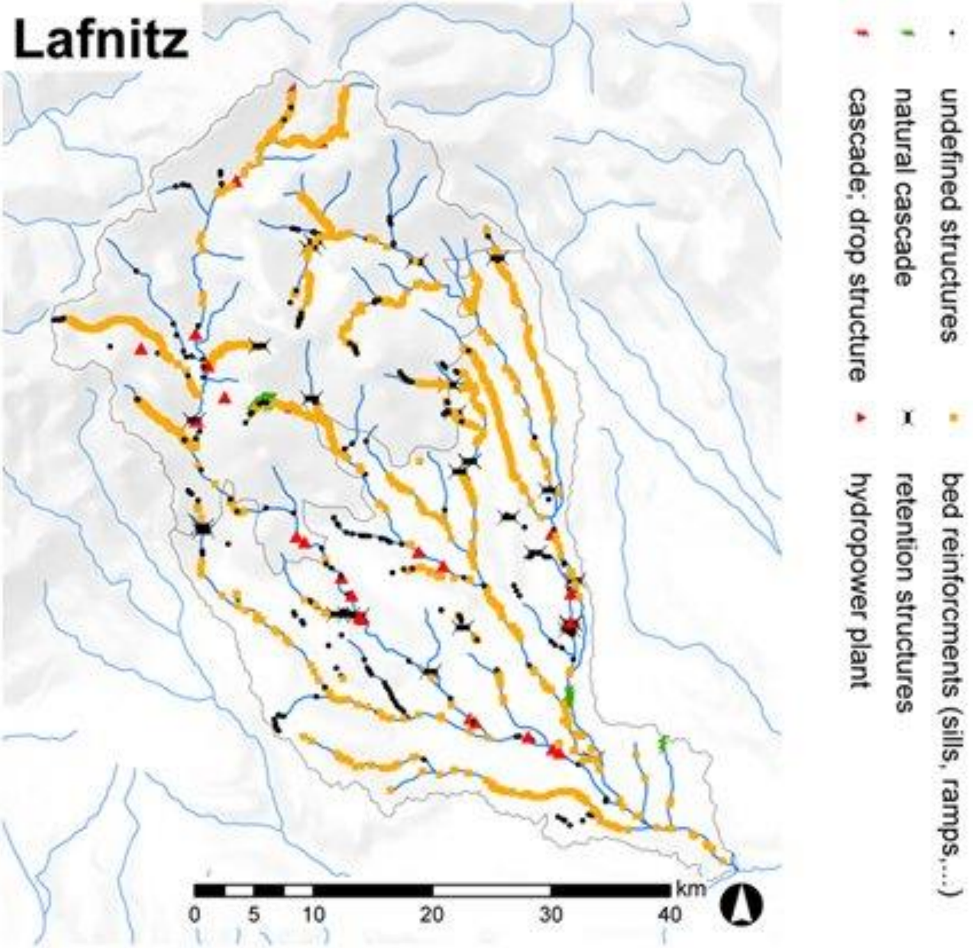

Figure 4.69 Physical pressures at the Lafnitz catchment (based on HAÖ, 2007 and Lebensministerium, 2010).

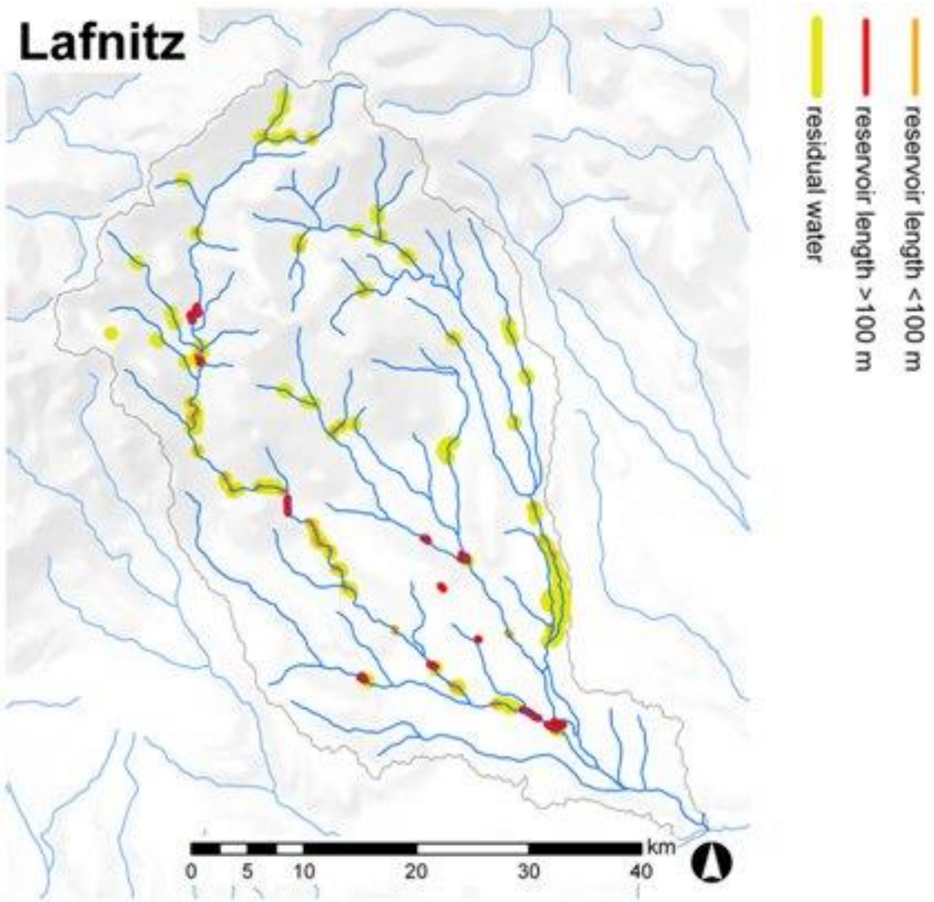

Figure 4.70 Physical pressures - reservoirs and residual water (based on HAÖ, 2007 and Lebensministerium, 2010).

Figure 4.71 Retention basin St. Lorenzen – Riegersberg (data source plan view: GoogleEarth, 2013)

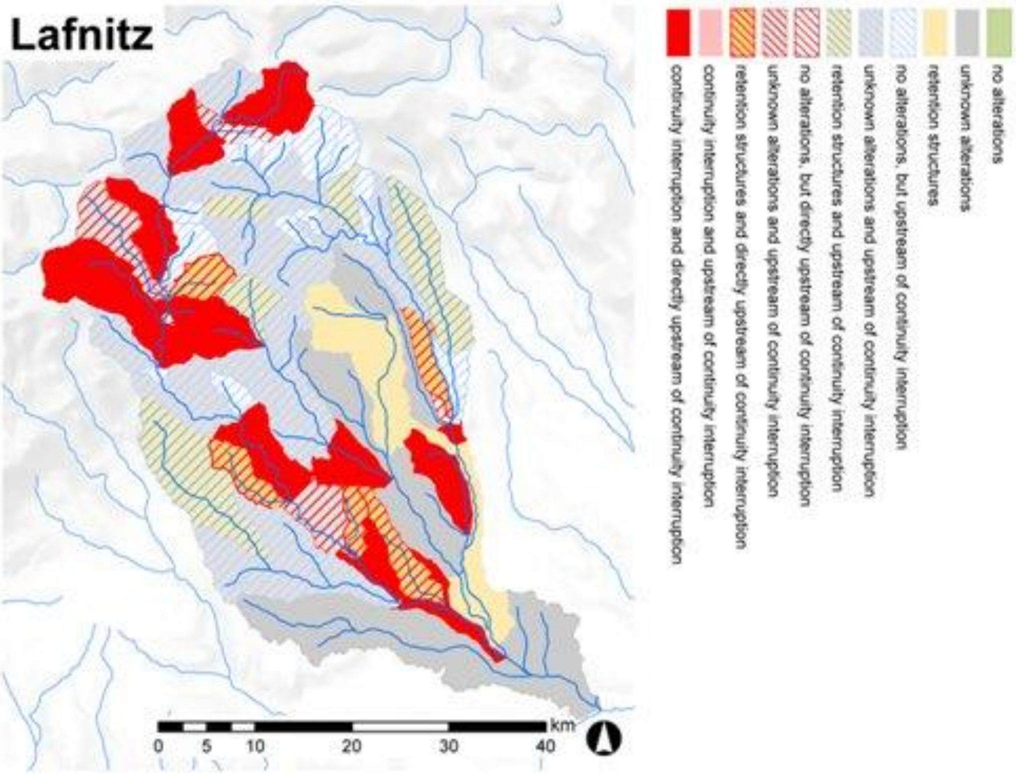

Figure 4.72 Illustration of alterations and continuity interruptions at sub-catchments (based on HAÖ, 2007 and Lebensministerium, 2010). Unknow alterations indicate that structures are present within the sub-catchment, but their impact on the downstream water and sediment continuity is unknown

4.5.4 Segment

Nine segments have been delineated on the Lafnitz River (for details seeTable 4.3). Each of them is characterised in terms of flow regime, valley characteristics, sediment and riparian vegetation. As for the Lech River, physical pressures have been described at the landscape unit scale and are thus not repeated here.

(i) Hydrological properties

Data from five gauging stations are available for the Lafnitz River. They are located at Rohrbach (segment 6), Hammerkastell (segment 6, downstream of Lafnitzer Haide), at Wörth (segment 7), at Dobersdorf (segment 8) and at Eltendorf (segment 9). No gauging stations are located in segments one to four. Some characteristic values for the gauging stations are given in Table 4.13. The hydrological regime is summer pluvial for all segments upstream of the junction with the Feistritz River, wher it changes into a pluvial nival regime. Both are complex flow regimes with more than one peak of mean monthly dicharge.

A summer pluvial regime is a regime where the maximum discharge occurs during the summer months, but which is not influenced by snowmelt. The annual floods are based on heavy precipitation events. The pluvio nival regime on the other hand is also influenced by snow melt as well as heavy rainfall.

The Feistritz is a right bank tributary of the Lafnitz and represents about 42% of the entire catc hment area. The catchment area of the Feistritz is partially located in higher mountainous zones, where precipitation occurring in the winter months might be stored as snow and released in the spring during snow melt. The hydrological regime of the Feistritz is thus pluvio nival and alters the character of the Lafnitz from their confluence downstream.

The complex hydrological regime of the Lafnitz is illustrated in Figure 4.73 for all gauging stations, and the lowest and highest flow for each month are given in Figures 4.74 and 4.75, respectively.

For 2008, hydrographs for several stations are shown in Figure 4.76. It seems that 2008 does not represent a typical hydrological year as shown in Figure 4.73. However, the flood peaks occur in the summer time and are caused by rainfall events.

Table 4.13 Hydrological regime and characteristic values for five gauging stations on the Lech River (in m^3/s)

	Rohrbach	**Hammer-kastell**	**Wörth**	**Dobersdorf**	**Eltendorf (Hackwiesen)**	**References**
Regime	summer pluvial				pluvio nival	Mader et al., 1996
NQ	0,33	0,55	0,37	0,48	1,80	BMLFUW, 2009
MQ	2,54	2,62	3,65	6,46	14,0	
HQ_1	35	-	40	47	138	Lebensministerium
HQ_2	66	-	68	152	288	2013
HQ_5	80	-	90	191	362	
HQ_{30}	-	-	-	256	480	

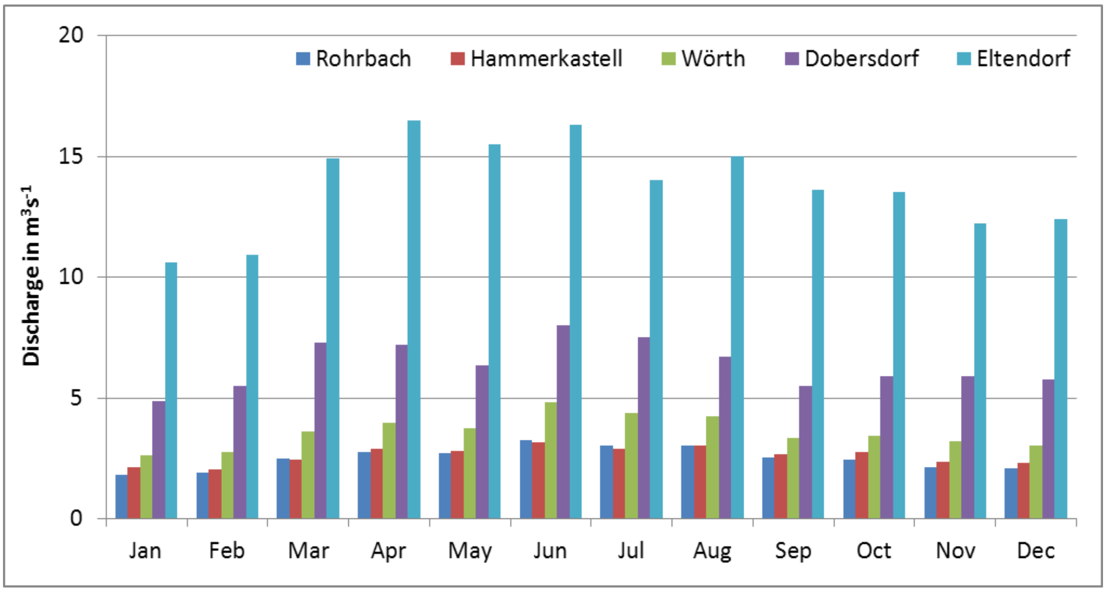

Figure 4.73 Mean monthly discharges for the four gauging stations at the Lafnitz. The time periods used are 1966-2008 for Rohrbach, 1982-2008 for Hammerkastell, 1961-2008 for Wörth, 1951-2008 for Dobersdorf and 1981-2008 for Eltendorf (based on BMLFUW, 2009).

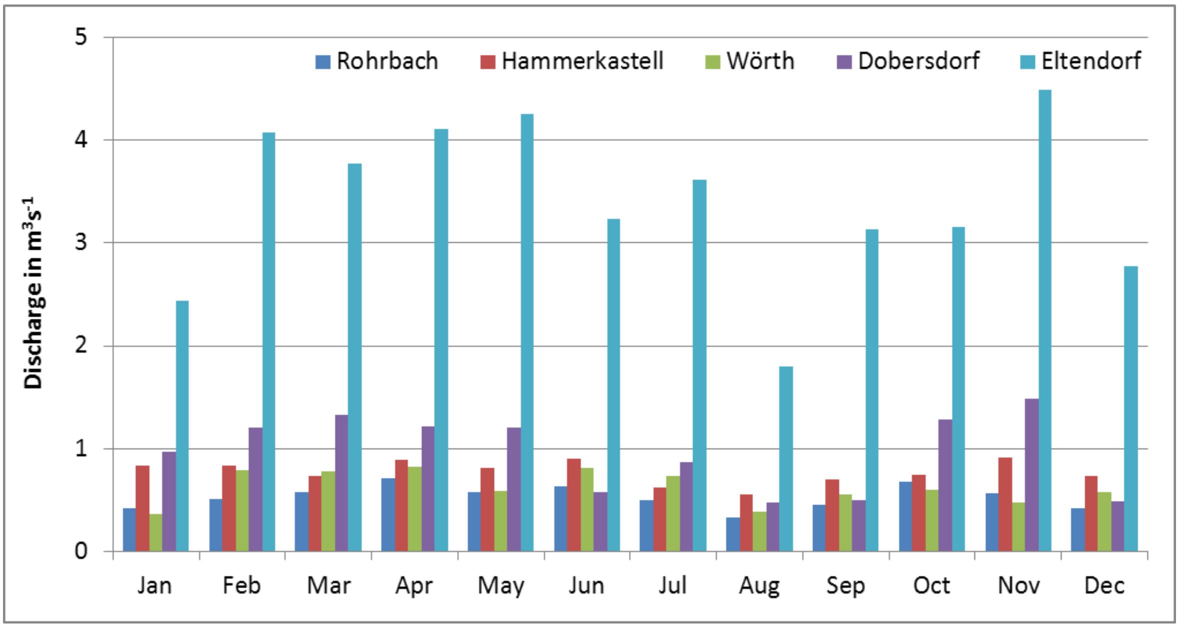

Figure 4.74 Minimum discharge for each moth over the period 1966-2008 for Rohrbach, 1982-2008 for Hammerkastell, 1961-2008 for Wörth, 1951-2008 for Dobersdorf and 1981-2008 for Eltendorf (based on BMLFUW, 2009).

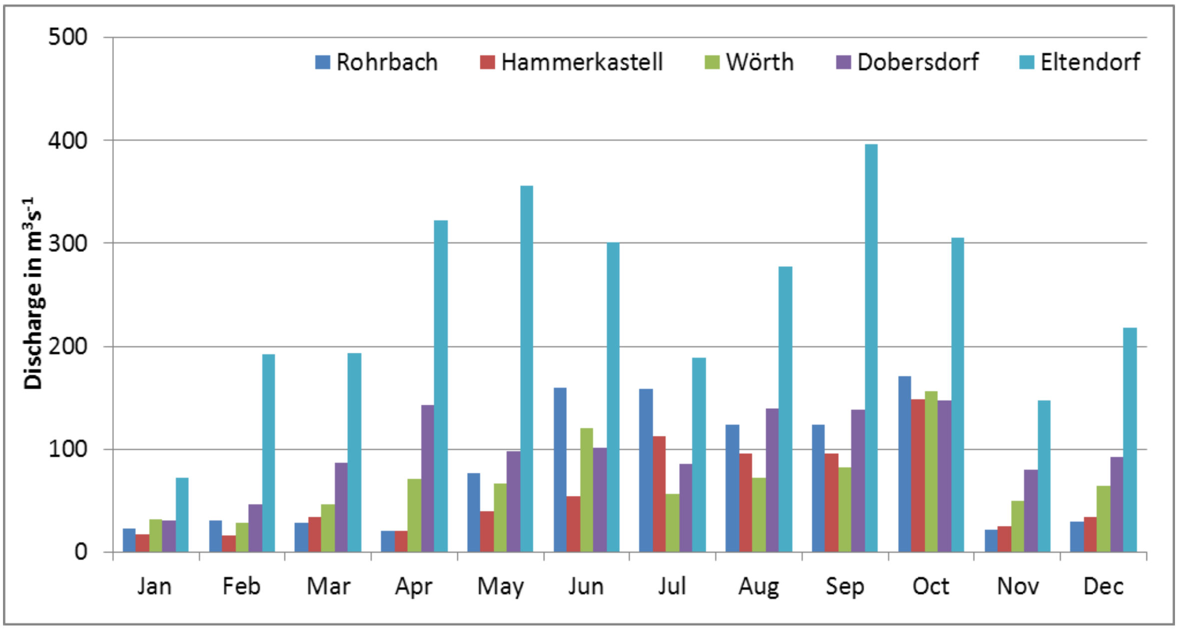

Figure 4.75 Maximum discharge for each moth over the period 1966-2008 for Rohrbach, 1982-2008 for Hammerkastell, 1961-2008 for Wörth, 1951-2008 for Dobersdorf and 1981-2008 for Eltendorf (based on BMLFUW, 2009).

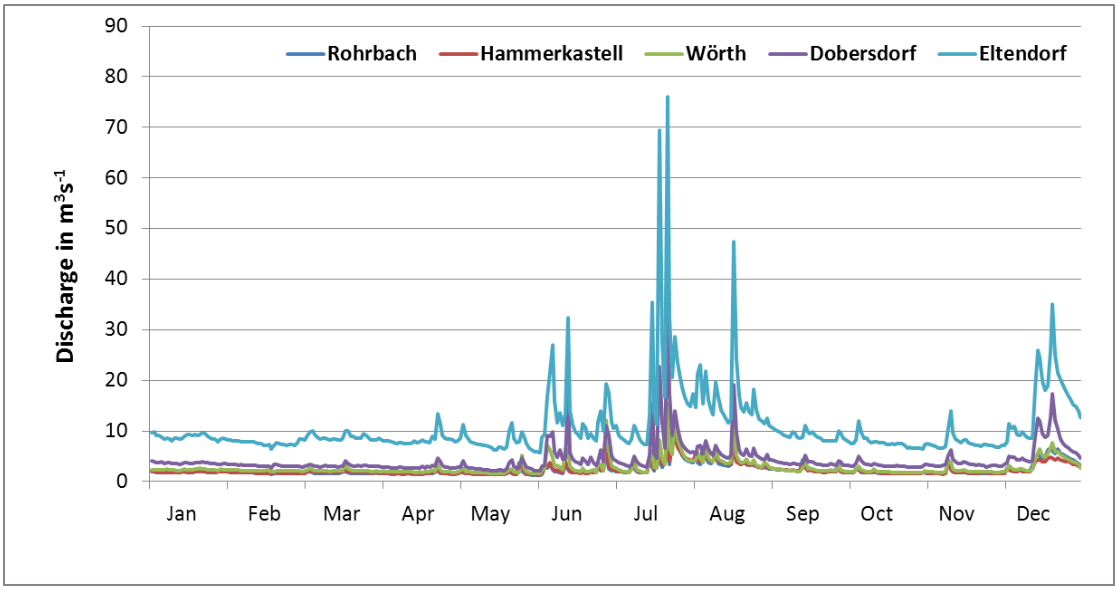

Figure 4.76 Hydrographs for the year 2008 for several gauging stations at the Lafnitz River (based on BMLFUW, 2009).

For the entire case study catchment, the annual flood occurs during the summer months, but the statistical significance of the timing is only medium to weak (Figure 4.77). In Figure 4.78, alterations of the mean annual discharge are illustrated. Two different areas can be identified, the northern part with no changes of mean annual discharge for the Lafnitz River (segments one to six) and significant increases for the Feistritz River, and a southern part where the mean annual discharge has decreased.

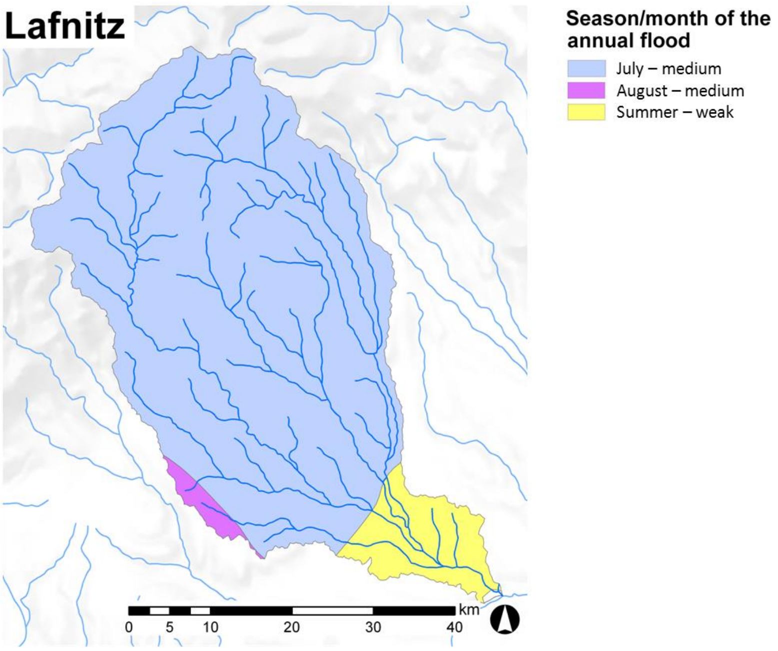

Figure 4.77 Season/month of the annual flood; medium and weak indicate the signigicance that the annual flood occurs in a certain month/season (data source: HAÖ, 2007).

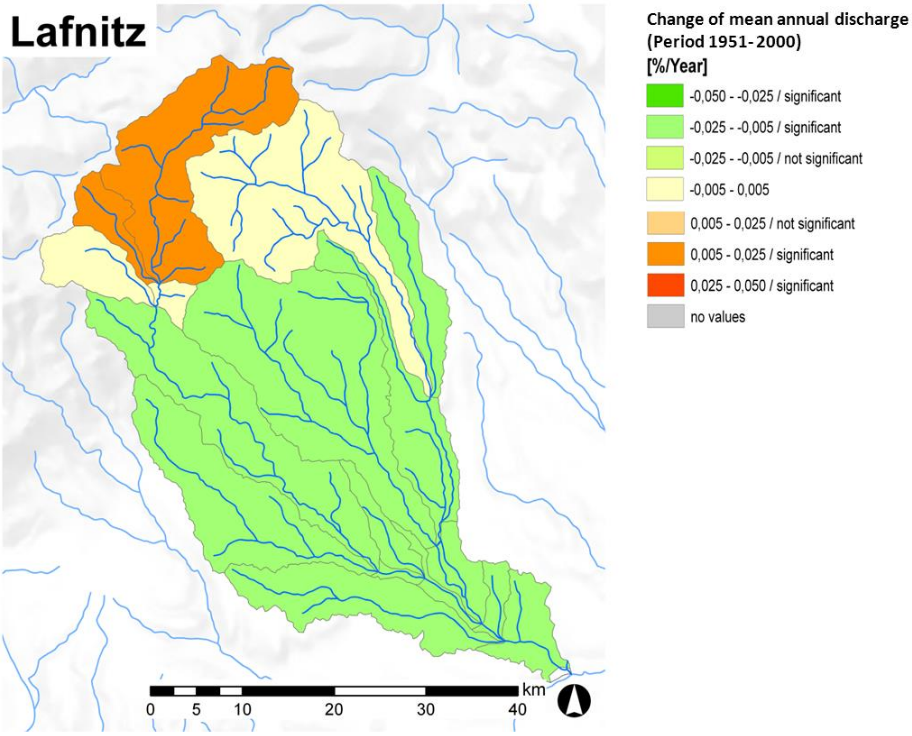

Figure 4.78 Change of mean annual discharge from 1951 to 2000 (data source: HAÖ, 2007).

(ii) Topography

An overview of some topographical features is given in Table 4.14.

Table 4.14 Characterisation of segments in terms of valley gradient, valley bottom extent, mean bankfull width, and presence (lateral extent) of riparian vegetation.

Segment	Valley gradient [%]	valley bottom extent [m]	Mean bankfull width [m]	Lateral extent of riparian vegetation*
1	>3	Not defined (n.d.)	n.d.	Small
2	1-3	<100	10	Small
3	1-3	<100	13	Small
4	1-3	100-200	16	Small
5	1-3	100-200	16	Medium
6	0,5-1	500-1000	20	Medium
7	0-0,5	1000-1500	20	Medium
8	0-0,5	1500-2500	25	Medium
9	0-0,5	>2500	40	Medium

* lateral extent of riparian vegetation based on Muhar et al. (2004)

(iii) Vegetation

Based on the classification of growing regions (Kilian et al., 1993), segments one to four can be assigned to the "Ost- und Mittelsteirisches Bergland", whilst segments five to nine are allocated in the "Subillyrisches Hügel- und Terassenland". The plant associations for the regions are presented in Tables 4.15 and 4.16.

Table 4.15 Plant associations of altiduinal zones in the "Ost- und Mittelsteirisches Bergland" (Kilian et al., 1993). A. oak-European hornbeam forest; B. European beech forest with fir and Scots pine; C. Scots pine forest (locally, at shallow soils); D. mixed leaf forest with sycamore maple, European ash and Scots elm (humid areas); E. fir-spruce forest; F. spruce forest; G. Latschengebüsch (*pinus mugo supsp.)* and green alder forest.

Altitudinal zone	Elevation [m]	Growing regions and plant associations						
		Ost- und Mittelsteirisches Bergland						
Submontane	300-700	A	B	C	D			
Montane	700-900		B	C	D			
Midmontane	900-1100			C	D	(E)		
Altimontane	1100-1400					E		
Subalpine (low)	1400-1700						F	
Subalpine (high)	1700-1800							G

Table 4.16 Plant associations of altiduinal zones in the "Subillyrisches Hügel- und Terassenland" (Kilian et al., 1993). A. oak – European hornbeam forest; B. Scots pine – oak forest (at acidic areas); C. European beech with oak, fir and Scots pine; Riparian forests: white willow riparian forest (larger rivers), black alder – ash forest (smaller rivers); mixed leaf forests (at nutrient-rich, humid locations).

Altitudinal zone	Elevation [m]	Growing regions and plant associations		
		Subillyrisches Hügel- und Terassenland		
Foothill	200-300	A	B	
Submontane	300-670	A	B	C

Segment 1: In this segment, stretches with continuous vegetation bands on both river sides alternate with discontinuous vegetation patches. The vegetation structure and density varies depending on the location.

Segment 2: The upstream part of segment two is mainly accompanied by continuous vegetation along both sides. As this segment is confined, the banks are in contact with the vegetated hill slopes. At the downstream part of the segment, the vegetation along the river becomes patchier and the lateral extent decreases. The floodplain increases in width, but a high percentage is covered with urban areas and agricultural lands (pasture and meadows).

Segment 3: The vegetation along this segment is characterised as a continuous band of vegetation on both banks, but with a very small lateral extent (about 10 m). The structure is heterogeneous and includes smaller and higher forms of vegetation. The stand density of the vegetation is more or less homogeneous over the entire segment.

Segment 4: This segment is similar to the previous one. Vegetation is present continuously at both sides of the river, but with a small lateral extent.

The valley bottoms of segments 5 to 9 are used for agriculture, which constrains the lateral extents of the riparian forests in this area.

Segment 5: Vegetation is present at both sides of the river, mostly with a small lateral extent. Only at areas where one of the banks is in contact with the vegetated hill slopes, the lateral extent is larger. The structure of the vegetation is mostly homogeneous. However, in the urban areas the longitudinal extent of the vegetation becomes discontinuous and the structure is patchier.

Segment 6: In this segment, the vegetation is characterised by a heterogeneous structure – in the longitudinal and lateral extent, the density and so on (Figure 4.79). Despite the variety, two main patterns can be identified based on the sinuosity of the river: straight to sinuous stretches show a small lateral extent and are more homogeneous than meandering stretches, where the lateral extent is larger.

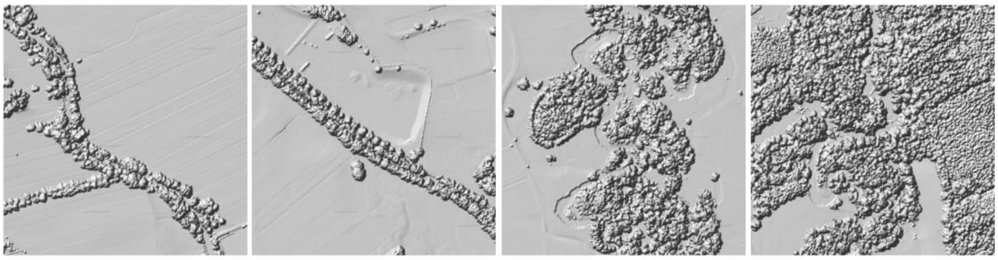

Figure 4.79 Vegetation variety in segment 6.

Segment 7: The vegetation in segment seven is very heterogeneous and the lateral extent is mostly small.

Segment 8: This segment is similar to segment seven. The vegetation structure is heterogeneous and the lateral extent is small. Only some stretches are characterised by a larger lateral extent of the riparian vegetation.

Segment 9: This segment is characterised by discontinuous patches of vegetation with small lateral extents.

4.5.5 Reach

Detailed data concerning bed material calibre, channel dimensions and flow parameters are only available for some very short reaches at the Lafnitz River and do not represent entire reaches. Thus, they are not presented here, but for details see Habersack et al. (2000).

Physical pressures limiting the vertical and lateral exchange of water and sediments are available for the entire river network of the Lafnitz. Impacts on the bed and the banks are illustrated in Figures 4.80 and 4.81, respectively. For the definitions of each class see section 4.2.5.

The river bed of the Lafnitz generally shows only minor alterations, e.g. some local reinforcements like sills and ramps (see also Figure 4.82), and bank protections are mostly limited to local reinforcements. Details for each segment can be found in Table 4.17.

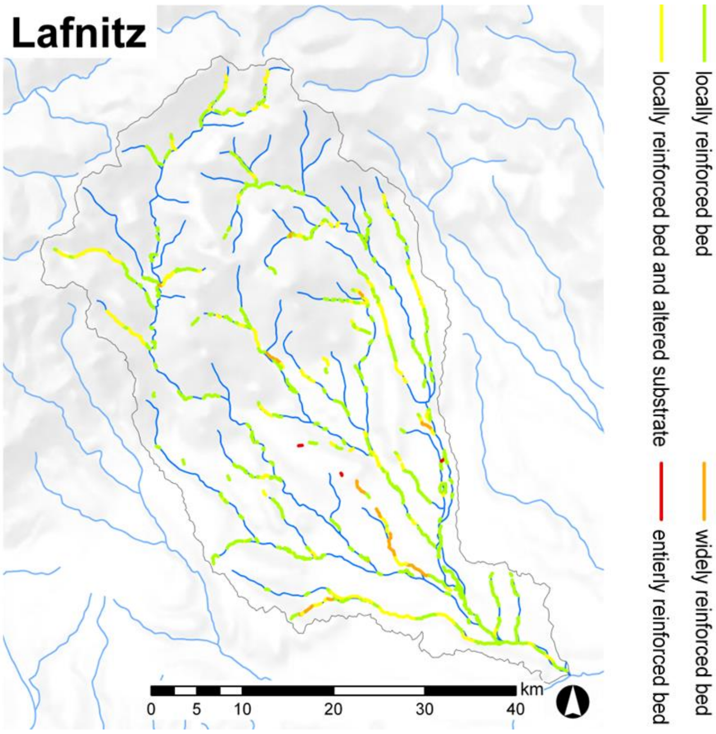

Figure 4.80 River stretches with anthropogenic impacts on the bed (based on HAÖ, 2007 and Lebensministerium, 2010).

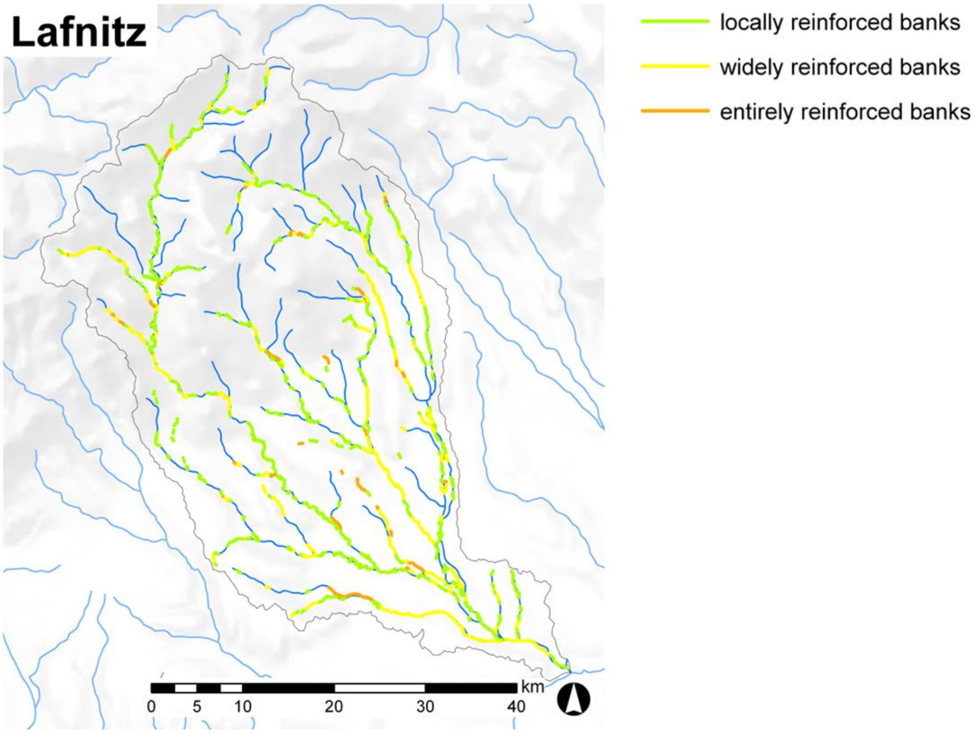

Figure 4.81 River stretches with anthropogenic impacts on the banks (based on HAÖ, 2007 and Lebensministerium, 2010).

Table 4.17 Overview of bed and bank alterations (data based on the NGP 2009 (Lebensministerium, 2010)).

Reach Nr.	Bank reinforcement	Bed reinforcement and alteration of sediments
1.1	no to negligible alterations	no to negligible alterations
2.1	approx. one quarter is locally, one widely and one entirely reinforced; the rest is not altered	locally reinforced bed, only at small sections the substrate is altered
3.1	locally reinforced banks	locally reinforced bed
4.1	locally reinforced banks	no to negligible alterations
5.1	locally reinforced banks	no to negligible alterations
6.1	The downstream half is not altered, the upstream one is locally to widely reinforced.	Almost at the entire reach, the bed is not or only negligilbe altered.
6.2	locally reinforced banks, at some parts widely reinforced	locally reinforced bed
6.3	no to negligible alterations	Almost at the entire reach the bed is not or only negligilbe altered.
7.1	widely reinforced banks	half of the reach is locally reinforced with bed alterations, the other half is not altered.
7.2	locally reinforced banks	half of the reach is locally reinforced, the rest is not altered.
7.3	Half of the reach is locally reinforced, one quarter is widely reinforced and the rest is not altered.	half of the reach is locally reinforced, the rest is not altered.
7.4	no to negligible alterations	no to negligible alterations
7.5	locally reinforced banks	locally reinforced bed
8.1	half of the reach is locally reinforced, the rest is not altered.	half of the reach is locally reinforced, the rest is not altered.
8.2	locally reinforced banks	locally reinforced bed
9.1	half of the reach is locally reinforced, the rest widely reinforced.	locally reinforced bed, only at small sections the substrate is altered

4.6 Summary

An overview of the characterisation and delineation properties is given in Table 4.18.

The Lafnitz River is located in one biogeographical region and is further delineated into two landscape units (the northern part and the southern part), nine segments (mean length: 9,2 km) and sixteen reaches (mean length: 5,2 km).

The catchment is located in two geological zones. The northern part belongs to the Austroalpine Crystalline Complexes which consist of orthogneiss, paragneiss, micaschist, amphibolite and quarzphyllite, and the southern part is located in a tertiary basin, consisting of clastic sediments like gravel, sand and clay. Apart from the geology, the topography, the soil and the land cover indicate the boundary between the northern and the southern part.

The northern area is mountainous and has a high altitude (elevations above 800 m a.s.l.). The hill slopes are generally steeper, the valleys are narrower and the main land cover classes are forest, pastures and heterogeneous agricultural crops. Only a few small areas of the northern part of the catchment are covered with arable land, which is one of the dominant land cover classes in the south. In the southern part, the topography is hilly and the ground level elevations are between 200 and 800 m.a.s.l. Less precipitation occurs in the south than in the north, causing a mean annual runoff of 146 mm in the south and 310 mm in the north, respectively.

Another major difference between the two landscape units is the mean annual soil erosion. Based on the differences in the geology, topography, precipitation, land cover and so on, the soil erosion rate is much larger in the south than in the north. Up to 1,2 t ha^{-1} yr^{-1} may be reached in the southern part.

The upstream part of the Lafnitz is located in a confined to semi-confined topography. In this area the valley gradient is higher and the river oscillates from one side of the valley to the other. Three retention structures for flood protection are installed in this area, which might alter the downstream transport of water and sediment.

With the change of the geology around the village of Rohrbach, the valley widens and the Lafnitz starts meandering, occasionally interrupted by sinuous stretches. Close to the village of Wörth there is a hydropower plant which represents a major discontinuity of the sediment transport. Additional to the hydropower plant, two retention structures are located in the middle section of the Lafnitz.

The downstream part of the Lafnitz is, except for the longitudinal interruptions (hydropower plant and retention structures), similar to the middle section.

Table 4.18 Overview of delineation and characterisation results for the Lafnitz River.

Reach			Segment							Landscape Unit									Catchment						Region	
Reach number	Reach length [km]	River planform	Segment number	Segment length [km]	Confinement	flow regime	valley gradient [%]	mean valley bottom extent [m]	mean bankfull width [m]		Landscape Unit length	Riparian complex	estimated annual soil erosion	hillslope	geology, elevation, relief	mean annual runoff	mean actual evapotranspiration	mean annual precipitation		Catchment / Region length	Land cover / land use	soil types	topography/elevation	catchment area		Bioclimatic and Bio-geographic Region
1.1	5.1	Sinuous	1	5.1	Semi-confined	summer pluvial	>3	n.d.	n.d.	I.	23.2 km	black and green alder dominate the riparian zone	no or negligible soil erosion rates	for most of the landscape unit >10 degree	crystalline rock, mountainous to hilly topography	309.7	590.5	915mm - ranging from 742 to 1031 mm	A	83.2 km	forest (54,9%), arable land 36,5%), pastures (5,9%) and less than 2% artificial surfaces like urban fabric, etc.	Cambisol in the north, Planosol and Fluvisol in the south; most soils ehibit a low fertility	mid altitude areas (200-800 m a.s.l.) in the south (72.1%), high altitude areas (>800 m a.s.l.) in the north (27.9%)	1990 km²	A	Illyrian biogeographic region, temperate continental climate
2.1	4.0	Single thread	2	4.0	Confined	summer pluvial	1-3	<100	10																	
3.1	5.8	Single thread	3	5.8	Confined	summer pluvial	1-3	<100	13																	
4.1	5.4	Sinuous	4	5.4	Semi-confined	summer pluvial	1-3	100-200	16																	
5.1	2.9	Sinuous	5	2.9	Semi-confined	summer pluvial	1-3	100-200	16																	
6.1	13.9	Meandering	6	20.6	Unconfined	summer pluvial	0.5-1	500-1000	20	II.	60 km	black alder with different willow species (crack willow in the upstream part and white willow in the downstream part)	negligible erosion rates up to 1.2 t/ha/yr	for most of the landscape unit <10 degree	tertiary sediments, hilly terreain	146.1	587.4	776 mm - ranging from 707 to 915 mm								
6.2	4.4	Sinuous																								
6.3	2.3	Meandering																								
7.1	3.7	Sinuous	7	18.1	Unconfined	summer pluvial	0-0.5	1000-1500	20																	
7.2	1.5	Meandering																								
7.3	6.6	Sinuous																								
7.4	4.1	Meandering																								
7.5	2.2	Sinuous																								
8.1	7.3	Meandering	8	10.9	Unconfined	summer pluvial	0-0.5	1500-2500	25																	
8.2	3.6	Sinuous																								
9.1	10.4	Straight	9	10.4	Unconfined	pluvio nival	0-0.5	>2500	40																	

5. Discussion

This study illustrates the application of the multi-scale framework on two, very different Austrian case study catchments - the river Lech and the river Lafnitz.

5.1 Lech

The results of the application of the framework illustrate that the Lech is dominated by bed load inputs from surrounding torrents, debris flow events and other mass movements. The characteristics of these torrents are that the material transport is pulsed, which means that during higher flow events enormous amouns of material can be transported and deposited in the the Lech River. The Lech might not be able to immediately transport all of the material, but continuous transport keeps the system more or less in a dynamic equilibrium.

Very important for the processes occurring at the Lech River are the material inputs from the side and the more or less continuous transport of material within the river. A feature of these processes is the temporal and spatial alternation of aggradation and degradation of bed material. Riparian vegetation, especially pioneer plants, may also play an important role in the occurring processes, e.g. as bed and bank stabilisation, water and sediment retention, etc..

In the Lech, these processes are to some extent altered. Stabilisation structures like sills, groins, bank protections and other bed and bank reinforcement measures are locally present within the Lech and its tributaries. Some of them have only a minor impact on the water and sediment regime, but for most of these structures the impacts are unknown.

Some major alterations of longitudinal sediment and water transport as a result of hydropower plants were also identified. Most of the hydropower plants are diversion plants. Beside the interruption of the water and sediment continuity, the impacts at the residual flow sections need to be considered. With the change of the discharge during the growing season, the extent of vegetation might change, affecting roughness and thus flow velocities, water depths, and sedimentation and erosion processes. Higher flood risk might also be caused. Important processes are the recruitment, succession and destruction of vegetation as functions of the changed hydrological, hydraulic and morphological conditions.

Based on the available data, the sediment and water continuum is little influenced until the village of Lech, where a hydro power plant exists. It can be assumed that the material produced upstream of the power plant contributes only partially and with temporal alterations to the downstream sediment regime. The section between the villages of Lech and Reutte is impacted by bed and bank reinforcements, groins, and in the braiding section the bridge “Johannisbrücke” causes a major contraction of the river. Processes within tributaries might also be altered by torrent control structures. However, detailed information about the functionality of these structures was not available.

The next major interruption, a hydropower plant, is located in Reutte. From there on downstream the natural sediment regime is strongly altered.

5.2 Lafnitz

In the Lafntiz catchment, two landscape units (a northern (NLU) and southern landscape unit (SLU)) were delineated, which are affected by different abiotic and biotic conditions.

In the NLU has few tributaries (torrents) and potential sources of coarse sediments are rare compared to other more alpine catchments. Bare soils and open areas are not present and the main land uses are forest and agriculture (pasture and heterogeneous agricultural areas).

Physical pressures like bed and bank reinforcements alter, at least to some extent, the sediment regime and thus naturally occurring processes. Additionally to these structures, three retention basins are located in the NLU which have definite impacts on the downstream hydrology and thus geomorphological processes.

Within the SLU, the valley is wider than in the NLU and the agricultural land use changes from pastures to arable land, which influences the potential soil erosion rate - annual soil erosion rates up to 1,2 t ha^{-1} yr^{-1} are possible.

Within the SLU, the Lafnitz alternates between a sinuous and a meandering planform. At unconfined meandering sections, the dominant processes are lateral migration, bank erosion, meander cut-off and so on. In some areas of the Lafnitz River, the lateral dynamics are disabled by bank reinforcements, in other areas they are, at least to some extent, possible. But as the temporal changes were not investigated here and so assessments concerning the lateral dynamics are tentative.

The interactions of the occurring processes with riparian vegetation are also important. Vegetation plays for example a key role in bank erosion (e.g. hydrological and mechanical alterations of the bank).

The available data indicate that the sediment regime of the Lafnitz is slightly modified by several retention structures along the river. Six retention basins are located on the Lafnitz. They cause a reduction of the peak discharge and thus have high impacts on the downstream and to some extent upstream hydrology and morphology. In particular, the changed flood peaks might have impacts on the meander development.

A major discontinuity in longitudinal transport of water and sediment, a hydropower plant, exists at Wörth.

Generally it can be said, that for the morphological development of the Lafnitz the lateral dynamics might be as or more important than the longitudinal transport of sediments.

5.3 Conclusion

The application of the multi-scale framework provides a good basis for the evaluation and interpretation of processes occurring within the river at different scales, and as functions of local conditions (like climate, geology, topography, and so on). This becomes evident when comparing the results of the two case studies. Different processes are dominant in the different regions with varying boundary conditions.

Further, the application has helped to identify alterations due to physical pressures. However, application of the entire framework is needed to gain a better insight into the processes and how they are influenced by anthropogenic impacts.

6. References

Amann, G., Schennach, R., Kessler, J. & Terzer, S. 2010. Handbuch der Vorarlberger Waldgesellschaften - Gesellschaftsbeschreibungen und waldbaulicher Leitfaden. *In:* Vorarlberger_Landesregierung (ed.). Dornbirn: Amt der Vorarlberger Landesregierung - Abt. Forstwesen (Vc).

Auer, H. 2012. *Flussmorphologische Grundlagenuntersuchung am Lech zur Bewertung des Schwasseinflusses bei unterschiedlichen Flusstypen.* Master, Universität für Bodenkultur.

BMLFUW (ed.) 2009. *Hydrographisches Jahrbuch von Österreich 2006,* Wien: BMLFUW Abteilung VII/3.

Brierley, G. J. & Fryirs, K. A. 2005. *Geomorphology and River management: Applications of the River Styles Framework*, Blackwell Science Ltd.

DigitalerAtlasSteiermark. 2013. *Digitaler Atlas Steiermark* [Online]. Available: http://gis2.stmk.gv.at/atlas/%28S%2844f2ef45ixngsrfchokrgr45%29%29/init.aspx?karte=adr&ks=das&cms=da&massstab=800000 [Accessed 2013].

EC 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy - EU Water Framework Directive. *Official Journal of the European Communities,* L327.

EEA 2002. Europe´s biodiversity - biogeographical regions and seas. European Environment Agency.

Egger, H., Krenmayr, H. G., Mandl, G. W., Matura, A., Nowotny, A., Pascher, G., Pestal, G., Pistonik, J., Rockenschaub, M. & Schnabel, W. 1999. *Geological Map of Austria*. Vienna: Geological Survey of Austria.

Habersack, H., Mayr, P., Gierlinger, R. & Schneglberger, S. 2000. *Mehrdimensionale Abflussmodellierung am Beispiel der Lafnitz.,* Wien, Wiener Mitteilungen Wasser - Abwasser - Gewässer, Band 165.

HAÖ 2007. Hydrologischer Atlas Österreichs. *3. Lieferung.* Vienna: Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft, Institut für Wasserwirtschaft, Hydrologie und konstruktiven Wasserbau.

Jarvis, A., Reuter, H. I., Nelson, A. & Guevara, E. 2008. Hole-filled seamless SRTM data V4. International Centre for Tropical Agriculture (CIAT).

Kilian, W., Müller, F. & Starlinger, F. 1993. Die forstlichen Wuchsgebiete Österreichs - Eine Naturraumgliederung nach Waldökologischen Gesichtspunkten. *In:* Bundesversuchsanstalt, F. (ed.). Wien: Forstliche Bundesversuchsanstalt.

Kirkby, M. J., Jones, R. J. A., Irvine, B., Gobin, A., Gobers, G., Cerdan, O., Von Rompaey, A. J. J., Le Bissonnais, Y., Daroussin, J., King, D., Montanarella, L., Grimm, M., Vieillefont, V., Puigdefabregas, J., Boer, M., Kosmas, C., Yassoglou, N., Tsara, M., Mantel, S., Van Lynden, G. J. & Huting, J. 2004. Pan-European Soil Erosion Risk Assessment: The PESERA Map, Version 1 October 2003. Explenation of Special Publication Ispra 2004 No. 73 (S.P.I.04.73). European Soil Bureau Resseach Report No. 16, EUR 21176, 18pp. and 1 map in ISO B1 format. Luxembourg: Office for Official Publications of the European Communities.

Lebensministerium 2010. Nationaler Gewässerbewirtschaftungsplan 2009 - NGP 2009. Wien.

Lebensministerium. 2013. *eHYD* [Online]. Wien: Lebensministerium. Available: http://ehyd.gv.at/ [Accessed 2013].

Mader, H., T., S. & Wimmer, R. 1996. *Abflussregime österreichischer Fließgewässer - Beitrag zu einer bundesweiten Fließgewässertypologie,* Wien, Umweltbundesamt.

Muhar, S., Poppe, M., Egger, G., Schmutz, S. & Melcher, A. 2004. *Flusslandschaften Österreichs - Ausweisung von Flusslandschaftstypen anhand des Naturraums, der Fischfauna und der Auenvegetation,* Wien, bm:bwk.

Mühlmann, H. 2010. Leitfaden zur hydromorphologischen Zustandserhebung von Fließgewässern. Wien: BAW-Institut für Gewässergüte und BMLFUW.

Pitschmann, H., Reisigl, H., Schiechtl, H. M. & Stern, R. 1973. Karte der aktuellen Vegetation von Tirol 1/100000 - III Teil: Blatt 5, Silvretta und Lechtaler Alpen. *Documents de Cartographie Ecologique,* XI**,** 33-48.

Rinaldi, M., Surian, N., Comiti, F. & Bussettini, M. (eds.) 2012. *Guidebook for the evaluation of stream morphological conditions by the Morphological Quality Index (MQI). Version 1.1,* Roma: Istituto Superiore per la Protezione ela Ricerca Ambientale.

Rivas-Martínez, S., Penas, Á. & Díaz, T. E. 2004a. *Bioclimatic Map of Europe - Bioclimates*. León, Spain: Cartographic Service, University of León.

Rivas-Martínez, S., Penas, Á. & Díaz, T. E. 2004b. *Biogeographic Map of Europe*. León: Cartographic Service, University of León.

TirisMaps. 2013. *tiris Kartendienste: Land Tirol* [Online]. Available: http://www.tirol.gv.at/statistik-budget/statistik-tiris/tiris-kartendienste/ [Accessed 2013].

VoGIS. 2013. *Vorarlberg Atlas* [Online]. Available: http://vogis.cnv.at [Accessed 2013].