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Understanding braided river landform development over decadal time scale: soil and groundwater as controls on biogeomorphic succession.

Bätz Nico

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UNIVERSITY OF LAUSANNE

FACULTY OF GEOSIENCE AND ENVIRONEMNT

INSTITUTE OF EARTH SURFACE DYNAMICS

Understanding braided river landform development over decadal time scale:

soil and groundwater as controls on biogeomorphic succession

Ph.D. thesis

presented at the

Faculty of Geoscience and Environment,
University of Lausanne

by

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To obtain the grade of
Ph.D. in Geoscience and the Environment,
mention "Geography"

Jury

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Prof. Eric P. Verrecchia	Thesis co-director
Prof. Paolo Cherubini	Expert
Prof. Dov Corenblit	Expert
Dr. Géraldine Bullinger	Expert
Prof. Michel Jaboyedoff	President of the jury

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Pour le Doyen de la Faculté des géosciences et de l'environnement

Professeur Michel Jaboyedoff

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Ph.D. thesis

Nico Bätz

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Acronyms and abbreviations

A	Organic matter enriched topsoil layer
a.s.l.	Above see level
A1	TOC proportion of labile fresh litter (Rock-Eval analysis)
A2	TOC proportion of stable litter components such as cellulose and lignin (Rock-Eval analysis)
A3	TOC proportion of humified litter such as humic and fulvic acids (Rock-Eval analysis)
A4	TOC proportion of stable humus components such as humins (Rock-Eval analysis)
A5	TOC proportion of resistant humus components/geopolymers such as black carbon and charcoal (Rock-Eval analysis)
Ab	Buried organic matter enriched topsoil layer
Ai	Initially organic matter enriched topsoil layer
C	Soil layer originating from fluvial gravel deposits
C. sand	Coarse sand
CorInd	Multiscale correlation Index (Chapter 5.1.4)
CorIndw	Weighted Multiscale correlation Index (Chapter 5.1.4)
dGPS	Differential Geographical Positioning System
DOM	Dissolved organic matter
E	East
e.g.	E*xempli Gratia*: for example
ERT	Electrical Resistivity Analysis
F. sand	Fine sand
GIS	Geographic Information System
GLK index	Coefficient of parallel variation (Gleichläufigkeit – Dendroecological analysis)
HI	Hydrogen Index; TOC proportion of hydrocarbons (Rock-Eval analysis)
I-Index	Immature Index; described the fresh organic matter pool
LGM	Last Glacial Maximum
LIA	Little Ice Age

M	Soil layer originating from fluvial organic matter-enriched sandy deposits
M. sand	Medium sand
MINC	Mineral Carbon content (Rock-Eval analysis)
N	North
OI	Oxygen Index; TOC proportion of oxides (Rock-Eval analysis)
OM	Organic Matter
PC	Principal Component
PCA	Principal Component Analysis
PC-SPD	Principal Component related Soil Profile Development index
POM	particulate organic matter
R-Index	Thermo-Resistant Index; described the resistant organic matter pool
SPD	Soil Profile Development index
TOC	Total Organic Carbon
TpS2	The temperature at which most hydrocarbons are liberated (Rock-Eval analysis)
WRB	World Reference Base of Soil
yr.	Year

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Nico Bätz, July 2016

Summary

The notion of biogeomorphic succession has recently been developed to describe the transition from a river deposit to a fully-developed floodplain terrace forest ecosystem in braided rivers over the time scale of decades. This successional process is characterised by a particular set of feedbacks between physical (erosion, sedimentation) and biological components (vegetation establishment, stabilisation). Studies have focused on the one hand on the impacts of vegetation (e.g. root reinforcement, recruitment speed) and braiding processes (e.g. aggradation rates, flooding rate, topography) on the formation of vegetated landforms in braided rivers, allowing quantification of biogeomorphic feedbacks at short time scales. On the other hand, studies tracing the development of braided rivers over the decadal scale have tended to be based on historical data (historic aerial images), which do not provide information on the ecosystem state during the biogeomorphic succession. However, a more process based understanding of decadal scale biogeomorphic successional processes is needed to understand, to protect and to restore braided rivers. To date, accounts of biogeomorphic succession have rarely addressed the question of soil, something that must develop during the transition of a river deposit into a fully-developed floodplain terrace. Moreover, the impact of groundwater access as a control on vegetation growth rates in gravely environments, has not yet been addressed. Both may facilitate faster plant growth which implies faster landform stabilisation.

Thus, the aim of this thesis is, in the context of biogeomorphic succession, to determine and to quantify the effect of soil and groundwater on the biogeomorphic processes associated with decadal scale braided river development. The study is carried out on a 2 km reach of a dynamic gravel-bed river in western Switzerland (the Allondon River, Canton Geneva).

A chronosequences approach of 20 soil profiles sampled from sites that ranges from fresh river deposits to fully-developed floodplain forest terraces was used to describe soil evolution. Soil horizons were characterised in terms of grain size distribution and organic matter content and quality (by RockEval pyrolysis). Plant growth was reconstructed via dendrochronological methods for 150 samples distributed all over the floodplain. These data were then related to the distance from the river and to the groundwater-depth gradient. The further geomorphological interpretation was aided by historical imagery interpretation.

Results show that organic matter dynamics and sediment grain size are of primary importance for explaining soil diversity in the Allondon floodplain. However, groundwater appears to mediate the dependence of biogeomorphic succession on soil evolution. Sites located farther

from the active channel and at higher altitude, in the groundwater distal and morphologically more active part of the river, needed fine sediment aggradation and humus development to aid water retention and to sustain the water demands of young vegetation. The geomorphological setting and its history appear to define the strength of these processes. Abandoned channels appear to provide the best conditions as sporadic connection to the main channel may allow the aggradation of fines and, although not measured directly in this study, allochthonous organic (woody) material. In these cases, soil is thought to drive the biogeomorphic succession: the accumulation and decomposition of organic components ameliorates local ambient conditions; in turn, locally more rapid biogeomorphic succession occurs. The fact that the groundwater distal zones remain more active suggests that this process does not occur sufficiently (either rapidly in time, or coherently in space) to counter the effects of disturbance.

In the groundwater upwelling and morphologically more stable part of the river, where water is available all year round, vegetation does not rely as much on the water and nutrient retention capacity of the soil, as the shallow ground water facilitates overall plant establishment. Consequently, vegetation develops at higher rates, increasing deposit stability via attachment and leading to a more stable reach morphology.

Overall, the results emphasise the dependence of biogeomorphic succession on the interplay between soil (organic matter) processes and (ground-) water availability in facilitating the progress of biogeomorphic succession, and crucially at a rate that is greater than the disturbance frequency, thus allowing greater stability as a function of time.

Résumé

La notion de succession biogéomorphologique a été récemment mise au point pour décrire la transition d'un dépôt alluvial récent vers une terrasse alluviale avec un écosystème forestier développé dans les milieux de rivières en tresses, à l'échelle de temps décennale. Ce processus de succession est caractérisé par un ensemble particulier de rétroactions entre les processus physiques (érosion, sédimentation) et biologiques (établissement de la végétation, stabilisation). Des études récentes ont mis l'accent d'une part sur les impacts de la végétation (e.g. le renforcement des racines, la vitesse de recrutement) et les processus de tressage (e.g. taux d'aggradation, taux d'inondation, topographie) sur la formation des formes alluviales végétalisées dans les rivières en tresses, permettant la quantification des réponses biogéomorphologiques à courtes échelles de temps. D'autre part, certaines études retraçant l'évolution des rivières en tresses à l'échelle décennale ont tendance à se fonder sur des données historiques (images aériennes historiques), qui ne fournissent pas d'information sur l'état de l'écosystème lors de la succession biogéomorphologique. Cependant, une compréhension basée sur les processus d'échelle décennale dans le cadre de la succession biogéomorphologique est nécessaire pour mieux comprendre, protéger et restaurer les rivières en tresses. À ce jour, la science a rarement abordé la question du sol dans l'étude des successions biogéomorphologiques. En effet, le sol est une propriété qui évolue au cours de la transition d'un dépôt alluvial récent à une terrasse alluviale entièrement développée. En outre, l'impact de l'accès aux eaux souterraines comme contrôle sur les taux de croissance de la végétation dans des environnements graveleux n'a pas encore été abordé. Ces deux facteurs favorisent un taux de croissance important des plantes qui implique une stabilisation plus rapide des formes alluviales.

Ainsi, l'objectif de cette thèse est, dans le contexte de la succession biogéomorphologique, de déterminer et de quantifier l'effet de l'évolution du sol et de l'accès aux eaux souterraines sur les processus biogéomorphologiques à l'échelle décennale dans les rivières en tresses. L'étude est réalisée sur un tronçon de 2 km d'une rivière en tresse graveleuse en Suisse occidentale (la rivière Allondon, Canton de Genève).

Une approche par chronoséquence fondée sur 20 profils de sols échantillonnés couvrant des sites qui varient d'un dépôt alluvial récent à une terrasse alluviale, a été utilisée pour décrire l'évolution des sols. Les sols ont été caractérisés en termes granulométriques et selon la qualité et la teneur en matière organique (analyse par pyrolyse RockEval). La croissance des plantes et sa dépendance aux facteurs environnementaux, ont été reconstruites par des

méthodes dendrochronologiques pour 150 échantillons distribués sur toute la plaine alluviale. Ces données ont ensuite été reliées à la distance de la rivière et la distance à la nappe. En outre, des interprétations géomorphologiques ont été effectuées via l'interprétation d'images aériennes.

Les résultats montrent que les dynamiques de la matière organique et les caractéristiques sédimentaires sont de première importance pour expliquer la diversité des sols dans la plaine alluviale de l'Allondon. Cependant, l'accès à la nappe semble influencer la dépendance de la succession biogéomorphologique sur l'évolution des sols. Les sites situés plus loin du chenal actif et à plus haute altitude, dans le tronçon distal de la nappe et avec une dynamique géomorphologique plus active, nécessitent l'aggradation de sédiments fins et le développement d'humus pour améliorer la rétention d'eau nécessaire pour subvenir à la demande en eau de la végétation pendant l'été. Le cadre géomorphologique et son histoire semblent définir la force de ces processus. Les chenaux abandonnés semblent offrir les meilleures conditions, vu que la connexion sporadique au chenal principal permet l'accumulation de sédiments fins et de matériaux organiques alluviaux (débris de bois), même si ces derniers n'ont pas été mesurés directement dans cette étude. Dans ce cas de figure, le sol est interprété comme conducteur de la succession biogéomorphologique: l'accumulation et la décomposition des composants organiques améliorent les conditions ambiantes locales; à son tour, la succession biogéomorphologique locale est plus rapide. Le fait que les zones distales de la nappe restent plus actives suggère que ce processus ne se produit pas suffisamment rapidement dans le temps ou de manière assez cohérente dans l'espace pour contrer les effets des perturbations fluviales.

Dans le tronçon avec des eaux souterraines peu profondes et une dynamique géomorphologique plus stable, où l'eau est disponible toute l'année, la végétation n'est pas dépendante de la capacité de rétention d'eau et des éléments nutritifs du sol. Les eaux souterraines peu profondes facilitent généralement l'établissement des plantes dans la plaine alluviale. Par conséquent, la végétation se développe à des taux plus élevés, ce qui augmente la stabilité des dépôts et garanti un tronçon morphologiquement plus stable par l'attachement rapide des formes alluviales.

Dans l'ensemble, les résultats soulignent la dépendance de la succession biogéomorphologique sur l'interaction entre les processus du sol (matière organique) et la disponibilité de l'eau (nappe) pour faciliter la progression de la succession biogéomorphologique à un taux qui est supérieur à la fréquence de perturbation fluviale, permettant ainsi une plus grande stabilité en fonction du temps.

1 Introduction

Braided river systems are a special type of river associated with typically sediment-laden flows and laterally unconfined floodplains that allow the formation of multiple channels (Figure 1). These channels are commonly dynamic, thus changing channel position over the daily to yearly time scale, and are also associated with strong interactions between biological and physical processes (Ashmore, 2013; Bertoldi et al., 2009; Gurnell, 2016; Gurnell et al., 2009, 2016; Hicks et al., 2007; Murray and Paola, 1994; Tockner et al., 2006, 2010).

However, changes in river basin properties and river engineering, notably during the 20th century, have reduced the presence of braided floodplains in the European landscape (Gurnell et al., 2009; Tockner et al., 2006). In particular the construction of dams and hydroelectric exploitation have interrupted or reduced sediment transfer and river discharge fluctuations (e.g. Bravard et al., 1997; Marston et al., 1995; Molnar et al., 2008); gravel mining has reduced sediment availability (e.g. Kondolf et al., 2002; Korpak, 2007; Landon et al., 1998; Surian et al., 2009; Surian and Rinaldi, 2003); changes in land use have impacted sediment delivery (e.g. Girel et al., 2003; Kondolf et al., 2002; Midha and Mathur, 2013; Piégay et al., 2009a; Stacke et al., 2014; Surian et al., 2009); and river channel canalisation has reduced accommodation space (e.g. Laigre et al., 2013; Vischer, 1989). In addition, changing climate, a result of more indirect human activity (i.e. greenhouse gas emissions), may have also impacted upon river hydrology and sediment delivery. For instance, enhanced fluvial geomorphic activity has been described during periods of temperature increase after the Little Ice Age (Rumsby and Macklin, 1996; Saucier, 1994), a consequence of climate change impacts upon mountain sediment production and hydrology (Christensen and Christensen, 2003; Kundzewicz et al., 2007; Lane et al., 2007; Zhang et al., 2007).

Scientifically, and recently, a focus on the physical dimensions of braided rivers has broadened to emphasise their ecological value. Due to their dynamic nature, braided river sections may provide significant habitat diversity (Figure 1) and so may provide important refugia for those species living in habitats at the interface between terrestrial and aquatic systems (Francis et al., 2008; Müller, 2005; Tockner et al., 2006).

Additionally, they may provide important landscape functions, such as carbon sinks (e.g. Cierjacks et al., 2010) or biogeochemical filters (e.g. Fisher et al., 2007). Moreover, it is possible that braided rivers have some capacity to buffer the impacts of climate change related extreme floods by slowing the downstream transfer of sediments (e.g. McDonald et al., 2004; Piégay et al., 2009b). It is not surprising that braided river ecosystems have been increasingly recognized as important elements of the fluvial landscape continuum (Vannote et al., 1980; Ward et al., 1999) and thus protected at the European level, such as in European Environmental and Strategic Impact Assessments and the EU Habitats Directive. In Switzerland, braided rivers are commonly the focus of Alluvial Zones of National Importance.

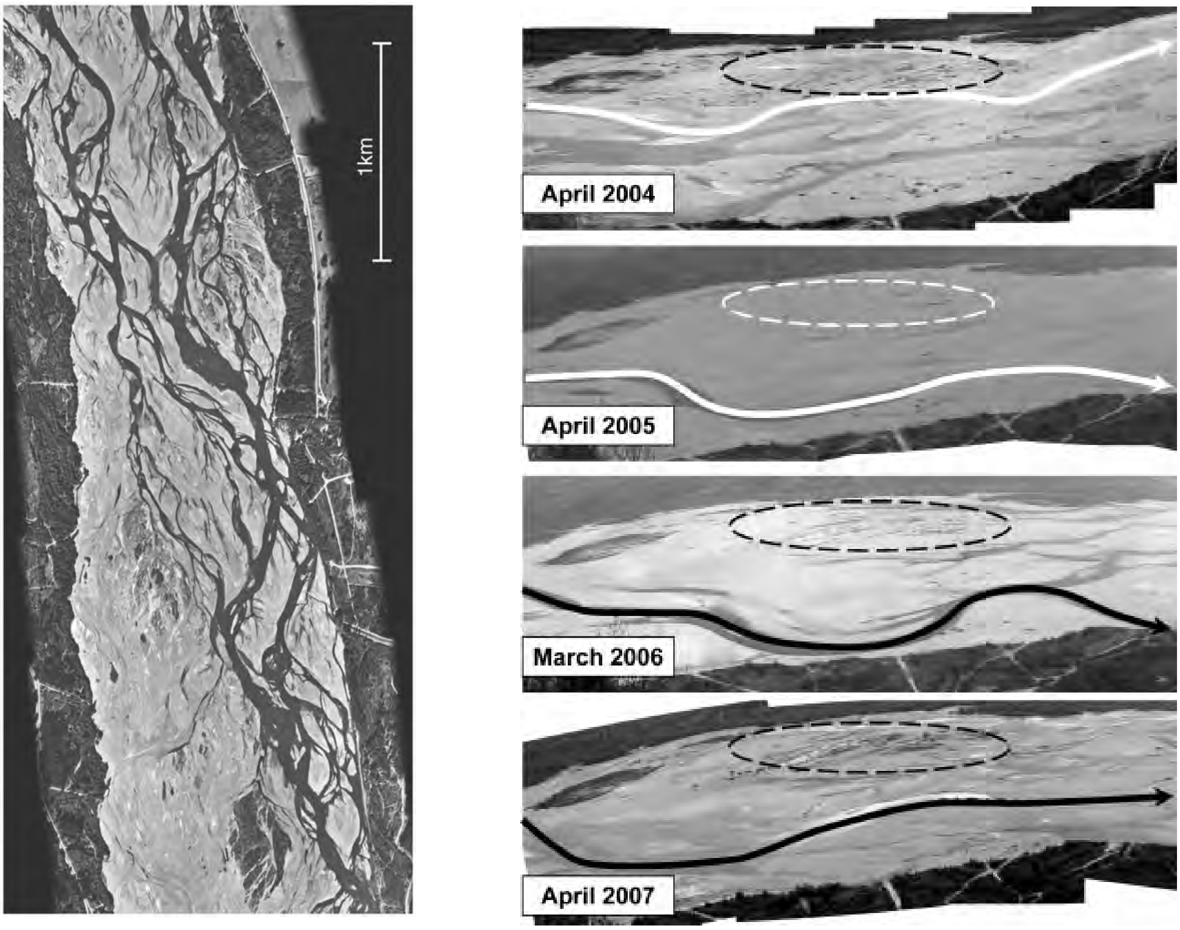


Figure 1 – Examples of braided rivers

On the left an example of the braided Waimakariri River in New Zeeland (taken from Hicks et al., 2007). On the right a time series of photos of a reach of the Tagliamento river in Italy, showing the dynamic development of the main channel (arrow), and the development of a vegetated patch (taken from Bertoldi et al., 2009)

Given the above, restoration of braided rivers has recently seen some wider interest (Wohl et al., 2015). This restoration needs to pay attention to their biogeomorphic functioning (Francis et al., 2009; Piégay et al., 2009b; Tockner et al., 2010; Vaughan et al., 2009; Ward et al., 2001). This is the wider context within which this research is situated.

1.1 Biogeomorphic interactions in braided rivers

Since the early 1960s braided river research focused on understanding the impact of different physical parameters (e.g. hydrology, valley slope, sediment availability) on braiding at various spatio-temporal scales (Lane, 1995), whether through statistical analyses (e.g. Leopold and Wolman, 1957) or laboratory scaled modelling (Ashmore, 1982). By the 1980s and the 1990s, this research field had developed to include quantification of braiding river processes in the field (e.g. Ashmore et al., 1992; Ashworth and Ferguson, 1986) including river bar formation and their dynamics (e.g. Ashworth and Ferguson, 1986). However, the focus of this work was predominantly “physical”.

More recently, it has been recognised that vegetation growing along rivers is able to interact with the physical environment (e.g. Keller and Swanson, 1979) by taking on a so called “engineering role” (Naiman et al., 1999; Osterkamp and Hupp, 2010; Piégay and Gurnell, 1997). Several recent reviews have addressed these biogeomorphic interactions (e.g. Corenblit et al., 2007, 2011, Gurnell, 2014, 2016; Gurnell et al., 2012; Tockner et al., 2006). Engineering pioneer species such as willows and poplars, have been shown to stabilise fluvial deposits through their roots (e.g. Pollen, 2007; Polvi et al., 2014), while above ground vegetation facilitates sediment aggradation processes during high river flows (e.g. Gurnell, 2016; Gurnell and Petts, 2002). By “engineering” fluvial deposits, such vegetation increases the size of events needed to cause erosion and/or destruction, so encouraging the persistence of vegetated patches.

The consequence of the engineering effects of vegetation on fluvial landform development has led to the notion of the biogeomorphic succession (Corenblit et al., 2007, 2009, 2014, 2016; Figure 2). This framework, which applies at the plant community (Corenblit et al., 2007) but also at the plant life cycle / population level (Corenblit et al., 2014), consists of four phases in which fluvial landform properties and vegetation succession codevelop (from a landform development perspective) under hydro-geomorphological forcing. The first phase is geomorphological, in which seedlings are dispersed by floods and germinate on potentially suitable bar surfaces. In a second, ‘pioneer’ phase, seedlings need to survive the first years and are challenged by water stress and erosion and deposition processes. In these first two phases, vegetation is highly exposed to the physical environment. Third, in the biogeomorphological phase, the interaction between plants and their physical environment is highest. The engineering action of the young trees allows deposits to become more resistant to erosion via roots and fine sediment to be trapped via the aboveground biomass, potentially improving local nutrient and water retention. Fourth, during the ecological phase, the vegetation patch becomes independent of fluvial processes and sustains its resource demands through autogenic processes. Only the

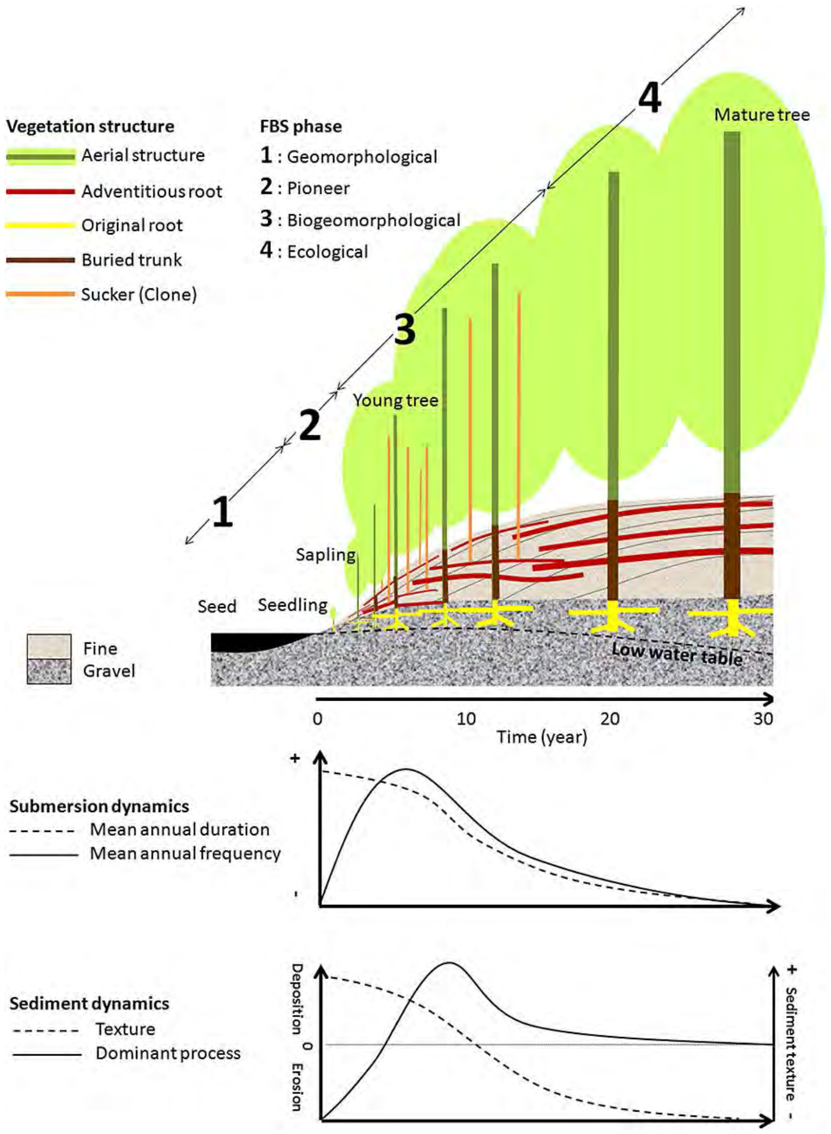


Figure 2 – The biogeomorphic succession

Schema conceptualising the Fluvial Biogeomorphic Succession (FBS) for the life cycle of poplar through time (X axis). The transition from phase 1 to 4 is accompanied by changes in the plant (green, brown and orange) and root structure (red and yellow). This process facilitates resistance to period of submersion and enhances (fine) sediment aggradation. More extreme events may return the system to phase 1 (taken from Corenblit et al., 2014).

most extreme flows interact with the vegetation in this phase, characterised by shallow overland deposition or lateral erosion processes (Corenblit et al., 2007, 2009, 2014).

In this study we address the functional part of the biogeomorphic succession, thus changes in plant community structure but also changes in plant physiognomy during the plant life-cycle, that enables the different kind of biogeomorphic feedbacks along this succession described above.

Biogeomorphic succession does not occur simultaneously everywhere within a river. Different parts of the river may be reset at different times due to spatially heterogeneous riverine disturbance and the succession may take place at different rates. This results in a floodplain-wide mosaic of shifting habitats and ecotones that react in terms of distribution (e.g. age, species, spatial) and biogeochemical cycles (e.g. nutrient turnover) to fluvial energy, fluxes of matter (e.g. deposition, erosion, organic matter) and gradients (e.g. disturbance, water availability - Tockner et al., 2006). In particular, the intensity of biogeomorphic succession has been shown to influence fluvial planform evolution. Both flume experiments and long term field observations have shown that the persistence of vegetated (island) braided reaches is a delicate equilibrium between destabilising riverine disturbance processes and stabilising biogeomorphic encroachment (e.g. Francis et al., 2009; Hicks et al., 2007; Picco et al., 2014; Tal and Paola, 2007, 2010; Zanoni et al., 2008). Figure 3 conceptualises this equilibrium, showing that with a reduction in disturbance frequency channel pattern transitions towards single channels. However, with increasing biogeomorphic succession rates (increasing vegetation dynamics), the river planform shows two distinct possible states for the same level of hydrogeomorphic disturbance frequency: straight or braided. The switch may be from multi- to single thread where a reduction in disturbance frequency is accompanied by rapid vegetation development to sustain a single thread channel (downward arrow in Figure 3); or single- to multi-thread where an increase in disturbance frequency causes the removal of the engineering effects of vegetation (upward arrow). The key point is that vegetation dynamics influence system resilience, with more abrupt channel pattern shifts under high vegetation establishment rates in relation to changes in disturbance frequency, and smoother morphological transition under lower vegetation establishment rates (Francis et al., 2009).

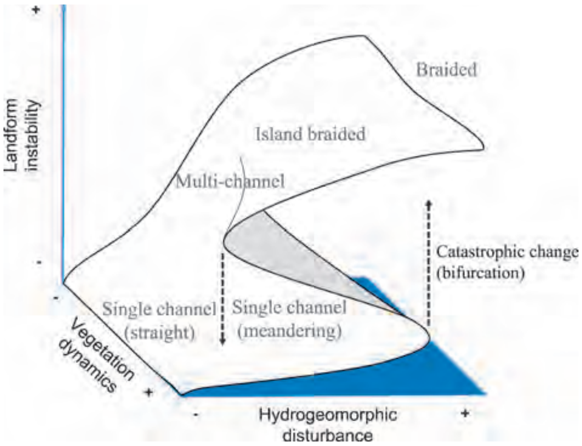


Figure 3 – Changes in river planform as a function of hydrogeomorphic disturbance and vegetation dynamics

Notice that high vegetation dynamics in relation to disturbance enhance system resilience (taken from Francis et al., 2009).

While research has mainly focused on understanding the transitional processes via changes in disturbance frequency (e.g. Ashmore et al., 2011; Bertoldi et al., 2010; Foreman et al., 2012; Kondolf et al., 2002; Lane et al., 2010; Marston et al., 1995; Zanoni et al., 2008), much less is known about processes affecting biogeomorphic succession rate and performance at both, the community and population scale, over decadal time scales (vegetation dynamics Figure 3). Recent work (e.g. Corenblit et al., 2011; Gurnell, 2016; Gurnell et al., 2012; Tockner et al., 2006) has concentrated on understanding the interacting impacts of vegetation (e.g. root reinforcement, recruitment rate,…) and braiding processes (e.g. aggradation rates, flooding rate, topography, …) on biogeomorphic succession, often over relatively short time scales. Studies tracing the development of fluvial landforms over the decadal time scales are fewer and have tended to focus upon system correlations (e.g. between the instrumental record and historic aerial images – e.g. Kondolf and Curry, 1986; Beechie et al., 2006; Zanoni et al., 2008; Bertoldi et al., 2011) rather than the processes that produce those correlations. As will be shown in a subsequent review of the literature (Chapter 2), pedogenesis is likely to be part of the biogeomorphic feedback system, since young soils have been observed on vegetated patches that formed within a few decades (Bureau, 1995; Doering et al., 2011; Gerrard, 1987, 1995; Langhans et al., 2012; Mardhiah et al., 2014; Viereck et al., 1993). Similarly, access to groundwater has been shown to influence vegetation growth rates (Boulton et al., 1998; Harner and Stanford, 2003; Mouw et al., 2009). It thus appears that soil evolution and access to groundwater potentially affect biogeomorphic succession rates at decadal time scales. In relation to disturbance frequency, this may then affect overall river morphological evolution.

1.2 Thesis aim

Based on above, this Ph.D. thesis aims to integrate issues regarding the interactions between soil and groundwater into the role that biogeomorphic succession plays in the dynamics of braided rivers. Specifically it considers the role that soil-groundwater processes play in defining the speed and trajectory of biogeomorphic succession. Their interaction may play an important role in defining the biogeomorphic succession rate at the plant community (Corenblit et al., 2007) but also at the plant life cycle (Corenblit et al., 2014) scale. The with the biogeomorphic succession associated engineering functioning, may thus lead to changes in riverine morphological response. Addressing this aim, implies a focus on the decadal scale.

Chapter 2 details the three main research questions considered in this thesis. In summary, these are:

I) **To what extent is pedogenesis able to influence the rates of biogeomorphic succession? Is it actively involved in the succession process or is it a passively adaptive process that follows from stabilisation of the river deposits?**

II) **To what extent does groundwater influence biogeomorphic succession performance and thus morphological stability at the reach scale?**

III) **How does the interplay between soil formation and groundwater availability influence biogeomorphic succession?**

1.3 Contributions of the thesis

This thesis is based on a series of peer reviewed articles, some of which are published whilst others are under review or accepted as indicated in the first page of the each contribution. After a short introduction on how each publication contributes to the theme of this thesis, the original text is reproduced. Each chapter finishes with a summary of the main findings and their relation to the overall thesis topic.

In detail, the manuscripts on which this thesis is based are:

BÄTZ N, VERRECCHIA EP, LANE SN. **2014**. SOIL IN BRAIDED RIVERS: AN OVERLOOKED COMPONENT OF BRAIDED RIVER MORPHODYNAMICS. IN RIVER FLOW 2014, SCHLEISS AJ, DE CESARE G, FRANCA MJ, AND PFISTER P (EDS). TAYLOR & FRANCIS GROUP: LONDON; 445–452

BÄTZ N, VERRECCHIA EP, LANE SN. **2015**. THE ROLE OF SOIL IN VEGETATED GRAVELLY RIVER BRAID PLAINS: MORE THAN JUST A PASSIVE RESPONSE? EARTH SURFACE PROCESSES AND LANDFORMS 40: 143–156. DOI: 10.1002/ESP.3631

BÄTZ N, VERRECCHIA EP, LANE SN. **2015**. ORGANIC MATTER PROCESSING AND SOIL EVOLUTION IN A BRAIDED RIVER SYSTEM. CATENA 126: 86–97. DOI: 10.1016/J.CATENA.2014.10.013

BÄTZ N, IORGULESCU I, LANE SN. **ACCEPTED**. THE ALLONDON RIVER: AN EVOLVING PIEDMONT RIVER SYSTEM. IN LANDSCAPES AND LANDFORMS OF SWITZERLAND, REYNARD E (ED). SPRINGER: BERLIN

BÄTZ N, COLOMBINI P, CHERUBINI P, LANE SN. **2016**. GROUNDWATER CONTROLS ON BIOGEOMORPHIC SUCCESSION AND RIVER CHANNEL MORPHODYNAMICS. JOURNAL OF GEOPHYSICAL RESEARCH: EARTH SURFACE. DOI: 10.1002/2016JF004009

1.4 Thesis overview

The articles that resulted from this research have been structured into four chapters. Two chapters have been added, which aim bringing these contributions together and define relevant ecosystem processes for braided fluvial landform evolution at the decadal scale.

Chapter 2 reviews the state of science regarding the development of vegetated fluvial landforms at the decadal scale, with a particular focus on soil-related processes. Soil is conceptualised as an emergent property of the developing ecosystem and in the meantime is thought to influence an ecosystem’s trajectory. However, other variables, such as groundwater fluctuations over the short- to long-term, potentially influence ecosystem processes. Vegetation establishment speed and spatial arrangement in gravelly-environments may be dependent on such water resource during the dry and hot summer months. The review is used to develop a detailed conceptual model that integrates soil-groundwater processes into biogeomorphic succession (at community and population scale) and which is then used to explain the research questions detailed above.

Chapter 3 introduces the study site for the research presented in the thesis and describes the decadal-scale morphological evolution of the chosen study site: the Allondon River. The Chapter emphasises the changes in river morphology and processes, land cover and hydrology over recent decades, thus establishing the frame for this research. Generally, the Allondon River experienced a transition from a bar/braided to wandering/meandering river system over the last century. Incision formed a series of terraces and a more meandering river planform, but the loose gravel material still allows rapid morphological changes and local braiding processes at the yearly time-scale, typical for wandering rivers. The wide and ecologically diverse floodplain creates a unique setting to study the impact and development trajectories of fluvial landforms, ranging from freshly formed bars to decadal stable and fluvially-decoupled terraces. Moreover, good historical documentation (historical aerial images and maps) allowed a detailed geomorphological reconstruction.

Chapter 4 focuses on organic matter processing and soil evolution in the Allondon River. Several chronosequences (replacing space for time – older fluvial landforms are higher and further from the actual main river channel) were defined along the study reach, covering several fluvial landforms over a wide range of ages, ranging from fresh bar deposits till old floodplain terraces. Organic matter quality, root density and sediment grain size was determined throughout the soil profile for each location. The position of each profile, in terms of elevation and distance from the river channel, was determined. The dataset was interpreted via a Principal Components Analysis (PCA). The results showed a wide range of soil states at different biogeomorphic succession phases indicating that local initial conditions (e.g. sediment size, exposure to fluvial processes) and feedbacks (e.g. vegetation establishment, associated engineering action and soil formation) drive ecological processes, and thus biogeomorphic development. Moreover, groundwater was identified as an important variable, which potentially influences biogeomorphic succession. At the end of this section, a detailed example is shown of how different types of interactions between plant establishment, initial conditions, vegetation-induced engineering action, soil formation and geomorphological processes lead to different biogeomorphic succession rates.

Chapter 5 assesses the influence of groundwater on biogeomorphic succession rates and its implications for river planform transitions. The study reach was associated with a strong gradient in groundwater depth, with a northern downwelling reach where the water table elevation varied significantly; and a southern upwelling reach where the water table remained generally at the surface. After a reduction in disturbance frequency during the last 60 years, the northern downwelling reach showed lower vegetation encroachment rates than the southern groundwater proximal and upwelling reach. The link between the different encroachment rates along the reach and the groundwater gradient (from downwelling to upwelling) was analysed using dendroecological methods on willows. Results showed that changes in water access along the reach influenced vegetation growth rates and thus the success and rate of biogeomorphic succession at reach scale (the vegetation dynamics in Figure 3). In the south, the engineering effect via rapid biogeomorphic succession was quickly established, increasing overall channel stability and reducing active channel width. Where groundwater is downwelling, deeper and more variable, biogeomorphic succession was slower, vegetated landform aggregation/attachment was lower than the disturbance rate and the engineering effect was reduced and a wider active width was maintained.

Chapter 6 explores the role of the combined effect of soil evolution and groundwater access on the biogeomorphic succession in braided rivers. The effect of groundwater described in Chapter 5 was added to the PCA analysis of Chapter 4 and integrated into a spatial analysis via a soil profile development index (SPD) to disentangle the scale effects of each of the two components. From this analysis it appears that groundwater modulates the intensity of ecosystem feedbacks at the reach scale. In groundwater proximal sites, biogeomorphic succession intensity is less dependent on soil, as the nutrient rich groundwater feeds the landform ecosystem processes. Conversely, in groundwater distal sites, soil can aid biogeomorphic succession by improving local ambient conditions (water retention and nutrient availability). However, this requires special geomorphic settings, such as abandoned channels, that may be temporarily connected to the river delivering fine sediments and possibly the organic matter necessary for early soil evolution in gravelly floodplains. This improves water retention and thus allows succession to proceed at a higher rate.

Chapter 7 concludes the thesis by briefly summarising responses to the three questions identified above. The wider implications of the research results are identified and remaining research questions are considered.

2 Decadal fluvial landform evolution

This chapter reviews those processes that influence decadal-scale biogeomorphic succession at the plant community (Corenblit et al., 2007) but also at the plant life cycle / population level (Corenblit et al., 2014), with a particular focus on soil. Although having a focus on soil, the relevance of other elements on the biogeomorphic feedback system, such as groundwater, is shown. At the end of this section, key research questions for the thesis are identified.

2.1 "The role of soil in vegetated gravelly river braid plains: more than just a passive response"

BÄTZ N, VERRECCHIA EP, LANE SN. EARTH SURFACE PROCESSES AND LANDFORMS 40, 143–156,
2015; DOI: 10.1002/ESP.3631

2.1.1 Abstract

This paper reviews the role of alluvial soils in vegetated gravelly river braid plains. When considering decadal time scales of river evolution, we argue that it becomes vital to consider soil development as an emergent property of the developing ecosystem. Soil processes have been relatively overlooked in accounts of the interactions between braided river processes and vegetation, although soils have been observed on vegetated fluvial landforms. We hypothesise that soil development plays a major role in the transition (speed and pathway) from a fresh sediment deposit to a vegetated soil-covered landform. Disturbance (erosion and/or deposition), vertical sediment structure (process history), vegetation succession, biological activity and water table fluctuation are seen as the main controls on early alluvial soil evolution. Erosion and deposition processes may not only act as soil disturbing agents, but also as suppliers of ecosystem resources, because of their role in delivering and changing access (e.g. through avulsion) to fluxes of water, fine sediments and organic matter. In turn, the associated initial ecosystem may influence further fluvial landform development, such as through the trapping of fine-grained sediments (e.g. sand) by the engineering action of vegetation and the deposit stabilisation by the developing above and belowground

biomass. This may create a strong feedback between geomorphological processes, vegetation succession and soil evolution which we summarise in a conceptual model. We illustrate this model by an example from the Allondon River (CH) and identify the research questions that follow.

2.1.2 Introduction

The last three to four decades have shown that understanding alluvial river dynamics requires more than just consideration of the linkages between flow, sediment transport and river morphology. This has been the case in studies of the active parts of gravelly braid plains in particular, where vegetation transport, colonisation and establishment have been shown to be critical components of river dynamics (e.g. Corenblit et al., 2011; Gurnell, 2014; Gurnell et al., 2012). Such processes may be crucial in the transition of active zones of the braid plain to more stable zones, even if any part of a braid plain may in turn be subject to either renewed erosion or burial by deposition. However, in this transition, pedogenesis, as a third component that interacts with riverine processes and plant succession, may also need to be considered. In this paper, we define the braid plain as the lateral extent of the river corridor that includes both the active zone, including exposed and inundated areas (e.g. bars and active channels) and less active zones such as vegetated patches and river terraces (e.g. Bertoldi et al., 2009).

Alluvial flood plains can have well-developed soils (e.g. Gerrard, 1987), as Cierjacks et al. (2010, 2011) report for a stable meandering reach of the Danube River (Austria). Such soils most likely have their origin in freshly-deposited (gravel or sand) layers. Within braid plains, embryonic soils have been observed on vegetated patches as young as a decade or two (Bureau, 1995; Doering et al., 2011; Langhans et al., 2012; Mardhiah et al., 2014; Viereck et al., 1993). However, the processes that lead to a transition from a barren fresh sediment deposit, as found in the active braid plain zone, to a vegetated and (young) soil covered braid plain landform as may be found on more stable terraces, over the time scale of decades, have been less well-considered. Thus, this paper reviews the role of soil development within braid plain systems, by considering both the processes of pedogenesis and the potential effects of soil development upon the evolution of the river-vegetation system.

Established soil development theory (e.g. Jenny, 1941, 1961; Schaetzl and Anderson, 2005) should provide a basic model for braid plain soil development: given enough time and, in the case of a river, assuming sufficient stability, a sediment deposit should evolve towards a soil, provided that there are no other limits to soil forming factors (e.g. weathering). Thus, soil development is, at the very least, a passive response in zones of a braid plain that have become geomorphologically more stable and/or colonised by vegetation (e.g. through isolation on a terrace). Soil scientists would not normally label most of the profiles found close to the most active zone of a gravelly braid plain as developed soils, because of the rudimentary expression of soil properties and horizons. Channel dynamics (lateral erosion and deposition, avulsion) may limit the time available for pedogenic processes to overprint sedimentological properties. Following the World Reference Base of Soil (IUSS Working Group WRB, 2006) most profiles would belong to either the reference soil group of Leptosols (channel proximal zone) or Fluvisols (woody vegetated islands and terraces). However, the question remains as to how soils develop from fresh sediment deposits. Herein, we do not restrict our review to a strict definition of soil, but we also include deposits with post-depositional pedogenic alterations that express initial and rudimentary soil horizonation.

The question of the impact of pedogenic process on fluvial landform evolution becomes more important given the rapidity with which active braided zones can become vegetated (e.g. Corenblit et al., 2011; Moggridge and Gurnell, 2009). Classically, soil scientists and ecologists see the development of soil as synergistic with the development of vegetation (Ellenberg, 1988; Frouz et al., 2008): the two coevolve by closely influencing each other. Phillips and Lorz (2008) and Phillips (2009), conceive soils as an emergent property of the combined effects of biotic processes (flora and fauna) on a mineral structured surface, that is the interaction between life (living organisms, organic matter) and rock weathering (sediment). During soil development, both mineral and organic matter are transformed and stored, which may provide vital resources for plant development. As plants grow, and succession advances, biomass production increases, adding more organic matter to the system. Organic matter decay assists the process of pedogenesis (e.g. production of humic acid and enhanced rock and sediment weathering; (Drever and Stillings, 1997; Huang and Keller, 1972). Thus, soil and vegetation coevolve. As vegetation development in braided rivers can develop so rapidly, at timescales of less than a decade, this process of coevolution may also be rapid and important.

In turn, the flora and fauna of braid plains have been recognised as performing an ecosystem engineering role, with the coevolution of vegetation and fluvial land forms over a few decades. This has led to the notion of biogeomorphic succession (Corenblit et al., 2009, 2014). Ecosystem engineering species are adapted to the fluvial environment as they can rapidly colonise frequently disturbed sites and facilitate the transformation of local site conditions to more favourable edaphic conditions (Corenblit et al., 2011; Gurnell, 2014; Phillips, 2009). In view of the time scale of this coevolution, there has been much less consideration of the role of soil in biogeomorphic succession, but also the extent to which the classical progressive soil model holds in systems where geomorphic processes can remain active for quite long periods of time.

The aim of this review is to consider the role of soil within biogeomorphic succession in an active geomorphic setting where there always remains the possibility of reactivation of a stabilising zone by braid plain processes. We structure the review by first a brief consideration of current thinking regarding the role of vegetation in river morphodynamics, with a particular focus on gravelly braid plains. Second, we consider the extent to which soil has been considered in such environments and review the key soil forming processes involved in the transition of a fresh sediment deposit to a vegetated and (young) soil-covered braid plain landform. Both, biogeomorphological interactions and soil evolution are then integrated together in a third section where we present a model for the coevolution of braided river morphodynamics, soil evolution, and vegetation growth and succession. Finally, we illustrate this conceptual model through a case-study of the Allondon River, in Western Switzerland.

2.1.3 Biogeomorphological interactions in gravelly braid plains: a short review

Up until the 1970s, research focused on the parameters controlling the average river channel morphology (e.g. pattern, channel width) as a function of catchment hydrological factors (Lane, 1995; Schumm and Lichty, 1965). During the 1980s, both flume (e.g. Ashmore, 1982) and field (e.g. Ashworth and Ferguson, 1986) research draw attention on the morphodynamics of active braiding, including processes such as bar formation, bar destruction, avulsion and sediment transport processes commonly at shorter time scales (days to weeks) and spatial scales of river reaches (e.g. Ashworth and Ferguson, 1986; Lane et al., 1995). These studies were predominantly based on laboratory and field measurements, chosen to be dynamic over short time scales, and hence consideration of vegetation was not necessary.

Although vegetation had long been recognised as an important control on both the average dimensions of river channels (e.g. Heede, 1972; Leopold and Wolman, 1957; Schumm, 1968) and lateral channel adjustment (e.g. Smith, 1976), the linkages between vegetation dynamics and erosion and deposition processes only became more explicitly appreciated by Keller and Swanson (1979). During the 1990s, vegetation dynamics became seen as part of the braid plain system (e.g. Hupp and Osterkamp, 1996; Kollmann et al., 1999; Osterkamp and Hupp, 2010; Piégay et al., 1999; Piégay and Gurnell, 1997), including explicit recognition that biotic processes are involved in morphodynamics processes (e.g. Naiman et al., 1999).

Corenblit *et al.* (2011), Gurnell *et al.* (2012) and Gurnell (2013) reviewed in detail the progress in this field. Only a summary is provided here. Figure 4 couples the conceptual morphodynamic model developed by Ashworth and Ferguson (1986) to what is known about vegetation dynamics in gravelly braid plains. The conceptual model illustrates how channel morphology, bed roughness, and surface sediments under the external forcing of discharge, determine in-channel flow velocities. Flow velocities control bed shear stress, and in combination with surface grain size and organisation, bedload transport rates. The latter may both feed back into changes in grain size but also into changes in channel morphology (Ashworth and Ferguson, 1986).

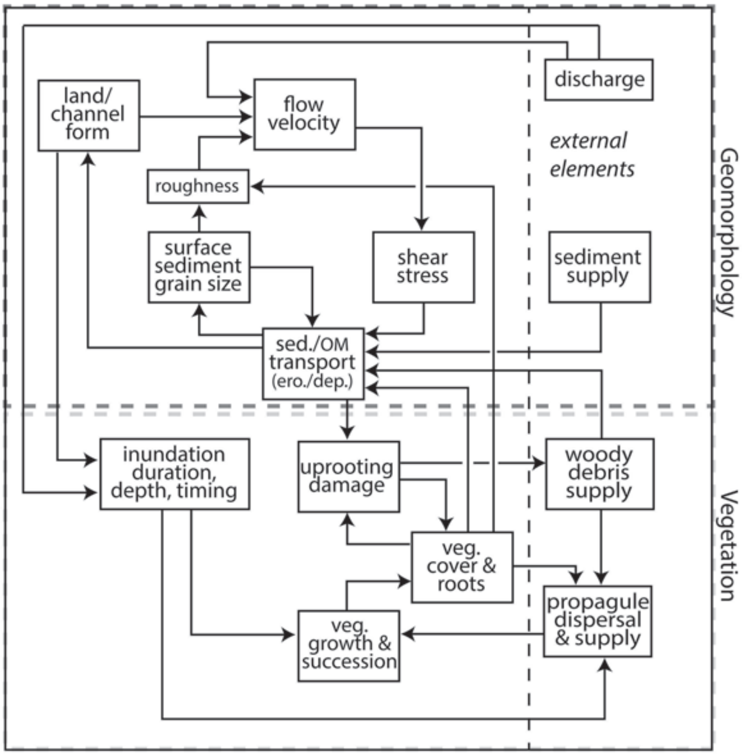


Figure 4 – Conceptual model of biogeomorphic feedbacks

Feedbacks between riparian vegetation colonization processes and the hydro-geomorphological system (synthesis using mainly Ashworth and Ferguson, 1986; Glenz et al., 2006; Gurnell et al., 2001).

The model then adds in vegetation. First, the river flow transfers plant propagules (Gurnell et al., 2012). Second, vegetation establishment and growth are controlled by hydrological processes, which may provide water and fine material, notably sand and silt, which encourages moisture retention in the normally well-drained gravelly braid plain deposits (Glenz et al., 2006; Gurnell et al., 2001). Zones prone to finer sediment aggradation are potentially more favourable for plant establishment (Corenblit et al., 2009). However, positions too low relative to the wetted channel involve higher and frequent inundations, and thus erosion or burial. Consequently, there will be an optimum elevation range for plant establishment in the active zone of a braid plain (e.g. Gurnell et al., 2001).

Vegetation establishment is more than just a passive response to fluvial processes: the active engineering role of pioneer plants (e.g. Moggridge and Gurnell, 2009) has been shown to modify the local physical environment, creating specific landforms and facilitating the establishment of other species by improving ambient environmental conditions such as moisture regime and erosion susceptibility (e.g. Francis, 2006). Plants, such as *Salicacea* (Willows), are thought to have evolved to perform this function (Corenblit et al., 2011; Moggridge and Gurnell, 2009) through their rapid establishment, vegetative reproduction, high resistance to physical disturbance, ability to fix nitrogen from the atmosphere and fine sediment trapping effects.

In natural high energy systems, such as braid plains, woody debris appears to play an additional major role by further facilitating and creating favourable sites for vegetation establishment (e.g. Bertoldi et al., 2014; Gurnell et al., 2005). The debris itself may re-sprout, allowing an extremely rapid increase in above and below-ground biomass and accelerating the colonisation processes even at low elevation at sites close to the low flow water limits (Francis, 2007; Francis and Gurnell, 2006). Woody debris may change local sedimentation and erosion processes, allowing many more species to be hosted and increasing local floodplain diversity (e.g. Francis et al., 2008).

As plant development and succession advance, bar sediment deposits may be protected by the flexible above ground biomass of, for instance, willows, and stabilised by the developing root system. Roots of young seedlings develop as a function of seasonal water table fluctuations, as the root network adapts to avoid water logging and to follow the falling water table to avoid drying (e.g. Glenz et al., 2006; Pasquale et al., 2012). Karrenberg et al. (2003) analysed the strength of roots and found that *Salix elaeagnos* (Rosemary Willow) had the greatest uprooting resistance as compared to *Alnus incana* (Grey Alder) and *Populus nigra (Black Poplar)*. This uprooting resistance reflects the colonisation zones of these three species, with the more resistant (*Salix)* growing in the most dynamic parts of the floodplain, and the last two species on more stable sites. Additionally, they found that uprooting resistance was higher in sand than in gravel deposits for all three analysed species, because of differences in the root structure (Karrenberg et al., 2003). Crouzy and Perona (2012) and Perona et al. (2012) analysed how vegetation establishment and related root development interact with water flow and sediment transport in a flume experiment. Their analysis shows a stochastic selective process of the weaker developed vegetation (defined as having short roots and stems). The stochasticity is introduced due to the spatial arrangement of the vegetation and the erosion and deposition processes, which can erode young plants by uprooting and established plants by scouring, but also protect less developed vegetation by deposition (Crouzy and Perona, 2012; Edmaier et al., 2011; Perona et al., 2012).

Propagule supply and establishment, woody debris dynamics, root development and sediment strengthening combine to determine floodplain vegetation dynamics and associated feedbacks into overall alluvial morphodynamics. This has been shown to impact channel dynamics and planform development in field (Bertoldi et al., 2009; Gurnell and Petts, 2002; Welber et al., 2012; Zanoni et al., 2008) and flume models (Murray et al., 2009; Tal and Paola, 2010).

Most recent work extends the timescale of consideration to more stable vegetation-mediated landforms. This can be thought as a process of landform coevolution through a series of biogeomorphic successional stages (Corenblit et al., 2009). Corenblit et al. (2014) reviewed the evidence of biogeomorphic succession for *Populus nigra* during its development from a seedling to a mature plant. Although assessed for poplar, this might be valid for other riverine pioneer species such as willows. The biogeomorphological life cycle of *P. nigra* encompasses four different phases. The first is geomorphological, in which seedlings are dispersed by floods and germinate on potentially suitable bar surfaces. In a second, 'pioneer' phase, seedlings need to survive the first years and are challenged by water stress, erosion and deposition processes. In these first two phases, *P. nigra* is completely exposed to the physical environment. Third, in the biogeomorphological phase, the interaction between plant and its physical environment is highest. The engineering action of the young trees allows fine sediments to be trapped and, due to endomycorrhizal fungi, access to a larger nutrient pool is guaranteed (Harner et al., 2011). Fourth, during the ecological phase, the vegetation patch becomes independent of fluvial processes and sustains its resource demands through autogenic processes. Only the most extreme flows interact with the vegetation in this phase, characterised by shallow overland deposition or lateral erosion processes (Corenblit et al., 2014).

The context for this paper follows from the notion of biogeomorphic succession that implies a consideration of fluvial landform development over periods of years to decades, a timescale which becomes relevant for pedogenesis. Thus, do conceptual models of braided river ecosystems also needs to consider soil forming processes?

Are pedogenic processes only actively involved in the ecological phase of Corenblit et al.’s (2014) model? Or are they important earlier in these cycles, such as in the transition from a fresh sediment deposit to a vegetated pioneer landform? If they are important early on, are they simply passive indicators of a developing ecosystem or do they both directly and indirectly impact on braid plain dynamics?

2.1.4 Early soil development in gravelly braid plains

Soil can be observed on many river floodplains, especially on their more stable surfaces, such as river terraces (e.g. Cierjacks et al., 2010, 2011; Gerrard, 1987). Commonly, such alluvial soils have developed from freshly deposited, sometimes gravelly, materials as can be found in the active zone of a braid plain. Subsequent deposition, especially of fine grained material, establishment of vegetation (and its engineering action) and related isolation from the geomorphological forcing (e.g. river incision) promotes pedogenesis. However, Gerrard (1995) argued that analysing alluvial soils is generally challenging because they do not follow standard soil development rules, as river morphodynamics (erosion and deposition processes) may prevent the simple assumption that soil profile development always correlates with the progression of time, progressive pedogenesis. Processes such as aggradation and erosion hamper or reset progressive pedogenesis.

A normal simplistic model of soil profile development follows the conventional ABC (horizon) model, in which an initial unaltered deposit (the parent material) is exposed to pedogenesis. With time, and the progress of biological activity, an organic (O) horizon may develop from organic matter input. The first A horizon may form as this organic matter is incorporated and mixed with mineral matter (formation of the humic-clay complex). With enough time, leaching from the A horizon and/or intense weathering of the C horizon may lead to the formation of B horizons. This is the standard simplified translocation conceptual model used in most soil science studies in more geomorphically stable environments (Phillips and Lorz, 2008). Vertical water movement and/or gravity are the main actors involved in soil horizon formation.

However, in rivers, and particularly in dynamic braided floodplain systems, things are more complex because of vertical aggradation and erosion processes. Both may perturb the progress of pedogenesis. In the case of deposition, a C horizon (that is mainly a chemically and physically slightly altered sediment deposit) can bury the former A topsoil horizon. Eventually a new A horizon will form, but with a buried A horizon below the C horizon. The new topsoil A horizon potentially promotes the formation of a new B horizon, which may include the ancient buried A horizons (Gerrard, 1995).

A "pedosedimentary" approach for analysing such dynamic systems might be more convenient (Phillips and Lorz, 2008). In this approach, pedogenesis and sedimentation processes are identified as antagonists in forming soil and sedimentary layers. Hence, alluvial soil horizon formation is influenced by the interplay of these two, but is also impacted by the ancient buried surface. This may lead to a multitude of soil profile development pathways, as has been shown by Kraus (1999) for fluvial systems. In this sense, it is more appropriate to talk about soil evolution (*sensu* Schaetzl and Anderson, 2005) rather than soil development due to the difficulty of defining a single soil trajectory (Huggett, 1998).

Several pedogenic models exist and have been reviewed by Schaetzl and Anderson (2005). While the widely accepted CLORPT-model (Climate, Organisms, Relief, Parent material and Time) of Jenny (1941, 1961) emphasises the frame in which soil processes develop soil horizons, other approaches focus more directly on processes (Schaetzl and Anderson, 2005). As we are interested in defining the processes that lead to the transition of a barren fresh sediment deposit to a vegetated and soil covered braid plain patch, we follow the second approach.

Johnson (1985) proposed a soil evolutionary model. Such formulations have been developed since the 1940s (Nikiforoff, 1942; Simonson, 1978). However, because it explicitly considers soil thickness, the Johnson (1985) model is the first which allows interactions with geomorphic processes in time (Schaetzl and Anderson, 2005). Soil thickness (T) is a function of deepening (D), upbuilding (U) and removal (R) processes:

[Eq. 1] $T = D + U + R$

Deepening processes include weathering and intra-pedon leaching processes that allow a soil profile to grow in depth. Upbuilding processes consist of external organic and inorganic additions to the pedon. Removals, involve erosion and mass wasting processes, but also include the loss from of biochemical elements via leaching (Johnson, 1985). Several studies have addressed processes related to D and U, with a special emphasis on biological processes and their interactions with R during pedon evolution (Johnson, 2002; Johnson et al., 1987, 2005a, 2005b; Johnson and Watson-Steigner, 1987). Braided fluvial processes have a direct influence on U and R, but may also influence D, less directly, through impacts upon the abiotic environment. Upbuilding processes may have opposite effects, either retarding or developmental, based on the magnitude, frequency and composition of the added material (Johnson, 1985; Schaetzl and Anderson, 2005). Whether retarding or developmental, upbuilding will aggrade the surface and potentially thicken the soil profile. Only extreme events will create a new higher elevated surface on which pedogenesis will act.

We will consider the impact of inorganic sedimentation (U of Eq. 1) and erosion (R of Eq. 1) processes on braid plain soil evolution in the next section and the role of organic matter in the subsequent section.

The balance of the processes included in these three broad process categories, which interact and change in rate, scale and time, may lead to either progressive or regressive phases of soil development. Progressive soil evolution leads to complication and differentiation of soil horizons, while regressive soil evolution simplifies the soil profile (haploidization). Progressive and regressive processes coexist but change rates in time, such that a soil may follow different development paths within the same environment and under similar initial conditions (Johnson, 1985; Johnson and Watson-Steigner, 1987; Phillips, 1993). Johnson et al. (2005a) illustrates this principle for a pedon, where there are both regressive and progressive phases under the influence of biological upbuilding processes (e.g. *in-situ* organic matter enrichment, bioturbation that cause volumetric increase) and erosional processes (removal). Thus, after the two sections that discuss sedimentation/erosion processes and organic matter impacts, we consider processes that influence early stages and pathways of alluvial pedogenesis.

The impact of fluvial erosion and deposition

Erosion and deposition have fundamentally different effects: erosion leads to removal of soil; deposition leads to its burial or cumulization. However, alluvial soil development following either erosion or deposition must pose the same question: how does vegetation and soil develop on the newly exposed/deposited sediments?

Answering this question, and understanding the polygenic character of alluvial soils, must recognise that whether or not a soil forms on newly exposed sediments depends on the magnitude and frequency with which the surface is perturbed (regressive processes), versus progressive soil formation rates (Birkeland, 1999; Daniels, 2003; Gerrard, 1987, 1995; Jacobson et al., 2005). While soil formation depends mostly on large scale properties (e.g. sediment mineralogy, climate,…), magnitude and frequency will be a function of local exposure to braided river processes. Figure 5 conceptualises the effects of the magnitude and frequency of sedimentation in terms of two end members: a fully developed pedogenic soil and a sedimentary-structured profile. Sedimentation rate is separated from sedimentation frequency to emphasise that either a high rate (e.g. from a low frequency high magnitude event) or a high frequency (e.g. from many high frequency low magnitude events) can lead to profiles that are more dominated by sedimentation. However, we also include buried profiles and cumulic profiles as intermediate states.

Cumulic soil profiles are soil profiles that form under slow aggrading conditions, allowing the rapid pedogenic assimilation of deposited materials via pedogenic processes. If the magnitude and frequency of aggradation exceeds pedogenic assimilation, the ancient surface horizons will be buried, leading to a buried soil (Daniels, 2003). Schaetzl and Anderson (2005) define a buried soil as an ancient surface horizon sequence that has been covered by a recent, even thin, alluvial deposit. This definition encounters some difficulties in differentiating between buried and cumulic soil, as thin deposits potentially can be integrated very rapidly into the profile, leading to a more cumulic profile. However, paleosols are distinguished from buried soils, as being formed on an ancient landscape surface under a different set of soil forming factors (Kraus, 1999).

Figure 5 notwithstanding, there are important similarities and distinctions between erosion and deposition. Both, high magnitude and/or frequent erosion and sedimentation events may not give enough time for pedogenesis, leading to the dominance of the regressive phase in Johnson's (1985) model. Low magnitude and/or rare sedimentation events may encourage pedogenesis (progressive pedogenesis), because they allow enough time for soil processes to develop horizons but may also supply valuable soil development resources (e.g. fine sediment that enhances water retention and has a higher reactive surface). As discussed below, one additional resource is organic matter deposition on sites with low biomass productivity such as gravel bars (Langhans et al., 2012). However, intermediate deposition rates with moderate frequency may create buried soil horizons interspersed between sediment horizons (Daniels, 2003). Erosion is distinctive because it tends to re-expose, or to reintegrate, buried soils into the active dynamics of the river.

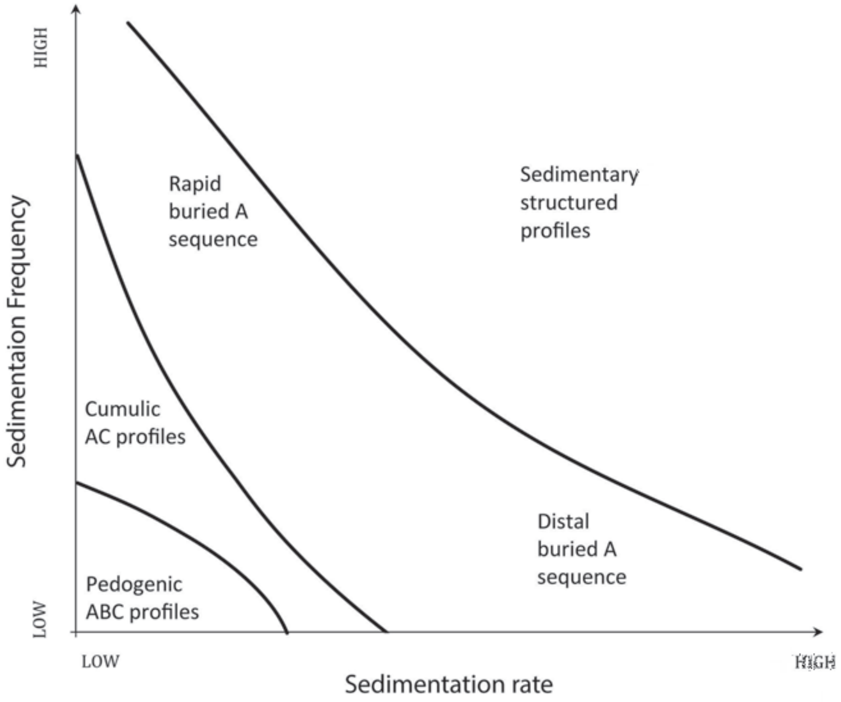


Figure 5 – Soil formation as a function of sedimentation rate and frequency

Relationships between sedimentation rate, sedimentation frequency, and the profile sequences that can be formed. Pedogenic profiles and sedimentary structured profiles are found at the two extremes. In-between, cumulic AC horions can be found that form under slow aggrading conditions (pedogenic assimilation of deposited materials). Rapid buried soil sequences can be formed in the case of low sedimentation rates with high frequency, which exceed pedogenic assimilation. Conversely, more distal buried soil sequences in a profile are formed under low frequency but high magnitude sedimentation events.

One additional difference exists between deposition and erosion: according to the extent to which the river bed elevation changes, deposition will generally create a higher elevation surface while the second a lower elevation surface relative to the river. Thus, whilst both erosion and deposition may create exposed sediment surfaces upon which soil development can begin, they may lead to very different local environmental conditions in terms of the magnitude and frequency of inundation. This influences future perturbation (erosion/deposition) as well as access to key landform ecosystem resources such as water.

Clearly, depositional environments where the magnitude and frequency of sedimentation are not too high are most likely to produce soil. Few studies have analysed how the complex spatial and vertical characteristics of soils are produced through the effects of the fluvial processes described above, and then most studies have focused upon deposition. Bullinger-Weber and Gobat (2006) and Guex et al., (2003) analysed soils from the Sarine River in Switzerland and this supports the model described in Figure 5. Bullinger-Weber and Gobat (2006) defined the sediment stratigraphy in terms of four facies models: (1) a homogeneously layered deposit sequence, (2) a thick sediment layer covered by several thin layers of sediment, (3) thin layers of sediments covered by a thick sediment layer, and (4) multiple sequences of thin and thick sediment layers that might present a buried A horizon. It was argued that these facies models mainly reflect the complex sedimentological history of the system rather than pedological processes: for instance, thick layers of sediment indicate catastrophic sedimentation events while thin layers indicate periods of relatively stable geomorphic periods with shallow overland flows (see Figure 5). Within their stratigraphy, they identified buried A-horizons, with weak soil aggregates, suggesting that such sites may have been colonised by plants during periods of reduced sedimentation such that initial pedogenesis was able to start and to alter the raw sediment (Bullinger-Weber and Gobat, 2006), and so influence plant succession and colonisation. Nevertheless, an organic matter enriched topsoil could form within 150 years in an embankment river reach, if geomorphic processes were reduced to shallow overland flows with slow deposition rates (Guex et al., 2003), as indicated in Figure 5.

Deposits: are they organically and chemically inert?

As reviewed above, the magnitude and frequency of both erosion and deposition will impact upon the time available for soil processes to transform river sediments into soil. In the second element of the Johnson (1985) model, it is necessary to consider organic material supply not simply as an upbuilding process, but also because of its influence upon local biological and chemical activity, something that may influence deepening as well as upbuilding. Generally, in the braided river literature, fine sediments and organic matter deposition are thought to support initial vegetation succession with biological and chemical processes considered as secondary controls (Bertoldi et al., 2011; Gurnell et al., 2012). It initially appears that initial *in-situ* soil forming processes (physical or chemical) are not particularly important for initial pioneer colonisation because many pioneer plant species (e.g. *Salix. spp.*) do not need access to anything other than water and a suitable C horizon for rooting. However, two caveats follow. First, fresh river deposits may not always be chemically or organically inert. Second, river deposits, whether actively created or exposed by erosion, have a stratigraphy that may impact upon initial alluvial soil formation. Both of these may create conditions in which the initial development of a soil organic horizon may be more rapid, influencing the D and U of Equation 1. Because this soil horizon formation can change local biochemical and biological conditions, important at least for further successional stages, understanding where rapid organic horizon development is possible (high progressive pedogenesis rates) is a critical question for the development of braid plain ecosystems.

Fresh river deposits may contain dissolved organic matter, plant residues, and other particulate organic matter, and thus are themselves not necessarily organically inert. This may accelerate initial biochemical soil forming processes (Baker et al., 2000; Fisher et al., 2007; Piégay et al., 1999; Piégay and Gurnell, 1997; Pusch et al., 1998; Schade et al., 2001). During plant succession, communities with low growth rates and low organic matter production rates (reinforced by nutrient scarcity) will be replaced by communities with higher growth rates and high organic matter production rates (Berendse, 1998). It follows that during the initial plant colonisation phase, allochthonous organic matter input from the river may be an important influence on initial pedogenesis and the overall riverine biochemical processing (Cabezas and

Comín, 2010; Tabacchi et al., 1998). In general terms, the additional organic matter is thought to enhance local microbial activity which in turn can speed up soil horizon formation (Gregory et al., 1991; Janssens et al., 2001; Pusch et al., 1998). However, relatively few studies have addressed this question in braid plain environments. Naegeli (1997) studied the storage capacity for particulate organic matter (POM) in a gravel bed river (Necker, Switzerland) and its implication as an energy resource for the river system. They found that the amount of POM varies spatially, but generally increases deeper in the deposit. The spatial heterogeneity is closely related to the seasonal variation of matter input and the geomorphological processes during peak flow, in which channel morphology and fluvial landform sequences create organic matter sinks/traps (Bridge, 1993; Naegeli, 1997). The lower POM content in the upper gravelly sediment layers is related to the out-flushing effect of lower flood peaks. Nevertheless, the POM stock in deeper layers, and its contact with the fluctuating groundwater table, was observed to create a “resource reservoir” (Naegeli, 1997) that could be activated by microbial activity depending on season and flood frequency (Doering et al., 2011; Pusch et al., 1998; Uehlinger, 2000). Doering et al. (2011) and Langhans et al. (2012) made similar observations in the braided Tagliamento River (Italy), in which fresh allochthonous produced organic matter, produced on river islands and terraces was identified as an important energy source for exposed gravel, which normally has low *in-situ* productivity. Likewise for the meandering Ebro River (Spain), in which sedimentation is the dominant processes for organic carbon accumulation on young fluvial landforms, while for older landforms (>60 years) *in-situ* production dominates (Cabezas and Comín, 2010).

Overall, this evidence emphasises the importance of the connectivity between different riverine habitats, in which organic matter is produced, such as islands and floodplain wood, and less productive sites, such as bars (Cabezas and Comín, 2010; Langhans et al., 2012; Tabacchi et al., 1998). However, to profit from additional resources, such gravelly sites need to be under the influence of the river flood pulse, which in some case, can also be destructive whether through erosion or through rapid sedimentation (and so upbuilding) that serves to isolate a zone from fluvial organic matter supply.

Studies of the colonisation of the fluvial zone of recently deglaciated landscapes, which are commonly well constrained chronologically, have challenged the assumption that braided river deposits are always chemically inert. For instance, Mavris et al. (2010) and Burga et al. (2010) found in a glacial forefield in the Swiss Alps, that chemical weathering and mineral transformation starts at high rates immediately after deglaciation. Even if the initial deposit is organically inert, if the deposit is located in the right environment, weathering processes may rapidly promote plant colonisation.

Hence, to understand alluvial soil development in a braided river, we need to consider not only the physical sedimentation and erosion processes themselves, but also the nature and turnover of organic and inorganic compounds included in the sediments (Doering et al., 2011; Gerrard, 1995; Kraus, 1999). In view of the multitude of braid plain landforms, their potential for plant colonisation and their spatial connectivity via the water flow, a multitude of landform development pathways is possible. We should be prepared to move away from simple time dependent models of soil development, to consider how geomorphic processes interact with soil evolution to condition the pathway followed.

Processes influencing braid plain alluvial pedogenic pathways

The accumulation and processing of organic matter in the topsoil and formation of an enriched organic matter horizon (A) is seen as the first soil forming process of braid plain alluvial soils (Bureau, 1995; Viereck et al., 1993). Its formation depends on geomorphic activity, which defines surface stability and the input of material from the river, but also upon sediment stratigraphy, drainage properties, microbial activity, soil flora and fauna, vegetation colonisation and its succession.

The vertical grain size distribution of the sediment below a newly exposed or deposited surface is likely to be critical for young alluvial soils because of its influence on drainage properties, weathering rates, plant establishment, and soil flora and fauna (Birkeland, 1999; Corenblit et al., 2009; Farine et al., 2009; Guenat et al., 1999; Pusch et al., 1998).

Biofilms, composed of a mixture of one or more of bacteria, fungi, and algae, live on and within the sedimentary structured profile. As explained above, they constitute a major possible source of autogenic organic matter, but also a main actor in material transformation processes. Biofilms have been identified (Claret et al., 1998; Pusch et al., 1998; Tabacchi et al., 1998; Valett et al., 1996) as playing a major role in the activation of deposited allochthonous organic matter. They can transform dissolved organic matter, particulate organic matter and fresh woody debris into plant available forms, and so activate resources for further local ecological processes. Yet, they have also been shown to be important for local fertilisation effects as, for instance, Harner and Stanford (2003) found that cottonwood stands on upwelling hyporheic water sites grow faster than downwelling sites because of additional nutrient production in the interstitial spaces and water supply. However, these studies show that it is difficult to disentangle controls on biofilm formation, and that they essentially relate to interactions between hydrographs, ground water fluctuations, water quality, deposited sediments and related drainage properties and matter fluxes, sediment structure and available oxygen.

Van Breemen and Finzi (1998) observed that soil physical and chemical properties change during vegetation succession, a process that can be particularly important during primary succession. Therein, plants start to modify directly or indirectly by promoting soil processes in ways that facilitate later successional stages (progressive pedogenic processes). Thus, the arrival of such species impacts the rate and quality of locally produced, or autogenic, organic matter input (Bureau, 1995). The decomposition processes (humification and mineralisation) relate to the micro flora and fauna found in the sediment/soil layers, as described above, the quantity and quality of the produced biomass (C/N ratio) and sediment lithology (carbonates can hamper humification).

Apart from biofilms, large soil animals are also an important actor for organic matter turnover, the creation of soil aggregates and soil related structure and bulk density. The influence of earthworms on alluvial soil evolution varies between species (Guenat *et al.*, 1999) and between deposits depending on sedimentological structure (Bullinger-Weber *et al.*, 2007). Guenat *et al.* (1999) identified four critical types of earthworms in terraces of the braided Sarine river, Switzerland: (1) epigeic earthworms, restricted to leaf litter and important in litter transformation, typically with low competition potential, high and rapid reproduction rate, high colonisation capacity and able to survive in shallow soils (e.g. in willow leaf litter) hence, often resistant to rapid local environmental change (e.g. drying); (2) anecic earthworms, which mix leaf litter with the upper soil horizons. They are important for bioturbation, but are characterised by slow-growth with low fecundity and mortality rates, medium colonisation capacity, needing deep soils, often with a silty texture; (3) endogeic earthworms, which affect soil structure through macro-aggregation; and (4) enchytraeid worms, which alter soil physical properties through burrowing but suffering from water stress (floods and droughts). Earthworm presence has been shown to be texture dependent: for instance, enchytraeid and epigeic worms prefer coarse sand and anecic worms more silty environments (Bullinger-Weber et al., 2007). These kinds of faunal differences, linked to deposit characteristics, were found to be sufficient to deviate the development of soil structure from a simple time-dependent pathway. The soil fauna, such as earthworms, but also organic acids, root exudates and weathering and precipitation products (e.g. carbonates, iron and sulphates) aggregate particles together to form soil aggregates and voids within the soil matrix. Soil aggregates/structure and voids influence bulk density and ambient conditions such as water retention, ground water capillary rise, drainage and aeration, plant rooting, as well as nutrient availability and stock. Advancing in time and with relatively low depositional/erosional disturbance and the further colonisation by plants, soil aggregates may develop in the A-horizon (Daniels, 2003; Graf et al., 2012). Harner et al. (2011) found that water stable soil aggregates can already be found on pioneer islands (34.4% of soil mass) and established islands (73.8% of soil mass) of the braided Tagliamento River which, as found by Zanoni et al. (2008), rarely persist more than 24 years. Similar results for the same site have been found by Mardhiah et al. (2014). The aggregation of soil particles is closely related to fungal activity. Mycorrhizal fungi, in particular, enter into symbiosis with pioneer plants such as poplar and willows species, and thus can promote aggregation during the early stages of alluvial soil formation (Harner et al., 2011; Mardhiah et al., 2014). Propagules (colonized roots, spores, and hyphae) are propagated by the floods and mixed within the deposits. This allows mycorrhizal fungi to colonise the deposits and to rapidly establish symbiosis with the pioneer plants. Pioneer plants on established islands present respectively 87% and 96% of their root length colonised by mycorrhizal fungi. Apart from contributing to soil aggregate formation, and thus ameliorating water retention, mycorrhizal fungi improve plant nutrient uptake and allow faster and better connection to the ground water especially on early succession sites (Harner et al., 2010, 2011). Better growing conditions lead to a higher biomass production, thus feeding the soil organic matter turnover machine at the surface.

Stagnant water may be observed in braided river environments and characterised in deposits via the redox properties of iron and manganese. Reduced iron is transported as a solute, leaving a continuous or mottled greyish soil layer. This process is called gleying. Nevertheless, under fluctuating ground water or above an impervious clay layer, the dissolved iron can oxidise again as long as it gets in contact with oxygen enriched areas, such as around soil voids, forming reddish mottles (Gerrard, 1995). In young alluvial soils, these two processes are mainly attributed to water table fluctuations, but are also dependent on the vertical grain size distributions of the deposits. In gravel-bed rivers, such features are difficult to find due to the high drainage properties of the sediments. Conversely on river terraces, more mature soils might have formed a layer that impedes drainage due to past deposition or in-profile translocation processes of clay. Nevertheless, to mobilise clay, decalcification of the upper soil layers and enough fines, e.g. from weathering of sediment parent material but also deposition processes, are required (Gerrard, 1995).

The biological processes described above are key processes in (early) pedogenesis, when compared with weathering processes. Johnson et al. (2005b) analysed and visualised the effect of biological processes on pedon evolution in time by applying Eq. 1. In this approach, direct and indirect biological induced processes influence the deepening *D* (eg. bioturbation, transfer, scouring) and upbuilding *U* (eg. accumulation of organic matter, increased in soil volume by root growth,…) of a soil profile. The balance of these two with the removal processes *R,* such as erosion, define the thickening, degradation and stability of the soil cover (Johnson et al., 2005a, 2005b). Similar processes may be associated with braided rivers, although removal processes may have a wider range of magnitudes, including resetting, as explained above. Moreover, upbuilding processes related to exogenous processes might be of great importance where they supply valuable resources (exogenous organic matter, see above). Both depend on position and exposure of the landform to fluvial processes.

2.1.5 The coevolution of braid plain morphodynamics, vegetation succession and soil evolution

On the basis of the above review, we have developed a conceptual model of braid plain morphodynamics which extends the braided river-vegetation model (Figure 4) to include related soil evolution processes (Figure 6). In this model, we see soil evolution as critical in reducing the dependency of an ecosystem (e.g. young pioneer landforms) upon allochthonous river water and matter inputs. Together with the functional advantages of pioneer species, it allows the transition to more autogenic self-sustaining ecosystems, as for instance observed on river terraces. We can define this as a coevolving process, involving feedbacks between river morphodynamics, vegetation dynamics and soil evolution.

To put soil into an understanding of braid plain development, we need to combine understanding of erosion and deposition history with that of relevant biological and chemical processes. The two are tightly coupled because erosion and deposition not only create the deposits upon which pedogenesis acts but also influence the overall pedogenic and vegetation setting, such as position on the floodplain, aggradation rate, matter supply and erosion susceptibility, and hence ambient environmental conditions. However, they also operate over different timescales: the inorganic component (e.g. river gravels) may increase rapidly during deposition events, changing the vertical sediment structure, but weathering of these gravels may be slow (depending upon the lithology); the organic component may be initially unimportant in a fresh deposit, but it can decay relatively quickly and produce compounds (e.g. organic acids) that may aid the weathering of inorganic components (e.g. Drever and Stillings, 1997; Huang and Keller, 1972). Especially with the colonisation of vegetation and its succession, biomass production rates increase and so alteration processes may accelerate (Van Breemen and Finzi, 1998). This in turn may impact river morphological stability (increased river bank stability by vegetation) and hence erosion processes as well as fine sediment deposition through enhanced surface roughness in the case of overbank flows.

Given the above, the model includes processes with different time scales of operation, generally speaking in the order geomorphology < vegetation < soil, but where their coupling, as suggested by the Johnson (1985) model, leads to a complex suite of feedbacks that may substantially influence landform evolution pathways at the scale of decades. A key hypothesis follows for investigation: initial geomorphic conditions (e.g. channel and landform position or quality of sediment deposits) and the variability and interplay of small scale processes (e.g. discharge, sediment and organic matter supply), may feed back into longer time scale processes such as land form vegetation dynamics and soil evolution, and thus reach scale river morphodynamics (Lane and Richards, 1997; Phillips, 1993; Richards et al., 2002). Based on the sensitivity of the system, such feedback may lead towards differing stable states that act as attractors (Thomas, 2001).

Although we have argued that the conventional progressive model of soil development through time needs to be modified for a system where there is active perturbation and resource supply, the processes in Figure 6 retain a time-dependence. Figure 7 illustrates the coevolution based on the processes illustrated in Figure 6 for a hypothetical landform under the assumption of progressive stabilisation (linear reduction of geomorphological perturbation). Initial landform properties and related plant establishment are highly dependent on the initial vertical sedimentation structure and the water and matter fluxes passing over it (inundation frequency and deposition rates are high). The interplay between aggradation of fine grained material, vegetation engineering, plant succession, and soil forming processes influences the direction and the speed of the secondary succession, and hence whether the landform will survive the next big erosive event (stabilising effect of roots). Gurnell and Petts (2002) argue that there is an optimal relationship between plant recruitment/establishment and the aggradation rate, which influences water and nutrient supply, but also the speed at which the landform is taken out of the zone where the magnitude and frequency of inundation is too great. Initial soil evolution, in terms of soil organic matter processing and soil structure formation, then, is critical in improving landform ambient conditions.

Exogenic organic matter, which has been deposited via fluvial processes or *in-situ* supplied by pioneer vegetation, may facilitate the coevolution by speeding-up ecosystem processes and hence ameliorate ambient conditions. This rapidly reduces the dependency upon riverine matter inputs and allows vegetation survival and its succession even with reduced inundation frequencies. Eventually, this might feedback

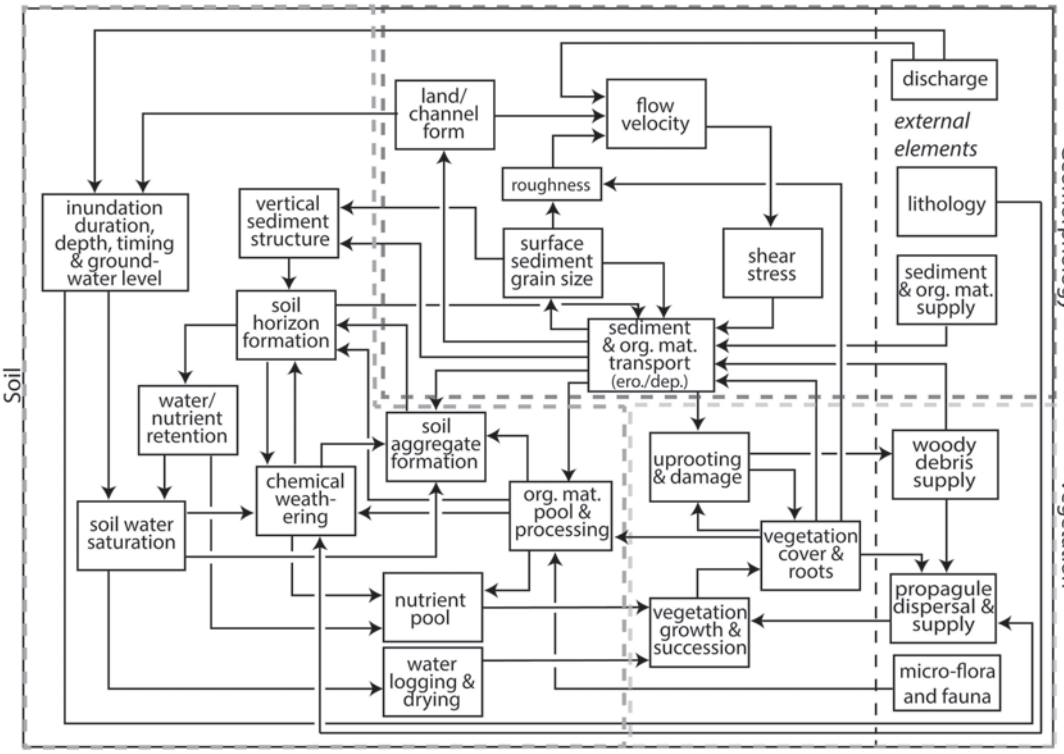


Figure 6 – Conceptual model of pedo-biogeomorphic feedbacks

Conceptual model of the co-evolution of braided river morphodynamics, soil evolution and vegetation succession and growth as reviewed in the text. The abbreviation ‘org. mat.’ stands for organic matter, while ‘ero./dep.’, respectively, for erosion and deposition.

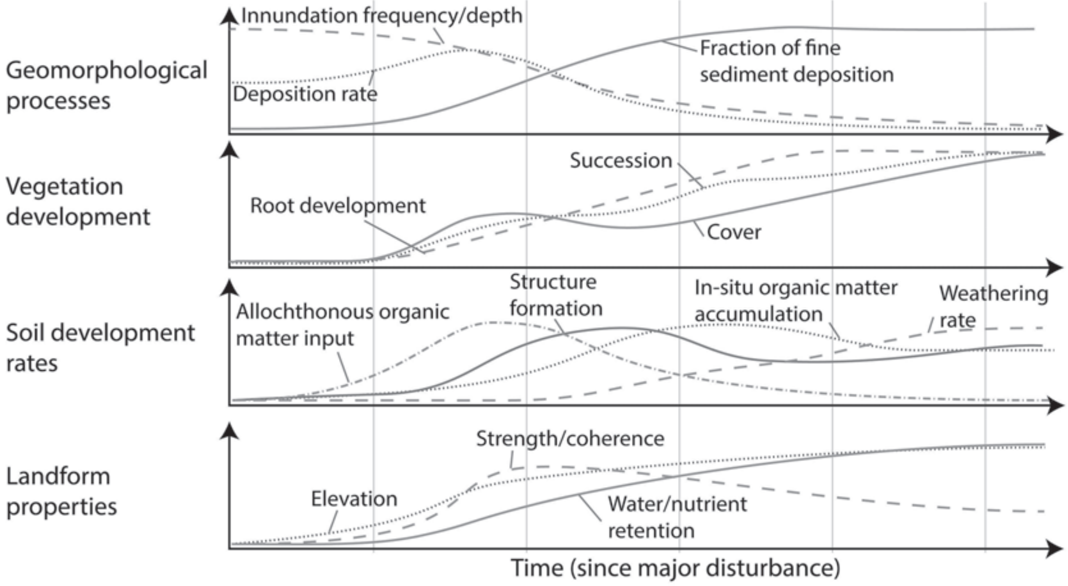


Figure 7 – Co-evolution of landform properties

Representation of the co-evolution based on the processes illustrated in Figure 6 for a hypothetical landform under the assumption of progressive stabilization (linear reduction of geomorphological perturbation). The trajectory of the different processes and properties are hypothetical and are only used to visualize the concept of co-evolution in alluvial braid plains.

into the overall river planform at larger scales due to the creation of more stable fluvial landforms. Again, Figure 7 is not based on field observations but rather a hypothetical landform evolution and should be considered with caution. It simply illustrates the concept of coevolving process rates and properties shown in Figure 6.

2.1.6 Example: coevolution of landforms, soil and vegetation in the Allondon River

Here, we illustrate the conceptual models described in Figure 6 and Figure 7 for the braided Allondon River, a protected nature reserve in the western part of Canton Geneva, Switzerland. This example comprises a braided river – terrace system, including active braiding processes, rapid vegetation colonisation, stabilisation of braid bar deposits and the development of soil profiles (SITG, 2014). The upper part of the 148km^2 basin is located in the karstic Jura Mountains with its highest point at 1718 m (CJB (eds.), 1990; Hottinger, 1998). At the base of the mountains, the Allondon River concentrates the karstic flow and several small tributaries to form a 3 km long braid plain before flowing into the Rhone River. In this reach, the river is incised into fluvio-glacial sediments deposited over the Swiss Molasses basin during the last glaciation (Hottinger, 1998). The hydrology is characterised by a pluvio-nival regime.

A 200m long soil toposequence, used as an analogy for a chronosequence, has been considered for a section from the active river channel and extending to the highest terrace (Figure 8). In the active channel, two areas have been defined with different vegetation cover and altitudes: (i) an area 0.3m above the river level with a 10 year old *Salix* spp. (Willow) vegetation cover; and (ii) an elongated area, 0.4m elevation and with almost no vegetation (a few grass stalks). Aerial imagery shows (Figure 9) that both areas were part of the main channel in 2001, but had been abandoned by 2005, confirming an indicative age of about one decade when combined with the dendrochronological data. The three terrace areas (at 1.3m, 2.5m and 3.7m elevation; Figure 8) are covered by forest with mainly *Quercus robur (French Oak)*, *Fraxinus excelsior* (European Ash) and *Corylus avellana* (Common Hazel). Because of ancient coppice management, no dendrochronological dates can be easily defined, and

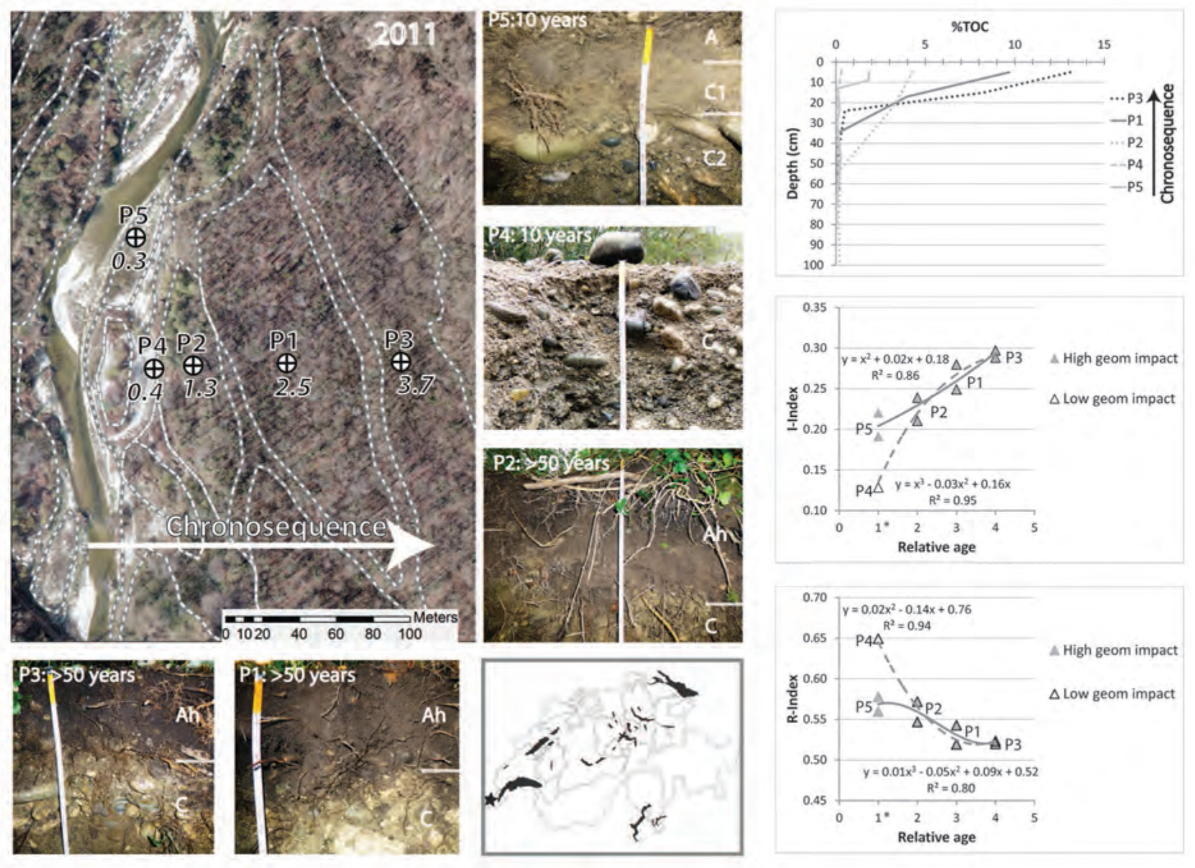


Figure 8 – Toposequence along four terraces of the Allondon

Aerial image of the study reach of the Allondon River (SITG, 2012), showing the chronosequence along four terraces (dashed line). Soil profile locations, related code (Pn) and elevation above the river, are given by white dots. The five photos show the studied soil profiles and the observed horizons (A = organic matter enriched topsoil; Ah = particularly organic matter enriched topsoil; C= gravely sandy fluvial deposits). The three graphs on the right show from top to bottom: the amount of TOC (Total Organic Carbon), the I-index, and R-index (see text for explanation) along the chronosequence. * = indicates the profiles that could be dated (10 years) based on aerial images.

consequently only relative ages are used in the terrace toposequence (the higher the older the terrace).

For each of the defined areas, one soil profile was dug in a representative site (vegetation cover and topography). Sedimentological and/or soil layers were identified in each profile. In Figure 8, the five soil profiles are shown and express the entire range of variability found along the section. The first profile (P5), found in the 10 year willow dominated 0.3m elevated area, shows three main layers: a soil horizon enriched in organic matter overlying a sandy deposit; a gravel sand sedimentary layer deeper in the profile. Following the WRB classification system (IUSS Working Group WRB, 2006)

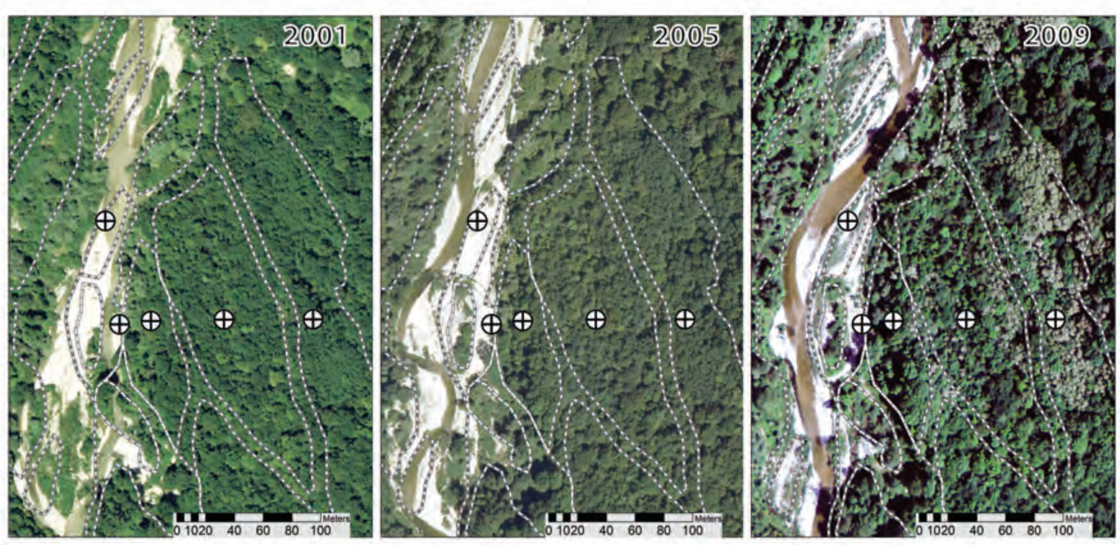


Figure 9 – Historical evolution of the four terraces of the Allondon

Aerial images of the study reach of the Allondon River (2001 and 2005: (SITG, 2014; SWISSTOPO, 2012), documenting the geo- morphological development of the chronosequence shown in Figure 8.

that would correspond to a fluvisol skeletic. The second 10 year profile (P4), was dug in the barren 0.4m elevated area, and no soil horizon could be defined but rather a gravel sandy deposit (leptosol skeletic). The terrace soil profiles P2, P1 and P3 in Figure 8, which continue the toposequence at respectively 1.3m, 2.5m and 3.7m elevations, show a thick organic matter enriched topsoil (mollic fluvisol skeletic). Note the difference between the P5 and P4 profile with same age (one decade) and also its comparison to the more developed terraces soil profiles (P2, P1 and P3).

For laboratory analyses, 200g of each sedimentological and/or soil layers were sampled. The Rock-Eval pyrolysis method defined by Sebag et al. (2006) was used to measure the Total Organic Carbon (TOC – Figure 8). Using this method, different pools of organic matter (OM) have been identified: fresh leaf litter, medium stable humus components (humic and fulvic acids), resistant biopolymers, such as lignin and cellulose, and very resistant components such as black carbon and charcoal. The results can be summarised into two indices (Sebag et al., 2006): the I-index defines the availability of fresh OM in the sediment/soil layer. Thus, high values indicate a large fresh OM pool. Similarly, the R-index, which refers to the amount of stable and resistant OM. Both indices can be used to assess initial soil forming processes related to organic matter dynamics.

TOC content increases along the soil toposequence as expected (Figure 8). Moreover, OM gets deeper in the profile with relative age. However, P5 shows a higher OM content than P4, although more exposed to fluvial processes due to its proximity to the main channel. Both profiles are characterised by the same duration of development of one decade.

The I-index generally increases along the chronosequence due to the increased plant biomass productivity, accumulation and mineralisation of fresh litter as succession progresses (Figure 8). However as for the TOC, the site at 0.3m elevation (P5), with higher potential geomorphological impact, has a higher I-Index than the 0.4m elevation (P4) area with lower potential geomorphological impact.

The R-Index decreases with time (Figure 8). The two youngest profiles (P4 and P5), which developed within one decade, have a low TOC content (Figure 8) and are characterised by a higher fraction of stable and resistant OM components, which persist more easily during sediment transport and OM decay processes. However, a lower value is observed in the 0.3m area (P5) with higher potential geomorphological impact than in the 0.4m (P4) area of similar age.

TOC content, I-index and R-index, but also the visual assessment of the profiles (Figure 8) indicates a deviation from the expected chronosequence of soil development. Despite a higher potential for geomorphic activity in the 0.3m area (P5) than in the 0.4m area (P4), soil and vegetation development at the P5 site is more rapid. Both sites developed within one decade (Figure 9). The observed variance may be due to a greater flux of water and nutrients at P5, and of fine sediments at a rate that encourages water retention but which is not so great that it leads to surface burial. Indeed, plants appear to be adopting an engineering role on this site, causing the aggradation of 20cm of sand on top of a gravel-sand layer on which the *Salix spp*. root base starts (Figure 8). The aggradation of fine grained material can favour soil development in a rather gravelly environment (cumulization). For the P4 site, this positive feedback between fluvial matter and sediment flux, plant colonisation and soil development is missing: soil as an emergent property of ecosystem development seems to be slowed down.

This example is perhaps surprising since, traditionally, geomorphological processes are seen as hampering soil formation (e.g. Schaetzl and Anderson, 2005). Rather, two major points can be emphasized: (i) soils can develop in braid plain within a decade and that, as suggested by the two contrasting profiles presented here, there are positive feedbacks between the river matter and sediment fluxes, vegetation establishment and related engineering action, and soil processes; and (ii) this feedback system potentially influences the speed and trajectory of early fluvial habitat and landform development. Both points merit exploration, to investigate when and under which conditions rapid soil development can be an active contributor to landform evolution.

2.1.7 Summary and conclusion

The impact of water and sediment discharge on braided river dynamics is well established (e.g. Ashmore, 1982; Ashworth and Ferguson, 1986; Bertoldi et al., 2009; Tal and Paola, 2010; Zanoni et al., 2008; Ziliani, 2011). Similarly, the development and the impact of vegetation and woody debris as geomorphological engineers have been widely recognised and studied (Corenblit et al., 2011; Francis et al., 2008; Gurnell, 2014; Gurnell et al., 2012; Welber et al., 2012). Nevertheless, much less is known about the nature and effects of soil evolution on the biogeomorphic succession of fluvial landforms and related braid plain dynamics (ranging from the active river zone to vegetated islands and the recent terraces). This is surprising because in more stable fluvial systems, such as meandering river floodplains, well developed soils with a link to vegetation have been described (e.g. Cierjacks et al., 2011; Gerrard, 1987), perhaps with origins which can be considered similar as found in braided river systems.

In this review, we have identified the processes involved in the transition from fresh sediments, as found in the active braid plain zone, to vegetated soil covered braid plain landforms as for instance fluvial terraces. This particularly involves considering a time scale of decades in which pedogenesis, as a third component, interacts with riverine processes and plant succession. We argue that the effects of erosion and deposition in the active zone of a river: (1) may create a mosaic of initial conditions (e.g. fine sediment deposits) that can lead to spatially different rates of soil evolution; (2) but also influence the extent of access to resources transported by the river flux that impacts upon soil processes rates. This access is complex because it may be both beneficial and problematic for soil development. Deposition, for instance, may supply organic matter and raise local altitude to reduce the frequency of fluvial geomorphic perturbation; but it may also isolate the sediment from necessary resources (e.g. water or fine grained sediments) for soil development. Within the active zone of the Allondon River in Switzerland, it is possible to identify markedly different rates of fluvial landform ecosystem development, which may be related to the initial local characteristics and (beneficial and/or harmful) geomorphic impact. It appears that landforms close to the geomorphic active zone results in very different levels of organic matter production and hence *in-situ* organic matter supply to the sediment/soil surface. Moreover, there is clearly a transition between landforms of the active zones with embryonic soil development and to terrace areas where it is possible to identify fully developed soil horizons. It is probable that the accumulation of fluvially supplied organic matter is critical to this transition: it is possible that exogenic sources are important where the deposition of organic matter with fine sediments (high reactivity), can facilitate organic matter accumulation on normally biomass poor sites (Baker et al., 2000; Fisher et al., 2007; Harner et al., 2011; Mavris et al., 2010; Naegeli, 1997; Pusch et al., 1998; Schade et al., 2001; Van Breemen and Finzi, 1998). Moreover, it can influence local water and nutrient retention, and processing releases nutrients and weathering substances, thus potentially promoting biogeomorphic succession (*sensu* Corenblit et al., 2007, 2014). The establishment of pioneer vegetation may be the critical driver of significant organic matter accumulation and thus, in addition to its geomorphic engineering role (e.g. Corenblit et al., 2011; Gurnell, 2013; Gurnell et al., 2012), vegetation establishment may be crucial in early soil development (soil engineering role).

This review implies at least two broad foci in future research: (1) soil forming processes in braid plains; and (2) in what soil development means for the evolution of braid plain ecosystems. In relation to soil forming processes, six broad questions arise for future research.

I) What are the effects of initial soil development, notably the formation of an organic matter enriched horizon, on vegetation succession (from a bar to a vegetated island or terrace), and the associated nutrient and water retention necessary to sustain it?

II) What is the contribution of exogenic versus autogenic organic matter production to early soil development and the formation of organic matter enriched soil horizon?

III) How are the processes of soil horizon development influenced by aggradation rates, including both the positive (e.g. reduction in sedimentation frequency) and negative (isolation from the water table and the exogenic organic matter supply) feedbacks that can result?

IV) How do soil aggregates form during initial organic matter horizon development with exogenic and/or endogenic matter supply and related geomorphic influence?

V) What are the conditions upon which rapid weathering of river sediments can occur, including their relationship to water-table dynamics, and how does this relate to organic matter inputs, thus early soil development?

VI) How can buried soils (and eventually paleosols) be used to infer past spatial and temporal development of braid plain systems?

Addressing these questions will need a mixture of careful field sampling, laboratory analysis and associated laboratory microcosm experiments. This understanding will then need to be combined with a larger scale and more extensive quantification of the effects of soil development upon the wider braided river ecosystem, including the extent to which early soil development processes can accelerate vegetation development and eventual succession; how this can then influence critical feedbacks such as increases in deposit stability through the development of roots; and how the braid plain morphology evolves in response. It will require the analysis of historical data on river channel dynamics (e.g. using archival image analysis) coupled with dating methodologies to establish information on the age of different zones of braid plain since the last disturbance. In turn, these data will need to be coupled to vertical and spatial data on soil properties, deposit stability and vegetation density and diversity to understand how sediment, soil and vegetation coevolve at different rates and scales in braid plain systems.

Acknowledgments

The authors would like to thank Friederike Lang (Albert-Ludwigs Univesity Freiburg - Germany) and Arnaud Temme (Wageningen University – The Netherlands) for inspiring the masters thesis of Nico Bätz, which they supervised, and further discussion during the last years. W.R. Osterkamp and a second anonymous reviewer for critical but extremely constructive comments on earlier versions of this manuscript.

2.2 Research questions

In the review above, a conceptual model was proposed (Figure 6), showing the links between key ecosystem elements involved in biogeomorphic succession. This section identified the key research questions that are addressed in the thesis given this review.

I) Although the geomorphic-vegetation link is well established via the notion of biogeomorphic feedbacks and succession (Corenblit et al., 2009, 2011; Gurnell, 2014; Gurnell et al., 2012; Tockner et al., 2010), the role of soil has not yet been addressed. The transition from a gravelly sedimentary deposit to an (initial) water retaining and nutrient storing soil substrate might be crucial for the transition between different biogeomorphic phases at community and population scale (*sensu* Corenblit et al., 2007, 2014). Higher succession stages are thought to have higher nutrient turnover rates (Berendse, 1998), thus requiring developed soil processes to sustain the ecosystem demands. River processes, such as the deposition of organic matter enriched sediments (Cabezas and Comín, 2010; Langhans et al., 2012; Pinay et al., 1992; Steiger et al., 2003; Tabacchi et al., 1998), can improve resource availability, thus potentially accelerating the biogeomorphic successional processes. The additional resource enhances biochemical activity (e.g. Gregory et al., 1991; Janssens et al., 2001; Pusch et al., 1998), promoting soil formation (evolution) as an emergent property (Phillips, 2009; Phillips and Lorz, 2008) of the ecosystem state.

Thus, there is a key question: **to what extent is pedogenesis able to influence the rates of biogeomorphic succession? Is it actively involved in the succession process or is it a passively adaptive process that follows from stabilisation of the river deposits?**

II) In the conceptual model (Figure 6) and review presented above, ground water appears as a key element for the developing ecosystem. As compared with river flow which tends to be highly variable through time, groundwater potentially provides a spatially and temporally more stable water supply. In gravelly environments, this is crucial to sustain juvenile plant water demands (e.g. Gurnell et al., 2001b; Gurnell and Petts, 2006). On the other hand, studies have shown that groundwater can influence nutrient productivity and transformation. Microbial activity at the hyporheic zone (the interface between ground and surface water) may transform dissolved and particulate organic matter into plant available forms, but also represents a valuable organic matter source in its own right (Claret et al., 1998; Doering et al., 2011; Naegeli, 1997; Pusch et al., 1998; Tockner et al., 2006; Uehlinger, 2000; Valett et al., 1996). Harner and Stanford (2003) and Mouw et al. (2009), showed how upwelling groundwater improves plant growth as compared to a downwelling reach (Montana and Alaska, USA). Similarly Gurnell (2014, 2016), suggested that differences in tree growth rate along a 125km section of the braided Tagliamento River in Italy, may be related to upwelling and downwelling reaches. The additional resources (matter and water) may sustain rapid vegetation succession and enhanced soil formation. The groundwater mediated changes in pedo-biogeomorphic succession rates and associated engineering functioning at both, the community and population scale (*sensu* Corenblit et al., 2007, 2014), may thus change the balance between disturbance and vegetation encroachment (Ashmore, 2013; Hicks et al., 2007; Tal and Paola, 2010), thus influencing reach scale river morphodynamics (Figure 3).

Consequently, it is important to ask **to what extent, does groundwater influence biogeomorphic succession and thus reach scale morphodynamics?**

III) After having assessed separately the role of soil and groundwater in braided river systems, the conceptual model (Figure 6) emphasises the need to define a more holistic picture. Groundwater is thought to accelerate ecosystem processes, including soil (Gregory et al., 1991; Janssens et al., 2001; Naegeli, 1997; Pusch et al., 1998). Upwelling sites, for instance, have been shown not only to provide water for plant growth, but also nutrients (phosphorus and nitrate) that may support the overall ecosystem productivity (Boulton et al., 1998; Harner and Stanford, 2003; Mouw et al., 2009). However, groundwater is not always available, in which soil formation may play a crucial role by ameliorating local ambient conditions. Thus, there is a likely interrelation between these two components that influences fluvial landform formation at the decadal scale.

Accordingly, the question rises, **how does the interplay between soil formation and groundwater availability influence biogeomorphic succession?**

3 Study site

This chapter describes and justifies the case study used in this research: the Allondon River (Canton Geneva, Switzerland). To achieve this, Section 3.1 identifies the criteria that the study site must fulfil. Section 3.2 presents the Allondon River on the basis of a published paper. Section 3.3 then evaluates the Allondon River against the criteria identified in Section 3.1 and concludes as to the suitability of the chosen case study.

3.1 Study sites requirements

The research questions formulated in Chapter 2 aim to increase our understating of natural vegetated braided river dynamics over the decadal time-scale. This resulted in a set of criteria that were used to identify a possible study site. The aim of this Chapter is to identify these criteria and to introduce the study site.

Central to the methodological approach was the use of a chronosequence, replacing space for time, that allowed determination of the influence of soil development on the functional engineering aspect of the biogeomorphic succession under active channel dynamics. Thus, five main criteria were used. First, the focus on a natural braided river emphasized the need to find a study site with a (near) natural state, that is relatively low levels of direct human impact, both historically and at present. Second, it was necessary to have sites within the river that covered the range of biogeomorphic succession phases, ranging from the geomorphic phase (recent deposits) to the ecological phase (relatively stable terraces with floodplain forest). Third, to have this range of ages, it was necessary to choose a river with both: (1) active channel change, such as avulsion processes, rapid bank erosion and bar deposition; but (2) not so active that later stages of the biogeomorphic succession could not be found. Fourth, a groundwater-depth gradient over a short distance was needed to determine the influence of groundwater access on decadal scale biogeomorphic succession processes. Finally, good historical documentation was necessary to be able to help to reconstruct decadal morphological change.

This Chapter presents the Allondon River (Canton Geneva, Switzerland) as the chosen case-study. The final section then evaluates the Allondon River against the five criteria identified above

3.2 “The Allondon River: an evolving piedmont river system”

BÄTZ N, IORGULESCU I, LANE SN. **ACCEPTED**. THE ALLONDON RIVER: AN EVOLVING PIEDMONT RIVER SYSTEM. IN LANDSCAPES AND LANDFORMS OF SWITZERLAND, REYNARD E. (ED). SPRINGER: BERLIN;

3.2.1 Abstract

The Allondon River (Canton of Geneva) is a historically well-documented piedmont river system that reflects interactions between an evolving climate, a changing catchment and local management practices, and the suite of internal biogeomorphological responses and feedbacks that result. Over the last century, the river has been evolving from a braided to a wandering system. This appears to be driven by two key factors: (i) changes in hydrological forcing (notably in flood seasonality and flood power) coupled to a decrease in sediment availability, which has increased river incision; (ii) the angle of the shallow groundwater table, which creates drier conditions in the upper reach and wetter conditions in the lower reach. The coupling of both effects influences vegetation encroachment rates and the associated channel stabilisation. Hence the change in the rate of disturbance versus the rate of stabilisation along the river reach causes the morphological evolution to be spatially heterogeneous and variably resilient to extreme events, validating observations of the effects of vegetation made in flume studies.

3.2.2 Introduction

Piedmont rivers are an important element of the Swiss Alpine landscape. In general, northwest European rivers appear to be more fluvially active (aggradation and incision) during climate transition phases, such as the cooling at the start of the Little Ice Age (LIA), around 1200 AD and the warming since the end of the LIA around 1850 AD (Rumsby and Macklin, 1996). Thus, climate cycles may impact river morphodynamics through time, such as by changing channel planform. However, most North-West Europe rivers have also been impacted upon by human activities, both locally (e.g. engineering for flood risk reduction) and across the wider catchment (e.g. hydroelectric exploitation, dam construction etc.). These impacts increased dramatically from the 18th century onwards in European Alpine piedmont rivers (e.g. Girel et al., 2003;

Vischer, 1989). In turn, a suite of recent new objectives for river management has developed. Rivers are recognised as both sustaining and being sustained by ecosystems, while taking on important functions for human civilisation (e.g. flood retention). Thus, what can be done to rivers and floodplains is increasingly regulated to protect or even to restore the ensemble of river and floodplain ecology.

The result of these climatic and human induced changes is that rivers are rarely stationary. Further, there may be few examples of especially braided piedmont rivers that have been unimpacted by direct human activities. This makes it difficult to appreciate the dynamic relationship between geomorphology and climate and its impact on river bio-geomorphodynamics in such systems. In this chapter, we present an exception: the braided-wandering reach of the Allondon River, as a rare example of a morphologically evolving piedmont river in Switzerland that has seen little direct human impact.

Unlike many other Swiss piedmont rivers (e.g. the Aare River, Canton Bern and the Saane/Sarine River, Canton Fribourg), and partly relating to its particular geomorphological and sedimentological setting, the Allondon River has not been straightened or embanked. The peculiarity comes from the fact that due to base level control, notably by the main Rhone River (Moscariello, in prep.), the Allondon River has incised into fluvioglacial and morainic deposits to create a relatively wide but incised floodplain given the catchment size. This floodplain is wide enough to support, historically, a braided river, but it is also largely uninhabited, meaning that the river generally reflects the interaction between evolving catchment processes, as influenced by factors like climate, and processes (e.g. channel change) internal to the river-floodplain system. Historical imagery reveals that its planform is evolving and given low levels of human impact, the Allondon provides a natural laboratory for quantifying and explaining morphodynamics over the decadal time-scale.

However, morphodynamics are influenced by different vegetation encroachment rates along the river reach due to a downstream trend in water table (Harner and Stanford, 2003). The associated stabilising effect of vegetation influences river system resilience to extreme events and may also lead to thresholds between different stable river

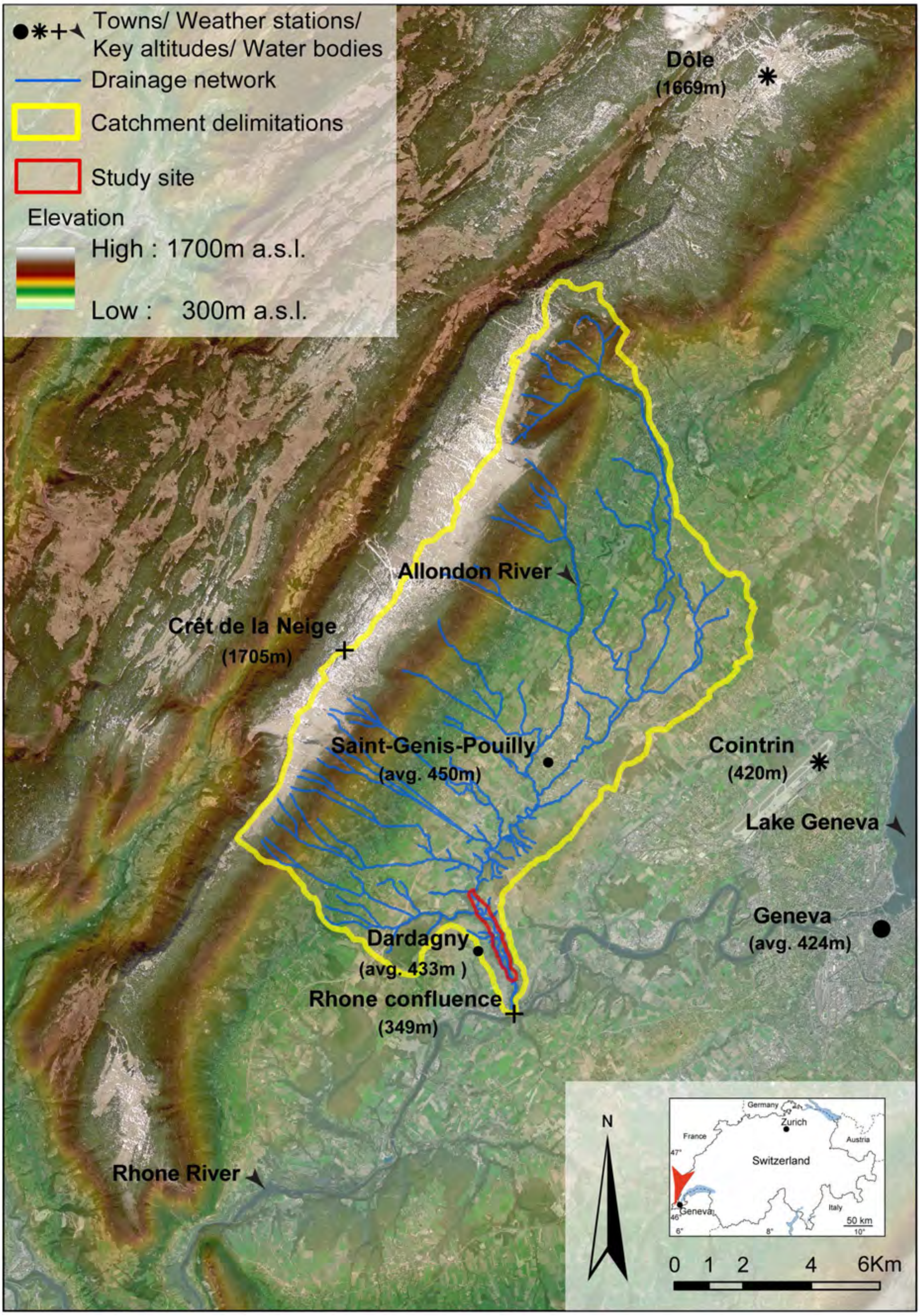


Figure 10 – The catchment of the Allondon River

Map of the catchment, showing the topography with the superimposed aerial image. Key locations that are mentioned in the text are shown.

morphologies (e.g. Francis et al. 2009). This makes the Allondon unique as compared with other Swiss braided piedmont rivers that have experienced much greater direct human impacts (e.g. the Maggia River, Ticino; Aare River, Bern/Thun; Saane/Sarine River, Fribourg).

3.2.3 Geographical setting

The Allondon River is fed by a small catchment (145 km^2) in the west of the Canton of Geneva (46°11'54"N, 6°00'07"E; Figure 10). Its altitude ranges from 1705 m a.s.l. at Crêt de la Neige to 349 m a.s.l. at the confluence with the Rhone River (mean 650 m a.s.l.). Its slope ranges from 155% to 0.0007% (mean 17%). The majority of the catchment is located in the karstic French Jura Mountains where a network of small torrent systems and creeks collects water, with relatively little sediment charge, and flows towards the Swiss Plateau. Only close to the Swiss-French border the runoff combines into a single river, forming a 3km long and 200-300m wandering/braided floodplain (Figure 11) until its confluence with the Rhone River.

Whilst the upper catchment controls flow accumulation, sediment availability and sediment dynamics relate to more local controls. As the river arrives at the base of the Jura Mountains, it encounters fluvioglacial and morainic deposits. The river has incised into these deposits (laterally and vertically). Thus, in contrast to its upstream tributary, this 3km reach clearly distinguishes itself from the surrounding landscape. It is this river reach, which for shorthand we refer to as the “Allondon River”, that is the subject of this chapter.

The entire river basin is characterised by a steep gradient in temperature and precipitation falling from an annual average of 3.9 °C and 1888 mm/year at 1669 m a.s.l. (La Dôle in the Jura) to 10.5 °C and 1005 mm/year at 420 m a.s.l. (Geneva Cointrin, to the east of the study site; data (MeteoSwiss, 2014). The altitudinal range of the basin means that the regime is “pluvial jurassien” (Pflaundler et al., 2011) with floods normally occurring within 6 hours of storm events (Hottinger, 1998). However, the hydrology appears to be strongly non-stationary in time and we discuss this below.

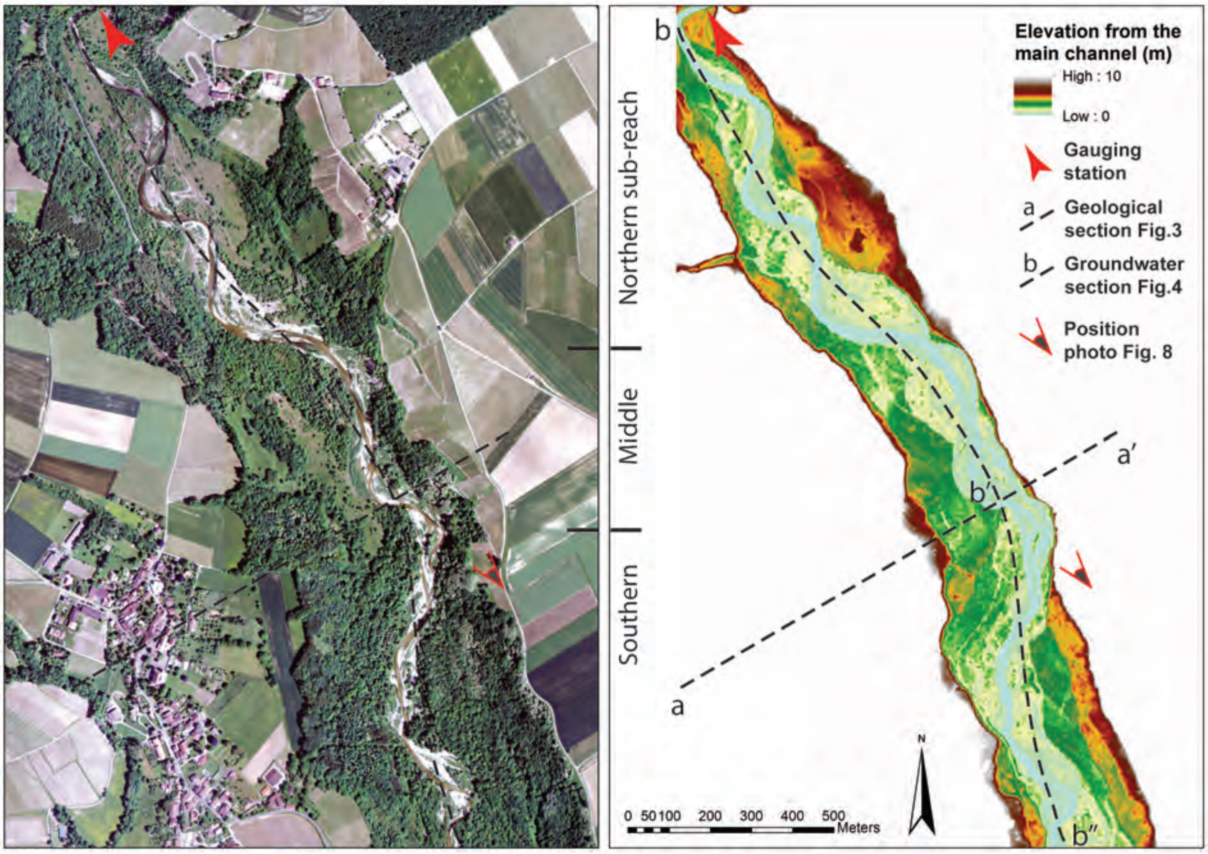


Figure 11 – The dynamic reach of the Allondon River

Aerial image (left) and river slope detrended topography (right) of the Allondon River (2009) (Source: Swisstopo). The locations of the geological section (Figure 12), of the groundwater section (Figure 13) and of the panorama photo (Figure 17) are indicated.

Land use in the catchment is mostly forest, meadows and pasture (70%), followed by agriculture (15%). There is some human impact: both industry and the CERN (European Organization for Nuclear Research) research centre near Saint-Genis-Pouilly use the water of the Allondon River. Despite extensive wastewater treatment, several polluting events impacted the river ecology between 1970 and 1990 (DIM, 2010). Since 2011, wastewater has been redirected into the Geneva wastewater treatment system and no longer reaches the river.

Generally, there is little physical river management within the 3km reach considered in this study and most of the interventions (e.g. spur dykes) are located on the edges of the steep incised valley slope to prevent slope failure or protect infrastructure. Many interventions were removed in 2000 during a revitalisation and renaturation program. A major invasion of the neophyte (*buddleia*) was brought under control in the year

2004. Nowadays, the river corridor is recognised both nationally and internationally as a protected site (DIM, 2010).

Only few comparable examples exist in Switzerland, as for instance the Sense/Singine River and Ärgera/Gérine River, both in the Canton Fribourg. This makes this site very particular as its morphological changes are mainly influenced by natural changes in the external forcing (hydrology) and changes in reach internal biogeomorphic feedbacks as explained below.

3.2.4 Hydro-geological setting

The floodplain valley slope direction follows the tectonic lineament of the Vuache Fault system, indicating that the ancient river floodplain was eroded into the molassic deposits by following a major geologic fault (Figure 12; Moscariello, in prep.). The molassic deposits (mainly sandstone and conglomerate) formed in the Oligocene due to massive erosion during Alpine orogenesis. The valley was then filled by a series of morainic deposits. The oldest has been mainly attributed to the Rhone glacier during the Riss (370.000-130.000 BP). However, the Jura ice cap and Arve glaciers (from the Mont Blanc Massif) also affected the landscape morphology of the area. Due to the recession of Rissian glaciers, a layer of fluvioglacial sediments was deposited, which was then covered again by morainic deposits during the Last Glacial Maximum (LGM), called Würm in Alpine context, 70.000-10.000 BP (Moscariello, in prep.). During the last recession of the Rhone glacier a large proglacial lake formed, with water levels reaching a maximum of 470 m a.s.l., compared with the altitude of the study reach close to 450 m a.s.l. Hence, the region corresponding to the present river reach was inundated, leaving a thin layer of glaciolacustrine deposits (Coutterand, 2010; Moscariello, in prep.). This layer has largely disappeared from the floodplain due to erosion. Between these three mainly depositional periods, the Allondon has incised into these deposits, preserving the incised floodplain along the fault (Figure 12). For more details about the overall long-term geomorphological development of the Geneva Basin, we refer to Moscariello (in prep.).

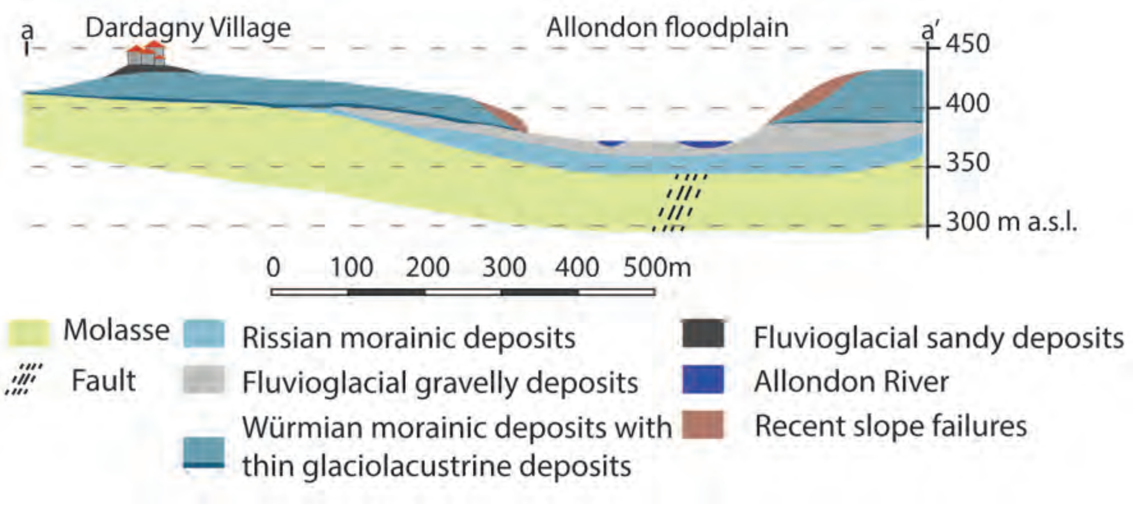


Figure 12 – Geological section through the floodplain of the study reach

(modified after SWISSTOPO, 1997; Wellhauser and Géroudet, 1978)

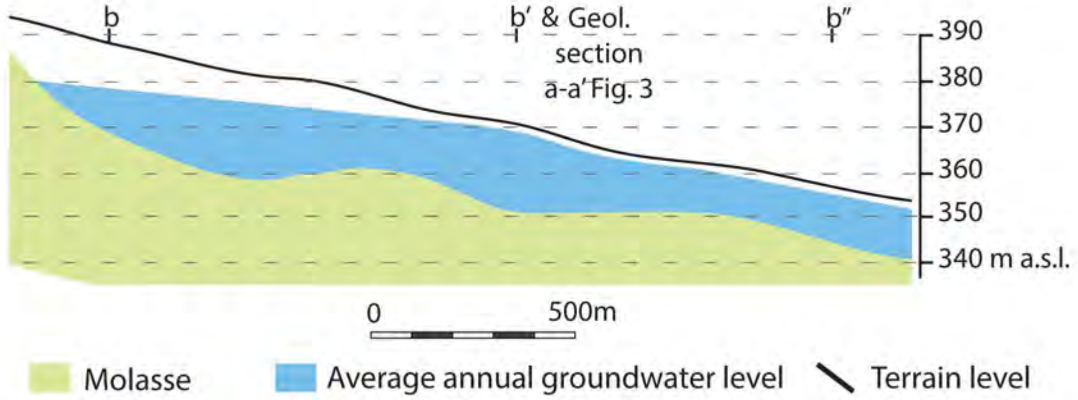


Figure 13 – Groundwater table depth along the study reach

(modified after Hottinger, 1998)

In terms of river morphodynamics, this geological setting is important. First, the moraine and fluvioglacial deposits create groundwater conditions that influence vegetation dynamics and so river dynamics. There is evidence of downwelling in the first kilometre of the reach (groundwater depth of about 10 m), and upwelling in the last kilometre where groundwater feeds the river flow (Figure 13; Hottinger, 1998). Second, the nature of the sedimentary deposits leads to a local source of erodible and transportable sand and gravel material. This is particularly important for the morphodynamics as it enables deposition of bars within floodplain as well as the formation of terrace systems.

3.2.5 The hydrology of the Allondon River

The Allondon streamflow has been monitored continuously since 1985 at Dardagny-Les Granges (Figure 11), 0.5 km upstream of the studied reach. The catchment area at the gauging location is 119 km^2. A stream gauge was operated at the same location between 1918 and 1935 (Figure 14A). The analysis of the historical record reveals that the hydrological regime has significantly evolved over the past century. As the changes in the hydrological forcing are highly relevant for the geomorphological and ecological processes in the study area, we present the current hydrological regime and compare it with the one that prevailed almost a century ago.

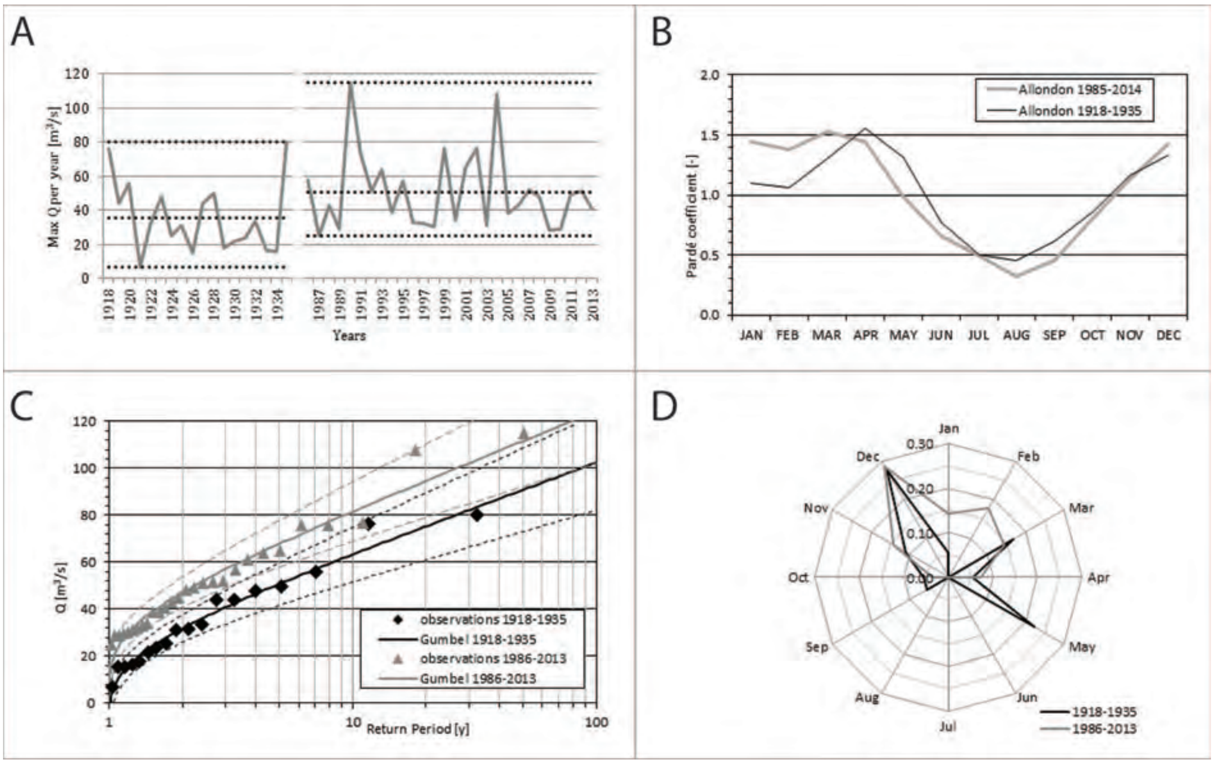


Figure 14 – Hydrology of the Allondon River

A) Peak annual discharge for the periods 1918-1935 and 1985-2013. B) Comparison of the monthly discharge regimes (Pardé coefficients) for the periods 1918-1935 and 1985-2013. C) Comparison of the recurrence intervals of observed (Gringorten plotting position) and fitted Gumbel distributions (method of moments) with 80% confidence peak annual flows for the periods 1918-1935 and 1986-2013. D) Comparison of the relative frequency of occurrence of maximum annual flows during each month (seasonality) for the periods 1918-1935 and 1986-2013.

The annual discharge regime is illustrated in Figure 14B using the monthly Pardé coefficients: the ratios between the mean monthly and the mean annual flows. The current regime is characterised by a late winter / early spring maximum and a late summer / early autumn minimum. During winter (December to February), the coefficients at the beginning of the twentieth century were considerably lower, with maximum discharges recorded later in the spring (March to May). Minimum flows correspond in both cases to late summer, but historical values were higher (Pardé coefficients, Figure 14B). However, absolute values of maximal discharge were generally lower in the past (Figure 14A). The classification of the discharge regime has also changed. Presently, the Allondon is one of the seven reference basins used to define the “pluvial jurassien” regime (Pflaundler et al., 2011). However, the analysis performed by Aschwanden and Weingartner (1985) on the 1918 to 1935 data, and included in the 1992 edition of the Swiss Hydrological Atlas, classified the discharge regime as “pluvial-nival jurassien”. Snow seems to be less important in the basin at present.

In terms of flows, a significant increase with respect to 1918-1935 can be noted. For example, the Q_{95} calculated for the 1986-2013 period (10.3 m^3/s) is 30% higher than during the 1918-1935 period (7.9 m^3/s). The statistical analysis of maximum annual flows shows a significant increase in the mean of the distribution, but not in terms of dispersion. This translates into an upward shift in the fitted Gumbel distributions (Figure 14A and C). As a consequence, a maximum relative effect is observed for frequent floods. For example, the median flood (the flow with a recurrence interval of two years) is 46 m^3/s, while during the 1918-1935 it was 31 m^3/s, which represents a 48% increase. These changes, as discussed in the next sections, are very important for fluvial dynamics as most sediment transport laws are a nonlinear function of discharge excess over a critical value, and so it is probable that sediment transport capacity in the river is now markedly higher.

Finally a change in the seasonality of the maximum annual flows is illustrated in Figure 14D. During the 1918-1935 period more than one in five, below-median snowmelt-type, annual floods occurred in May while none occurred in February. During the last 30 years none of the annual floods occurred in May while almost one in five occurred in February. This indicates a change in the flow regime from pluvial-nival to pluvial, associated with less seasonal snow storage (Figure 14B and C), and may be of great geomorphological importance. The present higher flows occur early in, if not before, the start of the growing season. Lower spring and summer flows may be making vegetation and hence fluvial dynamics more groundwater dependent.

The southern sub-reach has a much straighter channel morphology (sinuosity 1.11), and the active zone reaches a maximum width of only 60m. Rapid scrollbar processes and small scale avulsions discontinuously rework the active zone, with periodic erosion of the vegetated landforms. The terraces associated with this sub-reach have much denser vegetation and are much more resistant to erosion. Compared to the northern sub reach, fresh deposits appear to have faster pioneer vegetation colonization rates, which help to explain why the active channel is much narrower.

In the intermediate transitional section, weaker bank material and a larger active zone allows much larger-scale avulsions than in the southern sub-reach. There is evidence of recent strong coupling to the valley side walls. However, compared to the northern reach, the abandoned channels show faster pioneer vegetation recolonization, which through the associated engineering action enhances landform stability.

3.2.6 The geomorphology of the Allondon River

The recent morphology of the Allondon River is characterised by a wandering river system (Figure 11). Such systems can have high rates of channel change but, as compared with the continuous changes associated with river braiding, flow tends to be concentrated into a primary channel (Wang et al., 2012). The geomorphic activity of the river leads to an active zone that is sufficiently reworked to avoid vegetation colonisation and stabilisation. This zone is surrounded by a number of terrace levels, which can be up to 4 to 5 m above the active river channel (Figure 11).

Four key elements allow understanding the geomorphology of the Allondon River. First, erosion of the river terraces, but also slope failure of the undercut fluvioglacial

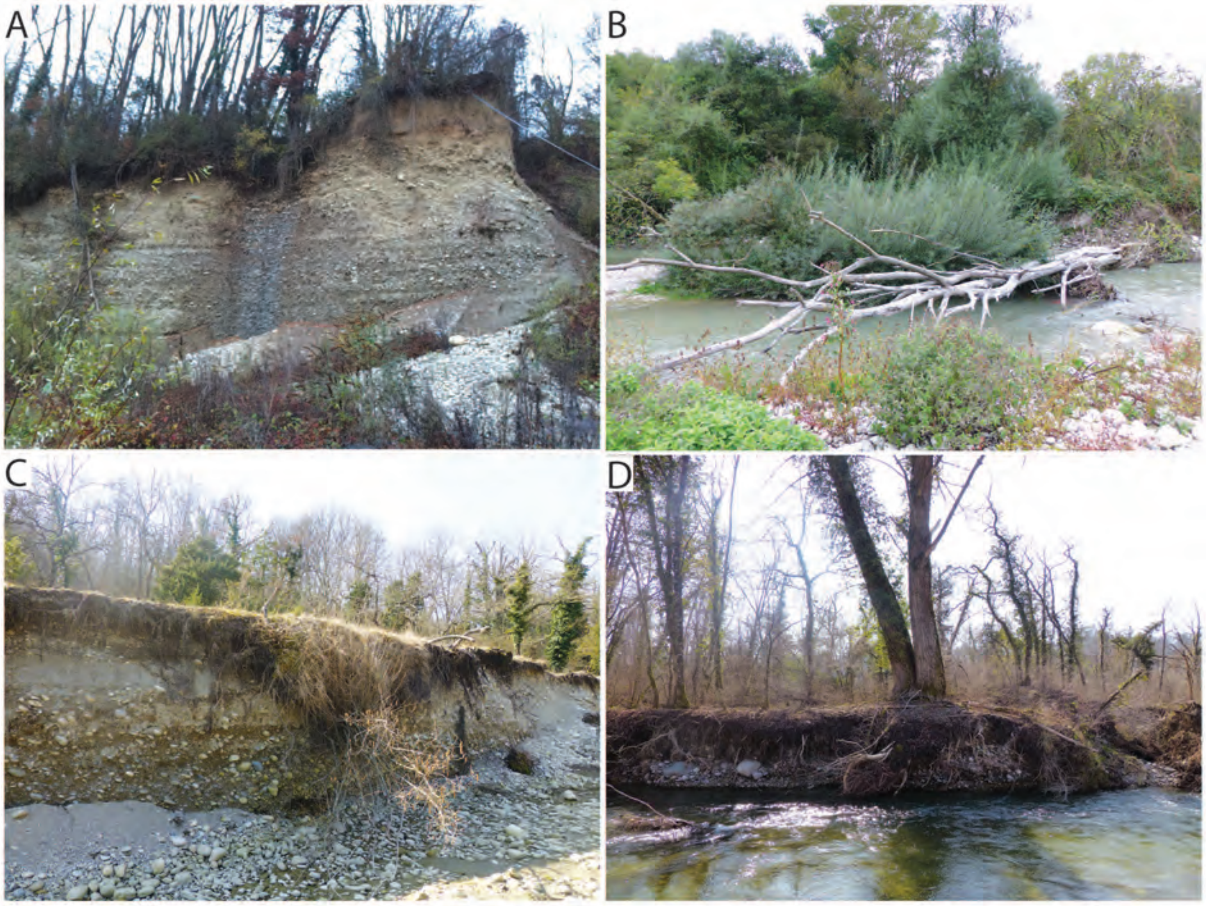


Figure 15 – Photos of observed geomorphic processes of the study reach

A) Slope failure processes of the fluvioglacial sediments of the valley side slopes, which are considered the main sediment source. B) Large woody debris deposit on an alluvial bar. Pioneer plants (*Salix ssp.*) colonised the lee of the bar, enhancing landform stability. C-D) Cut banks of a river terrace under heavy lateral erosion of the highest terrace (C) and the lowest terrace (D). Note the difference in rooting depth, which affects river bank stability (photographs: Nico Bätz).

deposits of the lateral valley slopes (Figure 15), appear to be an important sediment source for braiding and bar formation along the entire reach. Observations from aerial images indicate lateral erosion rates of 1.3-2.0 m/year and up to 10 m/year for the terraces in the northern and middle sub-reaches (Figure 16, images 1999-2012). Valley slope failure processes occur continuously, but are accelerated when erosion removes the slope talus and eventually undercuts the ancient deposits (Figure 15A and Figure 16, images 1999-2005).

Second, despite having a wandering morphology, the Allondon River can develop braiding sections (Figure 11 and Figure 16). Figure 16 shows several zones in which the flow braids around both bars and vegetated islands. It is well established that to maintain the braiding process, the river needs to be subject to a rate of perturbation that is greater than the rate of stabilisation, for example by vegetation development. Thus, maintaining braiding will require relatively frequent sediment delivery from upstream and so either active sediment sources or transport effective flow events. If these are able to lead to bar formation, reworking and migration, and these processes occur at a greater rate than the vegetation capacity to encroach the channel, that is lower than the geomorphic turnover rate (Murray et al., 2008; Tal and Paola, 2007), then braiding will be maintained. For most of the time, the Allondon River is transport limited. Braiding and (vegetated) bar dynamics can only be observed within the 250m downstream of the main sediment sources, often associated with major terrace or valley slope erosion. Vegetation dynamics in the Allondon River, as observed in similar environments (e.g. Corenblit et al., 2011; Gurnell, 2014), actively influence the morphological development by taking on an engineering role (e.g. Figure 15). Pioneer species such as *Salix spp*. and *Populus spp*. are capable of reinforcing stable river bank deposits with their roots and creating an above ground rough surface able to trap sediments at the time scale of years to decades. This promotes bar accretion and reduces lateral erosion. Only powerful events are able to reset the system (Corenblit et al., 2011; Gurnell, 2014). In the studied reach, the styles of channel change (e.g. Ashmore 2013) characteristic of a fully braided system are rare. However, because of different rates of vegetation encroachment along the reach current morphology is changing from wandering (upper sub-reach) to meandering (lower reach).

Third, deposition of large woody debris on young bars of the Allondon River has been observed to facilitate and to sustain pioneer vegetation colonisation within the active zone. The resprouting woody debris, but also the establishment of pioneer vegetation in the lee of (dead) woody debris, may stabilise deposited sediment and so enhance bar aggradation (Figure 15B). Such processes have been shown to influence fluvial landform development significantly (Corenblit et al., 2011; Gurnell, 2014). In the Allondon River it appears to take about 20 to 30 years to transform part of the active zone into a vegetated island. Such islands and also older vegetated terraces may in turn become the source of woody debris.

Fourth, despite not braiding in a more classical sense, high lateral erosion rates can lead to local increases in primary channel curvature until the flow cuts-off, causing local channel avulsion or chute cut-off (Ashmore, 2013). The gravelly material of cut banks appears to be very easily eroded (Figure 15C and D).

Despite being able to find elements of these four key processes throughout the reach, their importance varies from north to south down the river reach. The groundwater distal northern sub-reach (Figure 11) shows a sinuosity of about 1.23 and width of the active zone ranges from 50 to 100m. Here, vegetation colonisation and growth rates appear to be slower and there is much less resistance provided by older terrace vegetation (mostly *Fraxinus excelsior* and *Quercus robur* or dry prairies).

The groundwater proximal southern sub-reach has a much straighter channel morphology (sinuosity 1.11), and the active zone reaches a maximum width of only 60m. Rapid scrollbar processes and small scale avulsions discontinuously rework the active zone, with periodic erosion of the vegetated landforms. The terraces associated with this sub-reach have much denser vegetation and are much more resistant to erosion. Compared to the northern sub-reach, fresh deposits appear to have faster pioneer vegetation colonization rates, which help to explain why the active channel is much narrower.

In the intermediate transitional section, weaker bank material and a larger active zone allows much larger-scale avulsions than in the southern sub-reach. There is evidence of recent strong coupling to the valley side walls. However, compared to the northern reach, the abandoned channels show faster pioneer vegetation recolonization, which through the associated engineering effect on stable banks enhances landform stability.

3.2.7 Geomorphic evolution of the Allondon River

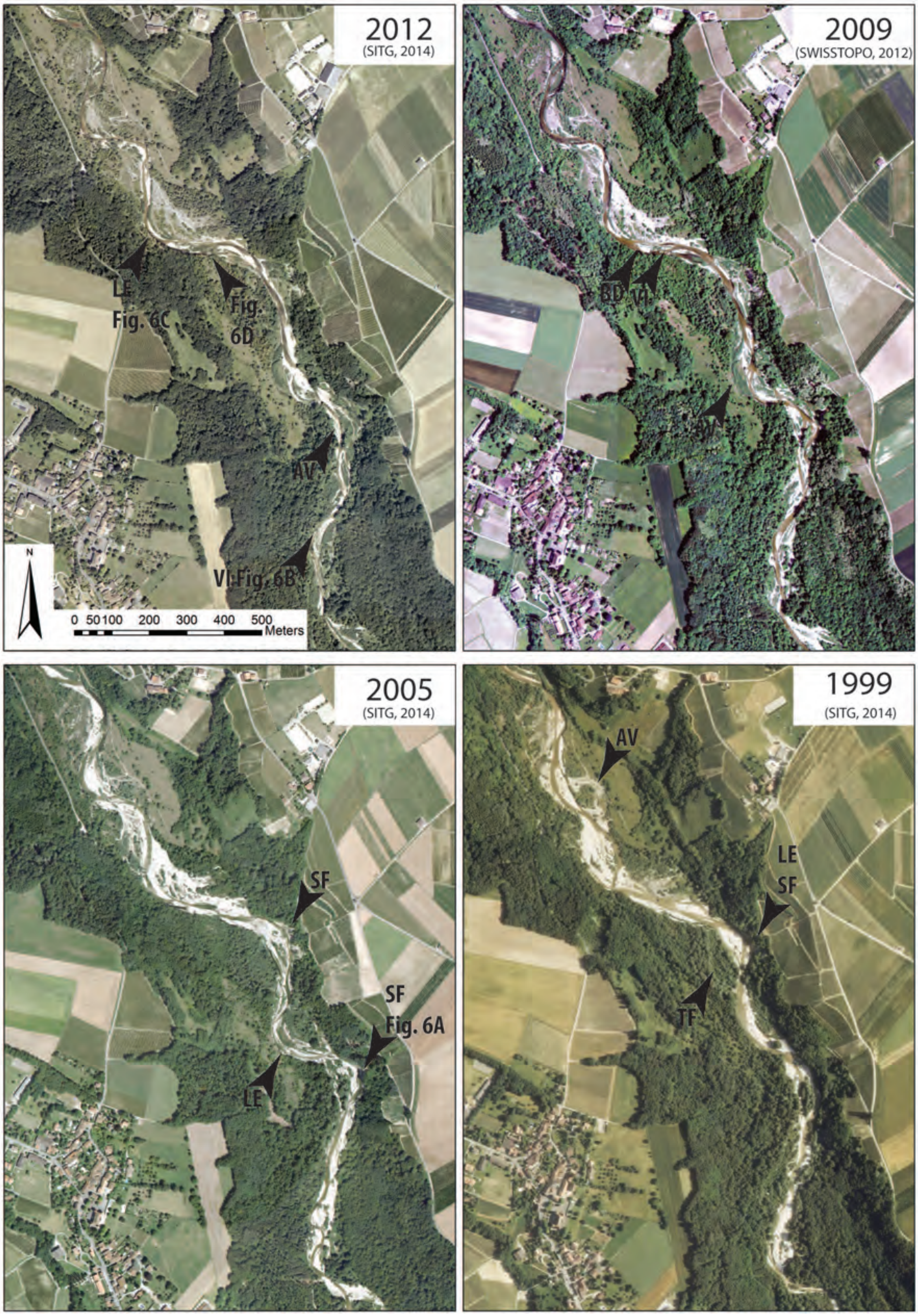
The geomorphic evolution of the Allondon River can be considered over two distinct timescales: annual to multi-annual; and decadal.

Annual to multi-annual changes

To consider the most recent evolution of the Allondon River, we consider the images 1986 to 2012, comparable to the second period described in Section 3.2.4: a generally higher discharge (Figure 14 A/C) but also greater differences between high and low flows (Figure 14B). The general trend during this period was characterised by high lateral erosion rates of the outer meander belts and rapid revegetation of the active zone after two major flooding events (1990 and 2004; Figure 14A). In detail, the active channel in year 1986 (Figure 16) rarely exceeded 50m over the entire reach. However, by 1991 the active width in the northern sub-reach had doubled, removing up to 80m of terrace material. The 1990 flood (115 m^3/s; Figure 14A) appears to be the main driver for the observed morphological changes. The middle and southern reaches appear more resilient to both events.

The following period (1991-1999) shows revegetation of the formerly exposed deposits, notably in the north. However, a channel avulsion can be observed in the north, with pioneer plants rapidly colonising the site (1999; Figure 16). The morphological changes in the middle reach during the same period were characterised by lateral erosion, transforming the straight channel into a more meandering flow. This suggests morphological adaptation of this sub-reach through erosion of relatively weak bank material, following the upstream responses to the 1990 flood.

The period 1999 to 2005 was characterised by greater activity due to wetter years and a major flood event in 2004 (108 m^3/s; Figure 14A). Meander dynamics (lateral erosion) dominate in the northern and middle sub-reach. The sinuosity of this reach increased from 1.03 (1999) to 1.24 (2005), with rapid vegetation colonisation of the generated point bars. The first meander of this sub-reach undercut the lateral valley slope, activating a sediment source through slope failure (e.g. Figure 15A). This caused bar formation during the following years. Lateral erosion of up to 18m in the northern sub-reach increased sinuosity from 1.10 to 1.19. At the same time the inner meander bends (point bars) were slowly colonised by vegetation. The 2004 flood event, but also the depth of groundwater (Hottinger, 1998), may have prevented rapid vegetation colonisation processes as compared to the middle sub-reach. The development of the southern sub-reach during this period (1999-2005) did not involve major morphological changes (Figure 16). Only the 2004 flood reactivated part of the floodplain by increasing the active width from about 35m to about 50m.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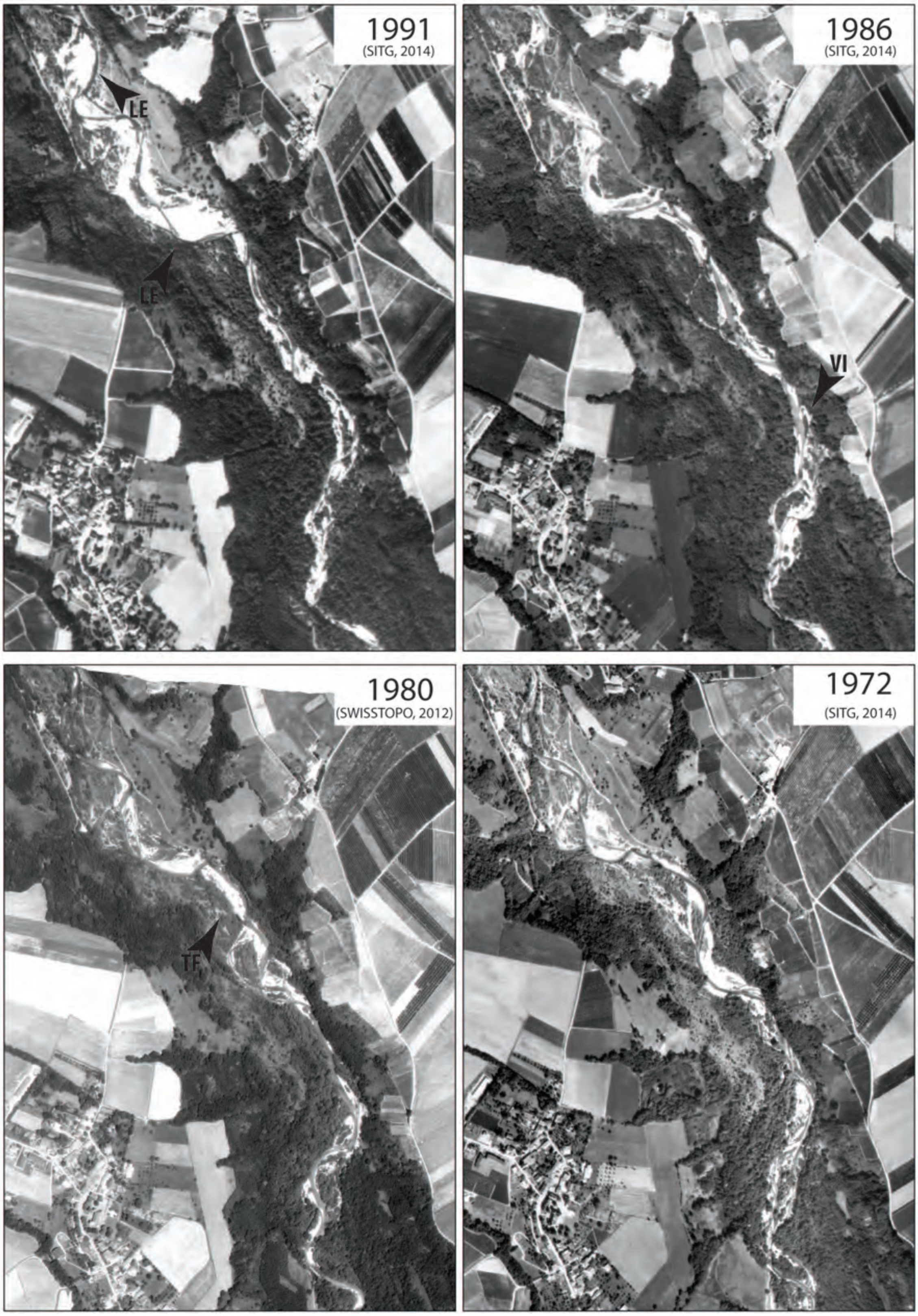
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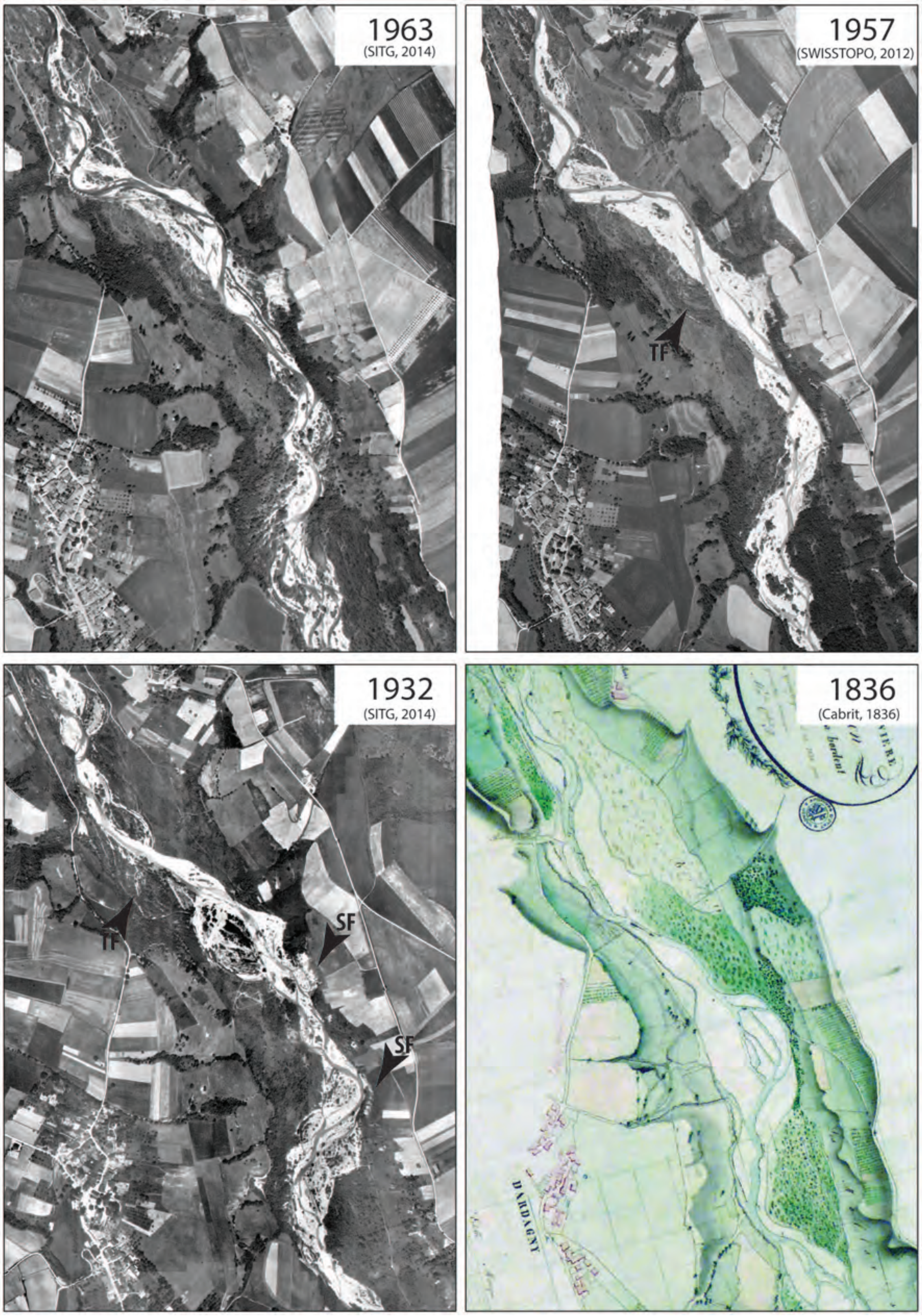

Figure 16 – Morphological evolution of the Allondon River over the last century

Series of aerial pictures and plan, documenting the morphological evolution of the Allondon River (Cabrit, 1836; SITG, 2014; SWISSTOPO, 2012). The arrows give some examples of prominent processes that can be compared to the previous image: SF= valley slope failure processes; LE: lateral terrace erosion; AV: channel avulsion processes; VI: vegetated island formation; BD: bar dynamics; TF: terrace formation.

The morphological development between 2005 and 2012 was characterised by a stabilisation of the morphology. No major flood occurred (Figure 14A), allowing overall vegetation encroachment. Lateral erosion in the north and associated cut bank slope failure increased local sediment input, and caused the formation of some bars (2005-2012; Figure 16). Although hydrological forcing was low in this period, high meander curvature encouraged rapid channel migration (2009 and 2012; Figure 16), showing how the continued occurrence of less hydrologically-intense events can still lead to major system changes. Compared to the northern reach, the former channels of the middle and the active zone of the southern sub-reach witnessed rapid vegetation colonisation.

A prominent example of vegetated island formation, and thus the vegetation-induced engineering, can be seen in lower middle sub-reach (Figure 16 from year 1986 on). The landform rapidly developed a vegetation cover (1986-2005; Figure 16) that stabilised the deposits. Only the major flood event of 2004 caused massive lateral erosion and a channel avulsion, partly removing the vegetated patch (2009; Figure 16).

Summarising, there is some spatial variability in the annual to multi-annual changes in this river. The series of recent aerial images (1986-2012; Figure 16) shows that to the north, the river remains more dynamic. To the south, it has developed a more stable meandering morphology. In gravel-bed rivers, such as the Allondon River, water is a limiting resource on vegetation growth rates during the hot and dry summer months, thus hampering vegetation establishment on fresh alluvial deposits (e.g. Wolman and Gerson, 1978). However, access to groundwater may significantly change vegetation growth and hence the associated engineering role. As noted above, groundwater depth of the Allondon shows a particular trend; the northern sub-reach appears as groundwater distal (10m), while in the southern sub-reach upwelling groundwater has been observed (Hottinger, 1998). This groundwater trend may change vegetation colonisation and growth rate (Harner and Stanford, 2003), suggesting differences in system resilience to exceptional perturbations (Figure 3; Francis et al., 2009) from north to south.

Decadal changes

These annual to multi-annual changes are superimposed upon the long-term evolution of the system (Figure 16). The floodplains of 1836, 1932 and 1957 appear to comprise a 110m to 140 m wide vegetated island braided system throughout the river reach. The high braiding activity is most likely to be related to high sediment remobilisation rates over large areas of the active zone, but appears also to be associated with floodplain incision (1936-1972; Figure 16). Several terrace levels that persist nowadays, formed during this period and are up to 2m higher than the current channel.

By 2012, notably in the southern sub-reach, the active width has decreased to about 40m and the aerial images of 1963, 1972 and 1980 (Figure 16) show the associated transition from an island braided to a wandering river morphology. This transition is correlated with progressive encroachment by vegetation and reflects similar transitions from braided to wandering systems observed in the laboratory (e.g. Tal and Paola 2007). Between 1963 and 1980 there was a substantial change in system morphodynamics either because of a reduction in perturbation rate (sediment dynamics and/or hydrological forcing) or an increase in vegetation encroachment rate. The latter may well be negatively correlated to the former, such that only small changes in the perturbation rate may be needed to achieve the observed transition.

The hydrological changes illustrated above suggested a general increase in discharge and related peak discharges during the last century. One result is that the enhanced sediment transport capacity may not be balanced by sediment delivered to the reach. This may have led to an increase in floodplain incision and to the associated narrowing of the active zone during recent decades. In turn, this should have helped the southern reach to establish a better connection with groundwater whilst incision may have also made it more difficult for avulsion to perturb the older terraces. Hence, terraces have developed and have continued to maintain a mature vegetation cover and so a relative resistance to erosion. Notwithstanding, the northern reach remains relatively vegetation free because the deeper groundwater reduces vegetation growth rates. Moreover, temperature and precipitation data suggest that climate may be becoming drier, something that should make vegetation development more dependent upon hyporrheic flows. This may be exacerbated by a shift in peak flow timing to the winter

Figure 17 – Historical view on the study reach

Recent (left: 9th September 2015; photograph: Nico Bätz) and historical (right: around 1945; SIG, 1948) morphological aspect of the northern reach of the Allondon River. Note the difference in vegetation cover and the related width of the active zone. A-D indicate the location of several places.

(Figure 14D) and hence a reduction of disturbance during the growing period. The associated stabilisation by vegetation, as controlled by the water table trend along the reach, may have increased the resilience of the fluvial system to the increased perturbation observed over the last few decades (Figure 14C), thus facilitating the morphological transition from a braided to a wandering river system. This is not to say that extreme events cannot still have a very big impact (Figure 16), but rather that the size of the event needed to have a substantial impact, notably in the southern reach, may be increasing (e.g. Francis et al., 2009).

Historical sources (Chapeaurougy, 1774) document the importance of the Allondon floodplain as a resource for the two neighbouring municipalities (e.g. fire wood, grazing). However, economic changes during the 20th century have led to the abandonment of most of the floodplain activities and steep slope agriculture. Woody and shrubby vegetation now dominates the floodplain cover, stabilising the river banks and south exposed slopes. Figure 17 shows the Allondon floodplain around 1945. Shrubby vegetation is restricted to the left bank. Moreover, the southern exposed floodplain valley slopes appear to be under agricultural use. The easily eroded, vegetated terraces and the steep and loose slopes (fluvioglacial sediments) would have provided possible sediment sources for braiding. Since then, reforestation may have disconnected the river from these sources (Figure 17; Figure 16, image 1932 and 2012). Similar processes have been observed in all the tributaries of the Allondon, but also in French Alps, Pyrenees and New Zealand.

3.2.8 Conclusions

The historical development of the Allondon River illustrated here shows how, for a river relatively uninfluenced by human activity, climate change interacts with hydrology, hydrogeology and vegetation to determine river morphodynamics. In turn, these morphodynamics induce an autogenic response, changing the feedbacks between river morphodynamics and vegetation encroachment. The Allondon is a classic case because most other Swiss braided piedmont river systems have been highly managed, and interpreting their morphodynamics is difficult given such strong historical human influences.

The data suggest that over the last century the river is in a non-stationary state, with the evolution from an island gravel bed braided system to a meandering/wandering gravel bed system, and an associated vegetation encroachment of the active zone (Figure 16 and Figure 17). Similar observations have been made in laboratory flume models (e.g. Tal and Paola 2007) and are thought to relate to changes in the rate of disturbance processes (power and frequency) versus the rate of stabilisation processes (e.g. vegetation encroachment rate). In similar environments, vegetation has shown to take on an engineering role and hence drive river morphodynamics by colonising the sufficiently stable river banks (Tal and Paola 2007; Corenblit et al. 2011; Gurnell 2014).

Data on the hydrological forcing of the last century show a general increase of about 15 m^3/s in discharge (Q_2) and an increase in difference between high and low flows. Moreover, a change in seasonality was observed, changing the hydrological regime from bimodal “pluvial-nival jurassien” to unimodal “pluvial jurassien” (Figure 14). During the same period, floodplain land use changed from an agro-pastoral system to a protected forested site, thus reducing sediment availability for transport due to the increased river bank and valley slope stability.

The observed change in hydrological forcing coupled to reforestation may have led to a considerable increase in incision rate. However, the observed change in hydrological seasonality may have a second crucial effect. The hydrological changes mean that perturbations and morphological changes are now concentrated into a single period outside the vegetation growth period. This may allow a longer growing season combined with greater river bank stability, thus increasing the chances of surviving the next bigger winter flood. The stabilisation of riverbanks and deposits by vegetation, further forces the channel into a single flow hence promoting incision.

Despite the general trend explained above, the morphological response of the Allondon River is spatially heterogeneous. The morphological transition shows a trend from north to south with higher vegetation encroachment rates towards south. The groundwater nappe follows this trend (Figure 13), suggesting that the vegetation establishment during the drier growing period is limited by the access to the groundwater table. Similar observations have been made by Harner and Stanford (2003), who observed different vegetation growing rates based on upwelling and downwelling river reaches in USA. The vegetation encroachment rates influence the morphological resilience along the reach, thus the critical threshold for the transition to a different stable state (e.g. braided to single channel; Francis et al. 2009).

Future morphological response of the Allondon River will potentially be different for the upper and the lower reach. A more pluvial regime will concentrate disturbing high-energy floods into winter, and summers will have the tendency to become drier. Thus, the longer undisturbed period (April-November; Figure 14D) may encourage vegetation encroachment in the groundwater upwelling southern reach. In the northern reach, due to the higher groundwater dependency of the vegetation during the warmer summer months, morphological response will largely depend on the groundwater depth (accessibility) during summer. Distance to the groundwater table has been increasing over the last 10 year (measurements available since 2003), mainly because of the reduction in summer precipitation. Vegetation establishment, and thus channel stabilisation, has become more restricted, to the low water line (images 2005 to 2012; Figure 16). Only sufficiently erosive winter floods, which are able to break through the stabilising vegetation along the channels, will cause avulsion, keeping a more braided character of the upper reach.

These observed morphological changes and their potential triggers also raise questions about future sustainable river management. To what extent could and should high turnover rates of the active zone be preserved to maintain braided river morphology? As this example shows, braided morphodynamics are highly dependent on the balance between disturbing and stabilising processes. Catchment processes, such as land use and climate change, but also reach scale human impacts may change this relation irrevocably, making local river preservation strategies ineffective. More holistic approaches may help in defining how boundary conditions have changed and the measures needed to maintain the relationship between vegetation, form and process necessary to sustain the Allondon River.

Acknowledgments

Special thanks to: the Canton Geneva - Department of Nature and Landscape, for data and access to the natural reserve for research purposes; Hans-Rudolf Pfeifer for providing valuable literature and inspiring discussions on the Allondon River; to the presenters Ion Iorgulescu, Erik Bollaert, Arielle Cordonnier, Marc Hottinger and the participants of the "Atelier Allondon" held in November 2014 who inspired this work. We also would like to thank the editor Emmanuel Reynard and the anonymous reviewer for the precious comments that improved this manuscript.

3.3 Study sites suitability

Section 3.2 showed that the Allondon experienced relatively little human impact in recent decades. Historical imagery revealed a diverse range of stages in the ecological succession, with vegetated river islands, recent deposits colonised by pioneer vegetation and landforms experiencing a transition from the active zone to a terrace under the influence of dynamic geomorphic processes (Figure 15). Thus the river has the diverse range of sites (age, geomorphic setting and history, vegetation cover) needed to assess the role of soil development and groundwater on the functional engineering aspect of the biogeomorphic succession.

The historical imagery revealed also a clear transition from braided to wandering (Figure 16), although this is spatially variable, so allowing a wide range of stages in the biogeomorphic succession to be present. Generally, the observed shift appears to be driven by a change in the nature of hydrological forcing by river flow (Figure 14), which may have allowed higher vegetation establishment rates. However, there is also a gradient in the depth to groundwater (Figure 13) that may also influence the biogeomorphic succession rate. The effects of the changing hydrological forcing may be moderated by this groundwater gradient, in terms of a spatially variable difference in the balance between the rate of disturbance and the rate of stabilisation by vegetation, and the associated morphological response, as found in flume experiments (e.g. Tal and Paola, 2007). Finally, it is clear that there is a good historical information upon which to base the research.

Taking these points together, the Allondon River seems to be a good candidate as a relatively natural field laboratory for understanding how soil development and groundwater interact during biogeomorphic succession in a relatively dynamic braided/wandering river, and whether these interactions are simply passive, or active controls on succession rates.

4 Soil evolution in braiding river systems

In this section we will address the extent to which soil evolution, especially through organic matter transformation processes, influences the biogeomorphic succession (*sensu* Corenblit et al., 2007, 2014). Young soils have been observed on vegetated patches in dynamic river systems (Bureau, 1995; Doering et al., 2011; Gerrard, 1987, 1995; Langhans et al., 2012; Mardhiah et al., 2014; Viereck et al., 1993) and their formation is mainly associated with organic matter accumulation and transformation. Thus, the transition from a gravelly sediment deposit into a (initial) water retaining and nutrient storing and transforming soil substrate, might be crucial for the transition between different biogeomorphic phases. A chronosequence approach on the wide range of fluvial landform ages of the Allondon River is used to address this question.

Figure 18 summarises the considered pedo-geomorphic feedbacks addressed in this Chapter and relates them to the conceptual model presented in Chapter 2.

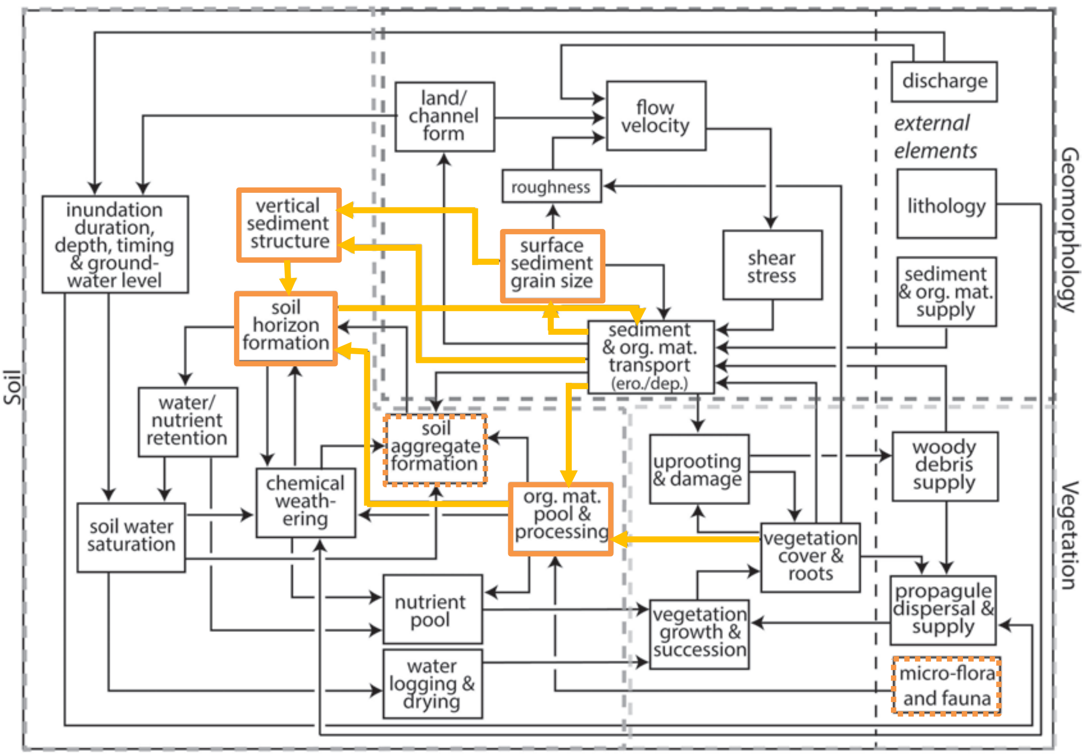

Figure 18 – Conceptual model (Figure 6) highlighting the components addressed in Chapter 4

The dashed elements refer to the complementary study of Mardhiah et al. (2014) on aggregate formation (Section 4.3).

4.1 “Organic matter processing and soil evolution in a braided river system”

BÄTZ N, VERRECCHIA EP, LANE SN. **2015**. ORGANIC MATTER PROCESSING AND SOIL EVOLUTION IN A BRAIDED RIVER SYSTEM. CATENA 126: 86–97. DOI: 10.1016/J.CATENA.2014.10.013

4.1.1 Abstract

Traditionally, braided river research has considered flow, sediment transport processes and, recently, vegetation dynamics in relation to river morphodynamics. However, if considering the development of woody vegetated patches over a time scale of decades, we must consider the extent to which soil forming processes, particularly related to soil organic matter, impact the alluvial geomorphic-vegetation system. Here we quantify the soil organic matter processing (humification) that occurs on young alluvial landforms. We sampled different geomorphic units, ranging from the active river channel to established river terraces in a braided river system. For each geomorphic unit, soil pits were used to sample sediment/soil layers that were analysed in terms of grain size (<2mm) and organic matter quantity and quality (RockEval method). A principal component analysis was used to identify patterns in the dataset. Results suggest that during the succession from bare river gravels to a terrace soil, there is a transition from small amounts of external organic matter supply provided by sedimentation processes (e.g. organic matter transported in suspension and deposited on bars), to large amounts of autogenic in-situ organic matter production due to plant colonisation. This appears to change time scale and pathways of alluvial succession (bio-geomorphic succession). However, this process is complicated by: the ongoing possibility of local sedimentation, which can serve to isolate surface layers via aggradation from the exogenic supply; and erosion which tends to create fresh deposits upon which organic matter processing must re-start. The result is a complex pattern of organic matter states as well as a general lack of any clear chronosequence within the active river corridor. This state reflects the continual battle between deposition events that can isolate organic matter from the surface, erosion events that can destroy accumulating organic matter and the early ecosystem processes necessary to assist the co-evolution of soil and vegetation. A key question emerges over the extent to which the fresh organic matter deposited in the active zone is capable of significantly transforming the local geochemical environment sufficiently to accelerate soil development.

4.1.2 Introduction

Geomorphologically active systems, such as braided rivers, exhibit a complex mosaic of fluvial habitats (Tockner et al., 2010) including bare sediment surfaces, islands within the active zone at various vegetation succession stages, and established river terraces with floodplain forest and well-developed soils. Thus, the river landscape comprises a range of ages with reworked zones, and ages at the sub yearly timescale, to much more stable zones, potentially many decades old.

Recent research has established that the transition from a bare sediment surface to a vegetated patch results in important changes in fluvial processes. Vegetation can be seen as a type of ecosystem engineer, critically involved in this transition during fluvial landform formation (Corenblit et al., 2011, 2014; Gurnell, 2014; Gurnell et al., 2012; Jones et al., 1994; Osterkamp and Hupp, 2010) by: (i) stabilising sedimentary deposits through rooting (Crouzy and Perona, 2012; Perona et al., 2012); and (ii) enhancing fine sediment deposition due to above ground biomass induced energy losses that lead to surface aggradation (Gurnell and Petts, 2002). Both plant-facilitated processes allow habitat development within the most active zones of the floodplain by improving local edaphic conditions (moisture and nutrient retention, reduced susceptibility to erosion) so allowing the progress of succession – from pioneer island species to stable terrace hardwood species (e.g. Francis, 2007; Francis et al., 2009; Gurnell et al., 2001b; Moggridge and Gurnell, 2009). Nevertheless, if the deposition rate is too high, vegetation may get buried, leading to an optimal aggradation range for successional processes (Gurnell and Petts, 2002). Conversely, if the erosion rate is too high, the entire vegetated patch may be removed and its materials redeposit elsewhere, where it may again facilitate plant development (large woody debris, e.g. Francis, 2007; Francis et al., 2008).

These processes have been recently conceptualised into a biogeomorphological life cycle model for *Populus nigra*, deemed to be valid for *Salicaceae* pioneer vegetation in general (Corenbilt *et al.*, 2014). The main phases of the life cycle identified are: (i) in the geomorphological phase, seedlings are dispersed by floods and germinate on suitable bar surfaces; (ii) in the following pioneer phase, seedlings are challenged by water stress, erosion and deposition processes. During these first two phases, *P. nigra* is completely exposed to the physical riverine processes without relevant feedbacks to river morphology; (iii) in the third phase, interaction between plants and their physical environment is highest, the biogeomorphological phase. Young trees take on an engineering role by fixing sediments and trapping fine sediments. Symbiosis with endomycorrhizal fungi improves their access to the soil nutrient pool and groundwater (Harner et al., 2011). Finally, (iv), during the last or ecological phase, the vegetated patch becomes relatively independent from the river and is able, via autogenic ecosystem processes, to auto-sustain its own resource demands. Rare shallow overland deposition or lateral erosion processes are the main riverine processes affecting this phase (Corenblit et al., 2014).

The latter two stages imply timescales of the order of years to decades. At these longer timescales soil, as an emergent property of the developing ecosystem, must also be considered as an element of the braided river system (Bätz et al., 2015b). In stable systems, such as river terraces of meandering systems, pedogenesis has been extensively studied (Cierjacks et al., 2010, 2011; Gerrard, 1987). However, this is much less the case in more dynamic alluvial environments, such as braided rivers, and hence the question arises: are soil forming processes passive process that reacts to stabilizing geomorphic conditions, or are they actively involved in controlling the rate of biogeomorphic succession (*sensu* Corenblit et al., 2007, 2014)? In other words, is pedogenesis able to change the rate of biogeomorphic succession?

Because the later stages of Corenbilt et al.’s (2007, 2014) model imply the presence of soil, a second question follows: to what extent is pedogenesis involved in the first two of Corenbilt et al.’s (2007, 2014) stages? For instance, flood pulses, that lead to deposition, may provide water but also exogenously produced energy rich organic matter (plant debris but also pedogenically transformed material), that is easily decomposed and humified into plant available forms by the sediment/soil micro-flora and fauna (Cabezas and Comín, 2010; Francis, 2007; Gregory et al., 1991; Langhans et al., 2012; Naegeli, 1997; Pusch et al., 1998; Tabacchi et al., 2000). This depositional process might significantly enhance the nutrient pool of nutrient-poor, young mineral sediments, and so accelerate initial ecosystem processes including soil forming processes (Doering et al., 2011; Guenat et al., 1999; Guex et al., 2003; Langhans et al., 2012). However, either massive deposition, leading to burial, or erosion events which lead to local loss of pedogenically transformed organic matter, may potentially hamper fluvial planform development. These interactions with the biogeomorphic component, can lead to a multitude of pathways and trajectories of alluvial soil formation, so that it is better to talk about soil evolution (Johnson, 1985; Schaetzl and Anderson, 2005). Yet, we know surprisingly little about initial soil development on active surfaces of braided river deposits and its interaction with biogeomorphological processes (Bätz et al., 2015b).

Addressing the question of initial soil evolution requires a multi-angled approach (Bernasconi and Biglink Project Members, 2008). In this paper we focus upon the question of organic matter processing (humification), which is considered an important part of young ecosystems. Initial soil evolution is a result of these processes and we can consider how soil horizons reflect and record organic matter processing of the developing fluvial landform (biogeomorphic succession), through its transition from a barren sediment surface to a vegetated soil covered patch. As explained above, organic matter may profoundly transform the local abiotic environment, increasing the nutrient pool, ameliorating water and nutrient retention through soil aggregate and soil structure formation, but also through production of humic acids, which may enhance weathering rates (Bätz et al., 2015b).

A Swiss braided river system, the Allondon River (Canton Geneva Switzerland), has been analysed for this study. We use a chronosequence (space for time substitution) approach, ranging from young surfaces close to the active zone of the river, to older stable floodplain terraces. On each area along the chronosequences, soil properties, mainly in terms of grain size and organic matter quality, were analysed. Principal components analysis is used to generalise the data obtained and to develop a model for organic matter processing in braided rivers soils. Moreover, we try to identify the time scales for soil formation and its link to the biogeomorphic succession.

4.1.3 Material and methods

Study site

The gravel bed Allondon River is located to the west of Geneva (Switzerland). A large part of the catchment is located in the calcareous French Jura Mountains. A number of small (karstic) torrents flow from the Jura and combine into a single river at the French/Swiss border. From this point, a 3km long reach of braided floodplain is formed before its confluence with the Rhône River. The catchment area above the study reach is about 120 km^2 (FOEN, 2014). This reach, incised by about 60 m into fluvioglacial sediments, overlays the Swiss Molassic basin. Fluvioglacial sediments were deposited during the last glacial cycle (the Würm and Riss glaciations), and their origin typical of the Rhône basin geology (CJB (eds.), 1990; Coutterand, 2010).

Erosion into these fluvioglacial sediments (valley side slopes) is thought to lead to slope failures, exacerbated during localised saturation during storm events and river lateral undercutting processes. These are thought to be the main source of sediments in the braided reach. There are terraces of fluvial origin within the reach and the river has a potentially wide range of surface ages, ranging from active sites with a high turnover, to mature floodplain terraces, which are much older (Beechie et al., 2006). Following the biogeomorphic succession model proposed by Corenblit et al. (2009), there is evidence of rapid vegetation colonisation on exposed sediments of engineering species (*Salix elaeagnos, Salix purpurea*) and progressive plant facilitated stabilisation of some braid bar deposits which eventually lead to more stable fluvial landforms such as alluvial terraces (*Alnus glutinosa, Corylus avellana, Quercus robur, Fraxinus excelsior and Carpinus betulum*). However, terraces covered by dry grasslands can also be found (CJB (eds.), 1990). Moreover, there is clear evidence of both contemporary and historical soil development (e.g. buried soils).

The hydrology is pluvio-nival, having two maximum flood probabilities: (i) during spring due to snowmelt and especially rain on snow in the Jura Mountains; and (ii) during autumn, when heavy and prolonged rainfalls occur. The catchment hydrology responds quickly, causing rapid hydrograph rise and high magnitude flood peaks, with return periods of 45 m^3/s (2 years), 66 m^3/s (5 years), 81 m^3/s (10 years), and 123 m^3/s (50 years). Baseflow conditions are between 0.5 and 7.5 m^3/s (FOEN, 2014; Fourneaux, 1998). The river flow is also closely coupled to groundwater. There is clear evidence of surface flow loss to groundwater in the upper part of the reach and the return flow of calcareous groundwater to the main river in the lower part (e.g. Fourneaux, 1998; Hottinger, 1998).

Land use in the catchment is mostly forest, prairies and pasture (70%), and agriculture (15%). Nevertheless, both industry and the CERN research centre use the water of the Allondon River and, despite extensive wastewater treatment, several polluting events impacted the river ecology between 1970 and 1990 (DIM, 2010). Generally, there is little river management within the 3 km reach considered in this study and most of the interventions (e.g. spur dykes) were removed in 2000 during a revitalisation and renaturalisation programme. The spur dykes did not significantly hamper braiding processes of the sections studied, which are still very active. However, whilst still in a braided/wandering state, there is evidence that the study reach is evolving from a 90m wide bar braided system (1957) to a c. 40 m narrower river with vegetated islands. These changes may be caused by land use changes of the alluvial terraces (pasture to forest) and changes in the hydrological regime. Nowadays, the river corridor is recognised both nationally (eg. Federal Inventory of Alluvial sites of National Importance) and internationally as a protected site (DIM, 2010).

Identification of sample sites

By means of an analysis of a series of historical aerial images, a Digital Elevation Model of 1m resolution (DEM; SITG, 2014; SWISSTOPO, 2012), Electrical Resistivity Analysis (ERT) and field observations (vegetation type and microtopography), four chronosequences covering a large range of ages has been defined. The historical aerial images and the DEM where used to reconstruct recent geomorphological development and to trace fluvial landform boundaries. Additional field observations have been integrated to validate the remote sensing data. Moreover, ERT data with 0.5m electrode spacing, following the method proposed by Laigre et al. (2013), have been used to visualise belowground soil/sedimentary structures along each chronosequence (see also Bätz et al., 2014). Within each mapped landform a representative site, in terms of microtopography, vegetation type and soil/sediment thickness/structure has been chosen for detailed soil analysis.

The chronosequence with the sample numbers 11 to 16 includes an active zone and three terraces (Figure 19). The increasing altitude is an indication of increasing age of the surface. Sites 12 (1.3m elevation above the river), 11 (2.5m) and 13 (3.7m) are already visible in the oldest aerial image (1957 Figure 19), consequently, only a minimum age can be assigned of about 60 years for the lowest terrace (12).

Site 16 (1.1m) is part of a large mid-bar in 1999 (Figure 19) and experienced fast vegetation colonisation, potentially due to (fast resprouting) large woody debris. Due to its island character, we expect this landform to interact (engineering action) with the floods (geomorphological processes). Site 14 (0.4m) and 15 (0.3m) are the youngest sites on this chronosequence. In 2001 they appear to part of the main channel system. From 2005 both sites are exposed, but different rates of vegetation colonisation can be observed.

The chronosequence with the samples 31 to 34, 21 and 22, cover medium to long time spans. 21 appears to be an old terrace at 2.2m from the river bed and is already visible in the oldest aerial image (1957 in Figure 19). In the aerial image of 1980, sites 22 (0.8m) and 31 (0.75m) are part of the main channel, while sites 34 (1.15m) and 33 (1.31m) recently experienced an avulsion process and are in the former outer and inner meander respectively. The island or cut-off terrace that has formed in this period has been almost completely eroded during an avulsion between 1980-1996. The same event created the base for the development of sites 31 (0.75m) and 32 (0.88m), which in 1996 show already vegetation colonisation of the avulsion channel with 32 being in the former inner and 31 in the former outer meander.

The shorter chronosequence of samples 41 to 43 cover mid to short time spans. In 1996 (Figure 19) site 41 appears as a barren surface whilst 42 shows already a pioneer vegetation cover. Based on the elevations above the river, which are respectively 1.1m for 41 and 1.59m for 42, and the avulsion pattern observed earlier for the sites 31-32, we might think of site 41 being part of former main channel and 42 being a former point bar. Site 43 (0.98m) has experienced a series of revegetation processes, but erosion processes reset the local system in 2006.

The chronosequence 51 to 55 covers young time spans of a decade. These sites have been continuously exposed to geomorphological disturbance and revegetation processes (Figure 19). However, site 5.3 (1.77m) is the oldest site on this chronosequence. In 2001 it is part of the main channel, but subsequent lateral erosion

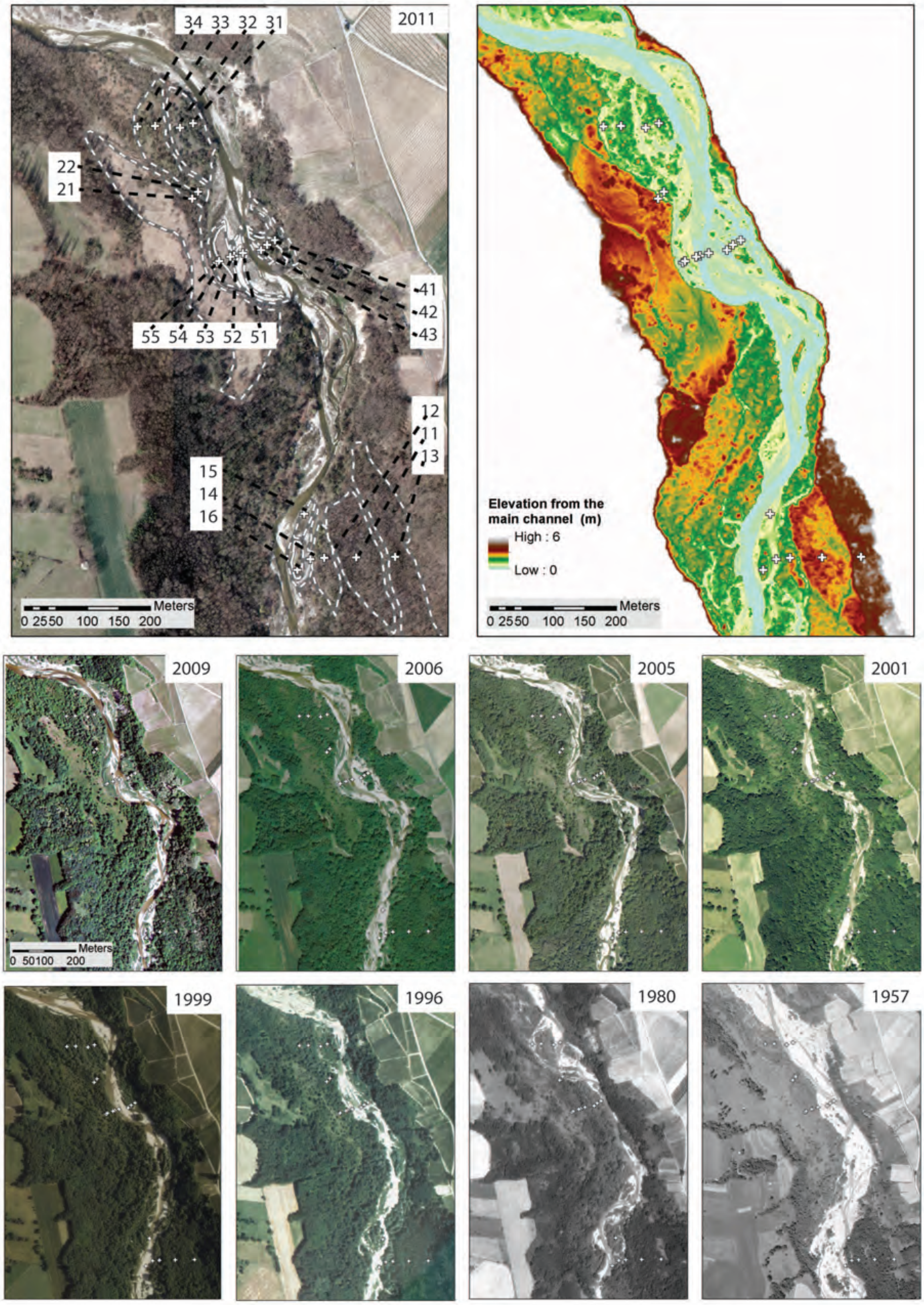

Figure 19 – Soil profile locations along the chronosequences

Aerial image of the study reach (Allondon river, Switzerland; SITG, 2014; SWISSTOPO, 2012), showing the soil profile locations (white crosses) along the chronosequences. Moreover, the elevation of the different sites are shown in respect to the main channel, and the geomorphological history documented with a series of historical images.

exposed the site (2005 – Figure 19). Vegetation colonisation appears to be slow on this site. The lateral erosion observed between 2001-2005 is also the starting point for the development for sites 55 (1.23m) and 54 (1.43) as part of the point bar system. In 2006 both sites became isolated from the main channel by avulsion processes. Only larger floods have impacted these two during recent years. Site 51 (0.86m) is still part of the main channel system in 2009, while site 52 (1.45m) appears to be a mid-bar as part of a riffle system. Between 2009-2011 site 51 became exposed due to avulsion.

Soil sampling strategy

In each of the six areas, a soil pit was dug at a representative location to a minimum depth of 50cm (P1 through P6). For each pit, soil/sedimentary layers were identified and described using standard soil description methods. The following parameters were recorded in the field: layer depth (H-layer), layer thickness, root density (nr./dm^2) and volume of soil stones (% > 2mm). Further data, such as the distance of each soil pit from the main river along the most likely line of connection, were acquired using a differential global positioning system (dGPS). For each layer in each profile, a sample was taken for laboratory analyses in terms of grain size distribution (<2mm) and organic matter quality, as explained in the next section. 116 soil/sediment samples were obtained in total.

Laboratory analysis

Each of the soil/sediment samples was analysed using laser diffraction to determine the grain size distribution (Malvern Mastersizer 2000) and by pyrolysis to determine organic matter quality and pools (Rock-Eval 6).

For the grain size distribution, 1g of <2mm sieved material of the bulk sample was used to remove organic matter with a H_2O_2 solution (first at 15% then at 35% concentration), making sure that the pH did not drop below 3. Before performing particle size analysis, samples were dispersed in a calgon solution (sodium hexametaphosphate) for one night. Measurement outputs were grouped into 5 classes of apparent diameters: clay (0.01-4µm), silt (4-63µm), fine sand (63-250µm), medium sand (250-500µm), and coarse sand (500-1000µm).

In order to analyse the organic matter quality, the Rock-Eval method was followed (Disnar et al., 2003; Lafargue et al., 1998; Sebag et al., 2006). Here, only a short summary of the main principles and methodological steps is given (for details see Disnar et al., 2003 and Sebag et al., 2006). The analysis needs little pre-treatment of the samples: untreated bulk raw samples were sieved at <2mm and then grinded (with an agate mortar) to powder.

The principle of the Rock-Eval method lies in the fact that the quality of organic matter components is closely related to their thermal stability. Thus, in a first step, samples are slowly heated to 650°C in an inert atmosphere (N_2) – the pyrolysis step. Organic matter components gradually undergo cracking while hydrocarbon, CO and CO_2 emissions are continuously measured. Hydrocarbon emissions can then be plotted versus temperature (labelled as the S2 curve) and, using signal deconvolution, different proportions of organic matter pools can be identified: labile fresh litter (A1), stable litter components such as cellulose and lignin (A2), humified litter (namely humic and fulvic acids; A3), stable humus components such as humins (A4) and resistant humus components/geopolymers such as black carbon and charcoal (A5). Note, that these data are expressed as proportions (pools) of the fraction of Total Organic Carbon (TOC).

The temperature at which most hydrocarbons are liberated (TpS2) is determined using the S2 curve. TpS2 refers to the predominant organic matter pool in the sample. Following Sebag et al. (2006), two indices are used to describe the relationships between the five different organic matter pools :

$$I = \log\left(\frac{A1 + A2}{A3}\right) \qquad [1]$$

"*I*" stands for immature and this I index represents the amount of fresh organic matter. Another index, "R" defined as:

$$R = \log\left(\frac{A3 + A4 + A5}{100}\right) \qquad [2]$$

represents the thermo-resistant or more humified stable/resistant organic matter components (R stands for thermo-resistant).

In a second step, the residue of the pyrolysis is heated from 450°C to 750°C in an oxygen enriched environment, allowing combustion of resistant organic matter. Again, CO and CO_2 emissions are measured continuously.

From the combined pyrolysis and oxidation steps, fractions of soil organic (%TOC) and mineral carbon (%MINC), a Hydrogen Index (HI) and an Oxygen Index (OI) can be obtained. The higher the HI, the less organic matter is transformed (fresh litter). The OI expresses the oxidation rate of organic matter and thus the humified and more resistant organic matter pools.

Statistical analysis

The field and laboratory data are highly inter-correlated. Thus, they were analysed using a principal component analysis (PCA; Matlab R2012b). A total of 22 variables were available for the 116 samples. The five grain sizes and the five organic matter pool variables, expressed as proportions, were first transformed by a centred log ratio function into a new metric system to avoid problems of co-linearity and the closed data effect. In a second step, all variables were standardized assuming a Gaussian distribution of the data set. The PCA was performed using eigenvectors and eigenvalues of the correlation matrix. The Pearson correlation coefficients between principal components and variables were calculated by multiplying eigenvectors by the square root of their associated eigenvalue. We set the level of significance (p=0.005) for the correlation of the variables with the principal components at $r>0.2540$ based on 100 degrees of freedom. However, we also consider correlations $r> 0.8$ to be strongly correlated with the related component. For the interpretation, we included all the components explaining more than 5% of the total variance.

4.1.4 Results

Figure 19 shows the analysed profiles and their position in the floodplain. The related data are summarised in Annexes A and B, while some examples of the analysed profiles are given in Figure 20. Based on the IUSS Working Group WRB (2006), the old terrace soils (11, 13, 21, 21) can be considered as mollic fluvisol skeletic, because they have a thick, organic matter enriched topsoil. The very young sites (14, 43, 51, 52) can be defined as leptosol skeletic. Most mid aged soil profiles would best fit the name fluvisol skeletic (15, 31, 32, 33, 34, 41, 42, 53, 54). However, profile 16 would be a classical fluvisol and profile 55 also shows stagnic properties.

The vegetation of the terraces (11, 12, 13, 21) is dominated by *Corylus avellana*, *Quercus robur* and *Fraxinus excelsior*. Location 16 is dominated by *Alnus glutinosa* and some *Robinia pseudoacacia* stands, while site 22 is dominated by a *Populus alba* stand. Most of the very young stands (14, 43, 51) do not show significant vegetation cover – only a few sporadic grass stalks. Site 53 is covered by dry grass land. Sites 14, 52, 54, 55, 41, 32, 31, 33, 42, 34, are dominated by *Salix elaeagnos* and/or *Salix purpurea* with increasing ages (14 young and 34 the oldest stand).

Grain size distributions (<2mm) and organic matter quality and quantity, but also data related to the position in the landscape (see Annexes A and B) have been used as input variables for the principal component analysis (PCA). Some samples have low Total Organic Carbon values (TOC<0.02%; Annex B) and thus, this absolute value should be considered with caution (Disnar et al., 2003; Sebag et al., 2006). Nevertheless, these data are coherent with the conceptual model described below and, as such, were not excluded from the analysis: they simply indicate samples with exceptionally low organic matter content.

The first four Principal Components (PC) explain 72.7% of the total variance (Table 1). From the fifth PC on, explained total variance drops below 5% and so these PCs are not considered further. The first PC explains 40.5% of the data variability (Table 1; Figure 21A). It correlates positively with the proportions of clay, silt and fine sands, TOC, with the proportions of more stable biopolymers and humified litter (A2 and A3), the root density and to a lesser extent with the HI. It correlates negatively with the fractions of coarse sands, the mineral carbon content (MINC), the OI, the resistant humus components (A5) and to a lower degree with the proportion of medium sand and the percentage of stones in the layer (%stones). Thus, the first PC appears to be representing the level of pedogenesis in the system with higher levels of pedogenesis associated with higher scores on this PC. Evidence for this is related to the higher quantities of organic matter and related humification processes, as shown by the presence of several organic matter decomposition stages (A2, A3 and to a lesser extent A4) a key process in early pedogenesis.

The second PC explains less variance, 17.2% as compared with PC1 (Table 1; Figure 21A). It is mainly associated with stable humus components (A4%) the R-index and it is negatively associated with fresh organic matter input (A1%; I-Index), but also to a lesser extent with TOC and HI. Thus, PC2 appears to be a measure of the fraction of fresh organic matter (negative values) versus stable organic components (positive values): high values of PC2 describe a lack of fresh organic matter input and where organic matter processing has transformed the available fresher pools towards more stable ones (R-Index). It is surprising that the fresh and resistant organic matter qualities (PC2) are, to a certain extent, independent from pedogenesis (PC1). This might be due to the fact that there are two main sources for organic matter: fluvial input, and endogenic vegetation production (e.g. Langhans et al., 2012; Naegeli, 1997; Pinay et al., 1992; Steiger and Gurnell, 2003)

PC3 explains 8.1% (Table 1; Figure 21B) of the variance and is mainly correlated with layers that have high values of clay and silt. A negative correlation exists with the medium sand content. We suggest that this PC represents the sedimentary processes the layers are or have been exposed to. With positive values for environments with rather silt and clay rich deposits (e.g. shallow overland deposits on terraces, or plant-colonised old avulsion channels) and negative values for sites exposed to more powerful events.

The PC4, explains 6.9% of the total variance (Table 1) and correlates positively with distance and elevation from the river. PC4 can be interpreted as representing the chronosequence, with the older terrace profiles being higher and more distant from the actual channel. However, it is interesting to note that this component actually explains very little of the total variance. We attribute this to the morphodynamics of the active channel, e.g. avulsion processes, which prevent simple substitution of time by space and create a complex mosaic of states of organic matter within the active zone. Depending on flood magnitude and position in the landscape, landforms can have different amounts and qualities of sedimentary inputs (Cabezas and Comín, 2010; Steiger and Gurnell, 2003). It is only when a part of the active zone is stable for sufficient time that the effect of time becomes dominant.

Figure 21C plots the sample sites onto the first two PCs for each of the 3 analysed zones. This plot spreads the samples based mainly on the organic matter quantity and quality. Organic matter enriched topsoil layers (Ah layers) of the older terraces (notably 13, 12, 11, 22) are grouped into the lower right corner of the plot. However, also some younger and fluvially exposed sites (54, 55) are found in this area of the plot. They are characterized by high values on PC1, that is they tend to have higher proportions of clay, silt and fine sands, TOC, higher proportions of the A2 and A3 organic matter compounds and lower mineral content and a lower thermo-resistant organic matter fraction (A5). They are also characterised by low values on PC2 that is they typically have a high fraction of fresh organic matter (A1% and I-Index). We argue that these samples are typical of the upper horizons of soils where pedogenesis processes tied to organic matter processing are very active, with high in situ organic matter production, which explains the relatively lower fraction of stable organic matter compounds.

Samples in the upper and lower left side of the plots shown in Figure 21, tend to be the subsurface layers (C horizons) of these older terrace soils (13, 12, 11, 22) but also the C horizons of younger profiles (53, 54, 55, 14), with low values of PC1, that is where TOC is low, with a high fraction of resistant organic components (OI and A5). These samples distribute along the entire range of PC2, indicating that subsurface layers are very variable in terms of fresh (negative PC2) versus stable humus components (positive PC2). Whilst these sites may be beneath surface layers where pedogenesis and in situ organic matter production is occurring, the young nature of these alluvial soils means that their C horizons can still be clearly distinguished as relatively inert. However, some M samples mix within this group. These are sandy deposits mixed with some exogenous pedogenically altered organic matter. Due to sediment transport processes only the most stable pools can be found in these layers, because they are attached to finer grains (e.g. Asselman and Middelkoop, 1995; Pinay et al., 1995; Steiger and Gurnell, 2003). However, because of the low TOC content on

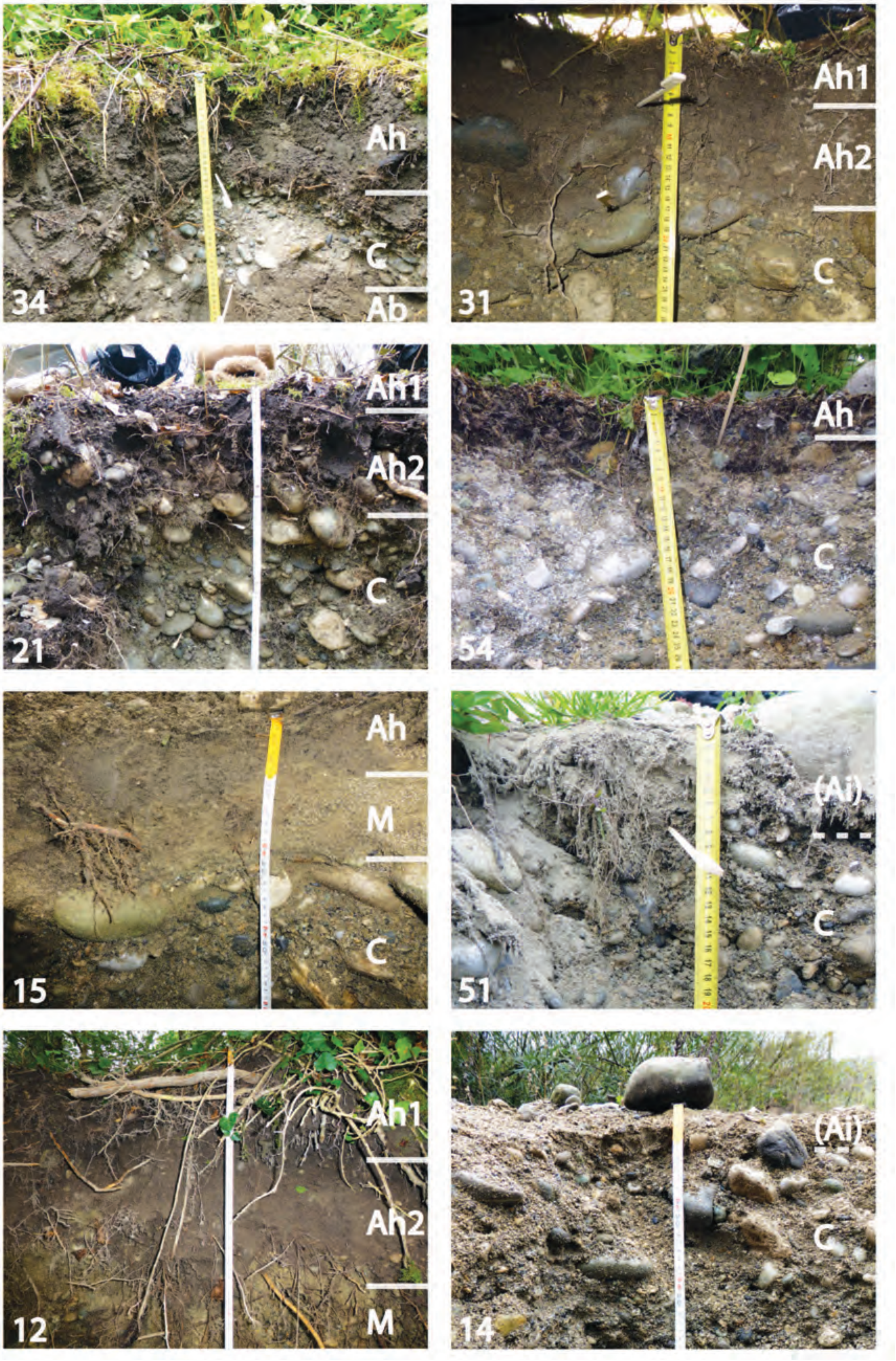

Figure 20 – Examples of analyzed soil profiles

Ah=humus enriched topsoil; Ai=initial topsoil formation; Ab=buried humus enriched topsoil; M=organic matter enriched sandy alluvial deposits; C=pure alluvial deposits with no or low organic matter content.

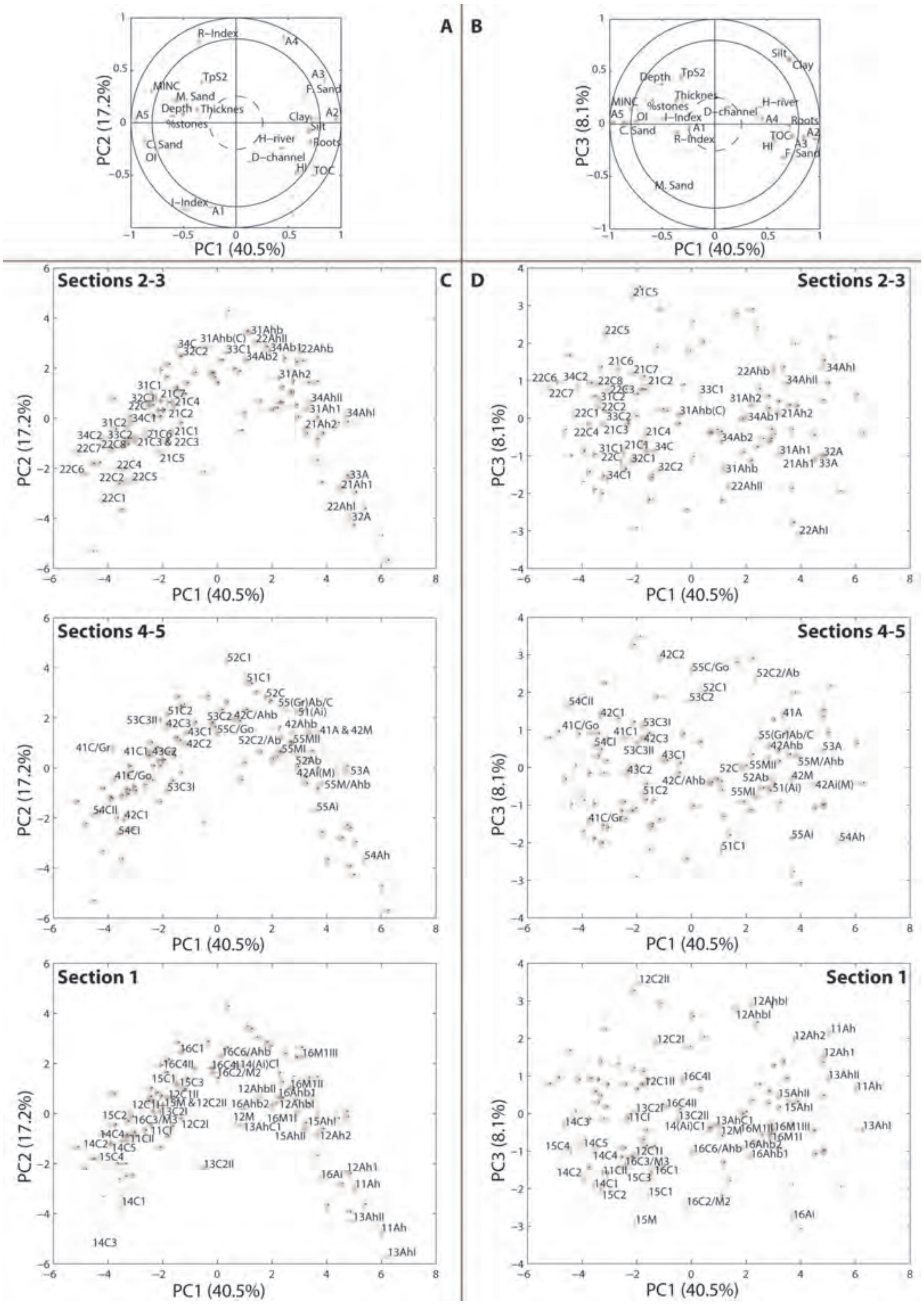

Figure 21 – Results of the PCA for the soil distribution in the study reach

A; B: correlations between variables and the first three principal components (PC) - the variables are described in Material and Methods. The inner dashed circle defines the significance level of the correlation set at r>0.2540 (*p*=0.005) based on 100 degrees of freedom. The intermediate continuous circle defines the level at which variables are considered to be strongly correlated with the PC (r > 0.8). Moreover, interpretation is based on plotting the samples on PC1/PC2 (C) and PC1/PC3 (D). For easier reading we subdived the dataset in three sections. The code of each sample states the chronosequence and profile number (e.g. 14), followed by the horizon type (Ah=humus enriched topsoil; Ai=initial topsoil formation; Ahb=buried humus enriched topsoil; M=organic matter enriched sandy alluvial deposits; C=pure alluvial deposits with no or low organic matter content).

Table 1 – Pearson correlation coefficients (r) between variables and the PCs

Variables correlation (r) with the first eight principal components. In bold the variables with the highest correlations for each principal component (PC). Note that variable show a significant correlation with r>0.2540 (*p*=0.005) based on 100 degrees of freedom. In the analysis only the first four PCs are considered because explain more that 5% of the total variance.

Variables	**PC_8**	**PC_7**	**PC_6**	**PC_5**	**PC_4**	**PC_3**	**PC_2**	**PC_1**
Depth	0.24	-0.32	0.41	**0.41**	-0.09	0.38	0.08	-0.50
Clay	-0.08	0.02	0.13	-0.07	-0.15	**0.61**	0.04	**0.72**
Silt	-0.02	0.00	0.03	-0.08	-0.14	**0.63**	-0.08	**0.70**
F. Sand	0.13	-0.08	-0.10	**0.49**	0.05	-0.32	0.28	**0.66**
M. Sand	0.20	0.00	-0.02	-0.13	0.23	**-0.63**	0.21	**-0.58**
C. Sand	-0.07	-0.02	0.09	**-0.36**	0.10	0.01	-0.16	**-0.86**
TOC	0.15	-0.03	0.14	-0.16	0.09	-0.11	-0.50	**0.73**
MINC	0.03	0.03	-0.01	-0.13	-0.16	0.16	0.31	**-0.80**
HI	-0.26	0.31	0.19	-0.18	-0.14	-0.17	-0.47	**0.57**
OI	**-0.40**	0.19	0.10	0.24	0.04	0.03	-0.27	**-0.75**
TpS2	0.03	0.02	**-0.60**	0.02	0.00	**0.44**	0.40	-0.32
A1	-0.12	-0.11	0.11	**0.37**	-0.01	-0.04	**-0.81**	-0.24
A2	0.12	0.06	0.08	-0.01	-0.03	-0.14	0.03	**0.95**
A3	-0.07	0.01	0.23	0.07	0.04	-0.13	0.41	**0.84**
A4	-0.06	0.00	0.04	-0.10	0.22	0.05	**0.81**	0.46
A5	-0.12	-0.05	-0.04	0.09	0.04	0.02	0.03	**-0.96**
R-Index	**-0.36**	-0.06	0.19	0.12	0.15	-0.07	**0.78**	-0.36
I-Index	0.12	0.00	-0.18	0.06	-0.09	0.04	**-0.82**	-0.49
%stones	0.31	0.26	0.31	**-0.24**	0.20	0.23	0.06	**-0.60**
Thickness	0.18	**0.55**	0.09	**0.36**	0.44	0.23	0.12	-0.37
D-channel	-0.05	-0.31	0.06	-0.13	**0.75**	0.16	-0.37	0.14
H-river	-0.10	-0.07	-0.16	-0.01	**0.72**	0.17	-0.24	0.44
Roots	-0.02	0.23	-0.23	0.21	0.07	-0.01	-0.19	**0.71**
Expl. total variance [%]	3.1	3.5	4.2	4.9	6.6	8.1	17.3	40.3
Cumulative variance [%]	88.0	84.9	81.4	77.2	72.3	65.7	57.6	40.3

the right side of the plot, the fractions of the different organic matter pools need to be considered with caution.

Samples in the higher right corner of the plots shown in Figure 21C have high values on PC1 and PC2: organic matter humification is active but, because of a lack or scarcity of fresh organic matter input (A1), the organic matter pool tends to be biased towards the mature and resistant components. The lack of fresh organic matter input and organic matter humification has transformed the available labile matter (first A1 then

A2) to more stable compounds. Samples in this area of the plot include very young (2-5 years old) A horizons (51(Ai), 14(Ai)) and some Ah horizons of profiles that are still impacted by shallow depositional events (41, 15, 22), mostly composed by humified litter and stable humus components in combination with fine sands. Nevertheless, most sites are related to the buried surface horizons (Ahb) and organic matter enriched sandy deposits (M). The first (Ahb) have been progressively decoupled from fresh organic matter input via burial, while the second (M) have been deposited together with large quantities of stable humus components.

Summarising, sites close to positive values of PC2 can arrive through three fundamentally different processes: (1) a stable surface deposit where pedogenesis has formed an initial organic matter enriched topsoil after a period of stability with good fresh organic matter input (transition from sediments into a soil); (2) a buried soil horizon and (3) deposits of upstream eroded organic matter enriched sands, with its fresh organic matter supply being cut off and the accumulated organic matter becoming progressively more resistant. Thus, even though the soil horizons show similar properties in this zone, their evolution may be very different. Indeed, the accumulation of stable humus compounds in Ahb layers is due to recessive pedogenic processes, which lead to degradation of the organic matter (Johnson, 1985; Schaetzl and Anderson, 2005). On the other hand, the initial accumulation of stable humus compounds in layer Ai is due to progressive pedogenesis, in which the sparse vegetation cover and/or fluvial litter input provides easily and fast transformable organic matter (Gregory et al., 1991; Langhans et al., 2012; Sebag et al., 2006).

When plotting the samples on PC1 versus PC3 (Figure 21D) the entire range of sedimentary composition gets clear and can almost be read like a classical grain size triangle. The organic matter enriched topsoils, which are placed on the positive axe of PC1, show high variability in clay to medium sand content (PC2), but with initial A horizons (55Ai, 51(Ai), 42 Ai(M), 14(Ai)C1, 16Ai) mainly placed in the upper right part of the plot (high fine sand content). The buried soil horizons (Ahb) distribute, as the Ah horizons, on the right part of the plot (Figure 21D). Most of the M horizons, as being organic matter enriched sandy deposits, concentrate in the fine to medium sand range.

The plot PC1/PC4 of the samples (not shown here) show the distribution of sedimentary and /or soil layers along the chronosequence, with samples being older on the positive axis of PC4. The plot is not shown here because it simply reflects the chosen sampling strategy along the chronosequences.

4.1.5 Discussion

Pedo-geomorphic interactions of the Allondon River

The shape of Figure 21C need special mention: as PC1 is defined as an axis of pedogenesis, as we move from the higher middle of the point cloud towards higher organic matter contents (from the left to the right), there is simultaneously an increase in amount of fresh organic matter supply (negative values of PC2) because of the establishment of vegetation with higher biomass productivity (e.g. Van Breemen and Finzi, 1998). This is supported by the correlation with the root density. It also suggests higher organic matter humification rates indicated by the presence of all the organic matter humification steps (A1-A2-A3). However, the same change in organic matter supply can be observed if moving towards negative values on PC1. Although, this increase in fresh organic matter supply is characterised by no increase in TOC and related humification steps (pools A2 and A3). Samples located in the lower left corner (14 and 22) tend to be geomorphic stable but still influenced by the fluctuating ground water (elevation from river is respectively 0.9m and 1.2m). Possible sources are, in the case of the terrace soils, illuviation products from the upper Ah horizons, while for younger sites dissolved organic matter from the fast infiltrating (gravelly material) river flow and related processes of the hyporheic zone may be a potential source.

It is interesting to notice that there is no clear correlation of topsoil maturity, thus moving from the top of the point cloud of Figure 21C towards the lower right corner, and landform age observed form the historical aerial images. We can find young sites with about one decade of development (54), mid aged (15-30 years) sites (22, 32, 33) and old terrace soils (13, 11, 21) in the same area of the plot. In connection with the low degree of explained variance of PC4, representing the chronosequence, this indicates that there is no clear impact of time on young alluvial soils. Local and reach scale geomorphological setting in conjunction with different flood magnitudes, create a complex pattern of geomorphological impact (Steiger and Gurnell, 2003), thus directing local soil evolution trajectory (Johnson, 1985; Schaetzl and Anderson, 2005).

The shape of Figure 21D does not show a clear pattern. However we can notice the affinity of fine sand, silt and clay for higher TOC as observed in other studies (e.g. Cabezas et al., 2010; Pinay et al., 1995). Moreover, the old terrace topsoil appears to have higher contents of fines (higher right corner), while younger sites are rather composed of medium to fine sands (lower right corner), indicating the kind of depositional processes each site is/has been exposed to. The C horizons, located in the left part of the plot (Figure 21D) are generally high in coarse sands, but show a wide range of silt/clay versus medium sand content. It is interesting to notice that there is a trend: section 2-3 and 4-5 have higher contents of silt and clay if compared to the C layers of section 1.

Based on the above interpretation, we can conceptualise braided river soil evolution (Figure 22). Pedogenesis starts from a large range of deposits in terms of grain size and organic matter quantity and quality (top of the PC1/PC2 plot – Figure 21C). If conditions are favourable (vegetation establishment, water and nutrient supply from low magnitude depositions events) a soil starts to form (towards the lower right corner of the PC1/PC2 plot –Figure 21C) and eventually form a mature terrace soil (Figure 22). However, young deposits can also get buried before pedogenic alteration occurred due to high magnitude events (taking a position in the left corner of the point cloud). Burial or erosion and re-deposition of pedogenically altered material can also occur whilst following the pedogenic trajectory, indicated by the presence of Ahb (buried surface horizons) and M (organic matter enriched sandy deposits) horizons in the right lower to mid right part of Figure 21C. Burial leads to the ageing of the organic matter pools of the ancient surface (Ahb) (e.g. Schaetzl and Anderson, 2005). The rates of ageing, thus following positive PC2 (A4 and R-Index), diminish in relation to the availability of unstable organic matter compounds and because of the missing fresh organic matter input. The thick organic matter enriched sandy deposits (M) may also contain rather stable compounds, because they tend to be attached to sand particles (e.g. Asselman and Middelkoop, 1995; Pinay et al., 1995; Steiger and Gurnell, 2003).

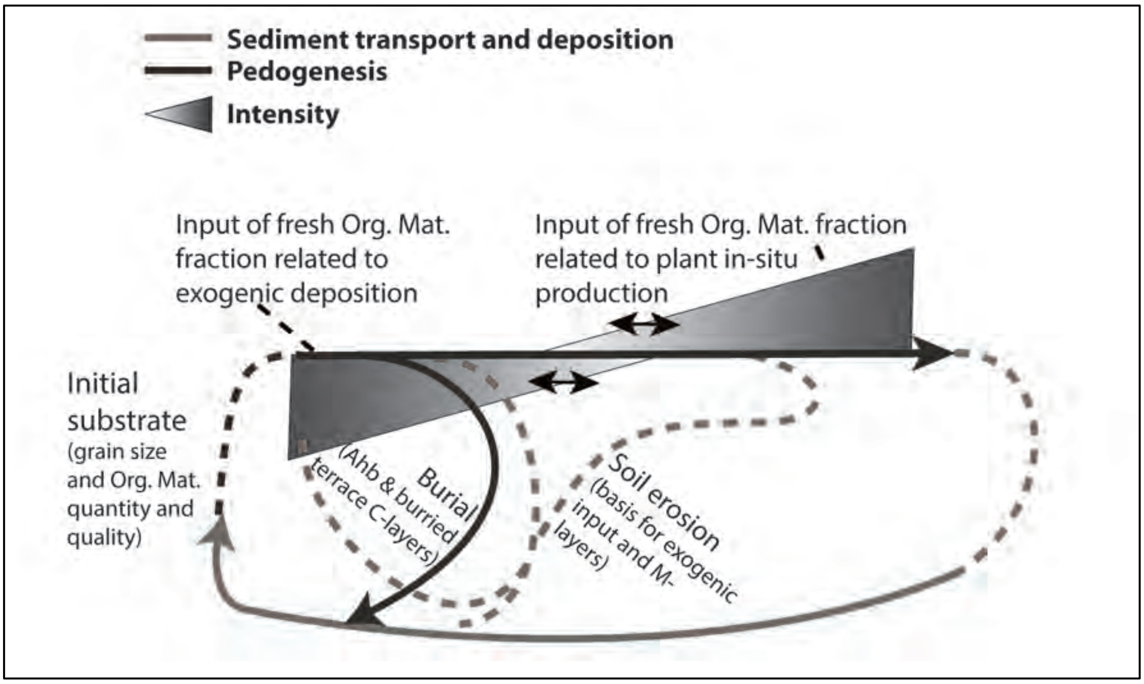

Figure 22 – Conceptual model of soil evolution based on observations in the PCA

The initial substrates are shown: they correspond to different young deposits, old reexposed buried deposits, and deposits influenced by soil development (M or Ahb). On these various substrates, rates of pedogenesis are influenced by deposition rates of exogenous organic matter (quantity and quality). However, too high sedimentation rates might lead to burial and thus to the end of soil development. Conversely, erosion processes can remove the upper layer. This removed layer might influence the soil development in other places downstream, hence proving a source for exogenic organic matter. With increasing stability, the contribution of in situ produced organic matter gets stronger, promoting the humification and mineralisation processes (high TOC and diversification of the different pools). The highest feedback occur at the beginning during strong self-enhancing processes between, organic matter enriched sediment supply, soil organic matter turnover and plant colonisation processes. The further we move down the pedogenesis arrow the closer we come to the conventional soil-vegetation system with little geomorphic contribution.

The geomorphic activity in this area of the plot suggests that there are close interactions between geomorphic processes and braided alluvial soil evolution. Especially during early stages of braided alluvial pedogenesis these appear critical. Major geomorphological events might reset the system, through either deposition or erosion. However, weaker deposition events may supply organic matter enriched fine sediments (Cabezas and Comín, 2010; Langhans et al., 2012; Pinay et al., 1992; Steiger and Gurnell, 2003) forming cumulic soils (Daniels, 2003; Jacobson et al., 2005), and act as an exogenic organic matter source that can accelerate initial ecosystem processes (Bätz et al., 2015b). This processes can potentially be facilitated by the engineering action of vegetation, thus during the biogeomorphic phase proposed in the biogeomorphic succession model of Corenblit et al. (2009).

Bätz et al. (2014) reconstructed the geomorphological, soil evolutionary and vegetation successional development of a section which includes profile 15 of this study. High temporal frequency historical images were used to infer past geomorphological changes. These were combined with a 2D grain size distribution model (Electrical Resistivity Analysis - ERT) of the entire section and soil profile 15 of this study to deduce soil maturity and distribution. The analysed section is characterised by two distinguished areas. A first low altitude zone with shrubby willow stands and a soil covered surface (Ah/M/C profile); this site can be attributed to the biogeomorphic phase proposed in the biogeomorphic succession model of Corenblit et al. (2009). A second higher elevated gravel/cobble barren surface with only a few grass stalks with no soil. The historical images show that the barren higher located area formed about 10 years before sampling. The lower located soil covered area was been created 8 years before sampling and experienced sand aggradation over the entire period due to the rapid colonisation of river engineering species. If the deposit is not too thick it can be integrated into the soil (Daniels, 2003; Jacobson et al., 2005), then the organic matter component of the deposit may act as an exogenic input. The close interaction between geomorphological processes (fine sediment and resources supply such as organic matter), vegetation development (trapping and fixing sediments with its biomass but also producing fresh litter) and soil processes (nutrient transformation and storage) has led to the rapid development of a more productive local ecosystem. Conversely the older site, which was cut-off from the river supply early, experienced a slow development (Bätz et al., 2014). This close interaction between these three components during fluvial landform formation has been defined as a coevolutive process (Bätz et al., 2015b; Corenblit et al., 2009, 2014). The time scale of coevolution of the two zones changes due to different rates and forms of interaction between geomorphic processes (Asselman and Middelkoop, 1995; Langhans et al., 2012; Pinay et al., 1992, 1995; Steiger et al., 2001; Steiger and Gurnell, 2003), vegetation colonisation (Corenblit et al., 2009, 2011; Gurnell, 2014; Gurnell et al., 2012) and soil evolution (Bätz et al., 2014, 2015b; Langhans et al., 2012; Mardhiah et al., 2014).

Similar observations can be made in the point distribution of Figure 21C. Samples 54Ah and 55Ai, with an approximate age of 10 years, estimated by a series of historical images, show similar properties (OM quality/ quantity and grain size) as mature terraces soils (13Ah, 11Ah, 21Ah, >50 years), thus indicating the changes in speed of the biogeomorphic succession due to pedo-biogeomorphic feedbacks. Thus, sedimentation processes appear to either constrain or contribute to initial soil development by facilitating the accumulation of an organic matter stock before isolation from the river flux (shown by the intensity triangles in Figure 22). Initial deposits are commonly very low in organic matter content (Figure 21– annexe A). Fluvial fresh input of exogenic organic matter may then be a main source. The young deposits in Figure 21, are exposed to (weak) fluvial sedimentary processes. The associated organic matter deposition ages quickly because of the limited fresh input and the relatively high biological activity of alluvial environments (Bullinger-Weber et al., 2007; Guenat et al., 1999; Langhans et al., 2012; Pusch et al., 1998). The more stable litter compounds, such as lignin (A2), accumulate in the topsoil with time (Doering et al., 2011; Langhans et al., 2012) because transformed more slowly into more stable compounds such as humic and fulvic acids and humins (A3+A4) - higher right part of Figure 21C. Moreover, the deposited material, as the M horizon shows, has a high fraction of more stable and resistant humus components (A4 and A5). However, when plants establish and the biomass production increases, the organic matter transformation chain is established and organic matter pools arrange in the order A2-A3-A4 (Annex B), as the position of mature terrace soils in the lower right part of Figure 21C suggests.

Plant colonisation, is particularly dependent on ambient and geomorphic conditions (Cierjacks et al., 2011; Francis, 2007; Gurnell et al., 2012; Hupp and Rinaldi, 2007). These might be favourable from the beginning (e.g. access to water in a gravelly environment) but can also develop within a few decades (e.g. water retention through fine sand or silt deposition), changing the timing in the shift of main fresh organic matter input (exogenic to endogenic as indicated by the intensity triangles in Figure 22). This means that there are locations in which soil evolution can be fast (high exogenic and endogenic input) and others which develop relatively slowly (low exogenic and endogenic input), thus changing the time scale and pathway of landform coevolution processes in gravelly braided river systems.

Comparison with other river systems and future research challenges

Clearly a major question arises from this research: even though the amounts of total organic matter are relatively low in the most recent deposits (Annexe B) as compared with those sites where in situ production can occur (Cierjacks et al., 2011), are these sufficient to enhance the rate of initial soil-forming processes? Tabacchi et al. (2000) noted that the riparian corridor may be seen as a recycling zone of exogenous inputs coming from the entire upland catchment. They argue that there will be a dependence of fluvial habitats on such organic matter supplies, with supply closely related to geomorphological riverine processes. Cierjacks et al. (2011) found that the difference in organic matter quantity and quality found in alluvial soils of the Danube River (Austria) are related to flooding history. Floods can import significant amounts of particulate OM (Hein et al., 2003). Based on sediment trap analysis of meandering rivers Garonne (France) and Severn (UK), Steiger et al. (2001) and Steiger and Gurnell (2003), found a strong relationship between the quantity of deposit fine grain sizes (silt/clay) and quantity of TOC and organic nitrogen. Only phosphorous showed a dependence on the quantity of deposition, regardless of its grain size distribution. This research also emphasises the importance of the geomorphological setting and flood magnitude in defining the spatial distribution of deposits and related quality (grain size, and the elements NPC) confirming findings of Pinay et al. (1992, 1995). Low magnitude events in constrained meandering river reaches, show deposition peaks on landforms closely located to the main channel (e.g. point bars). As flood magnitude increases, the deposition peak shifts towards higher located and distal fluvial landforms (e.g. side channels, higher benches). However, less constrained and more geomorphologically complex river reaches will have a less clear shift in the sedimentation peak (Steiger et al., 2001; Steiger and Gurnell, 2003).

Cabezas et al. (2010) and Cabezas and Comín (2010) analysed the spatial pattern of deposition in terms of OM quantity/quality and grain size for different landforms of the meandering Ebro River (Spain). Similar to this research historical aerial images were used to estimate landform age and to deduce hydrological connectivity. Moreover, sediment traps were used to quantify fluvial deposits. Results indicated that on old sites, endogenic OM production dominates, while on younger sites river depositional events were the main source of OM. Their results also show that the exogenic input is also dependent on the position in the fluvial landscape, with higher values for fluvially exposed sites (point bars compared to side channels), and from the floodplain morphology. However, in their research, time since formation was well- correlated with net carbon accumulation (Cabezas et al., 2010; Cabezas and Comín, 2010). This might be related to the higher geomorphological activity of braided river (e.g. avulsion). Bechtold and Naiman (2009) developed a modelling approach, which combines the CENTURY model for predicting changes in the soil organic matter pools with a simple fluvial deposition model and a forest growth/production model. The model was tested for the meandering Queens River (Washington – USA). Results confirmed that fluvial OM, but also the deposition of fines, are especially important during the first decades of fluvial landform development, because they influence moisture retention and nutrient regime. These results are deemed to be less clear in higher energy systems (Bechtold and Naiman, 2009).

Similar observations have been made by Doering et al. (2011) and Langhans et al. (2012) for the braided Tagliamento River (Italy). Riparian forest and especially vegetated islands have a high productivity. Pre-processed fresh organic matter can then be exported from these sites by wind and fluvial processes and deposited on less productive sites such as river bars. This influx could provide a high quality resource (Doering et al., 2011; Langhans et al., 2012) to initialise ecosystem processes such as soil forming processes, and notably to enhance local weathering processes and plant nutrient availability due to the decomposition processes. Naegeli (1997) has studied the spatial and temporal variability of particular organic matter in gravel bed river deposits of the Necker River in Switzerland. The spatial and temporal variations of particular organic matter stocks were found to be closely related to river dynamics. This resource reservoir can be activated and transformed by microbial activity (Bridge, 1993; Doering et al., 2011; Gregory et al., 1991; Naegeli, 1997; Pusch et al., 1998; Uehlinger, 2000). Especially, earthworms, bacteria, algae and biofilms can transform such organic matter inputs and make resources available for plants (Bätz et al., 2015b; Bullinger-Weber et al., 2007; Pusch et al., 1998). Even if sediments free of fresh organic matter are considered to be highly reactive (as for those found on glacier forefields for instance; Burga et al., 2010; Mavris et al., 2010), the organic matter found in alluvial deposits will provide an even more accessible resource (Bardgett et al., 2007; Gregory et al., 1991; Guelland et al., 2013), potentially functioning as a start-up for plants and thus the biogeomorphological succession. The mycorrhizal fungi symbiosis that *Salicaceae* can establish may further promote resource up-take from the sediment, soil and groundwater stock (Harner et al., 2010, 2011).

Whilst the dynamics of organic matter in fluvial systems have been addressed, there are fewer studies that investigated the extent to which it is important or, more precisely, the conditions under which it is important. For instance, if the source of exogenous organic matter is the erosion of river banks and/or terraces, then this will require the highest flows. Nevertheless, these are the flows that are also likely to mobilise large amounts of sediments, so diluting the organic matter concentration. The large variations of initial substrate (C and M) of our analysis show the large variability of fluvial inputs in terms of grain size distribution and organic matter quality and quantity. Additionally the amount and frequency of the deposition determines whether or not the active river surface aggrades or is even buried (Bätz et al., 2015b). We know very little about organic matter delivery in braided rivers during flood events and its relationship to sediment delivery rates and thus the balance between the benefits (organic matter delivery) and risks (burial) of deposition. If it can be shown that exogenous organic matter does enhance pedogenesis, even at relatively low concentrations, then we may conclude that geomorphological processes not only disturb negatively the soil-vegetation development (through erosion for instance), but may also facilitate, or even trigger, more rapid plant colonisation in braided rivers. In turn, because of the engineering action of plants (Gurnell, 2014; Gurnell et al., 2012) overall landform development speed and trajectory (biogeomorphic succession *sensu* Corenblit et al., 2009, 2014) might be affected.

A second broad group of unanswered questions relates to the likelihood of erosion and burial, which will equally locally reset the surface organic matter dynamics. Deposition is an interesting process, because it may have a range of competing effects. On the one hand, it may progressively aggrade the landform surface and so isolate it from the active river channel (Daniels, 2003; Jacobson et al., 2005). This may make it more stable, inundated less frequently and, provided water supply and nutrient stock does not become a limiting factor, colonised by plants. It is established that typical early colonisers are able to adapt their root network so as to avoid water logging whilst also follow the falling water table to avoid drying (Glenz et al., 2006; Pasquale et al., 2012).

But if the deposition is too great, or it involves grains that are too coarse, this may prevent plant recovery and/or development as well as isolate the ancient topsoil from the potential benefits of exogenous organic matter input. Indeed, Gurnell and Petts (2002) proposed an optimal range of (fine) sediment aggradation and vegetation recruitment types (propagules, resprouting of woody debris) that promote rapid fluvial landform development. Similar for the development of a topsoil in a fluvial setting: only deposition events that are within a certain magnitude, frequency and quality (grain size and organic matter) can be integrated into cumulic topsoil (Bätz et al., 2015b; Daniels, 2003; Steiger and Gurnell, 2003).

In relation to erosion, sites closer to the riverine matter flux, will also be exposed to a certain risk; soil profile 15 (Bätz et al., 2014), for instance, has now been removed by a later channel migration during a large flood in winter 2013. Whilst such a site may have higher resource availability due to riverine matter fluxes, thus a faster pedo-biogeomorphic evolution, it also bears a higher risk of being eroded and destroyed. Hence, braided rivers morphodynamics can be described as a continuous battle between destructive processes (e.g. powerful floods) and stabilising processes (aggradation, vegetation establishment and soil matter transformation) that coevolve (from a landform development perspective) as fast as possible to prevent damage and/or destruction.

4.1.6 Conclusion

In this paper, we have considered the relationship between geomorphic processes and organic matter processing (humification) in relation to initial braided alluvial soil evolution. Soils form as an emergent property and are deemed to represent the state of ecosystem organic matter processing. In the field, identified soil and sedimentary layers were sampled and analysed in the laboratory for organic matter quality and quantity (Rock-Eval method) and grain size distribution <2mm. Additionally, variables describing the position of the layers in the fluvial landscape, and the rooting density were added to the dataset. To explore possible relations, a principal components analysis has been performed. Results lead to three main conclusions:

1. the amount and quality of organic matter, as well as grain size distributions, may be key variables in understanding pedo-biogeomorphological feedbacks;
2. results suggest that geomorphological processes may add organic matter and fine grained sediments to the normally inert sedimentary sites and change the rate of fluvial landform development (biogeomorphic succession *sensu* Corenblit et al., 2009, 2014). Research needs to establish the extent to which this additional resource can facilitate initial fluvial landform ecosystem matter turnover processes and soil formation. The enhanced overall ambient conditions (enhanced nutrient and water availability), potentially promotes vegetation growth/succession and eventually may lead to a river independent and self-sustained fluvial landform (e.g. river terrace).
3. data suggest that, during the coevolution mentioned above, there might be a shift from small amounts of external organic matter supply during fluvial deposition (e.g. bars) to large in situ production due to vegetation colonisation and related biomass production (terraces). The extent to which these two organic matter sources interact, changes biogeomorphic succession time scales and pathways.

Although the data show an impact of organic matter dynamics on fluvial landform development, the spatial and temporal variability of these processes is not yet clear. Our future work will focus on quantifying the impact of initial organic matter supply on the vegetation-soil system and its relation to fluvial geomorphic processes. Moreover, the general validity of the concept should be investigated, by trying to identify these processes in other river systems but also, for instance, in alluvial fans.

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4.2 “Soil in braided rivers: an overlooked component of braided river morphodynamics” – an example

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4.2.1 Introduction

Research over the last decade addressed the feedbacks between fluvial processes and the engineering action of vegetation, such as pioneer *Salicaceae* in braided river systems (Corenblit et al., 2011, 2014; Gurnell et al., 2012; Osterkamp and Hupp, 2010). Such plants appear to play a critical role in braided rivers as they are perfectly adapted to this harsh environment and impact fluvial landform development by promoting fine sediment aggradation (Gurnell and Petts, 2002) and fixing these with their roots (Crouzy and Perona, 2012; Perona et al., 2012). Aggradation causes higher elevation bars and terraces to form that are more stable but also enhance ambient edaphic conditions for plant growth by ameliorating water and nutrient retention (Francis, 2007; Francis et al., 2009; Moggridge and Gurnell, 2009). Moreover, plants such as *Salicaceae* may be able to enter into symbiosis with fungi, which facilitates nutrient and water up-take especially during initial vegetation establishment (Harner et al., 2011). However, (initial) soil formation processes, such as organic matter transformation, have been less considered even though they may play a major role in controlling the resources needed for plant growth (Bätz et al., 2015b).

Bätz et al. (2015a) show that organic matter input from a river is an important part of initial fluvial landform development, influencing the speed and timing of bio-geomorphic succession (Corenblit et al., 2009). Therein, there is a transition from an allochthonous organic matter dependency during initial succession stages to a self-sustained *in-situ* production during later stages. Thus, erosion and deposition processes play a double role: on the one hand, erosion processes are destructive and reset local landform development; on the other hand, to a certain degree, deposition processes facilitate landform development by potentially adding allochthonous organic matter to the normally poorly productive pioneer sites. This “start-up aid” may accelerate amelioration of edaphic conditions through soil formation and organic matter turnover. However, the spatial position relative to the channel influences the potential of such positive feedbacks. Moreover, a channel can shift in time, impacting the organic matter input, water supply and geomorphological stability. The timing of isolation from the channel processes during fluvial landform development can be considered as crucial: if too early, vegetation and soil development is slowed down and might even stop; however, if not isolated from the river, there remains the risk that the embryonic soil-vegetation system is eroded.

In this paper we test this model and explore how initial conditions and access to fluvial matter inputs affects the initial development of fluvial landforms within braided rivers. In particular we assess the co-evolution of geomorphological processes, plant establishment and soil development (Bätz et al., 2015b) and how feedbacks between these three components affect ecosystem processes.

A 36m section of the braided meandering Allondon River (CH) has been chosen for this study. The section has experienced several channel changes in the last decade which are well documented by a series of historical aerial images. Soil samples and vegetation cover have been sampled to characterise the impact of different deposits, the effects of organic matter supply and channel dynamics on the trajectory and speed of the fluvial habitat development.

4.2.2 Material and methods

Study area

This study was carried out at the Allondon River, a catchment located to the west of Geneva (Switzerland) in the calcareous French Jura Mountains. Three kilometres before the confluence with the Rhône River, the Allondon forms a braided/meandering floodplain reach, incised about 60m into fluvioglacial sediments. The fluvioglacial sediments are associated with the last glacial periods (Würm and Riss glaciation), and are typical of much of the Rhône basin (CJB (eds.), 1990; Coutterand, 2010).

The catchment area above the study reach is about 120 km^2, characterised by several (karstic) torrents (FOEN, 2014). The primary land uses are forest, prairies and pasture (70%) and agriculture (15%). Few, but heavy, industries use the water of the Allondon River just a few kilometres from the study reach. This severely impacted the river ecology between 1970 and 1990. A revitalisation and renaturalisation program has been established and the alluvial valley is now a nationally and internationally protected site (DIM, 2010).

The basin hydrology is pluvio-nival and responds quickly to rain events, notably rain on snow events, but also heavy autumn storms, causing floods at the following return periods: 45 m^3/s (2 years); 66 m^3/s (5 years), 81 m^3/s (10 years) and 123 m^3/s (50 years). The average flow ranges between 0.5 and 7.5 m^3/s (FOEN, 2014; Fourneaux, 1998). The unconsolidated fluvioglacial sediments through which the river flows combined with flooding events and slope failures supply large quantity of sediments and support a braiding channel pattern.

Site selection

A 36m transect of the recent active floodplain was selected by means of a series of historical aerial pictures and a Digital Elevation Model (DEM) (SITG, 2014; SWISSTOPO, 2012). Because of the aim of this paper to define the impact of initial sediment deposits and their relation to fluvial matter input, we concentrated our efforts on the last few decades because of the higher time frequency and higher resolution of historical aerial images.

From the 2011 aerial image, the chosen section shows four main areas (Figure 23): starting from the left, a first zone with shrubby willow stands (1-18m), followed by a barren surface with only a few grass stalks (18-25m), a wet swampy zone (25-32m) and finally the shrubby terrace vegetation. In this paper, we will not further consider the last two zones; the river terrace is relatively stable and the swampy zone matter flux is largely impacted by the nearby terrace vegetation.

Electrical Resistivity Analysis (ERT)

In order to understand the sedimentary environment within which the embryonic soil-vegetation system develops, resistivity to an injected electrical field is measured (Loke, 2001). Studies have used this technique to deduce for instance historical and paleo-environmental river systems (e.g. Laigre et al., 2013). We use this technique to determine the spatial diversity of (near) surface deposits and soils in this gravelly setting without the need to excavate the entire section. To aid interpretation of resistivity values, a soil profile has been dug in the same ERT section and was later used also for the soil analyses. In detail, we followed the method of Laigre et al. (2013) briefly summarised here. 48 electrodes were inserted in the ground along the section with spacing of 0.5m and connected with a cable to the measuring unit (Syscal R1). For every measurement, an array of four of the 48 electrodes is needed: on the two outer electrodes, the current is injected into the ground; the two inner electrodes measure the resistivity to the generated electrical field. We used a Wenner-Schlumberger array with equal spacing between the four measuring electrodes because of the good horizontal resolution. By combining electrodes with a greater distance between them, it is possible to measure the resistivity of deeper sediment layers. Thus, the software controls the electrodes to sample across all possible electrode spacing and hence depths, leading in our case to 551 measurements arranged into a depth cone, deeper in the middle of the section. The measured resistivity is an apparent resistivity – of a fictive homogeneous material. Modelling (the RES2DINV program) is required to invert the apparent resistivity values into a heterogeneous model of the subsurface resistivity. Additionally, this can be mapped in space by measuring the position of each electrode with a differential GPS (precision X=±0.03m, Y=±0.02m, Z=±0.06m). We used a least-square inversion method and considered the models as good with RMS (Root Mean Squared) error of less than 5%. For more detail see Laigre et al. (2013) and Loke (2001).

Soil sampling

A soil pit was dug on a representative site in the willow stand close to a willow plant. In the pit, soil and sedimentary layers were identified and described. Samples of each identified layer were analysed in the laboratory for grain size distribution (<2mm) and organic matter quality and quantity.

For the grain size distribution analysis, carbonate (using 10% HCl solution) and organic matter (first 15% and then 35% concentrations) were removed from 1g of <2 mm sieved material. During the entire sample preparation procedure, pH was maintained above 3 to avoid destruction of the clay fraction. This is a standard sample preparation method before measuring the grain size distribution by means of laser diffractometer (Malvern Mastersizer 2000).

The organic matter assessment was done following the Rock-Eval method for soil samples proposed by Disnar et al. (2003) and Sebag et al. (2006). The basic principle of this method is the thermal stability of different organic matter compounds. For this, 0.4-0.7g of the <2mm sieved and grinded samples was heated in an inert atmosphere (N2) and the pyrolysis-released hydrocarbons were measured continuously (Technologies Vinci, Rock-Eval 6). Hydrocarbon emission is then plotted versus temperature and, by deconvolution, different pools of organic matter litter compounds such as cellulose and lignin (A2), humified litter namely humic and fulvic acids (A3), stable humus compounds such as humins (A4) and resistant humus compounds like black carbon and charcoal (A5). For more details about this method see Lafargue et al. (1998), Disnar et al. (2003) and Sebag et al. (2006)

The proportions of organic matter found in each pool, allows deduction of the stage of soil organic matter (OM) turnover processes (Bätz et al., 2015a). Active soil OM turnover is characterised by high fractions of fresh litter (A1; A2), followed by an intermediate fractions of humified litter (A3) and low fraction of stable and resistant humus compounds (A4; A5). The longer a soil has not experienced fresh OM input the more the fraction biases towards the stable and resistant fraction (A3 then A4 and A5).

4.2.3 Results

Electrical Resistivity Analysis (ERT)

The two zones of interest can be defined in the ERT section by the topography and sediment resistivity: starting from the left (Figure 23; 1-18m), first there is a low altitude zone with shrubby willow stands. Resistivity values are medium (medium grey colour) with several low value lenses at the surface (light colour). Then (Figure 23; 18-25m), a higher located barren surface can be defined with very high resistivity values (dark colour).

In order to interpret the resistivity values, we need to consider the soil profile that was dug in the willow stand. As shown in Figure 25 and Table 2, the first 20cm (Ah and M layers) are characterised by a sandy, sometimes loamy, texture with no gravels, followed by a gravel/sand mixture (C layers). Thus, the light ERT values found at the surface (lenses) can be attributed to the sandy layer (light bottom – below 366m elevation - is related to the highly conductive ground water) and the medium grey zone to the gravel/sand mixture. From field observations, we attributed the dark ERT zone to a gravel/cobble mixture with no sands.

In summary, the lower altitude sand and gravel/sand mixture has more favourable conditions for plant growth (groundwater connection and water retention), while the higher altitude gravel/cobble mixture has lower water retention capacity and poorer groundwater connection, thus having a high risk of drying for plants during summer.

Soil profile

A soil profile was dug on the lower altitude shrubby zone. No soil sample was taken in the higher altitude barren zone because it lacked fine material (<2mm).

Looking at the soil profile in detail (Figure 25; Table 2), several soil and sedimentary layers can be defined. A discontinuous sandy deposit is covering the profile as a result of a recent flood. A first organic matter enriched soil horizon (TOC=1.84%) and a second medium sand layer poor in organic matter (TOC=0.10%) were found below.

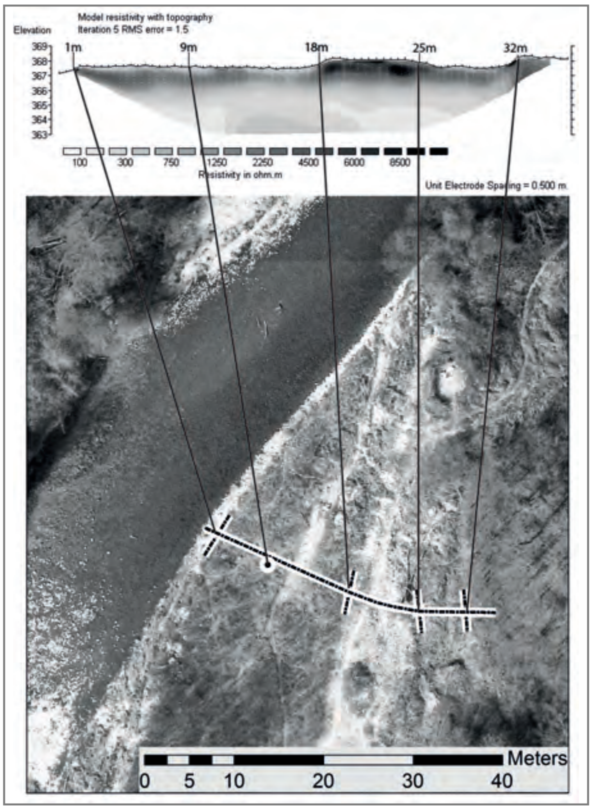

Figure 23 – 2011 aerial image and Electrical Resistivity Analysis - ERT of the study section

Light colours of the ERT are sandy deposits, while dark colours are coarse deposits (gravel and cobbles). The dot shows the position of the soil pit (Figure 25).

Figure 25 – Soil pit (15) of the study section

The position of the soil pit along the section is indicated in Figure 23. M=sandy deposits enriched with allochthonous organic matter; Ah= organic matter enriched soil layer; C= mineral layer (sand, gravel, cobble).

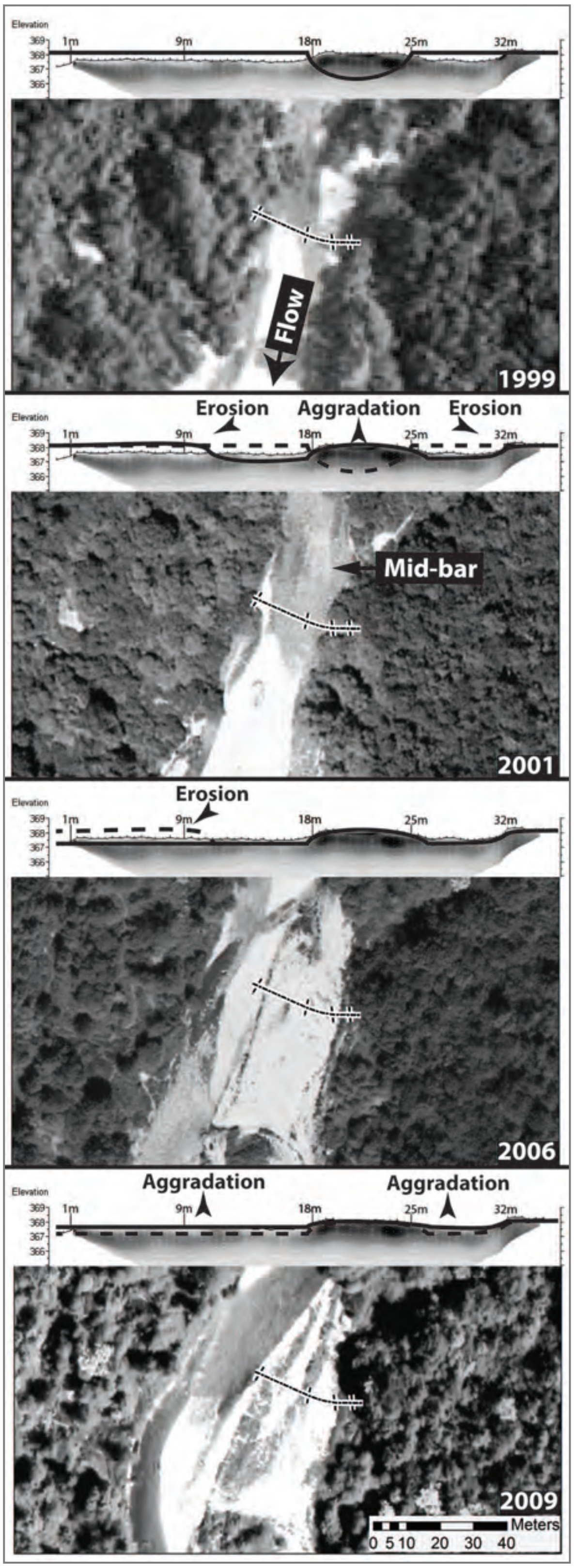

Figure 24 – Series of historical aerial pictures documenting the geomorphological development of the study section

Table 2 – Soil profile (15) description

*The largest stone that could be assessed visually in the layer.
**Medium size out of 5 random stones of the layer.
***No sample has been taken because of the discontinuity of this layer.

Horizon name	Depth (cm)	Soil fine texture				Soil coarse texture			TOC (%)
		Clay (%)	Silt (%)	Sand (%)	Name	Volume (%)	Biggest* (cm)	Medium** (cm)	
(M1)***	-5-0	-	-	-	Medium sand	0	-	-	-
Ah	0-9	11	40	48	Sandy loam	0	-	-	1.84
M	9-20	3	16	81	Medium sand	0	-	-	0.10
C1	20-26	4	19	77	Medium sand	50	11.6	4.1	0.22
C2	33-60	4	19	78	Coarse sand	80	4.0	1.1	0.07
C3	33-60	4	21	75	Medium sand	80	13.5	2.9	0.28
C4	60-68+	4	20	76	Coarse sand	60	13.0	4.1	0.04

The gravel sand mix layers below (C) have a low TOC (<0.28%) and show no visual signs of pedogenic transformation.

In terms of organic matter quality (Figure 26A), there are high levels of fresh organic matter input (A1; A2) in the upper 10cm of soil which is rapidly humified (A3; A4) by the soil processes. Because of the young age of this soil, not many resistant compounds accumulated (A5). However, values are slightly higher than for the lower sedimentary layers.

Fractions (Figure 26B), in the upper 10cm of the different organic matter pools almost decrease in the order A1+A2, A3, A4+A5, showing that the pedogenically organic matter transformation chain of this young soil is currently being set-up. The pedogenic active organic matter turnover of the soil allows better ambient conditions for plant growth to start (nutrient availability, water retention,…) and is in strong contrast to the higher altitude zone, where no soil could be found.

Below 10 cm of soil depth, the sedimentation properties are more dominant with little organic matter, which mostly comprises resistant compounds (Figure 26B high fractions of A4+A5 and low fractions of A1+A2). Such compounds may be attached to sediment particles and thus survive the flushing effects of sediment transport. Moreover, they are more resistant to degradation processes after deposition. On this layer, the rooting base of the willows were found, suggesting that the deposition of an upper sandy layer has been facilitate by the engineering action of these plants (Corenblit et al., 2011; Gurnell, 2014; Gurnell et al., 2012).

Historical aerial pictures analysis

The historical aerial images allow the geomorphological history of the section to be established (Figure 24). In 1999, the channel is generally narrower than at present. Maximum monthly discharge (Figure 27) has been lower or close to the overall mean maximum yearly discharge (Max Q) of the Allondon River, allowing vegetation to extend and to constrain the channel. The flood of 1999 happened in February but apparently did not affect the analysed section (the aerial picture was taken afterwards during the growing season). However, by comparing the ERT section with the 1999 channel position, it appears that the main channel in 1999 flowed on the dark ERT zone identified at present (Figure 24; 1999; ERT section 18-25m). That is, the present gravel/cobble deposit (dark ERT zone) was created after the channel had moved away from this zone. We can then identify the probable 1999 section topography using the ERT data, shown in Figure 24.

In 2001, a shallow mid-bar a few meters upstream is visible in the aerial image, causing the main flow to diverge and slowly widening laterally the channel (Figure 24; 2001). It appears that the mid-bar slowly migrated downstream, forming the gravel/coble mixture deposit found in the present day ERT section (dark zone – 18-25m).

In 2004, a major flood event occurred (Figure 27), close to the maximum recorded flow, and resulted in lateral erosion and incision. This created the base surface on which the willow propagules developed, shown in the 2006 image (Figure 24; Figure 23 medium grey sandy/gravel ERT zone – 1-18m). The deposition of some large woody debris about 25m upstream might have facilitated plant establishment. However, no big flood

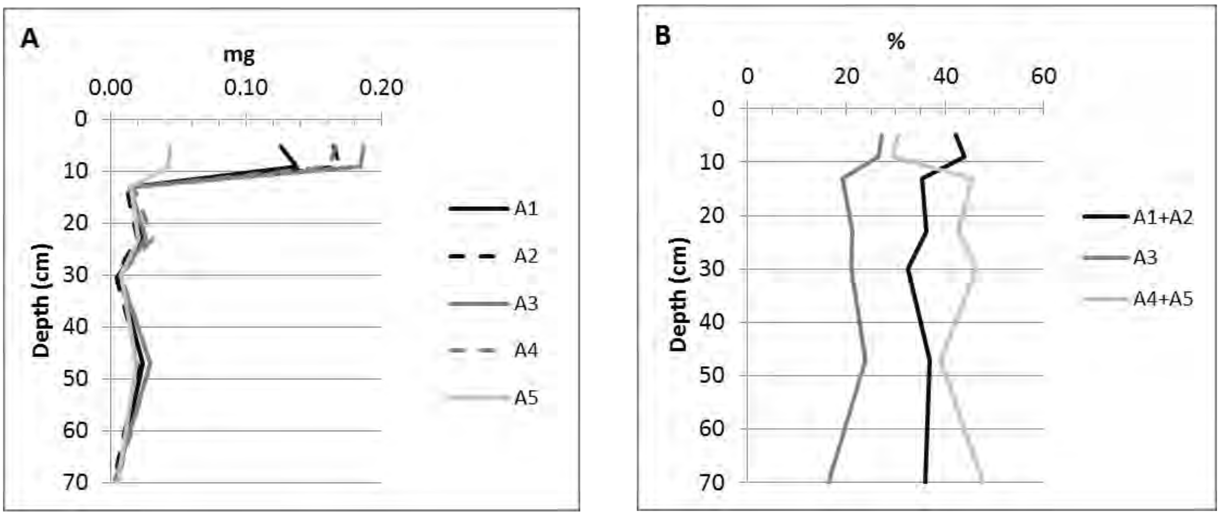

Figure 26 – Organic matter characterization of the soil pit (15)

A; Quantity of the different organic matter pools along the soil profile. A1) fresh litter, A2) stable litter compounds, A3), humified litter, A4) stable humus compounds, A5) resistant humus compounds. B; Proportion of the different organic matter pools to the total organic carbon along the soil profile.

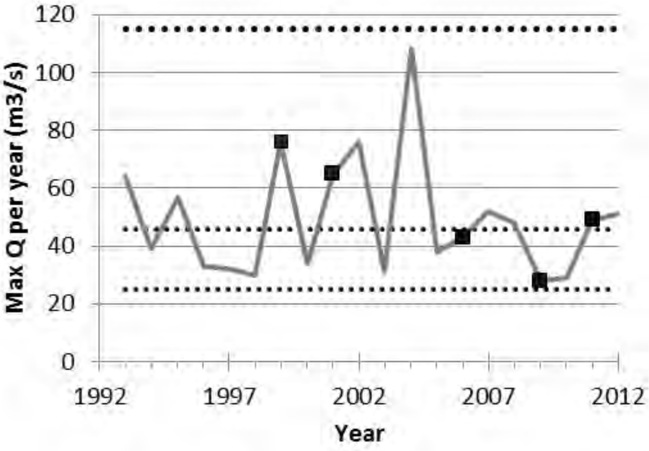

Figure 27 – Maximum discharge (Max Q) for the period 1993-2012

The dashed lines represent the minimum, mean and maximum yearly max Q. Black squares refer to dates of the aerial images of Figure 24.

events are registered in the following years and on the lower altitude gravel/sand mixture layer (Figure 23; medium grey ERT zone – 1-18m) vegetation developed to a thick shrub cover, visible in 2009 (Figure 24; 2009) and 2011 (Figure 23). This may have aided the aggradation of the sandy layer described in the soil profile (Figure 25; 2009; light grey sandy lenses – ERT zone 1-18m).

4.2.4 Discussion

In summary, initial results are surprising: a willow shrubby vegetation cover with a related (initial) soil cover was found on a lower altitude and more geomorphologically active zone of the analysed section; but on the higher and more stable zone, no soil and only some sparse ruderal grass stalks could be observed.

This is surprising because the lower zone is geomorphologically younger due to the continuous aggradation of fine sediments, assisted by the engineering action of willow sprouts. On the other hand, less geomorphological activity was observed on the higher altitude zone, but also no soil was found. Classical soil science views geomorphological impact as hampering soil formation (e.g. Schaetzl and Anderson, 2005). However, as found by Bätz et al. (2015a) for a larger number of soil pits in the same section of the Allondon River, geomorphological processes not only hamper soil development, but may also facilitate its development if in the right range of magnitude and frequency. Pioneer landforms and their vegetation cover have a low productivity (Berendse, 1998; Doering et al., 2011), so that their development is largely dependent on external organic matter inputs coming from more productive sites such as river terraces (Latterell et al., 2006; Van Pelt et al., 2006). The river flow itself, but also erosion processes, can redistribute organic material and provide valuable allochthonous produced organic matter for less productive sites (Doering et al., 2011; Langhans et al., 2012; Pusch et al., 1998; Tabacchi et al., 2000). Such inputs speed-up ecosystem processes by improving local ambient conditions and promoting biogeomorphological succession (Corenblit et al., 2009) and soil formation.

Thus, nature of a sedimentary deposit and its position in the landscape (e.g. elevation) impacts the potential sites for pioneer vegetation sprouting (Bullinger-Weber and Gobat, 2006; Gurnell and Petts, 2006). The ERT shows that willow seedlings could establish on the lower altitude gravel/sand mixture layer (on which the root base is found), because of a better access to water (proximity to the ground water and higher capillary rise) than in the higher altitude gravel/cobble deposit. The engineering action of the plants traps fine sediments and ameliorates water and nutrient retention due to the higher storage capacity of sandy loamy deposits (e.g. Francis, 2007). However, allochthonously produced organic matter is trapped by the vegetation. Both, the availability of fines and organic matter are the preconditions for initial soil formation. In combination with higher moisture availability, soil processes are speeded-up in comparison to geomorphologically isolated and more stable sites (higher located zone of the section – Figure 23 18-25m) and ambient conditions improve significantly during this process (e.g. nutrient provision from organic matter degradation). Thus, the engineering action of willows not only causes aggradation of fines and surface elevation rises (Corenblit et al., 2011; Gurnell, 2014; Gurnell et al., 2012) but also filters valuable resources from the river matter flux that speeds-up local ambient improvement processes such as soil formation. Fluvial landform formation is thus characterised by a geomorphological, vegetation and soil co-evolution process (see Bätz et al., 2015b). The different rates and especially feedbacks between these three components, as illustrated for this example, influence the speed of ecosystem processes and cause a decoupling between time (as a function of landform stability) and vegetation succession.

This finding not only enhances our understanding of the ecological interactions of fluvial landforms within the river corridor, but also implies a major issue for the interpretation of historical aerial imagery. In the aerial image for 2011 (Figure 23) the bare surface (18-25m) can be interpreted as the result of a recent avulsion process on which plants had not yet established. The vegetated surface on its left (1-18m) would be considered older because of the dense vegetation cover. However, as shown above, the co-evolution processes change the time scale of biogeomorphic succession. Both areas have the same age, but in the lower altitude willow stands, ecological processes are faster because of an enhanced positive feedback between geomorphology, vegetation growth and its engineering action as well as soil development.

4.2.5 Conclusion

The example presented here, shows that the quality of the deposit and its history of formation together with the topographical position in relation to the main river channel control the potential for initial plant establishment. The speed and trajectory of the biogeomorphological succession is then controlled by the feedback between plant growth and its ability to trap fine sediments and allochthonously produced organic matter. The soil organic matter transformation processes, that ameliorate ambient conditions and thus favour plant growth and succession, and the right dose of geomorphological processes which add sediments and matter to the pioneer landform, are crucial processes for the landform development. This leads to a mosaic of habitats (Tockner et al., 2010), each with a specific development speed and trajectory that is a function of the positive feedback strength explained above.

Because of this, inferring the time of stabilisation from the vegetation cover of aerial imagery is difficult. Landform co-evolution processes impact the speed and trajectory of biogeomorphic succession and so, falsify the assumption that the visual appearance of vegetation is related to time since the last geomorphic perturbation.

Acknowledgments

Thanks to L. Laigre, J.-B. Bosson, F. Dietrich, N. Diaz, T. Adatte, H.-M. Saleh for help in the field and laboratory; N. Micheletti for helping in the orthorectification of aerial images; H.-R. Pfeifer for informations and discussions on the Allondon River; Canton Geneva – Department Nature and Landscape for data and access to the natural reserve.

4.3 Summary – the importance of soil evolution on decadal fluvial landform development

This chapter described soil development in a braided/wandering river system from fresh deposits into fluvial terrace soils. Soil organic matter transformation processes (humification) were identified the first and most dominant soil processes involved in this transition (e.g. Bureau, 1995; Viereck et al., 1993). Soil organic matter properties, including organic matter quality and total content, and grain size distribution were shown to differentiate the state of the soil in the floodplain. However, the state of the soil along the biogeomorphic succession at community and population scale (*sensu* Corenblit et al., 2007, 2014) appears to be highly non-linear with no clear correlation with deposit age.

Complementary to this study, Mardhiah et al. (2014) studied soil aggregate formation along the biogeomorphic succession in the large braided gravel bed river Tagliamento (Italy). Generally, aggregate formation was reported to be very high if compared to other ecosystems and related to the landform age. However, they reported that on medium term (<10 years) quantity of aggregates augments as a function of organic carbon content and extraradical hyphae content, while on longer term plants roots and fungal content appears to drive aggregate formation. Although we did not measure aggregate formation in this study, these results may be seen complementary and thus highlight the potential interaction between the organic matter, plant development, and aggregate formation as illustrated in Figure 18 (dashed line).

From the interpret soil evolutionary traits (Figure 22) and the conceptual model developed in the review (Figure 18), initial substrates (grain size and organic matter quantity and quality) appear as highly variable and mainly driven by the spatial variability of geomorphological processes (e.g. Naegeli, 1997; Steiger and Gurnell, 2003). Thus geomorphic and pioneer phases of the biogeomorphic succession, appears to be highly dependent on hydrogeomorphic processes (Corenblit et al., 2007, 2009, 2014; Gurnell, 2014). Fine-grained deposits have higher water and nutrient retention, favouring plant establishment and thus local biomass production for soil formation. However, depositional process may also add organic matter enriched material, therefore adding essential resources for the first biogeomorphic phases and favouring plant growth and establishment. Higher organic matter contents in association with fungal activity also influence soil aggregate formation (Mardhiah et al., 2014). Because of the organic riverine supply, initial soil processes, such as organic matter transformation and aggregate formation, may also act independently from the vegetation cover, hence leading to different local soil evolution trajectories (Johnson, 1985; Schaetzl and Anderson, 2005).

Once vegetation has established (biogeomorphic phase), the associated engineering action is able to trap fine sediments, and possibly organic matter (Corenblit et al., 2014; Tockner et al., 2006). In conjunction with local biomass production, initial soil formation linked to humification - and soil aggregate formation (Mardhiah et al., 2014) - can be very fast (10 years), enhancing local ambient conditions and thus in turn vegetation growth and succession. However, other sites might be less prone to such a dynamic response, so that the local ecosystem develops at much lower rates. Groundwater, as addressed in the next chapter, may explain part of the variability found here.

However, once the deposit raised its elevation to the river, through aggradation and/or river channel incision (Gurnell et al., 2001b), flood inundation falls and the system is mainly driven by local ecosystem processes with little impact from the river. This may include an increase in vegetation-related resistance to erosion. At this stage, soil development follows the classical soil-vegetation relation observed for geomorphically more stable landscapes.

5 Groundwater influence on braided river systems

Chapter 4 suggested that soil processes may play an important role in adjusting ambient conditions in ways that can sustain biogeomorphic succession. However, local groundwater dynamics may provide a crucial support for the local evolving ecosystem. Especially, in dynamic, gravelly, fluvial environments, such as the Allondon River, and during the hot and dry summer months, water may be a factor that limits the rate of operation of ecosystem processes, including soil processes. The strong gradient in groundwater-depth in the study site provides a unique opportunity to study its influence on vegetation recruitment, establishment and generally river channel encroachment (the engineering function of biogeomorphic succession *sensu* Corenblit et al., 2007) via its influence on summer plant water stress.

In the following chapter we explore the role that groundwater has in influencing biogeomorphic succession, focusing on the elements highlighted in the Figure 28 below.

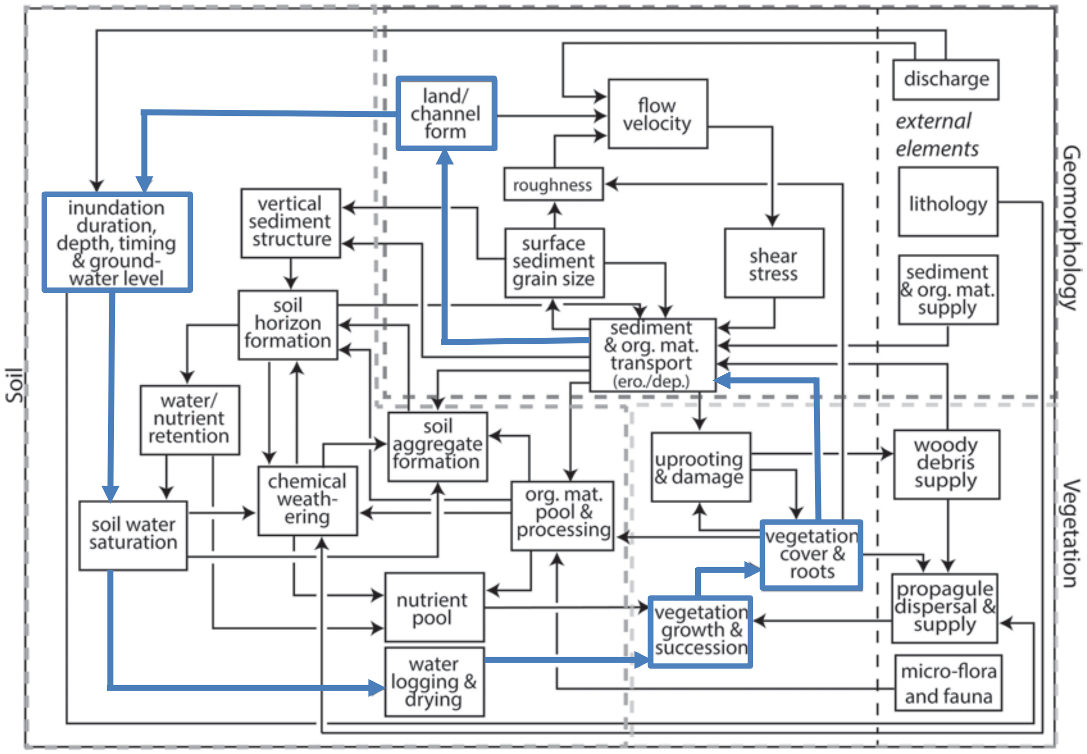

Figure 28 – Conceptual model (Figure 6) highlighting the components addressed in Chapter 5

5.1 " Groundwater controls on biogeomorphic succession and river channel pattern"

BÄTZ N, COLOMBINI P, CHERUBINI P, LANE SN. **2016**. GROUNDWATER CONTROLS ON BIOGEOMORPHIC SUCCESSION AND RIVER CHANNEL MORPHODYNAMICS. JOURNAL OF GEOPHYSICAL RESEARCH: EARTH SURFACE. DOI: 10.1002/2016JF004009

5.1.1 Abstract

Biogeomorphic succession describes feedbacks between vegetation succession and fluvial processes that, at the decadal time-scale, lead to a transition from bare river-deposited sediment to fully-developed riparian forest. Where the rate of stabilization by biogeomorphic succession is greater than the rate of ecological disturbance by fluvial processes, a river is likely to evolve into less dynamic states. While river research has frequently considered the physical dimensions of morphodynamics, less is known about physical controls on succession rates, and how these impact stream morphodynamics. Here, we test the hypothesis that groundwater dynamics influence morphodynamics via the rate of biogeomorphic succession. We applied historic imagery analysis in combination with dendroecological methods for willows growing on young gravelly fluvial landforms along a steep groundwater-depth gradient. We determined: floodplain morphodynamics and plant encroachment at the decadal-scale; pioneer willow growth rates; and their relationships to hydrological variables. Willow growth rates were correlated with moisture availability (groundwater, discharge and precipitation variability) in the downwelling reach, while little correlation was found in the upwelling reach. After a reduction in ecological disturbance frequency, data suggest that where groundwater is upwelling, biogeomorphic succession is fast, the engineering effect of vegetation is quickly established, and hence channel stability increased and active channel width reduces. Where groundwater is downwelling, deeper and more variable, biogeomorphic succession is slower, the engineering effect is reduced and a wider active width is maintained. Thus, groundwater is an important control on biogeomorphic feedbacks intensity and, through the stabilizing effect of vegetation, may drive long-term river channel morphodynamics.

5.1.2 Introduction

Recent work has suggested that the natural state of a river faced with no lateral constraints (i.e. unlimited occupation or accommodation space) and high rates of coarse bedload sediment supply should be braided or wandering (Ashmore, 2013; Murray and Paola, 1994; Schumm and Khan, 1971). On this basis, where rivers enter piedmont zones, and valley slope falls and accommodation space rises, the active width of rivers should increase. In addition to a reduction in coarse sediment supply, two processes may counter the development of actively wide channels. First, human impacts (e.g. levées, straightening, gravel extraction for mining and dam construction, etc.), may prevent this from being the case notably where they constrain active river channel width (Piégay et al., 2009a; Surian and Rinaldi, 2003). Second, research has shown that vegetation has the capacity to 'engineer' river systems, notably by constraining active channel width, over both short and long time scales (e.g. Bertoldi et al., 2009; Corenblit et al., 2011; Gurnell, 2012, 2014; Hicks et al., 2007; Picco et al., 2014; Tal and Paola, 2007; Zanoni et al., 2008). Crucial here is the stabilizing effect of rooting vegetation (e.g. Van Dijk et al., 2013; Edmaier et al., 2011, 2015; Karrenberg et al., 2003; Manners et al., 2015; Pollen, 2007; Polvi et al., 2014; Scippa et al., 2008) and the influence of vegetation on flow and sediment transport around the vegetation (e.g. Edmaier et al., 2015; Manners et al., 2015).

Vegetation development in rivers involves a process of succession (Gurnell et al., 2001b; Gurnell and Petts, 2002; Rood et al., 2010) and it can be hypothesized that with succession the engineering effects of vegetation should increase. Because this succession is influenced by river channel processes, but at the same time exerts influence on them, the process has been described as 'biogeomorphic' (*sensu* Corenblit et al., 2007, 2009, 2014). Following Corenblit et al.'s definitions, a fluvial deposit begins in a geomorphic phase largely devoid of vegetation; passes through a pioneer phase where high flow disturbance and water stress challenge the persistence of young vegetation (e.g. willow seedlings and sprouts); enters a biogeomorphic phase, where the shrubby vegetation becomes capable of influencing fluvial form and ambient environmental conditions, actively interacting with riverine processes; and ends with an ecological phase. In the latter, the influence of fluvial processes on the landform is much reduced and the vegetation structure becomes dominated by woody willows and mature successional species (e.g. Corenblit et al., 2007, 2009, 2014, 2016). A reduction in disturbance may lead to the dominance of higher biogeomorphic successional stages, which stabilize river banks at the reach scale, reducing the rate of lateral erosion and so the active width. If this happens in a braided river, it may be responsible for a shift in channel pattern from a morphodynamically more active system to a transitional wandering system or even a meandering system as observed in both field data and flume experiments (Gurnell et al., 2009; Hicks et al., 2007; Tal and Paola, 2007).

The fluvial deposits upon which plants must develop can be extremely well-drained gravels and sands and so water stress may limit this biogeomorphic succession (e.g. Amlin and Rood, 2003; Busch et al., 1992; Busch and Smith, 1995; Gurnell, 2014, 2016; Perucca et al., 2007; Singer et al., 2014). The timescale of variation in groundwater levels tends to be longer (months to years) than the variability in river discharge (hours to days- e.g. Sophocleous, 2002) such that systematic shifts in groundwater behavior could change the level of seasonal water stress. As water availability is essential for plant recruitment and establishment (e.g. Gurnell et al., 2001b), the rate of biogeomorphic succession may change as a function of access to groundwater. Such shifts may be driven by long-term climate change (Betancourt et al., 2000; Foreman et al., 2012; Lamb et al., 1995; Maxwell and Kollet, 2008; Rinaldo et al., 1995; Rodell et al., 2009) as well as the effects of human activity, such as irrigation (Aeschbach-Hertig and Gleeson, 2012) and flow abstraction (Kondolf and Curry, 1986). If groundwater depletion translates into the loss of the engineering effects of vegetation, then this could have an impact upon river morphodynamics (Perucca et al., 2007). It may also impact upon the success of river restoration projects if the limiting effects of groundwater depletion are not recognized during restoration (e.g. Amlin and Rood, 2003; Busch and Smith, 1995; Cooper et al., 2003; Sargeant and Singer, 2016; Scott et al., 1999, 2000).

Studies have considered the relationship between groundwater dynamics and vegetation growth rates in riparian forests (e.g. Rains et al., 2004; Sargeant and Singer, 2016; Singer et al., 2014). Harner and Stanford (2003) and Mouw et al. (2009) compared groundwater downwelling and upwelling sites and found that potential water stress on the downwelling site reduced vegetation recruitment and mature tree growth.

Vegetation at the upwelling site profited from the nutrient enriched water coming from the hyporheic zone (Boulton et al., 1998; Harner and Stanford, 2003; Mouw et al., 2009; Stanford and Ward, 1988). Similarly Gurnell (2014, 2016) confirmed this difference in alluvial pioneer vegetation growth performance based on upwelling or downwelling reaches of the braided Tagliamento River (Italy).

Recent research has shown a direct impact of groundwater availability on riparian forest stands (e.g. Amoros et al., 2005; Rains et al., 2004; Sargeant and Singer, 2016; Singer et al., 2014; Snyder and Williams, 2000). Further work has suggested that vegetation degradation can follow from changes in groundwater dynamics (Amlin and Rood, 2003; Cooper et al., 2003; Scott et al., 1999, 2000; Stella et al., 2013).

This research aside, fewer studies have been able to associate changes in groundwater-dynamics with changes in geomorphic activity associated with changes in the engineering effects of vegetation (Kondolf and Curry, 1986) and there is no study that has tested the hypothesis that groundwater (upwelling and downwelling) can mediate the rate of biogeomorphic succession, vegetation encroachment, and related shifts in river channel morphodynamics. The aim of this paper is to test this hypothesis by combining historical image analysis and dendroecological analysis along a reach of the Allondon River (Canton Geneva, Switzerland) with a steep longitudinal groundwater-depth gradient in relation to the floodplain gradient.

5.1.3 Study site

The Allondon River system is located west of Geneva (Switzerland) and its characteristics are described Bätz et al. (accepted) and summarized briefly below. The ~145 km2 catchment is mainly located in the French karstic Jura Mountains and ranges from 1705 m a.s.l (Crêt de la Neige) to 349 m a.s.l. at the Rhône River confluence. A network of small steep torrents from the Jura Mountains supplies waters with little sediment discharge into the flat Swiss Molassic basin. Close to the Swiss/French border, the torrents combine into a single channel, which have allowed incision into fluvioglacial sediments, forming a 3km long, 200-300 m wide and 50-80 m deep floodplain valley with 1.02% slope. This section is the reach generally referred to as

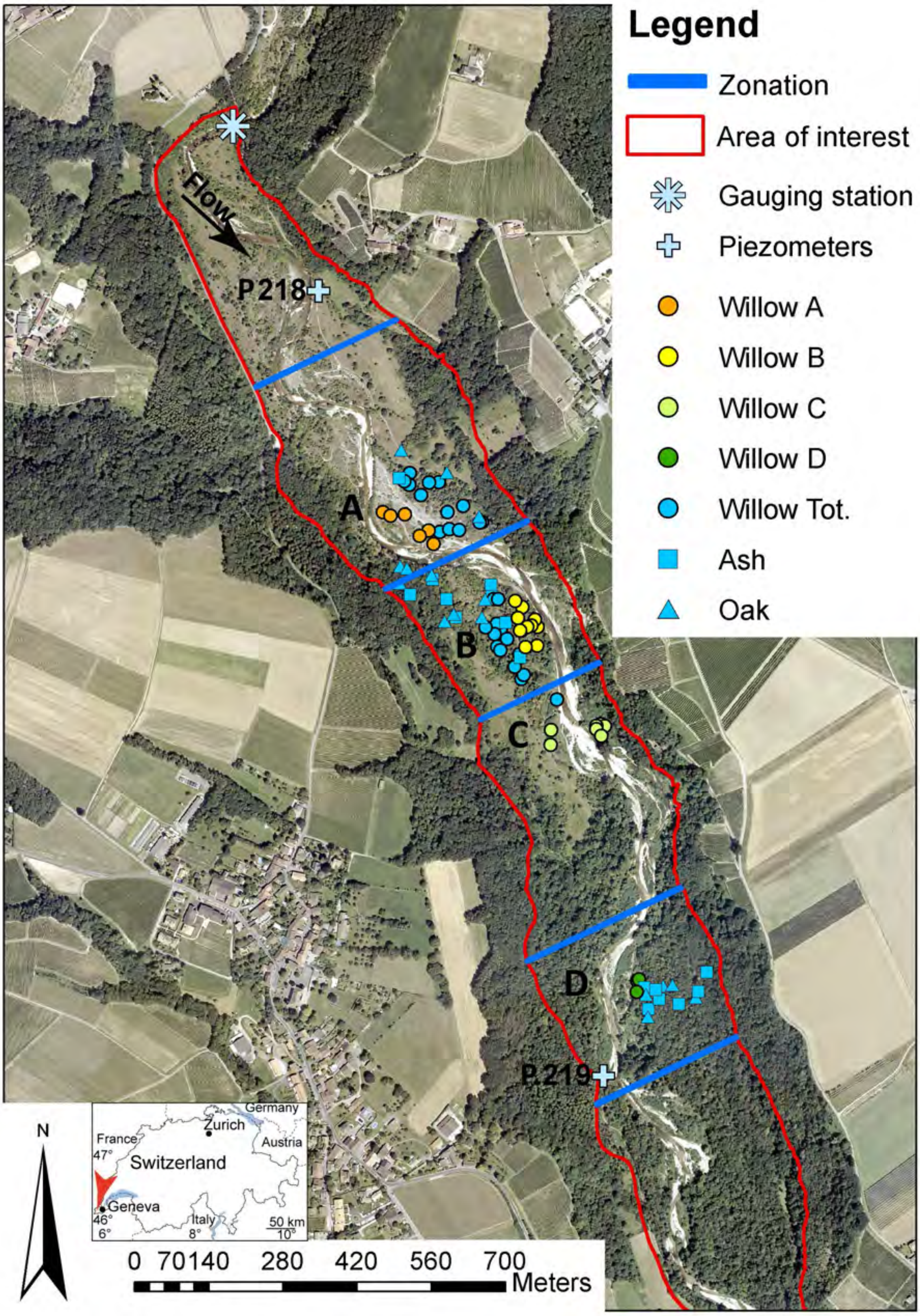

Figure 29 – Dendroecological sampling along the study reach

Aerial image showing the study reach of the Allondon River (canton Geneva, Switzerland - 46°12'5.08"N; 5°59'56.59"E). Flow is from north to south. The blue lines bound the four morphologic evolutionary zones observed from historic aerial images (Figure 37). The dots show the location of dendroecological sampling. The color code of willow corresponds to the chronologies shown in Figure 33.

the Allondon River (Figure 29). The floodplain comprises an active channel that is weakly sinuous and that appears to migrate laterally, including some evidence of the rapid abandonment of previous channels, meander cut-offs and pioneer vegetated bars (e.g. islands, point bars etc.). The river flow is largely unimpacted by human activities (e.g. abstraction), with a base flow of ~ 0.5 m3/s, and extreme flows (with return periods) of 43.2 m3/s (2 years), 79.9 m3/s (10 years), 117 m3/s (30 years) and 176 m3/s (100 years) (period 1986-2014 - FOEN, 2014).

Historical maps and aerial images show the morphological evolution of the studied river reach over the last decade (Bätz et al., accepted). They suggest a braided pattern before the 1960's (the earliest map dates to 1836), and a recent change towards more stable meandering/wandering river morphologies accompanied by vegetation encroachment. However, initial inspection suggests that morphological changes are spatially and temporally variable, following a north-south trend in depth to groundwater observed by Hottinger (1998 - Figure 30). The upper northern reach has deep groundwater levels (2-7 m deep); while the southern lower reach has shallow upwelling groundwater. It is this relation between spatial and temporal variability in channel morphodynamics and the groundwater-depth gradient that we aim to quantify in this study.

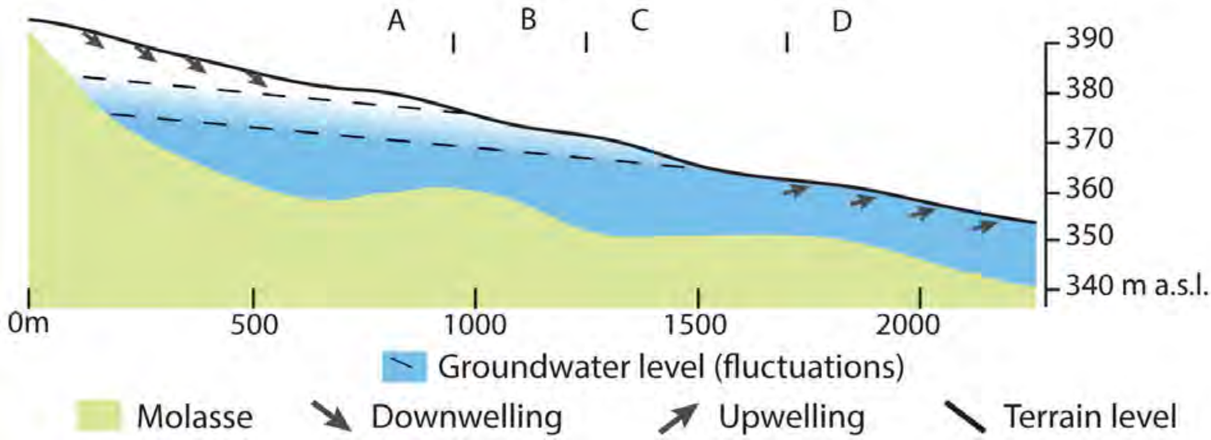

Figure 30 – Groundwater table depth and fluctuation range along the study reach

Groundwater table depths along the studied river reach (based on GESDEC, 2015; Hottinger, 1998). The dotted line indicates the range of fluctuations of about 3.2m (2σ) around the mean stage. Moreover, the letters indicate the location of the dendroecological sampled along the morphologic evolutionary zones (Figure 29 and Figure 33).

5.1.4 Materials and methods

To assess the role of the groundwater-depth gradient in controlling vegetation encroachment rates along the reach, we combined historical image classification methods with dendroecological techniques. First, we synthesized available climatological and hydrological data for the reach, including river flow and groundwater, the latter needing some basic transfer modeling from a longer record upstream, of the study reach. Second, we orthorectified historical imagery of the reach as a basis for the analysis of reach-scale morphodynamics evolution, focusing in particular on the spatial and temporal variability of active width. This required image classification (Lillesand et al., 2004) and development of indices to allow us to compare reaches spatially, and to quantify their evolution through time. Third, we used dendroecological techniques to quantify more directly the extent to which groundwater dynamics influence plant growth (Linderholm and Leine, 2004) and so the engineering effects of vegetation encroachment upon the active channel. Thus, we reconstructed ring-width series using tree cores and disks for willows growing on landforms in the pioneer and biogeomorphic phases of the biogeomorphic succession (Corenblit et al., 2007, 2009, 2014) along the groundwater-depth gradient. We focus on willow because it is a common pioneer in biogeomorphic succession in this kind of setting (e.g. Corenblit et al., 2009, 2014; Karrenberg et al., 2003) and because willows are observed to have an engineering function (e.g. Gurnell, 2014, 2016), responsible for stabilizing channel and floodplain morphology (e.g. Van Dijk et al., 2013; Hicks et al., 2007; Tal and Paola, 2010). However, determining willow growth rates is a challenge because, in alluvial systems, geomorphological and hydrological processes can rapidly change local ambient conditions (e.g. the level of water stress), leading to double and missing rings in the willows (Cherubini et al., 2003). Thus, the methods adopted needed careful application to ensure the reliability of this method (see below). Fourth, a non-parametric multi time-scale dendroecological analysis was performed to quantify the level of dependence of the tree-growth rates upon climatological and hydrological variables (e.g. groundwater).

Climate, river flow and groundwater data

Monthly precipitation and average temperatures at Geneva Cointrin (Geneva airport – 11 km east of the study site) were available for the entire period 1957-2014 (MeteoSwiss, 2014). Average temperature and total precipitation were calculated for three periods: (1) growing season (March-October); (2) summer (May-September); and (3) hydrological year (October-September). Daily average discharge series were available for the years 1927-1935 and 1985-2014 for a gauging station located 500m upstream of the study reach (FOEN, 2014) and were used to determine maximum, minimum and mean discharge for the same periods as for the climatic data (growing season, summer and hydrological year), but also to assess changes in maximum flow occurrence in the last decade.

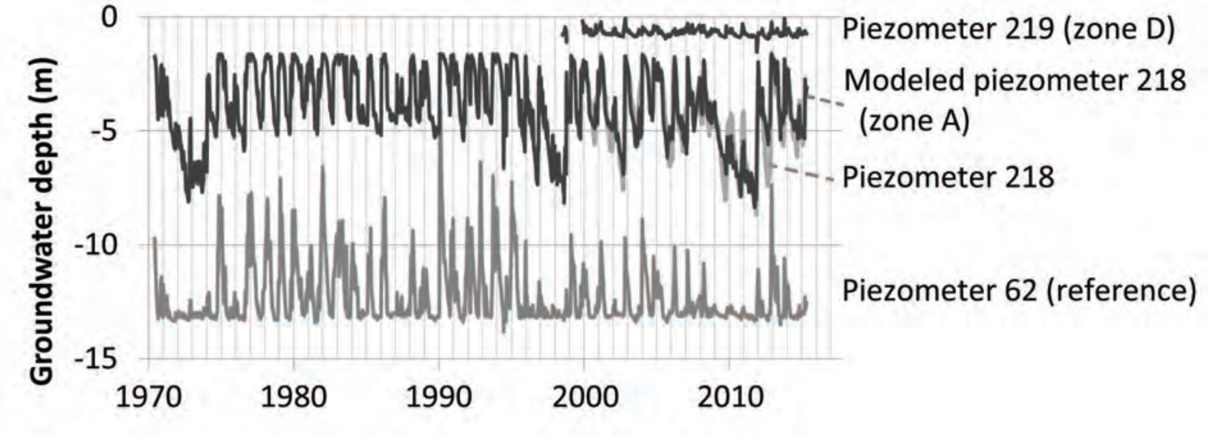

Figure 31 – Groundwater levels in relation to the Allondon floodplain surface level

The elevation difference between piezometer reference level and river level has been removed.

Groundwater data were available for the period 1998-2014 at two sites, labeled P218 (upstream – Figure 29) and P219 (downstream – Figure 29) (GESDEC, 2015), and were used to represent the groundwater fluctuations along the gradient observed by Hottinger (1998 - Figure 30). Hottinger (1998) reconstructed the groundwater levels and subsurface permeability of the study area based on 17 RMT (Radio Magneto Telluric) profiles. The comparison of his results with the piezometer records (Figure 31) showed that whilst P218 has groundwater levels that were highly variable, those of P219 had a very small variability (we report the variability below) and the water table was generally close to the floodplain surface throughout the measured period.

Because the upstream P218 series was short, we modelled groundwater stages for a longer period, based on a third piezometer located 1800 m upstream (site P62 not shown in Figure 29) which had continuous data available from 1972 (GESDEC, 2015). First, the respective minima were moved from the two measured datasets. Second, qualitative inspection of the overlapping data period, with 109 observations, showed that there were periods when the water table fell to a minimum at P62 but continued to fall at P218. Thus a new variable was created which was the duration since P62 had been at minimum whilst P218 continued to fall. We call this the P62 duration index. As the first 14 observations of the overlapping period were when the piezometer P62 was at a minimum, we did not use the first 14 observations, leaving 95 observations. Third, the data for P218 were inverted exponentially. Fourth, a multivariate relationship was fitted between the inverted P218 data (dependent) and the raw P62 data and P62 duration index (independent variables, pairwise uncorrelated at $p < 0.05$). The quality of the fitted model was good, with an R2 of 88.9% (Figure 31). This relationship was then applied to the full P62 dataset, but with the rule that the duration index was not allowed to exceed the maximum duration of minimum water table level measured at P62 during the period of overlapping data. This means that some of the water levels at P218 may be over-estimated for periods of prolonged minimum at P62. In the absence of further data on the possible minimum water table realizable at P218, this is an assumption that we cannot evaluate.

Because of insignificant fluctuations in the upwelling southern reach (site P219) (GESDEC, 2015) and the evidence of the spatial gradient as observed by Hottinger (1998), no modelling was undertaken for P219.

River morphodynamics and the evolution of vegetation cover

ERDAS Imagine Software (2014) was used to orthorectify historical images from 1957, 1972, 1980, 1986, 1991, 1996, 2001, 2006 and 2012 (SITG, 2014; SWISSTOPO, 2012). These were used to allow us: (1) to develop a qualitative description of river morphodynamics; and (2) to quantify both river morphodynamics and vegetation encroachment through time, using classified images.

Classification was undertaken using standard methods (e.g. Lillesand et al., 2004). First, a fuzzy supervised classification was performed by selecting reference signatures for the morphodynamically-active zone as well as various vegetation covers. Second, fuzzy convolution (by distance) was then applied to define a single class with the highest probability per pixel. Finally, a statistical filter was applied to reduce the "salt and pepper" effect. The window size for convolution and filtering was set according to image resolution such that, for instance, tree crown size was not exceeded. Tree crown size was assessed visually from the aerial images. We initially aimed to distinguish between five surface classes: water, bare sediments, herbaceous, shrubs and wood. There was some difficulty in distinguishing classes in the coarser resolution black and white historic images (e.g. water reflecting the color of wood) and so: (1) reference signatures had to vary between different image dates; and (2) for some classes more than a single signature had to be chosen in the same image date. After classification, we merged the classes shrub and forest (woody vegetation), representing those land covers that required channel stability; and water, bare sediment and non-woody plants (e.g. sparse herbaceous grasses), representing the morphodynamically-active zone. Non-woody plants are included in the definition morphologically-active because field evidence suggests that they can appear rapidly over the timescale of as little as a year and because they are functionally different in having rooting systems that do not add significant stability to the gravel deposits in which they grow (e.g. Andrews, 1984; Corenblit et al., 2007; Hey and Thorne, 1986; Micheli and Kirchner, 2002).

Classification accuracy was measured by randomly selecting 250 points. A Kappa analysis was used to evaluate the classification performance and interpreted according to Altman (1990) and Reid et al. (2007). Figure 32 shows three examples of classified historic images, while Table 3 summarizes the overall historical images classification performance. Active width and wooded vegetation cover identification was generally classified as "Very Good", with only the oldest images performing less well with "Good".

The primary focus of the classification was the determination of active zones in the river. One of the long-established problems of acquiring stream channel patterns from historical imagery is that the information obtained may vary with discharge (Werrity and Ferguson, 1980). This may be particularly acute in braided rivers where changes

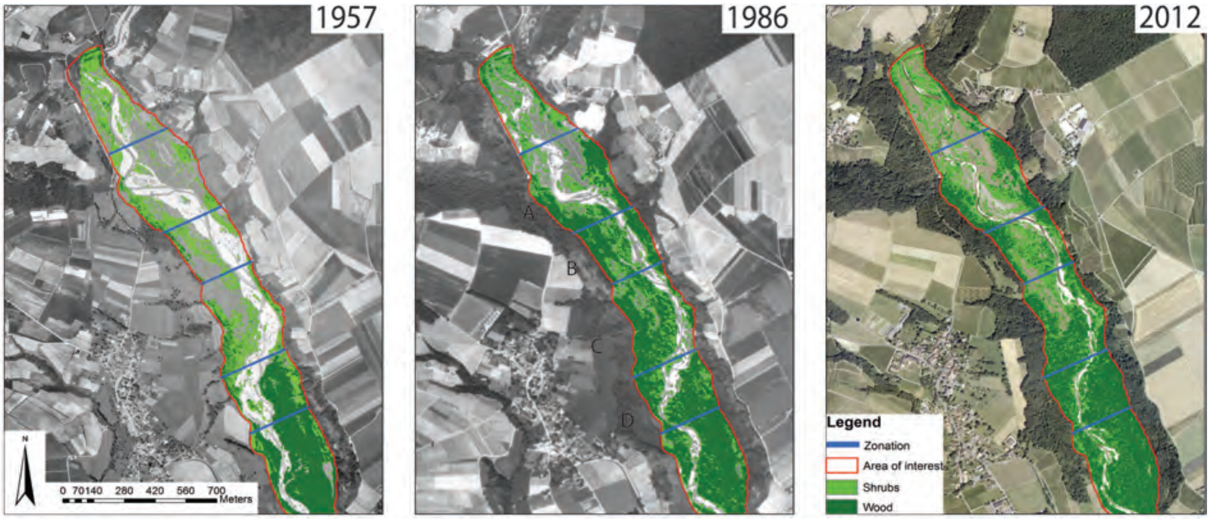

Figure 32 – Examples of historical aerial image classification

Examples of historical aerial image classification for three periods, showing the morphological changes and associated vegetation encroachment. The blue lines define the zones A, B, C and D.

Table 3 – Kappa values for the historic aerial images classification

Kappa statistics have been calculated for woody vegetation (shrub + forest) and active width (water + sediments + grass covered). Additionally the associated strength of agreement following Altman (1990) is shown: <0.20 poor; 0.21-0.40 faire; 0.41-0.60 moderate; 0.61-0.80 Good; 0.81-1.00 very good.

	Conditional Kappa value (strength of agreement)	
Image year	Woody vegetation	Active width
2012	0.967 (Very good)	0.981 (Very good)
2006	0.933 (Very good)	0.962 (Very good)
2001	0.991 (Very good)	0.955 (Very good)
1996	0.830 (Very good)	0.914 (Very good)
1991	0.900 (Very good)	0.943 (Very good)
1986	0.933 (Very good)	0.962 (Very good)
1980	0.843 (Very good)	0.907 (Very good)
1972	0.690 (Good)	0.795 (Good)
1957	0.808 (Good)	0.875 (Very good)
Total average	0.877(Very good)	0.922 (Very good)

in discharge are manifest as substantial changes in wetted width, meaning that determination of changes in channel pattern from the wetted width are not reliable. One alternative way of approaching this problem is to focus directly on morphological activity, using parameters like the active width (e.g. Ashmore, 2013; Belletti et al., 2015; Bertoldi et al., 2011; Boruah et al., 2008; Zah et al., 2001; Zanoni et al., 2008). The active zones of a river, defined here as those zones that are not covered by woody vegetation, are a direct consequence of geomorphic activity, the latter being required to prevent the onset of biogeomorphic succession. It also has implications for river channel pattern, as a greater active width requires high rates of bank and lateral erosion, preventing vegetation encroachment and subsequent evolution towards a meandering state (Tal and Paola, 2007, 2010).

To determine the spatial variability in river morphodynamics at the scale of the reach, we quantified a measure of turnover rates: morphological age, following from a method first used by Lane and Richards (1997). Using the time-series of classified images (see Figure 32), and starting in 1957 (time $t = 0$), any site that was no longer active (i.e. vegetated) at the next time period for which photography was available ($t = n$) was deemed to have aged morphologically by n years. The morphological age was then accumulated through to the last date of imagery in 2012. To avoid the possibility that a site undergoes both erosion and then woody revegetation within the time between images, it is important that the rate of woody vegetation development is relatively slow as compared with time between images. Chronologically from 1957, there were 15, 8, 6, 5, 5, 4, 5 and 6 years between images and it is likely that with the exception of the 15-year period between 1957 and 1972, this criterion is met. The result is a map of morphological age that allows the identification of the most active morphodynamic reaches. We were also able to determine the distribution of morphological ages by the four zones (Figure 29) used for the dendroecological analysis described below.

The analysis of morphological age identifies those reaches that have remained morphodynamically active and those that are more stable. This spatial analysis was accompanied by an analysis of the evolution of the width of the active zone of the channel (the active width) through time both at the scale of the river reach and zones shown in Figure 29 and Figure 32. Additionally, we defined a vegetation encroachment rate, which is the rate at which the active zone becomes occupied by vegetation. The active width and vegetation encroachment was determined for 5 m sections perpendicular to the main river slope (parallel to the blue lines Figure 32). A 50 m moving average was then applied to remove small-scale classification errors/variability (e.g. trees crowns covering the channel). The rate of vegetation encroachment (i.e. the inverse of the rate of active width reduction) for each 5 m section was defined by calculating the slope of the relationship between the wooded cover and time. Where this slope was significant (at $p < 0.05$), the rate of width reduction was deemed to be significant across the image dates.

Dendrochronological methodology

Standard dendrochronological methods (Cook and Kairiukstis, 2013; Schweingruber, 1988; Wilford et al., 2005) were applied to reconstruct yearly vegetation growth rates (tree-ring width) for pioneer fluvial and biogeomorphic landforms (Corenblit et al., 2007) colonized by willows (*Salix elaeagnos* Scop., *S. nigricans* Sm., *S. purpurea* L. (Theurillat and Matthey, 1987) so as to establish the link between groundwater patterns and vegetation response. Applying dendrochronology to pioneer plants growing in a geomorphically-active fluvial environment is challenging because of the possible occurrence of missing rings and/or annual-double rings. For instance, because willows colonize young fluvial landforms, they may be strongly exposed to fluvial stress (e.g. flooding, geomorphological changes, burial) and drought (e.g. Corenblit et al., 2011; Gurnell et al., 2012). Stress across an entire growing season can cause a missing ring, while stress occurring for a prolonged period during a growing season leads to double ring formation (for a review see Cherubini et al., 2003). To address these issues, we adopted four basic steps in the methodology. First, we sampled two cores as low as possible on the sampled plant to assure the largest number of rings, and thus the longest ring-width series. Longer series allow better error correction and crossdating. Second, we undertook steps to keep rings as visible as possible during core preparation and measurement to guarantee that annual rings were correctly identified. Third, crossdating (the intercomparison between single ring-width series, or cores, of the same species) was needed to ensure the accuracy of dendrochronological methods and the production of reliable species specific average chronologies (Cook and Kairiukstis, 2013; Schweingruber, 1988). Averaging reduces the impact of variability in the ring-width of individual samples due to variability in ambient conditions over small spatial scales (e.g. in local sedimentology, and hence water retention capacity), and so allows characterizations of the species specific average growth rate (chronology) for a given zone. However, double and missing ring formation in willows could lead to incorrect growth rate chronologies. So, we extended crossdating to comparison with the average chronologies of other species, in this case, species associated with later biogeomorphic succession stages on the stable terraces (e.g. ash, oak). This allowed insertion of very narrow rings where a ring was identified as missing (1/100mm) or joining rings where a double ring was identified. The chronologies from these other species could themselves also be crossdated using both independent knowledge of local floodplain history and comparison with chronologies from elsewhere within the region. We also used the presence of the effects of environmental extrema in chronologies to assist with crossdating. Finally, we extracted the average chronologies for the species and the single fluvial landforms (in contrast to the overall/floodplain willows chronology) and measured their consistency within each other (Cook and Kairiukstis, 2013; Schweingruber, 1988). Each of these four steps are explained in detail below.

Dendrochronological methods: field sampling

Willows, both shrubs and trees, located on pioneer and biogeomorphic stages of the biogeomorphic succession were sampled and spatially referenced (*sensu* Corenblit et al., 2007, 2009, 2014) along the observed groundwater-depth gradient. As the sampling was carried out at the beginning of the vegetation period (April) and leaf cover had not yet fully developed, we were not able to reliably distinguish between different willow species (*Salix elaeagnos* Scop., *S. nigricans* Sm., *S. purpurea* L. - Theurillat and Matthey, 1987). We sampled two cores (where feasible) from each plant as low as possible. Where the tree or shrub had experienced damage and/or heavy burial, and it was possible that this had complicated its growth history, 3 or 4 cores were taken. Disks were taken from smaller plants, because taking an increment corer would have split the plant stem and damaged the sample. The plants, as judged to be the oldest on the basis of their girth and crown size, were selected for sampling and the position of each mapped using a differential GPS. The dGPS position made sure that we could trace the historical development of the surrounding landform in the historical imagery. To aid crossdating, we also sampled oak (*Quercus robur* L.) and ash

(*Fraxinus excelsior* L.) trees. The last two species were found on the older terraces which are largely fluvially independent ecosystems (Bätz et al., 2015a, 2015b; Theurillat and Matthey, 1987), and thus reference sites for correcting willows ring-width series which may be disturbed by the main river flow, leading to double or missing rings. In total 95 willow trees/shrubs, 19 oak trees and 25 ash trees were sampled during field work in 2014 and 2015 with an average of 1-2 cores per tree.

Dendrochronological methods: core/ disk preparation and ring-width measurements

Cores and disks were sanded and/or cut using a core-microtome (Gärtner and Nievergelt, 2010). Cutting, instead of sanding, maintains the wood cells clean and unfilled with swarf, allowing clear visualization of the cell walls thus identification of ring boundaries (Gärtner and Nievergelt, 2010). After core/disk preparation, yearly ring widths were measured using a digital position table, with 1/100mm accuracy, connected to a working station with TSAP software (LINTAB 6-P; Rinntech). This produced an initial ring-width series for each core/disk. A correction for the juvenile effect (standardization) of this short young series has not been performed as tests showed that this would have removed the desired ecological signal (Briffa et al., 1996; Cook and Kairiukstis, 2013; Tognetti et al., 2000). Thus, we assume that the tree ring widths react more strongly to environmental variables than to the plant specific tendency of having larger rings during the juvenile phase.

Dendrochronological methods: cross-dating

Each ring-width series was crossdated against other series of the same species. This involved a two stage process: (1) identification and correction of possible missing/double rings by comparing each ring-width series within each species and then calculating an overall average chronology for each species; and (2) identification and correction of possible missing/double rings by comparison of the average species chronologies and with environmental extrema, and the quantification of the level of agreement among them once missing/double rings had been identified. Once the latter had been done, average growth rates were determined for willows growing on pioneer and biogeomorphic landforms of each zone. These steps are explained in turn below.

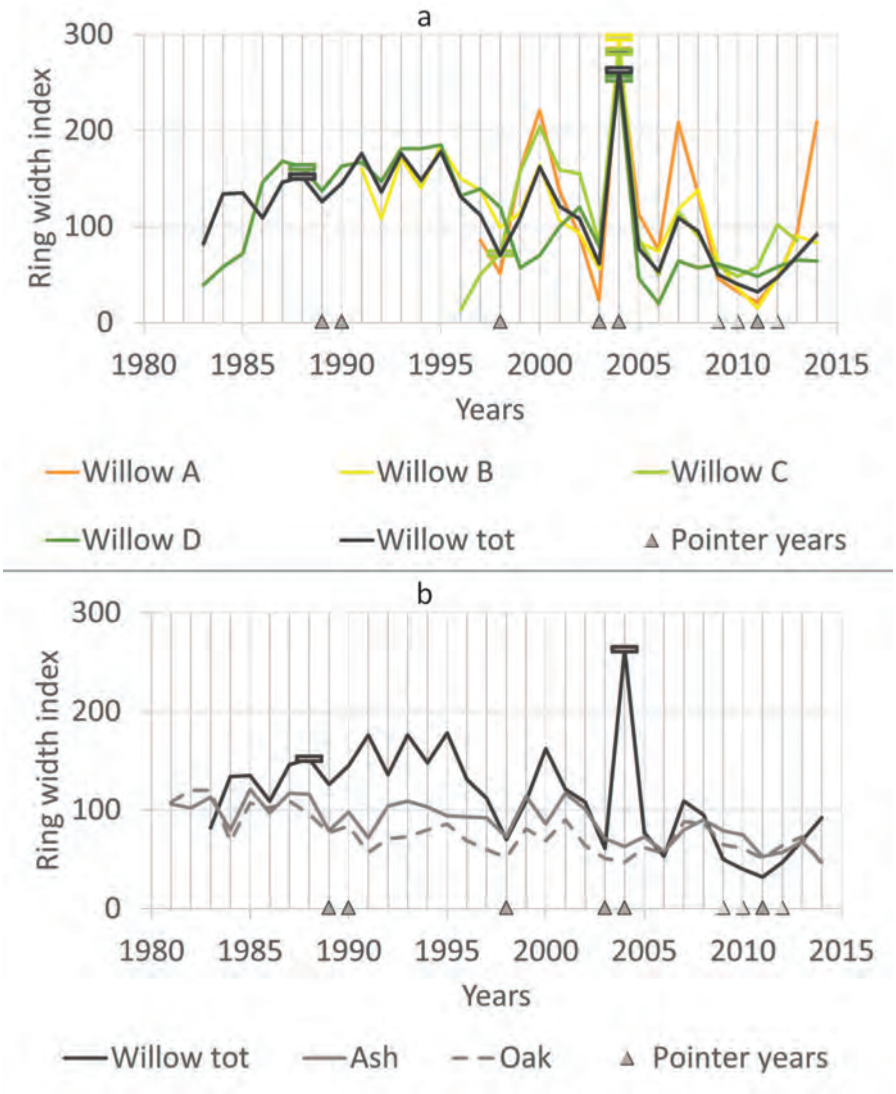

Figure 33 – Tree chronologies of the Allondon floodplain

a: Coloured lines show the willow chronologies for the zones A, B, C and D (color-coded as for Figure 29 and Figure 37). In black, the overall willow chronology used for crossdating with (b) ash (continuous gray) and oak (dashed grey) chronologies. The triangles in both figures show pointer years (Table 4), while the boxes show corrected years (double/missing rings).

In step 1, the aim was to identify those tree ring series that were in agreement with each other. This was aided by the GLK index. The GLK index (Gleichläufigkeit - coefficient of parallel variation), used as a standard tool in dendrochronology (e.g. Bernard, 2003; Cherubini et al., 2002; Malik and Owczarek, 2010; Schweingruber, 1988; Trouet et al., 2006, 2010), assesses the degree of agreement between two width series. In detail, it calculates the level of correlation between the slopes of the lines connecting the year to year tree-ring width variations and expresses this as a percentage (Eckstein and Bauch, 1969; Schweingruber, 1988). Initially we identified series that could be used to define an initial average willow chronology. Only those measurements with a significant GLK index ($p < 0.05$), thus with year-to-year ring-width variations that follow each other, were allowed to be used for the initial average chronology.

The ring-width series that were rejected from the average chronology were then considered. Visual crossdating and sample inspection was used to identify series measurement errors, displacements, double and/or missing rings, starting with the tree series that had the highest GLK against the average. If after a series correction, the GLK between that series and the average was significant ($p<0.05$), the related ring-width series was added to the average willow chronology. The analysis then considered the next best, uncorrected, width series against this new average. These steps were repeated until no further width series could be added.

Second, the application of the GLK for creating an initial average willow chronology was accompanied by crossdating against the oak and ash average chronologies, to avoid the possibility that there was a double ring or a missing ring in all the cores obtained. These themselves were checked using the GLK, but also the COFECHA software (Grissino-Mayer, 2001; Holmes, 1983). COFECHA is a standard dendrochronological statistical tool for assisting crossdating by identifying potential errors and mismatches in especially long time series (series that are at least 50-60 years old - for more details see (Grissino-Mayer, 2001). Once the long time-series of oak and ash were identified, we also checked that they were consistent with a known oak reference site at Jussy, located 21 km east of Geneva (Bräcker and Zingg, 2015; Cherubini, 2015). We also controlled consistency of the chronologies with environmental extrema also called pointer years (Table 4), notably two large floods (February 1990 and 2004) and three hot and dry summers (1989, 2003 and 2011). As expected, no double and missing rings were identified for the oak and ash chronologies, which showed significant GLK values when compared with the reference site at Jussy (Table 5). The oak and ash chronologies, supported by the known years of extreme events, were then used to double check the corrections applied to the initial average willow chronology. This comparison confirmed the conclusion that double rings were likely in the willow series in 1988, 1998 and 2004 (Figure 33). The 1988 double ring is thought to relate to a wet spring and autumn in combination with a particularly dry summer. In 1998 low groundwater stages might have interrupted ring

Table 4 – Pointer years

List of extreme events for the considered environmental variables to which chronologies should have produced pointer years

Extreme environmental events	
1989	Dry and hot
1990	Flood (February)
1998	Low Groundwater
2003	Dry and hot
2004	Flood (February)
2009	Low Groundwater
2010	Low Groundwater
2011	Low Groundwater; dry and hot
2012	Low Groundwater

Table 5 – GLK index values after crossdating

GLK index (Gleichläufigkeit) calculated between two chronologies. The asterisks indicate the level of significant at respectively * α = 0.05; ** α = 0.01 and * α = 0.001.**

GLK	Willow A	Willow B	Willow C	Willow D	Willow Tot	Ash Tot	Oak Tot	Oak Ref
Willow A	-							
Willow B	***88	-						
Willow C	**81	**72	-					
Willow D	*71	*72	50	-				
Willow Tot	***100	***91	**78	**76	-			
Ash Tot	65	**74	50	53	64	-		
Oak Tot	*71	*70	56	60	*65	***78	-	
Oak Ref	-	*83	-	54	50	**64	***75	-

growth of the young plants. The double ring formation in 2004 was attributed to a flood, which removed vegetation (concurrence) coupled to a dry late spring.

In summary, a total of 134 trees/shrubs samples could be used to build the final chronologies (Figure 29): 30 cores from 19 oak trees, 26 cores from 18 ash trees and 78 cores from 57 willow trees/shrubs. Comparison of the willow chronologies with the ash and oak average chronologies gave GLK values of 64% and 65% respectively (Table 5). The last two also significantly correlate (GLK) with the oak reference site.

Dendrochronological method: zone-specific ring-width indices

From the total willow chronology, samples of the trees/shrubs growing on the pioneer and biogeomorphic landforms were identified to create zone specific (Figure 29) average growth rate indices. Before calculating the final average chronologies, the tree-ring width series were indexed by dividing each individual series by its mean. This reduces the impact of strong growing samples on the average chronology (Berner et al., 2011). Four willow chronologies for the four zones (A, B, C, D) were then defined (Figure 29 and Figure 30). For zone A, 6 plants were sampled with a total of 10 cores. The ring width index covers the time range 1996-2014 with a mean standard error of ±21.9 (Figure 33a). The growth rate index of zone B is determined from 14 samples taken from 10 plants with a mean standard error is ±15.1. The maximum age is 1990. The zone C ring width index was derived from 15 samples taken from 8 plants. The record goes back to 1994 and has a mean standard error of ±13.5. For zone D, 11 samples on 3 trees have been used to create the index with a mean standard error of ±13.9. The large number of cores per tree is due to the fact that this site, being the oldest, experienced heavy aggradation. Because the main trunk was difficult to sample (buried), three to four samples had been taken from the biggest branches close to the ground surface.

At this stage we included a consistency check by comparing the zone specific growth rate indices between themselves and to the study area average growth index. If our processing is correct, we would expect the GLK values to be significant when zones are compared because there should be a general correlation between the zones in terms of growth rate changes (slopes) reflecting broad-scale growth conditions. The detailed yearly growth values represent the effects of local hydrology and groundwater conditions. This between zone comparison showed that the GLK values were significant ($p>0.05$; Table 5). Only the comparison of willows in zones C and D have a very low GLK, which is caused by the fact that the zone D willow chronology has a different growth pattern in the period 1998-2003.

Dendroecological analysis

The environmental variables explained above were compared with the indexed willow growth rates, growing on pioneer and biogeomorphic landforms, for the different zones using a multi scale approach. The latter was necessary because of the possibility that the association between variability in a given environmental parameter and willow growth rates for a given landform might only be present for certain time periods in the record: it has been observed that interactions between biota and fluvial processes during biogeomorphic succession, may change in their nature as a function of time - abruptly, periodically and/or gradually (e.g. Corenblit et al., 2011, 2014; Gurnell et al., 2012). Thus, non-parametric Spearman correlations were calculated for moving windows with a range of window lengths, ranging from a minimum length of five years, through two-year increments, to a maximum length corresponding to the total length of the data-series. Statistical significance tests ($p = 0.05$) were applied. The significant Spearman correlations, calculated for different window lengths were then summarized using two indices. First, for each window length the fraction of (moving) windows that was significant at that length was calculated. These fractions were summed for all window lengths and divided by the number of window lengths to give CorInd. This index summarizes the general level of correlation between each environmental parameter and the growth rate by accounting for the scale effect. However, this summation does not recognize the magnitude of the correlations. Thus, second, we also calculated CorInd^{w}, which weights the fraction of significant correlations for each window length by their mean significant correlation at that length. This allows particularly strong correlations to be taken into account.

5.1.5 Results

Climate, discharge and groundwater variability

Figure 34 shows the development of the temperature and precipitation for each hydrological year over the last century. Generally an increase of about 2℃ degrees in the average temperature can be observed, the trend increasing from the 1980's. Precipitation follows this trend notably with an increase in the magnitude of extreme events (alternation of years with high and low maximum precipitation – Figure 34). Only the last decade shows a reduction in maximum precipitation, but also in average and minima, indicating dryer conditions.

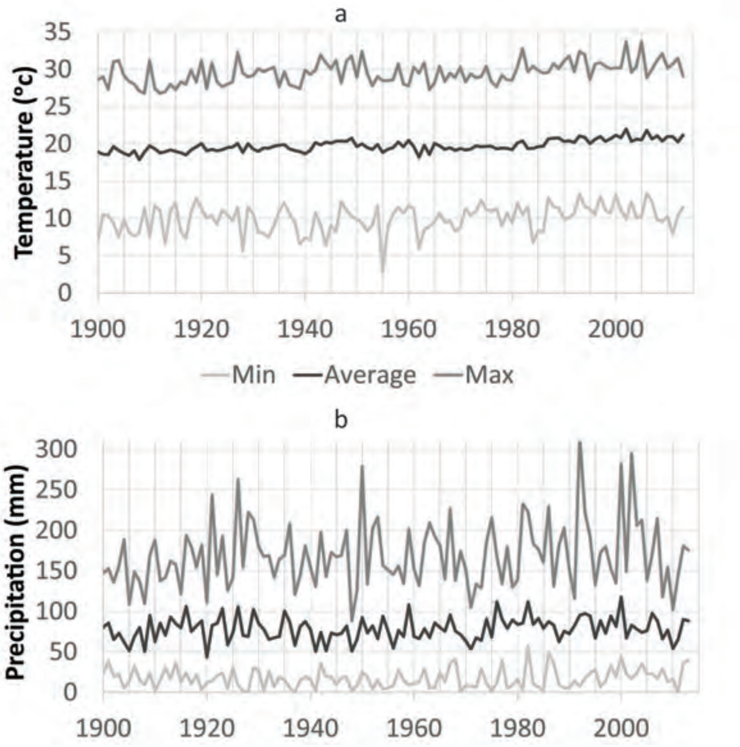

Figure 34 – Temperature and precipitation variability over the last century

Minimum, average and maximum monthly mean temperatures (a) and precipitations (b) per hydrological year for Geneva Cointrin 10 km east of the study site (MeteoSwiss, 2014).

The observed long-term climatic change was associated with a regime shift from pluvio-nival to pluvial. Figure 14D (page 56) shows the probability of having a flood (yearly maximum discharge) in each month for two different periods. Between 1918 and 1935 the occurrence of maximum flows was mainly associated with winter storms (December) and rain on snow events in spring (March-May), while more recently

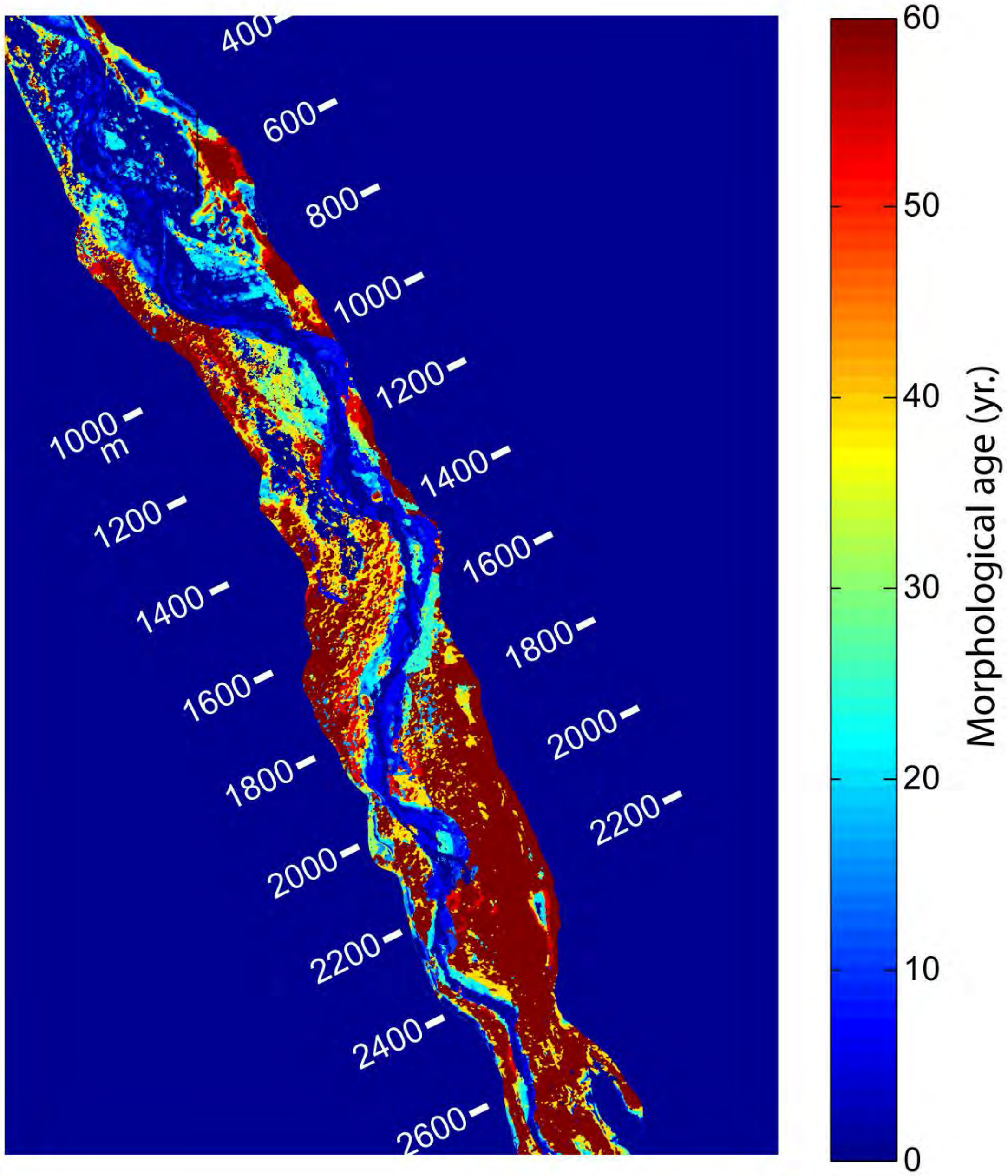

Figure 35 – Floodplain age map derived from aerial image classification (see method section 5.1.4)

(1986-2013; Figure 14D - page 56), maximum flows have become concentrated in the winter months only (December-March), thus reducing the annual high flow frequency from every 6 months to once a year. In parallel, because of the higher magnitude of extreme precipitation events, flood magnitude increased by about 30% during the last 50 years (Bätz et al., accepted).

Figure 30 shows a strong groundwater-depth gradient along the reach (Hottinger, 1998), with predominantly downwelling and deep water table in the upper reach (zone A in Figure 29 and Figure 30) and, from 700 m downstream, the onset of upwelling (zones B, C and D in Figure 29 and Figure 30). The partly modeled piezometer data (Figure 31) were located in zone A (P218) and in zone D (P219) on Figure 29. In the downwelling upstream reach (represented by P218, Figure 29 and Figure 31), the average groundwater depth from the river level was 4.4 m (standard deviation σ = ±1.6 m) with median lowering rates during recession periods of 0.02 m/day (1st interquartile = 0.01 m/day, 3rd = 0.04 m/day). Downstream, in the groundwater upwelling zones (represented by P219, Figure 29), mean groundwater depth from the river level was 0.7 m with little change around this value (σ = ±0.2 m – Figure 31).

Reach-scale fluvial morphodynamics

Figure 35 shows the morphological ages of the reach as of 2012 (see also Figure 32). Moving from upstream to downstream there is a clear gradient in morphological age. Active morphodynamics are able to maintain a young morphological age (high turnover rate) in the upper reaches, to about a distance from upstream of 900 m. Between 900 m and 1200 m, the range of ages present increases. The range of ages present here suggests the progressive narrowing of the active zone as part of a transition from a wide and more braided state towards a single thread channel. On the true right, between downslope distance of 900 m and 1500 m, there is a zone of apparently low morphological ages. This is a forest area that has been clear-cut recently. From, distance 1200 m to 2000 m downstream, there is still a high range of morphological ages, but this shifts towards being generally older, suggesting an earlier reduction in rates of morphodynamic change. From distance 2000 m downstream, the morphological age is largely binary, either being old (> 60 years) or part of the active channel. Nevertheless, the thin lines of slightly older age, adjacent to the active channel, still suggest relatively slow rates of lateral migration and channel adjacent recolonization.

In order to relate these results to the subsequent dendroecological analysis, Figure 36 shows the distribution of ages by Zones A through D. Zones A and B have wide ranges of morphological ages, with the highest percentage in active floodplain and the lowest

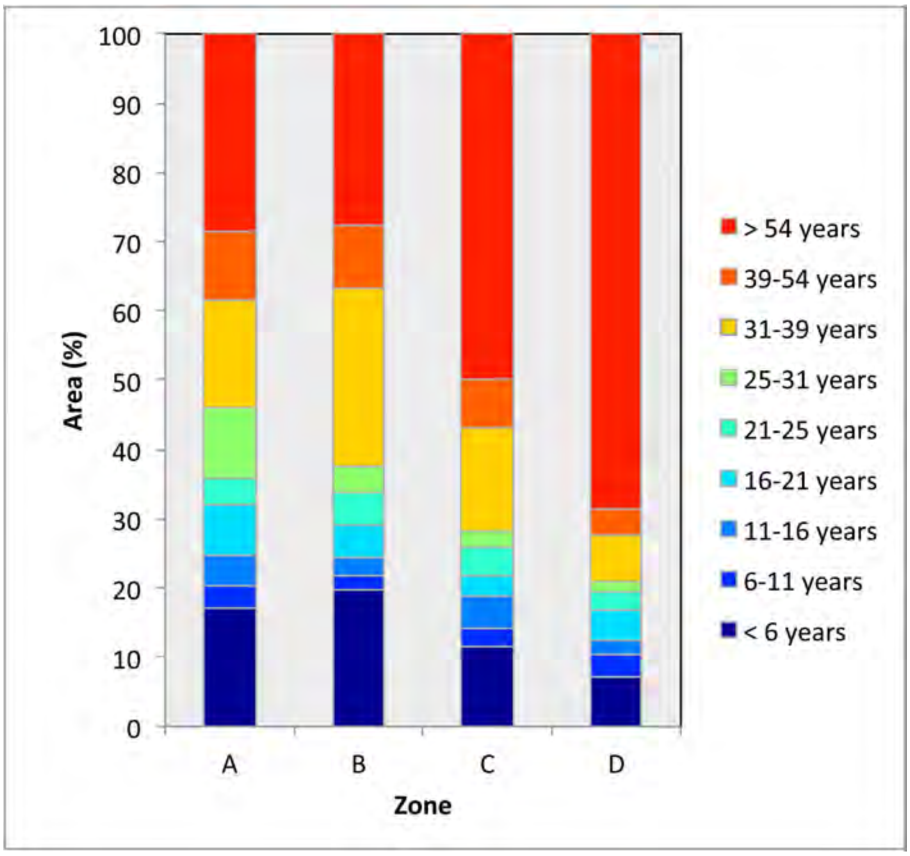

Figure 36 – Floodplain age distribution along the groundwater gradient extracted from Figure 35

percentage in the oldest age class. At the other extreme, Zone D has the smallest proportion active floodplain and the highest proportion in the oldest age category (Figure 36). Indeed the percentage of the zone in the 6-11 through 39-54 age category is the lowest (27%, compared with 55% for Zone A and 53% for Zone B - Figure 36), reflecting a more binary distribution (most of the zone is either old or active) Zone C has an age distribution intermediate between Zones A/B and Zone D.

A general trend in active width and its evolution through time along the reach and significant vegetation encroachment rates are evident from Figure 37. In the upper reach (zone A), woody vegetation cover by the end of the period was between 40% and 70%, and in the lower reach (zone D) it was between 55% and 95% of the potentially reworkable floodplain, reflecting the analysis of morphological age shown in Figure 36. In the upstream most zone (A), from 500 to 950m along the studied reach (Figure 37), width reduction and vegetation encroachment are slow until 1991. From that point, a markedly increase to 1996 can be observed, but overall levels of woody vegetation cover were still relatively low in 2012. This zone has the highest active width ratio between 2012 and 1957 (Figure 37). That is, the river here is able to maintain a higher active width with more frequent rates of lateral channel migration and channel shifts.

In Zone B between 950 and 1250m upstream (Figure 37) there are very low levels of woody vegetation cover and relatively high active widths in 1957. Cover rises continually, most notably between 1980 and 1991, which corresponds to the 31 to 39 year period in Figure 36. This zone has the maximum annual increase in woody vegetation cover (or decrease in active width) of 1.4% per year, although it remains able to maintain a substantial zone of higher channel activity as reflected in the highest percentage of morphologically young ages (Figure 36) and the intermediate active width ratio (Figure 37).

Zone C also has a major increase in encroachment and reduction in active width, but earlier than in zone A and B, notably between 1972 and 1980 (Figure 37). Rates of encroachment (or width reduction) are high (0.6 to 0.9 % points per year) and significant across the whole zone, except during the middle part of the zone where channel reworking between 1996 and 2012 causes some loss of vegetation. Indeed, zone C shows a very different morphodynamic behavior in recent years. Whilst the active zone generally comprises a smaller percentage of the reworkable floodplain by 2012 (Figure 37) it can be locally higher. This reflects the local development of channel curvature, the stabilization of point bars by the development of woody vegetation, and then chute cut-off when the sinuosity becomes locally very high. This is reflected in Figure 32, which shows the formation of islands with woody vegetation, created during sudden channel shifts.

The same behavior is found in Zone D, between 1700 m and 2000 m downstream (Figure 37), where woody vegetation cover is the highest of all the zones by 2012. However, the active width here was already low, as reflected in the high percentage of the oldest morphological ages (67%, Figure 36 and Figure 37) and it is maintained as such. Sudden channel shifts and associated meander cut-off is apparent, as per Zone C.

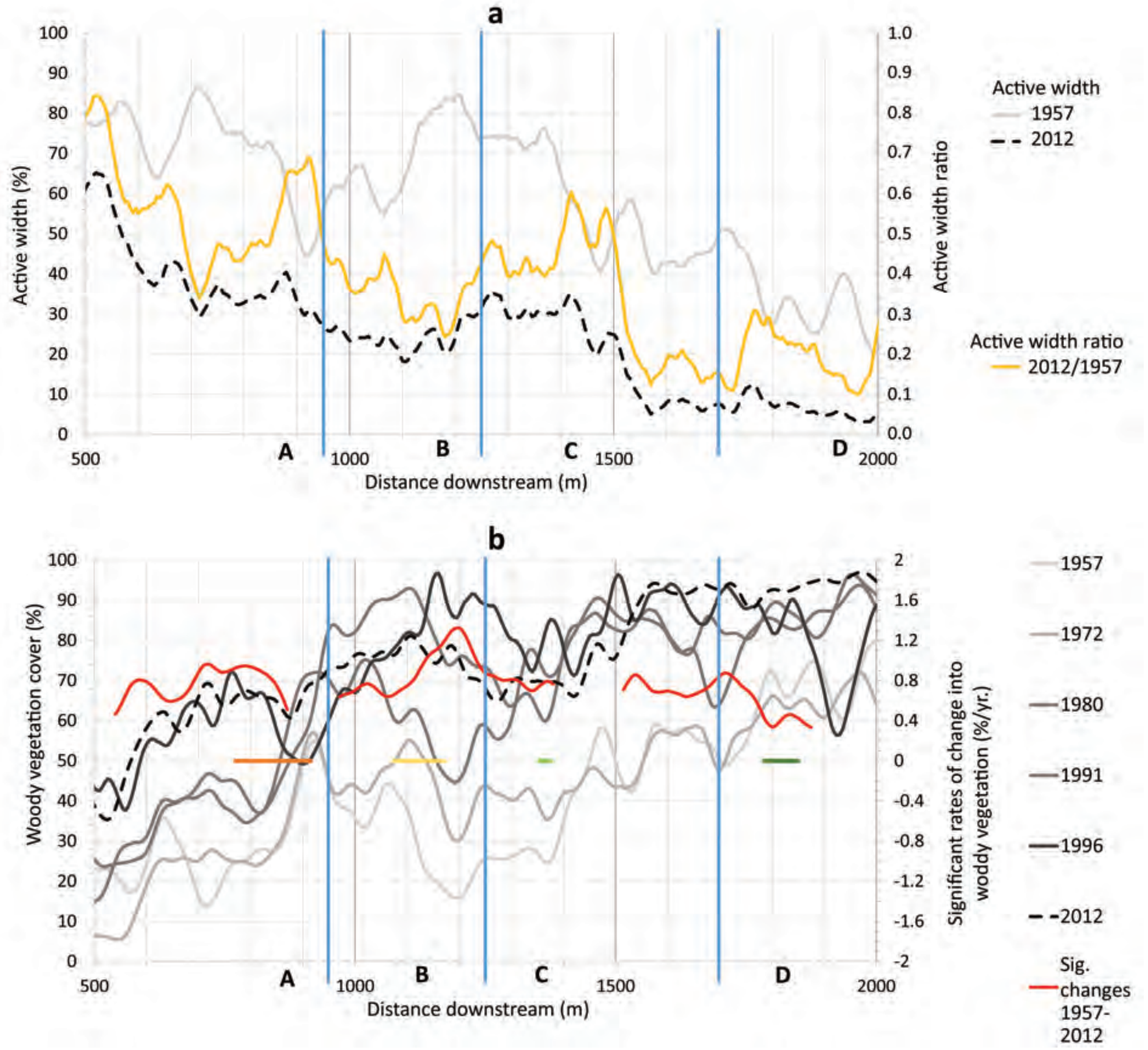

Figure 37 – Morphological evolution of the study reach

a: Shows the active width evolution for every 5 m section perpendicular to the main river slope (a 50 m moving average was applied for noise reduction) extracted from aerial image classification (see method section 5.1.4) for the first and the last available image. Moreover, the active width ratio is plotted for these two dates.

b: Similarly, the grey/black lines show the temporal evolution of the vegetation cover for every 5 m section. Vegetation cover is the inverse of the active width. The dotted black line represents the actual vegetation cover. The red line shows the significant encroachment rates over the entire period (at α=0.05). The blue lines indicate the different morphologic evolutionary zones (see section 5.1.5). The colored lines show the location of the dendroecological survey. The color code corresponds to the location in Figure 1 and the chronologies shown in Figure 5: Orange = willow of the chronology A; yellow = willow of the chronology B; light green = willow of the chronology C; dark green = willow of the chronology D.

Table 6 –Table summarizing the main properties of the four analyzed zones along the groundwater-depth gradient

Zones	Slope 2009 (%)	Mean active width			Mean rate of significant encroachment (%/yr.)
		1957 (%)	2012 (%)	ratio	
A	0.96	71.8	40.2	0.56	0.77
B	0.80	69.3	24.3	0.35	0.90
C	1.27	56.7	20.8	0.37	0.75
D	1.13	34.3	6.5	0.19	0.56

The results exposed above for the different zone are summarized in Table 6. Data on the morphological age of the reach, combined with analysis of active width / woody vegetation encroachment, suggests that the morphodynamics of this reach were associated with the progressive reduction in the active width of the river through time. This trend was most marked in the middle of the reach (Zones B and C), it was slower upstream (Zone A) and less notable downstream (Zone D), the latter because the active width was already much reduced at the start of the study period.

Dendroecological analysis

Figure 38 shows an example of the multi scale Spearman correlation analysis and the related correlation (CorInd) and weighted correlation indices (CorInd^{w}) for three example environmental variables and the willow growth rate indices developed for pioneer landforms along the four zones. Zone A shows the highest correlations over all scales for groundwater minima during the hydrological year and the maximum discharge during the growing season. Precipitation during summer becomes critical during the last ten years due to the hotter and drier climate conditions (see above; Figure 34). However, moving from Zone A to Zone D, that is following the downstream groundwater-depth gradient, willow growth rates shows progressively reduced dependence on groundwater minima, maximum discharge and summer precipitation.

The strongest trend can be observed for the maximum discharge during growing season, which moved from a CorInd of 81.9 (CorInd^{w} = 69.7) to a minimum of zero. Groundwater minima during the hydrological year still show some significant correlation with the willow plants growing in the upwelling river zone (D in Figure 38), but the level of correlation is much reduced. Precipitation correlations with growth rates also decrease markedly from Zone A to D, suggesting that downstream growth rates are independent of precipitation. Taken together, a general trend appears towards zone D, in which the correlation with the hydrological variables decreases with the groundwater depth. It also suggests that the CorInd and CorIndw variables provide a picture of the spatial variability in the association of hydrological and climate variables with willow growth rates.

Table 7 summarizes the correlation indices for the wider range of variables, while the entire set of figures can be consulted in annex A. The correlation index values for groundwater in zone A are generally higher and tend to decrease towards zone D. The highest correlation index values are observed for the mean groundwater level during the growing season, for the minimum annual groundwater level and mean groundwater level by hydrological year. High correlation index values are also obtained with the maximum discharge during the growing season in zone A (Figure 38; Table 7). Willow growth rates at the same site, tend not to correlate with maximum discharge during a hydrological year, which stands as an index of all possible flood perturbations: values are amongst the lowest found in Table 7. Indeed, only exceptional flooding events (e.g. the 2004 event – Table 4) are visible in all the chronologies and this may reflect the substantial resilience of willow to large flood events, if not exceptional flood events, in this system. Minimum discharge for the hydrological year, growing season and summer, show similar correlations with the willow growth rates with a slower but decreasing trend along the reach. The total precipitation during the growing season and during summer have similar correlation index values that decrease with distance downstream until nearly no correlation. Mean temperatures during the growing season and during summer have low correlation index values with a weak tendency to increase with distance downstream.

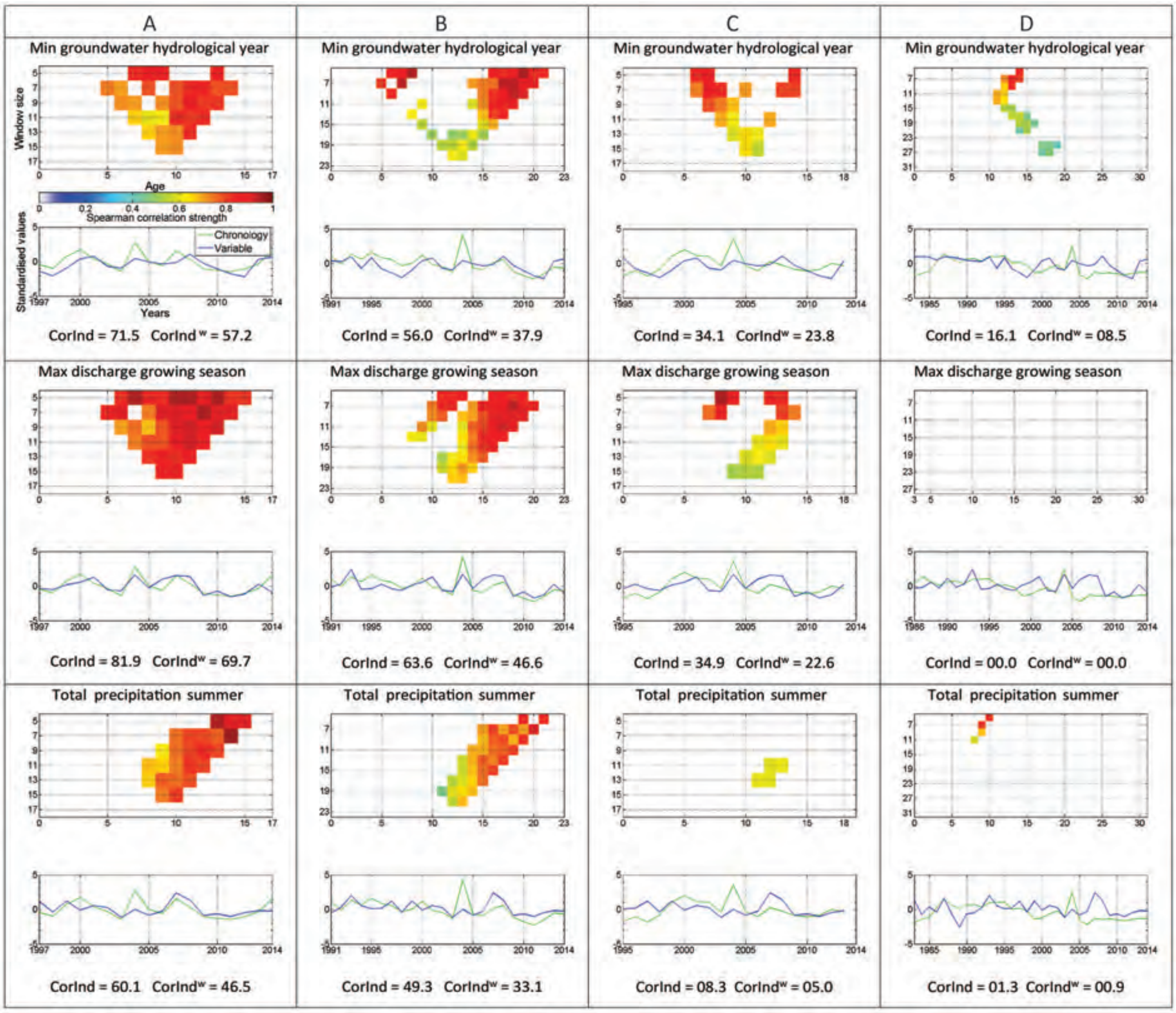

Figure 38 – Examples of the multi scale Spearman rank correlation analysis

Examples of the multi scale Spearman rank correlation approach for three variables (lines) and the four willow chronologies/units (columns). For each combination, a colored-square plot shows the strength of significant (α=0.05) correlations with varying window size along the chronology. Additionally, a line plot shows the evolution in time of the chronology and the related variable. Below the correlation indices (CorInd) and weighted correlation indices (CorInd^w) are plotted. Note the decline in correlation along the reach.

Table 7 – Summary of the correlation indices (CorInd) and weighted correlation indices (CorInd^{w})

Indices for different environmental variables (e.g. Figure 38) along the four dendroecological sampled zones (A, B, C, D – Figure 29 and Figure 33). The green gradient represents the strength of the correlation indices (max. 100). Note how the decrease in correlation follows the groundwater-depth gradient of the reach (Figure 30).

Variables		A	B	C	D
Groundwater - maximum growing season (March-Oct.)	CorInd	58.9	51.7	14.3	24.4
	CorInd^{w}	42.5	33.0	8.0	11.4
Groundwater - maximum summer (May-Sept.)	CorInd	58.9	45.5	14.3	3.0
	CorInd^{w}	42.5	27.7	8.0	1.5
Groundwater - minimum hydrological year (Oct.-Sept.)	CorInd	71.5	56.0	34.1	16.1
	CorInd^{w}	57.2	37.9	23.8	8.5
Groundwater - minimum growing season (March-Oct.)	CorInd	68.7	44.6	43.9	12.5
	CorInd^{w}	52.1	27.9	30.6	5.3
Groundwater - minimum summer (May-Sept.)	CorInd	67.5	46.9	38.7	9.8
	CorInd^{w}	50.7	28.8	25.9	4.0
Groundwater - mean hydrological year (Oct.-Sept.)	CorInd	64.5	53.5	32.5	41.0
	CorInd^{w}	48.2	35.3	21.8	21.8
Groundwater - mean growing season (March-Oct.)	CorInd	75.1	63.3	24.3	35.0
	CorInd^{w}	60.6	43.8	15.8	17.3
Groundwater - mean summer (May-Sept.)	CorInd	59.8	44.6	13.6	6.3
	CorInd^{w}	44.6	28.6	8.4	2.8
Discharge - maximum hydrological year (Oct.-Sept.)	CorInd	21.5	3.3	11.0	1.4
	CorInd^{w}	13.5	2.4	6.5	1.2
Discharge - maximum growing season (March-Oct.)	CorInd	81.9	63.6	34.9	0.0
	CorInd^{w}	69.7	46.6	22.6	0.0
Discharge - maximum summer (May-Sept.)	CorInd	2.6	36.5	11.0	47.0
	CorInd^{w}	2.1	21.1	8.1	27.0
Discharge - minimum hydrological year (Oct.-Sept.)	CorInd	50.0	34.4	5.6	0.0
	CorInd^{w}	35.7	21.2	3.2	0.0
Discharge - minimum growing season (March-Oct.)	CorInd	47.4	31.7	0.0	0.0
	CorInd^{w}	33.1	19.6	0.0	0.0
Discharge - minimum summer (May-Sept.)	CorInd	46.0	17.2	0.0	0.0
	CorInd^{w}	29.8	10.5	0.0	0.0
Precipitation - total growing season (March-Oct.)	CorInd	58.1	37.6	27.3	0.6
	CorInd^{w}	43.9	23.3	16.2	0.4
Precipitation -total summer (May-Sept.)	CorInd	60.1	49.3	8.3	1.3
	CorInd^{w}	46.5	33.1	5.0	0.9
Temperature - mean growing season (March-Oct.)	CorInd	0.0	39.3	6.9	42.9
	CorInd^{w}	0.0	22.5	5.5	22.1
Temperature - mean summer (May-Sept.)	CorInd	3.8	29.7	7.6	31.3
	CorInd^{w}	3.3	15.1	5.8	15.0

Summarizing the dendroecological analysis (Table 7), pioneer willow growth rates correlate more strongly with groundwater variability upstream than downstream, following the strong groundwater-depth gradient. Willow growth rate correlations with discharge and precipitation also follow this trend, with the exception of the maximum discharge during the hydrological year, emphasizing that it is most likely that we are seeing a growing season control more than perturbation effects in the growth rate data we have. Thus, the upstream growth rates tend to be controlled by water availability, with the groundwater and discharge providing a highly variable resource. Downstream growth rates tend to be independent of hydrological drivers, due to the reliable and stable upwelling groundwater levels, allowing temperature to become limiting for growth rates.

5.1.6 Discussion

Linking dendroecology, vegetation cover changes and river channel morphodynamics

Historical image classification suggested morphological evolution of the Allondon river between 1972 and 1996, in terms of the progressive reduction in active width, but at a rate that varied from upstream to downstream (Figure 37). Upstream sites remained morphologically more active (younger age, Figure 35) than downstream sites. These changes were closely linked to vegetation encroachment, which is generally high over the entire period, with significant changes ranging in the order of 0.4-1.2 %/yr. (Figure 37). This evolution initially appears to be due to a regime shift from bimodal pluvio-nival to unimodal pluvial (Figure 14D page 56), with maximum flows moving from spring and early summer to winter. This may allow a longer time for vegetation recruitment, establishment and growth, and progressively increase the morphological resilience to winter disturbances (e.g. Francis et al., 2009; Hicks et al., 2007). However, closer inspection of dendrochronological growth rates did not suggest that annual maximum flood magnitude (a proxy for yearly perturbation) was negatively correlated with growth rates, pointing to other controls on tree growth.

We argue that in the presence of reduced spring/summer disturbance, access to water replaced disturbance as the limiting factor for plant establishment and subsequent growth. However, this was not a spatially uniform process due to the strong groundwater-depth gradient (Figure 30 and Figure 31), with mean groundwater levels lower (4.4m deep) and more variable (σ = ±1.6 m) upstream (downwelling) and higher and less variable downstream (upwelling). The dendrochronology-derived growth rates for the four zones within the reach showed that willow growth rates (Figure 38 and Table 7) were associated with hydrological variables (groundwater variability, precipitation and discharge) upstream, but were independent of these variables downstream, as the higher and less variable groundwater table means that growth rates were largely independent of other hydrological processes. However, the data also suggested that in the meantime temperature control has become more important as a limiting factor for vegetation growth downstream. Water and nutrients are easily available all year around, so that temperature is supposed to be the only factor controlling plant photosynthetic activity (e.g. Hopkins and Hüner, 2008).

At the most upstream site, Zone A, median rates of groundwater decline of 20 mm/day (1st interquartile = 10 mm/day, 3rd = 40 mm/day) in the gravelly aquifer, were greater than the maximum root growth rates of 1-13 mm/day typically reported for willow seedlings (Naumburg et al., 2005). Moreover, the minimum groundwater depths of about 5 m, and recently up to 7 m, during summer (Figure 31) may not be accessible by young roots during the first year of establishment (Guilloy et al., 2011; Mahoney and Rood, 1998). This reduces the rate of success of seedling establishment (e.g. Gurnell et al., 2012). Likewise for established willows, whilst it is likely that the deep taproots may be able to develop access to groundwater during times of extended drawdown (Francis et al., 2005; Naumburg et al., 2005; Pockman et al., 1995; Rood et al., 2000), there is also likely to be some plant stress because of high drawdown rates. The relationship between growth rates and precipitation and discharge in the upper reach (Table 7) confirmed the importance of water as a limit on growth rates, with discharge and precipitation becoming alternative water sources during periods of water table draw down.

The aerial imagery (e.g. Figure 29) suggests in zone A that only seedlings germinating close to the river can establish themselves, with moisture from the river countering the effects of summer droughts and deep groundwater levels. Dendroecological results show some dependency on river minimum flows in this zone (Table 7), albeit less than groundwater and growing season high flows, which is likely to reflect spatial variability in access to water according to the position of the plant with respect to the river. However, Zone A is also the most dynamic geomorphologically, such that there is also likely to be a temporal variability in when plants benefit from being river-proximal. Young seedlings that develop close to the river may only be able to survive river migration if they have been able to develop deeper roots with access to the water table before the river migrates. In turn, this may be a core feedback that serves to maintain vegetation encroachment at low rates and hence lower levels of ecosystem engineering and channel stabilization and a higher active width.

The influence of groundwater variability decreased at sites B and C, the latter being on the margin between upwelling and downwelling. A reduction in correlation (Table 7) follows the increase in the mean groundwater level with respect to the surface (Figure 30), and by zone D, the willow growth rates have low correlations with groundwater variability as compared with zone A. Groundwater levels at upwelling site D are closer to the surface and vary less ($\sigma = \pm 0.2$ m). Precipitation and discharge also do not show high correlation indices values suggesting that there is no water stress present. In terms of plant recruitment, no spatial restrictions on water access exist, allowing successful recruitment and establishment on all low and moderately disturbed fresh deposits and fluvial landforms.

In summary, a strong groundwater-depth gradient from upstream to downstream mediated the level of water stress in this system. Where the mean groundwater table level was lower compared to the surrounding river bed (upstream), plant growth rates were more dependent upon groundwater variability, discharge and precipitation. Where the mean groundwater table level was higher (downstream), thus guaranteeing year-long water access, such relationships were found to a lesser extent and other controls on growth rate, notably temperature, became apparent.

Groundwater as a driver of biogeomorphic succession

Changes in channel morphology due to pioneer vegetation dynamics have been documented in flume experiments (e.g. Bertoldi et al., 2015; Van Dijk et al., 2013; Hicks et al., 2007; Tal and Paola, 2007, 2010) and historical image analysis (e.g. Beechie et al., 2006; Bertoldi et al., 2011; Kondolf and Curry, 1986; Picco et al., 2014; Zanoni et al., 2008). Links to field experiments and observations suggest that roots reinforce river sediment stability (e.g. Edmaier et al., 2011; Karrenberg et al., 2003; Pollen, 2007; Polvi et al., 2014), while the flexible branches are able to protect against erosion during flooding and promote fluvial landform formation and associated ambient conditions for vegetation succession (e.g. Corenblit et al., 2011, 2015; Gurnell, 2016; Gurnell et al., 2012, 2012). The engineering action of the pioneer plants, in association with fluvial landform evolution has led to the notion of biogeomorphic succession (Corenblit et al., 2007, 2009, 2014), in which landform, vegetation type and structure co-evolve in time.

The results in this paper suggest that the efficiency of these biogeomorphic feedbacks may be controlled by groundwater. As shown by many studies (Corenblit et al., in Press; Francis, 2006; Hervouet et al., 2011; Karrenberg et al., 2003; Mahoney and Rood, 1998; Moggridge and Gurnell, 2010; Shafroth et al., 1998), fluvial pioneer plant propagules are highly adapted to dynamic fluvial environments and propagate throughout the floodplain mainly via the river flow/flood pulses and wind. Because of complex interactions between the timing of propagule release, available transport mechanisms and geomorphic processes, a complex (stochastic) pattern of patches forms in the floodplain (Crouzy and Perona, 2012; Gurnell et al., 2008; Perona et al., 2012). These vary in terms of propagule availability (species, quantity) and ambient conditions (elevation, sedimentary structure). However, propagules may (re-)sprout if enough water for germination is available and may grow further if suitable conditions persist. We observed above a linkage between growth rates and groundwater dynamics. It is well-established that groundwater dynamics have a longer time-scale of variability (i.e. a function of long-term aquifer recharge and drawdown) than stream flow (i.e. a function of individual precipitation events). Thus, groundwater is likely to be a more reliable water resource at the scale of a growing season than streamflow, because of its lower sensitivity to precipitation (e.g. Sophocleous, 2002): it takes a longer-term precipitation deficit to cause aquifer drawdown than it does for river low flows; and the latter themselves may be sustained by hyporheic flow. As pioneer willow roots grow at maximum rate of 0.013 m/day a maximum groundwater decline of 0.02 m/day (1st interquartile = 0.01 m/day , 3rd = 0.04 m/day) is likely to be tolerable but may still lead to potential water stress symptoms (Guilloy et al., 2011; Naumburg et al., 2005) for plants trying to colonize this area. However, in this study, with a general change in groundwater dynamics from 1995 onward, with prolonged regular periods in which the groundwater drops to extremely low values (Figure 31), and the drier climate of the last decade (Figure 34), plant water stress has increased in the upstream part of the study reach. Downstream, in the groundwater upwelling zones (represented by P219, Figure 29), groundwater levels change insignificantly (σ = 0.2 m – Figure 31), and do not appear to have periods of systematic lowering that might limit vegetation growth.

We argue that the observed importance of groundwater has two important impacts for the biogeomorphic succession. First, the surface proximity of the groundwater will significantly affect moisture availability, thus affecting the spatial distribution of successful germination and plant establishment sites (Guilloy et al., 2011; Mahoney and Rood, 1998; Shafroth et al., 1998). What controls the resistance to erosion is not the individual pioneer plant but the total river encroachment rate (the sum of the congregated plants recolonizing a reach), which is lower where the groundwater table is deep because of greater water stress. Second, as shown by others (e.g. Naumburg et al., 2005; Pasquale et al., 2012; Shafroth et al., 2000; Sprackling and Read, 1979; Tron et al., 2014), plants concentrate their root distributions, and especially fine root distributions, in the zones with the highest probability of finding moisture. Depth to groundwater, in well-drained gravelly sediments, influences the depth at which pioneer plants build the highest root-induced effective cohesion (Imada et al., 2008; Pasquale et al., 2012; Perucca et al., 2007; Pollen, 2007; Polvi et al., 2014). For instance, the field experiment of Pasquale et al. (2012), at the Thur River (Switzerland), showed that willow cuttings adapt maximal rooting density on gravel bars just above the mean water table. They conclude that this may have major implications for riverbank stability. In our data, upstream (Zone A), root systems should therefore concentrate in the deep groundwater fluctuation zone (2-5 m), which is below the reworkable layer of fluvial processes (approximately to a maximum of 1-2 m depth) and therefore less effective in channel stabilization. Only plants colonizing the river flow margins may have access to water, and a higher root density close to the surface. Taken together, the formation of vegetated patches with groundwater mediated lower encroachment rates (Perucca et al., 2007), where the roots have to grow to greater depths (Naumburg et al., 2005; Pasquale et al., 2012; Pollen, 2007; Polvi et al., 2014; Tron et al., 2014), leads to reduced engineering effects, so maintaining greater active widths. We argue that this is why zone A remains in a more active state. Downstream, the plant root system concentrates in the first 1 m depth to access the shallow and more stable groundwater, thus providing spatially continuous additional resistance to erosion over the entire zone, aiding the advancement of the biogeomorphic succession. We do not have data to support this conclusion. However, as research has shown a clear relationship between root distribution and water table levels (Imada et al., 2008; Pasquale et al., 2012), it would seem logical to explore this conclusion further, in terms of quantifying the possible contribution of groundwater-mediated root-resistance to biogeomorphic succession.

More generally, we argue that groundwater controls the spatial variation in the lateral extent of active channel change. By slowing upstream vegetation encroachment rates, groundwater stress slowed the rate of development of vegetation related resistance, so allowing the river to remain dynamic and further limit vegetation encroachment (Francis et al., 2009).

5.1.7 Conclusions

This paper suggests that groundwater dynamics, both spatially and temporally may have a significant impact upon biogeomorphic succession and its related engineering effect. This can be seen in the eventual response of river morphodynamics. In the example studied here, a regime shift from bimodal pluvio-nival to unimodal pluvial appears to have reduced the frequency of perturbations during the growing season. This allowed a general increase in vegetation establishment and encroachment. However, active width reduction and encroachment were greater downstream than upstream and this appeared to be correlated with a downstream gradient in the depth to the water table: lower, downwelling and more variable upstream; upwelling and less variable downstream. A carefully designed dendrochronological approach to determine woody plant growth rates was used to interrogate the reasons for the correlation between active width reduction and depth to groundwater. Where groundwater was downwelling and groundwater depth was more variable (upstream), growth rates were found to be correlated to hydrological variables (groundwater, precipitation, discharge); water was a limiting factor; and the active channel width reduced more slowly. On the contrary, where groundwater was upwelling and groundwater depth was less variable, growth rates were no longer related to hydrological variables, as groundwater provided a more reliable water resource, insulating the system from other hydrological variables (precipitation, river flow). Active width was narrower and morphodynamics were more associated with the progressive development of sinuosity followed by a chute cut-off.

We argue that this study has important implications for biogeomorphic succession (Corenblit et al., 2007, 2009, 2014), as it shows that the intensity of feedbacks between geomorphic and vegetation processes, which leads to this succession, may be conditioned by other variables; in our case groundwater. We emphasize that the groundwater impact is conditional upon the presence of water stress as the limitation of vegetation growth and establishment, and so may not be relevant in all cases. However, groundwater levels are one of the most strongly impacted elements of the hydrological cycle. If groundwater levels condition biogeomorphic succession, as we show here, they may have major impacts upon river channel morphodynamics through t effects upon the balance between disturbance frequency and vegetation encroachment rate. In turn, with attempts to revitalize braided rivers in the face of a changing climate, consideration will have to be given to the extent to which groundwater is likely to condition restoration success.

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5.2 Summary – the importance of groundwater availability for vegetation recruitment and succession

In this chapter, the influence of groundwater as a control on biogeomorphic succession was investigated. Willows are important pioneers in biogeomorphic succession (e.g. Karrenberg et al., 2003; Rood et al., 2010) and are often the key ecosystem engineer in braided rivers (Corenblit et al., 2007; Karrenberg et al., 2002). As such, although the implications of groundwater access were mainly assessed for willows (life cycle scale of the biogeomorphic succession – Corenblit et al., 2014), it has also implications for the biogeomorphic succession at the community level (Corenblit et al., 2007).

This Chapter shows that in a groundwater distal environment, willow growth rate was strongly correlated with hydrological variability, relating to the importance of local water stress. Where the groundwater table was higher plant growth did not show major correlation with hydrological variables as water was available throughout the growing season.

Gurnell et al., (2001b) propose an earlier version of the biogeomorphic succession model (Figure 39). Similar to Corenblit et al.'s (2007) model, several phases of landform construction are shown and linked to fluvial processes. This Chapter suggested that groundwater is a critical factor as a control upon summer moisture availability and that it is likely that groundwater access controls the ability of plants to establish before the next disturbance.

In detail, in the Allondon River, groundwater levels in the northern reach were deep and highly fluctuating. Willow seedlings (first geomorphic phase) may not always be able to access this water resource with their roots (Mahoney and Rood, 1998), so limiting successful colonization to sites nourished by laterally infiltrating river water. This partly explains the development of vegetation only along the main channel. However, in the case of rapid channel changes (e.g. sudden channel shifts or bank erosion) they may potentially die (Gurnell et al., 2001b) if no groundwater has been tapped beforehand and the root systems are not sufficiently developed to prevent erosion. The associated water stress, notably in summer, causes the time scale for the development of patchy vegetation patterns into an aggregated / attached form to be

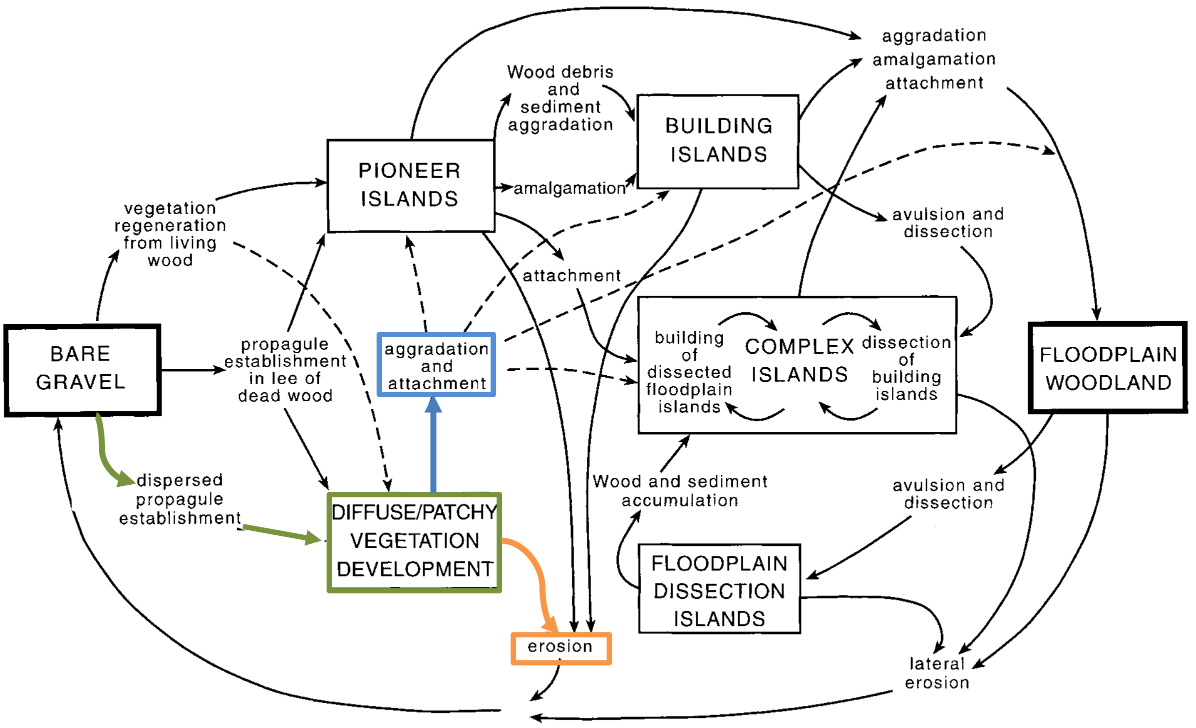


Figure 39 – Conceptual model of island development for the Tagliamento River

Black arrows show predominant pathways, while dotted less probable trajectories (taken from Gurnell et al., 2001). However we highlighted the predominant paths for the groundwater distal site (orange) and the groundwater proximal site (blue) of the Allondon River. The blue path needs higher vegetation growth rates than disturbance. Summer access to groundwater guaranties this relation. In case of summer water stress (missing aces to the groundwater) plant growth is reduced, hence vegetation encroachment lower that the disturbance, allowing higher erosion rates.

lower than the disturbance rate (Figure 39), thus allowing higher erosion rates (predominance of the orange path; Figure 39). Moreover, we hypothesize that the engineering effect of vegetation is weakened, as roots have been placed rather deep in the sediments (Naumburg et al., 2005; Pasquale et al., 2012; Shafroth et al., 2000; Sprackling and Read, 1979; Tron et al., 2014), thus below the potentially geomorphologically reworkable substrate.

On the contrary, the southern reach is characterized by a shallow and stable groundwater levels. Pioneer vegetation can establish on all undisturbed surfaces (Gurnell et al., 2001b), quickly creating a continuous “carpet” of willow bushes (biogeomorphic phase). As the vegetation aggregation /attachment versus disturbance frequency is higher (predominance of the blue path Figure 39) a better resistance to disturbance and greater opportunity to trap fine sediments and organic matter during higher river flows is achieved (Bätz et al., 2015a; Corenblit et al., in Press; Gurnell et al., 2001b). The additional sediment coherence via roots is thought to be higher than in the north, as roots access water close to the surface (Naumburg et al., 2005; Pasquale et al., 2012; Shafroth et al., 2000; Sprackling and Read, 1979; Tron et al., 2014).

Taken together, the biogeomphic succession (vegetation establishment, aggregation/attachment, resistance to erosion) appears to be more rapid in groundwater proximal sites that in distal sites. Climate and groundwater changes, may affect the balance between disturbance and vegetation encroachment efficiency, which in the long term may lead to changes in river morphodynamics (Ashmore, 2013; Francis et al., 2009; Gurnell et al., 2001b; Hicks et al., 2007; Tal and Paola, 2010; Figure 3 page 7).

6 Integrating groundwater availability and soil evolution

Chapter 4 focused on the influence of soil evolution on biogeomorphic succession, while Chapter 5 on the influence of ground water on biogeomorphic succession (Corenblit et al., 2007, 2014). This Chapter aims to determine the combined influence of these two factors on biogeomorphic succession (Figure 40). Both biogeomorphic succession scale are relevant here (plant community and population level; Corenblit et al., 2007, 2014). Groundwater has been recognised as an important control on the rate at which processes contribute to build the various compartments of an ecosystem, including soil (Boulton et al., 1998; Gregory et al., 1991; Harner and Stanford, 2003; Janssens et al., 2001; Mouw et al., 2009; Naegeli, 1997; Pusch et al., 1998). As soils are an emergent property of ecosystem development (Phillips, 2009; Phillips and Lorz, 2008), we might expect a groundwater signature in their development because of its control upon water availability within sediments. Following the results in Chapter 5, Figure 40 suggests that the main relationship between groundwater and soil development is likely to be through the groundwater access supporting vegetation growth and thus organic matter production for the soil. However, there might be also the possibility by which soil processes, aided by geomorphic processes (deposition of fine sediment potentially enriched in organic matter), ameliorate local ambient conditions such that, even under groundwater-driven moisture stress (higher groundwater depth), vegetation establishment is facilitated (dashed orange box in Figure 40). This hypothesis is tested in this chapter.

6.1 Methods

The interrelated impact of depth to groundwater and soil forming processes, was assessed via a principal components analysis (PCA), as used in Chapter 4 to evaluate the impact of soils on the biogeomorphic succession. For a detailed description of the method, see Section 4.1.3. The analysis was repeated for the soil data set presented in Chapter 4, but excluding sites associated with the ecological phase of biogeomorphic succession. This followed from conclusions in Chapter 4 and the dendroecological analysis in Chapter 5, which taken together imply that the mature

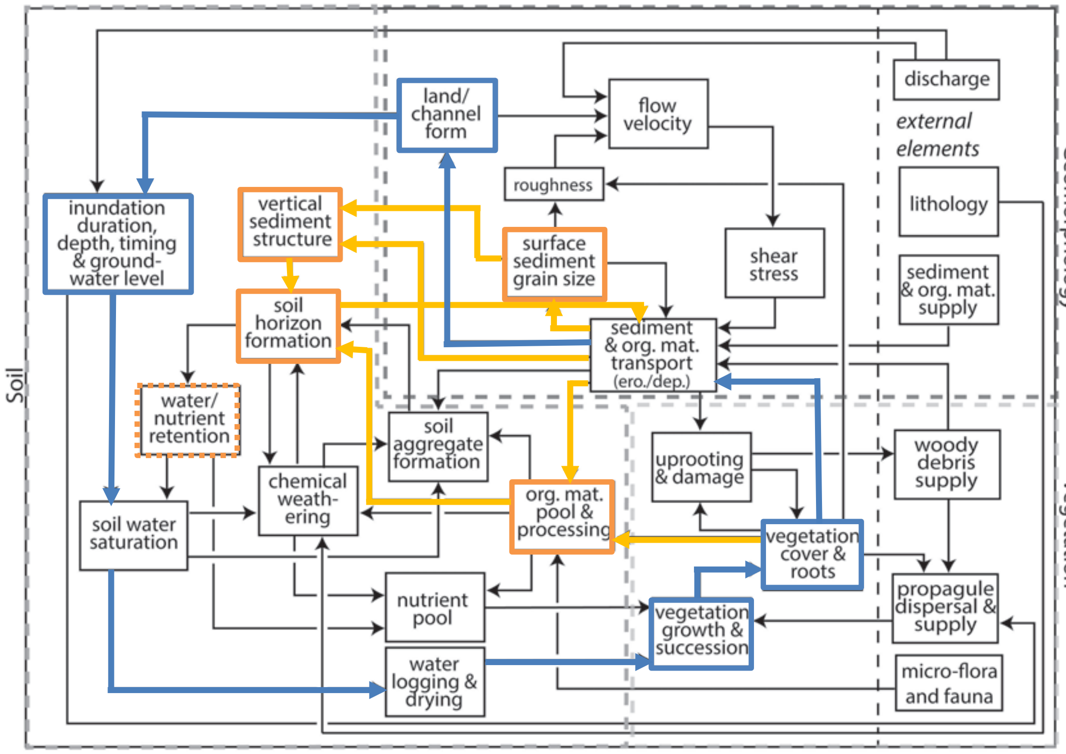


Figure 40 – Conceptual model (Figure 6) highlighting the components addressed in Chapter 6

The components related to organic matter and soil formation are shown in orange. Blue refers to the interactions related to water availability in river bed sediments/soils, as influenced by both river discharge and depth to groundwater. The dashed orange box defines the possibility by which soil formation can facilitate plant development under groundwater distal conditions.

terraces soils of the ecological phase are likely to be less dependent on fluvial processes and more self-sustaining in terms of associated water demands (see also (Corenblit et al., 2007). They can be considered as ecosystem separated from the fluvial influence. The processed database included 62 samples from locations 51, 52, 53, 54, 41, 42, 31, 32, 14, 15 and 16 (Figure 19 page 81), covering the zones B, C and D analysed in Chapter 5 in dendroecological terms (Figure 29 page 122). Unfortunately no soil data were available for zone A.

A set of 25 variables was used to describe the soils of the Allondon River:

(1) soil layer depth and thickness, gravel content, clay content, silt content, fine, medium and coarse sand content were used to describe the variability of physical properties of each layer;

(2) root content, total organic carbon (TOC), mineral carbon (MINC), hydrogen index (HI), oxygen index (OI), temperature at which most hydrocarbons are released (TpS2), fresh litter (A1), stable litter compartment (A2), humified litter (A3), stable humus components (A4), resistant humus components (A5), R-index and I-index were used to determine the respective amount and relationships between the various organic material compounds found in the soil layers via the Rock-Eval method (Disnar et al., 2003; Lafargue et al., 1998; Sebag et al., 2006; see Section 4.1.3);

(3) distance to the channel (dist.- channel) and elevation from the river (H-layer) were used to represent the proximity to fluvial processes that might rework or deliver sediment, but also influence soil moisture supply from river sourced wetting fronts (see Section 4.1.3);

(4) the variable “distance from south” (Dist. from south) was added as a surrogate for the groundwater-depth gradient following from Chapter 5; with increasing distance from south the Allondon floodplain changes from an upwelling reach to a downwelling reach, thus from shallow and more stable groundwater levels to deeper and more dynamic groundwater levels (Figure 30 page 123 and Figure 31 page 125); and

(5) the aerial imagery-defined surface ages (Figure 35 page 139) of each site were added. In comparison to the results of Chapter 4, this variable could be added here via the exclusion of the ecological phase, which was generally associated with sites that were at least as old as the oldest aerial image and so of unknown absolute age.

In order to improve the link between the overall soil profile characteristics (the sum of the layers) represented by the principal components (PC) and each profile’s geomorphological setting, an index based on an adaptation of the Soil Profile Development index (SPD) presented by Birkeland et al. (1991) was calculated.

First, the PC value of each layer was multiplied by its thickness. This allows weighting the properties of each layer based on its thickness, such that thin layers have a lower impact to the overall soil profile characteristics than thicker layers. This is important as, plant growth may not depend only on topsoil properties but also on the below ground characteristics.

Second, we summed the weighted layer PC values and divided their sum by the profile depth to obtain the PC-SPD. This step was necessary to account for differences in profile depth. Younger soils were sampled to lower depths, because reaching more rapidly pure gravel layers, if compared to older sites. Normalising the profile to the same depth, allows a better index comparison between the profiles (Birkeland et al., 1991).

Third, as PC1 and PC2 can be considered as process related (humification and fresh organic matter supply - see results and methods below), we divided the index by the landform age to get a PC-SPD representing the related process rates.

Finally, after standardisation, the PC related indices (PC-SPD) were summed to give the total SPD. The resulting map was then interpreted.

6.2 Results

6.2.1 Principle component analysis

Adding the groundwater-depth and age effect to the analysis of the first three phases of the biogeomorphic succession did not change considerably the relations between the variables and the first two principal components (Figure 41a) when compared to the results in Chapter 4 (Figure 21 page 89). Only the fresh organic matter component (A1) increases its correlation with PC1 to a significant degree (R = 0.47). The HI falls below significance ($p<0.330$ –Table 8). The HI refers to the chemical composition of the organic matter in terms of amount of hydrogenised components (e.g. not oxidised) which generally are linked to the fresh organic matter composition (e.g. different litter types) and/or soil layer maturity (HI decreases with the pedogenetic transformation – e.g. Sebag et al., accepted). HI and TpS2 were more correlated with PC2 (Table 8, Figure 41a) as compared to the results in Chapter 4 (Table 1 page 90). Fine sand content and the humified litter (A3) lost their significant correlation with PC2. However,

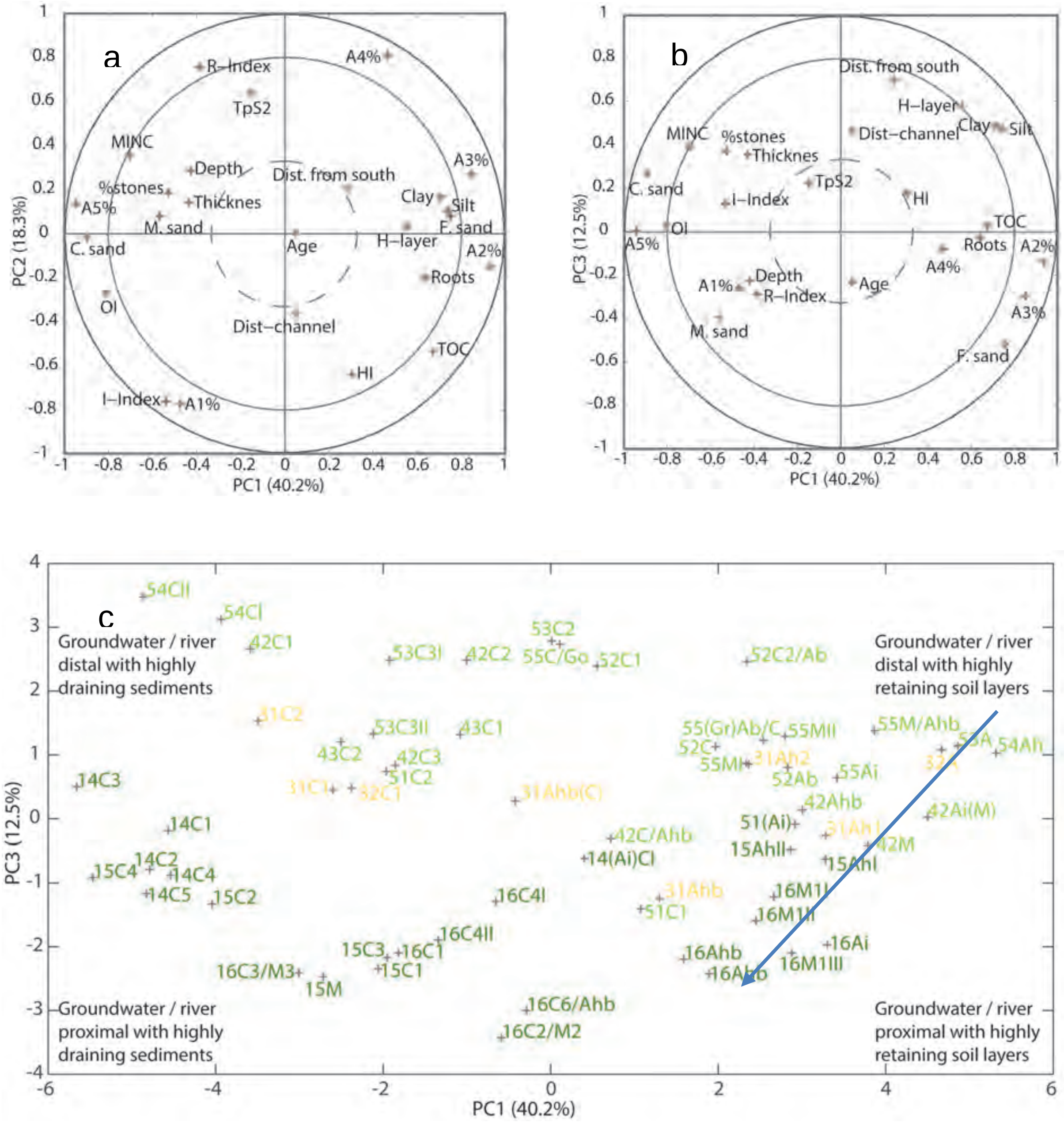


Figure 41 – Results of the PCA including the age and groundwater-depth effect (first part)

Correlations of variables with PC1 and PC2 (6.2a) and PC1 and PC3 (6.2b). The inner dashed circle defines the significance level of the correlating variables set at r > 0.330 (*p*=0.005) based on 60 degrees of freedom. The intermediate continuous circle defines the level at which variables are considered to be strongly correlated with the PC (r > 0.8). For the variable descriptions see Section 6.2.1. 6.2c shows the plotting of individual samples. The code of each sample states profile number (e.g. 14), followed by the horizon type (Ah=humus enriched topsoil; Ai=initial topsoil formation; Ahb=buried humus enriched topsoil; M=organic matter enriched sandy alluvial deposits; C=pure alluvial deposits with no or low organic matter content). The colour code refers to the zones B (orange), C (light green) and D (dark green) presented in Chapter 5, thus from downwelling (B) to upwelling (D).

their correlations were already low compared to the other variables defining PC2.

In both first PCs, distance from south and age did not reach significant correlations. It is not surprising, then, that the explained variance did not change significantly when compared with Chapter 4: PC1 lost 0.1% and PC2 gained 1.0% of total explained variance. In summary, these first two PCs look very similar to the ones presented in Chapter4: PC1 is positively associated with the degree of humification; and PC2 is negatively associated with the level of fresh organic matter present. Humification in braided systems is mainly associated to earthworms, bacteria, algae and biofilm activity, which transform the fresh organic matter into plant available resources (Bätz et al., 2015a; Bullinger-Weber et al., 2007; Bureau, 1995; Guenat et al., 1999; Langhans et al., 2012; Pusch et al., 1998).

That said, the new groundwater-depth representing variable ("dist. from south") appears clearly in PC3 (Figure 41b, r =0.69), with higher values on PC3 being associated with sites that are further north and therefore with a greater and more variable depth to groundwater. Elevation and distance to the channel also appear as significant contributors to PC3 and are positively correlated. Finally, PC3 also correlates positively with clay and silt, while negative correlations are found for fine and medium sands. Thus, it appears that PC3 is describing an access to water effect, which is lower with higher values of PC3 (that is sites that are further to the north, further away from the channel, at higher altitudes and have higher sediment water retention). Total explained variance of PC3 is 12.5%, an increase of 4.1% when compared to the results in Chapter 4.

As the nature of PC3 has changed, Figure 41c plots the sample distribution on PC1 and PC3. On the negative axe of PC1 and PC3, samples relate to deep freely draining sediments and groundwater/river proximal layers of the southern reach (locations 14, 15, 16, Figure 41 and Figure 19 page 81). On the negative axe of PC1 and positive axe of PC3, deep freely draining sediments and groundwater/river distal layers of the northern reach are found (locations 54, 53, 51, 31 32). On the positive axes of PC1 and PC3, groundwater/river distal soil layers with high water retention are plotted. On

Table 8 – Pearson correlation coefficients (r) between variables and the PCs including the age and groundwater-depth effect

In bold the variables with the highest correlations for each principal component (PC). Note that variables show a significant correlation when r>0.3300 (*p*=0.005) based on 60 degrees of freedom. In this analysis, only the first six PCs are considered because explaining more that 5% of the total variance. Finally we also included the PC variance found in the analysis not including the groundwater-depth and Age variables (Chapter 4).

Variables	PC8	PC7	PC6	PC5	PC4	PC3	PC2	PC1
Depth	0.03	-0.13	**-0.71**	-0.20	-0.16	-0.22	0.28	**-0.42**
Clay	0.01	0.11	-0.11	**-0.37**	-0.06	**0.49**	0.18	**0.71**
Silt	0.01	0.16	-0.10	-0.32	-0.16	**0.46**	0.11	**0.74**
F. Sand	-0.01	-0.16	-0.01	0.13	-0.10	**-0.52**	0.07	**0.76**
M. Sand	-0.09	-0.02	0.01	**0.58**	0.26	**-0.38**	0.08	**-0.56**
C. Sand	-0.08	0.12	0.00	-0.01	0.17	0.28	-0.01	**-0.89**
TOC	-0.07	0.04	-0.21	0.13	0.16	0.04	**-0.53**	**0.67**
MINC	-0.09	0.15	-0.01	-0.07	-0.10	**0.38**	**0.36**	**-0.70**
HI	0.32	0.11	0.00	-0.03	**0.40**	0.20	**-0.63**	0.31
OI	0.20	0.05	0.16	-0.14	0.08	0.04	-0.26	**-0.81**
TpS2	-0.02	**-0.38**	0.23	-0.20	-0.16	0.21	**0.64**	-0.15
A1	0.01	-0.03	-0.04	-0.24	-0.10	-0.25	**-0.78**	**-0.47**
A2	0.03	-0.05	-0.11	0.10	0.09	-0.13	-0.15	**0.94**
A3	0.05	0.04	-0.14	-0.03	0.23	-0.29	0.27	**0.85**
A4	0.05	0.00	0.02	0.03	0.20	-0.09	**0.81**	**0.47**
A5	-0.01	0.06	0.13	-0.03	-0.13	0.00	0.14	**-0.94**
R-Index	0.02	0.10	0.06	-0.14	0.24	-0.28	**0.75**	**-0.38**
I-Index	-0.03	-0.10	0.06	-0.01	-0.22	0.14	**-0.76**	**-0.53**
%stones	0.30	**0.34**	**-0.43**	0.26	0.00	**0.37**	0.19	**-0.52**
Thickness	**0.39**	**-0.61**	-0.21	0.19	-0.04	**0.35**	0.15	**-0.43**
D-channel	**-0.43**	-0.31	-0.30	-0.02	0.32	**0.49**	**-0.35**	0.06
H-river	-0.03	-0.14	0.28	0.18	-0.14	**0.56**	0.04	**0.56**
Roots	**0.36**	-0.01	0.14	0.07	**-0.38**	-0.03	-0.20	**0.64**
Distance from south	-0.08	0.14	0.03	**0.50**	-0.08	**0.70**	0.21	0.27
Age	-0.18	0.14	-0.18	0.22	**-0.80**	-0.24	-0.01	0.05
Expl. total variance [%]	**3.3**	**4.1**	**5.1**	**5.4**	**6.7**	**12.5**	**18.3**	**40.2**
Cumulative variance [%]	**95.7**	**92.3**	**88.2**	**83.1**	**77.7**	**71.0**	**58.5**	**40.2**
Expl. total variance [%] Ch.4	3.1	3.5	4.2	4.9	6.6	8.1	17.3	40.3
Cumulative variance [%] Ch. 4	88.0	84.9	81.4	77.2	72.3	65.7	57.6	40.3

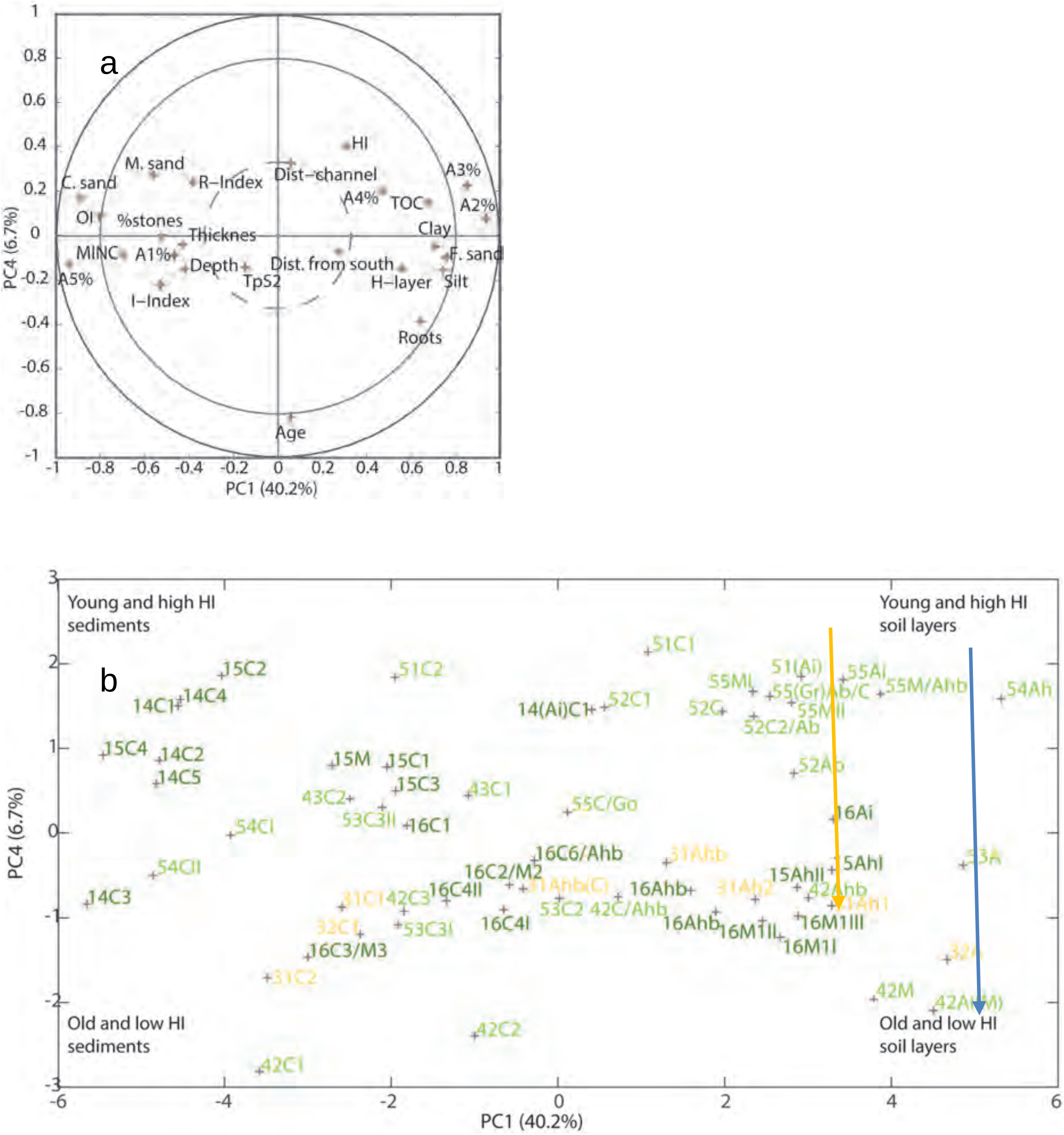


Figure 42 – Results of the PCA including the age and groundwater-depth effect (second part)

correlations between variables and the first and fourth principal component. The inner dashed circle defines the significance level of the correlation set at r > 0.330 (*p*=0.005) based on 60 degrees of freedom. The intermediate continuous circle defines the level at which variables are considered to be strongly correlated with the PC (r > 0.8). The sample site plots on PC1/PC4 are also shown (6.3b). The code of each sample states profile number (e.g. 14), followed by the horizon type (Ah=humus enriched topsoil; Ai=initial topsoil formation; Ahb=buried humus enriched topsoil; M=organic matter enriched sandy alluvial deposits; C=pure alluvial deposits with no or low organic matter content). The colour code refers to the zones B (orange), C (light green) and D (dark green) presented in Chapter 5, thus from downwelling (B) to upwelling (D).

The blue path refers to high topsoil pedogenic rate in relation to stabilisation and associated succession observed for abandoned channels in the groundwater distal zones. The orange path shows the standard lower topsoil pedogenic rate for the other samples on different geomorphic settings.

the negative axe of PC1 and positive axe of PC3, the optimal sites for vegetation growth, with year-round groundwater connection and good water retention are plotted.

PC4 in chapter 4 correlated strongly with elevation and distance from the river. This has been interpreted as representing the soil chronosequence with 6.6% of the variance. However, PC4 in the analysis presented here is dominated by Age (r = -0.82) and is also associated with root density (r = -0.38) and the HI (r=0.40; Figure 42a;). Thus, greater ages indicate later biogeomorphic succession stages with greater root density and litter poorer in hydrocarbons (HI). The HI, as defined above, may refer here to the chemical composition of the fresh organic matter composition, as the pioneer willow vegetation litter and fluvial inputs (e.g. lignin) have generally higher values of HI, than more advanced succession stages (Hodkinson, 1975; Isidorov and Jdanova, 2002; Sebag et al., accepted). This axis can thus be interpreted as indicating the time since the last destructive disturbance, thus reflecting landform fluvial stabilisation (age) and, to some extent, the related biogeomorphic succession (lower correlations with root density and HI). Interestingly, this “age” PC is not linked to any extent to distance or elevation to the channel, as the morphodynamics of the Allondon River (e.g. avulsion – Chapter 3 and 5) create a complex pattern of ages (Figure 35 page 139). As shown for PC3, channel proximity (distance and elevation) appear to be a control on water supply rather than a surrogate for geomorphic disturbance frequency. However, in comparison to the previous principal components PC1 to PC3, PC4 only explains 6.7% of the total variance. Figure 42b shows the sample distribution in the PC1/PC4 space, thus plotting the soil state as a function of age. Note that the soil processing rates, represented by positive PC1 values, are not linked to age (negative PC4), indicating a large diversity of soil layer states at each age.

The fifth principal component, explains 5.5% of the total variance (Table 8). In Chapter 4, this PC was not considered because it fell below the 5% threshold of explained variance. As shown in Table 8 for the analysis presented here, PC4 correlates negatively with layers with higher clay content, and positively with medium sand content and with distance from the south. This could indicate the effect of the geological setting, as in the southern floodplain valley, fine (clay rich) glaciolacustrine deposits are and have been locally incised by the river (Coutterand, 2010; Moscariello, in prep.), thus raising the clay component of the sediments with decreasing distance to the south. However, the reason remain speculative for this trend, so we generally associate this PC as describing the clay and medium sand content.

PC6 is the final component to reach the limit of 5% explained variance (Section 4.1.3). In Chapter 4, PC6 was below this threshold and was not considered in the analysis. However, with groundwater added, PC6 represents the increasing gravel content with depth in the soil profiles. This is a conventional relationship in soil science.

6.2.2 Soil profile development index and geomorphological setting

In order to be able to interpret soil profile evolution in relation to its geomorphological setting in the floodplain, the PC values of each layer (Figure 41c and Figure 42b) were integrated into an index for each profile (PC-SPD and total SPD). This is deemed to summarize the total and complex sum of soil layer characteristics (A, Ai, Ah, Ab, M and C horizons) observed in the floodplain based on the PCA analysis above. Although, based upon a limited number and distribution of sites in the floodplain, this section also tries to find some relationships between the different biogeomorphic phases and the SPD index.

Table 9 summarises the SPD index values for the first 6 PCs (PC-SPD) and its standardised sum (total SPD), including a colour code, in relation to site age and biogeomorphic phase. As negative values of PC2, PC3, PC4, PC5 and PC6 generally indicate better soil characteristics for plant growth (see above), their indices were multiplied by minus one, so that positive values (green colours) indicate better, while negative (red) worst profile characteristics.

Soil profiles of the first geomorphological phase of biogeomorphic succession, were sampled in zone C and D. In zone C, sites were located on recent point bars (43) and abandoned channels (51, 53; Figure 43). In the upwelling zone D, site 14 has been formed after gravel deposition in a channel abandoned due to an avulsion in 2005.

Generally, sites of the geomorphological phase show a wide range of profile humification and fresh organic matter accumulation rates, although humification rates are generally low (Table 9). Access to water is best for site 14, as located in the groundwater upwelling zone D. In terms of age since last destructive disturbance (stability), PC-SPD index values show a large range, but generally have lower values if compared to the other biogeomorphic phases (pioneer and biogeomorphic). The clay content shows a wide scatter and is positively correlated to the humification and the fresh organic matter accumulation rates. The gravel-depth shows a wide range, with values among the lowest for the entire set of sites.

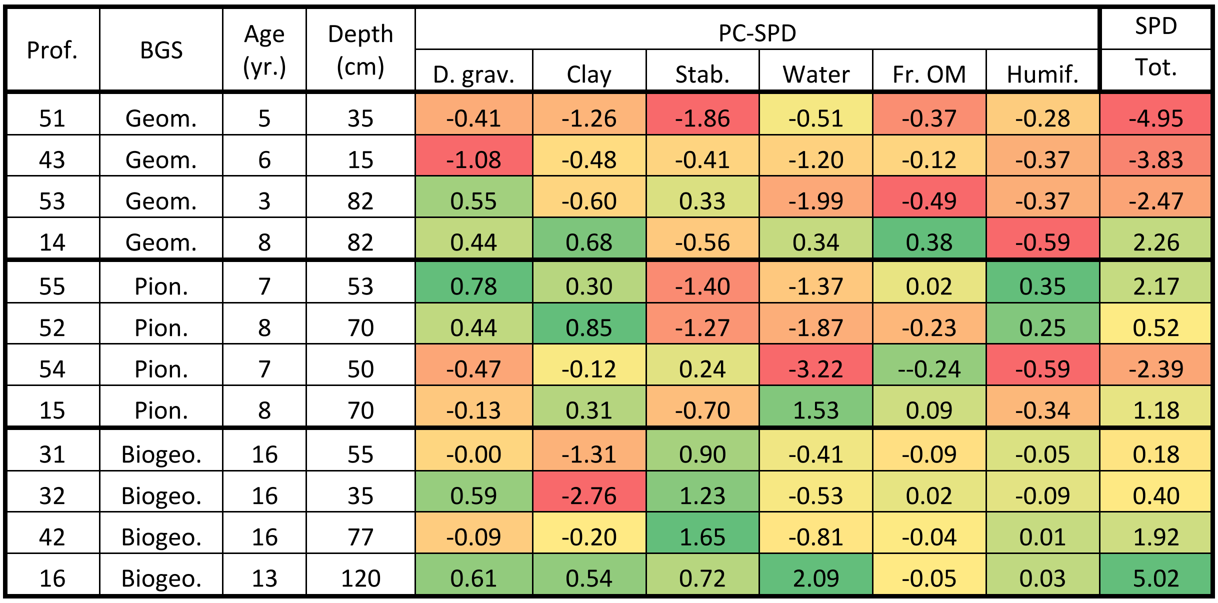
Pioneer sites are mainly found in zone C. The profiles are located in recently abandoned channels (point bar 54 and channel 55) and a vegetated patch (52), the later a remnant after formation of a secondary channel in 2009 (Figure 43). In the upwelling zone D, pioneer site 15 formed after a heavy flood in 2004, which caused massive lateral erosion in the true right terrace in association with channel incision (see Chapter 4.2 for details).

Humification rates for the pioneer sites have the highest scatter when compared to the entire set of biogeomorphic phases represented in Table 9, with sites 52 and 55 showing the highest rates, while values of site 54 and 15 are among the lowest. The fresh organic matter accumulation rates still shows a wide range, but are less scattered than for sites in the previous geomorphic phase. The access to water (retention and supply) shows the widest scatter of all the biogeomorphic phase sites, with values that are among the highest (15 is located in the groundwater upwelling zone D) and lowest (54) for all the profiles. Similarly to the pioneer phase, stability shows a wide range. Clay content is highest for the profiles of this biogeomorphic phase, with site 52 showing the uppermost observed value. The gravel-depth still shows a wide scatter, but is generally lower than for the pioneer phase. An inverse correlation is suggested with the humification rate, while stability appears to be correlated positively. This may suggest aggradation of fines, which may disturb humification.

Samples for the biogeomorphic phase include the downwelling zone B, intermediate zone C and upwelling zone D. Site 31 and 32 stabilised after abandonment of a secondary channel around 1996 (Figure 43). Site 32 was part of the channel, while site 31 is located on a lateral bar. This is still reflected in the topography (Figure 19 page 81). Site 42 is the only site at the biogeomorphic phase in zone C and is placed on an

Table 9 – Summary of the profile development index values for each soil profile

PC-SPD refers to indices calculated for each PC, with PC1 representing the humification rate (humif.), PC2 the fresh organic matter accumulation rate (fr. OM), PC3 the access to water resources such as groundwater, river water or in-situ retention (water), PC4 defining the age since the last disturbance (age), PC5 the clay content in relation to medium sand (clay), PC6 the depth of gravel (d. gravel) and SPD tot defining the sum of the standardised values of the PCs. The green colours indicate better, while red worst profile characteristics for plant growth. Moreover, for each site, the age estimated by aerial imagery interpretation, depth of the soil profile and its biogeomorphic phase (BGS; Geom.= geomorphological; Pion.= pioneer; Biogeo.=biogeomorphological) is listed.



Prof.	BGS	Age (yr.)	Depth (cm)	PC-SPD						SPD
				D. grav.	Clay	Stab.	Water	Fr. OM	Humif.	Tot.
51	Geom.	5	35	-0.41	-1.26	-1.86	-0.51	-0.37	-0.28	-4.95
43	Geom.	6	15	-1.08	-0.48	-0.41	-1.20	-0.12	-0.37	-3.83
53	Geom.	3	82	0.55	-0.60	0.33	-1.99	-0.49	-0.37	-2.47
14	Geom.	8	82	0.44	0.68	-0.56	0.34	0.38	-0.59	2.26
55	Pion.	7	53	0.78	0.30	-1.40	-1.37	0.02	0.35	2.17
52	Pion.	8	70	0.44	0.85	-1.27	-1.87	-0.23	0.25	0.52
54	Pion.	7	50	-0.47	-0.12	0.24	-3.22	--0.24	-0.59	-2.39
15	Pion.	8	70	-0.13	0.31	-0.70	1.53	0.09	-0.34	1.18
31	Biogeo.	16	55	-0.00	-1.31	0.90	-0.41	-0.09	-0.05	0.18
32	Biogeo.	16	35	0.59	-2.76	1.23	-0.53	0.02	-0.09	0.40
42	Biogeo.	16	77	-0.09	-0.20	1.65	-0.81	-0.04	0.01	1.92
16	Biogeo.	13	120	0.61	0.54	0.72	2.09	-0.05	0.03	5.02

old point bar (since 1996) which was then dissected from the floodplain by a channel shift in 2006 and 2009 (Figure 43). The biogeomorphic site 16, has formed as an island, potentially from woody debris resprouting since 2001 (at 80cm depth, a piece of rotten woody debris was found).

The biogeomorphic phase generally shows the smallest scatter and intermediate values for humification and fresh organic matter accumulation rates, if compared to the other successional phases (Table 9). In terms of water access and supply, values range from medium to high. Stability is the highest and clearly distinguishes this phase from the lower successional phases. The clay content, shows the widest range of values, with site 32 having the lowest of all profiles. Depth to gravel is generally high if compared to the geomorphic and pioneer phase.

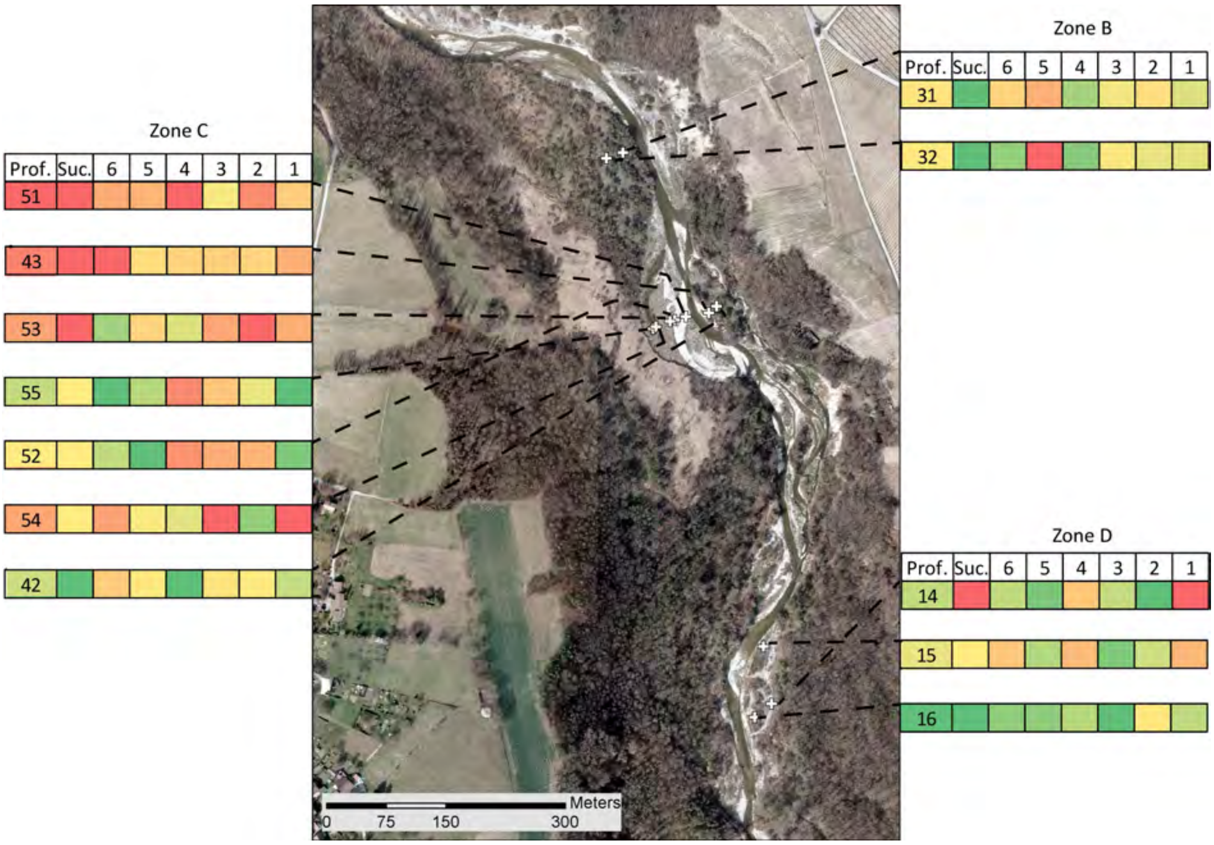


Figure 43 – Summary of soil profile development (SPD) index values within the floodplain

Prof. indicating the profile number, while the colours indicate higher (green) and lower (red) total SPD index values. Suc. then indicates the observed succession stage (red geomorphic, yellow pioneer, green biogeomorphic). As for the SPD, the a colour coding is used to represent the PC-SPD index values, with 1 representing the humification rate (humif.), 2 the fresh organic matter accumulation rate (fr. OM), 3 the aces to water resources such as groundwater, river water or in-situ water retention (water), 4 defining the age since the last disturbance (age), 5 the clay content in relation to medium sand (clay), 6 the depth of gravel (d. gravel).

6.3 Discussion

6.3.1 Principal component analysis and topsoil processes interpretation

Including variables related to depth to groundwater and age did not change significantly the two primary principal components (PC1 and PC2 - Figure 41a) when compared to the results shown in Chapter 4 (Figure 21 page 89). This suggests that the organic matter dynamics and related humification processes best explain soil variability in the Allondon River. Here we only show the correlation space between variables and PC1 and PC2 (Figure 41a), as the plot representing the samples on these two PCs remains largely unchanged if compared to the results of Chapter 4 (Figure 21 page 89). PC1 represents the soil evolutionary trajectory, with more negative values showing more sedimentary properties (high in gravel, coarse sand, little TOC, high refractory (A5) organic components), while more positive values indicate higher humification process (high TOC, high A2 and A5 organic components, finer sediments). PC2 has been interpreted as a measure of fresh organic matter, with more negative values indicating fresh organic matter and more positive values indicating stable organic compounds.

The correlation space between PC1 and PC3 changed when compared to the results presented in Chapter 4. As such, we can reinterpret this space as describing the moisture availability in terms of water retention (grain sizes, sedimentary environment), groundwater-depth (dist. from south) and fluvial water availability (H-layer, Dist.-channel). These results suggest some similarities to the results of Chapter 5, but allow a clear distinction of the groundwater effect based on geomorphic setting.

Figure 41c plotted the samples on PC1 and PC3 so that an interpretation of the interplay between groundwater and soil formation for the early biogeomorphic succession phases is possible. In the following interpretations we focus mainly on the upper soil horizon, thus on the actual soil processing acting at the surface and its relation to the geomorphic position in the floodplain. The main processes for young soil formation are mainly linked to organic matter topsoil processing and to geomorphological processes. The complex history of the entire soil profile will be addressed in the next section via an interpretation of the SPD indices.

Not many topsoil samples (A layers) have very high values in both PC1 (>2) and PC3 (>2), apart from buried soils (52C2/Ab). Instead A layers samples tend to have intermediate-positive values of PC3 and medium to high values on PC1. This suggests that with increasing distance to the groundwater table, biogeomorphic succession can only compensate for increased water stress (groundwater and river), where fine material and organic matter is retained and drainage reduced (high values on PC1). As the Allondon is a dynamic gravel bed river, it only provides sufficient moisture retaining (potentially organic enriched) sediments in special sedimentary conditions. Sites found in recent abandoned channels, such as site 32, 53, 54 and 55 (Figure 41c, Figure 43), may rapidly accumulate fine sediments, and potentially allochthonous organic material and propagules (e.g. Hughes, 1997; Steiger et al., 2003; Steiger and

Gurnell, 2003). From Figure 21 (page 89) these sites appear at lower elevation in respect to the river channel (light blue/light green colours), indicating that they are potentially connected to the main river channel during higher flows. The high values of A2 components (lignin) on PC1 (Figure 41b/c) for the topsoil samples 32, 53, 54 and 55 indicate higher amounts of particulate organic matter (e.g. branches). Such organic matter has been described as an important resource in such environments (e.g. Cierjacks et al., 2011; Langhans et al., 2012; Pusch et al., 1998). The decomposition of A2, indicated by the high A3 values on PC1, allows increasing water and nutrient retention, necessary to support propagule establishment and plant growth (e.g. Corenblit et al., 2007; Gurnell, 2014). The presence of many buried horizons (Ahb) and fluvial organic matter-enriched sandy deposits (M layers) at these sites indicate this aggradation processes. Indeed, in the layer 55M/Ahb a half decomposed 5cm thick piece of woody debris was found. However, this indicates that these aggradation events can also be very rapid, cutting of the atmosphere connection of the topsoil. In comparison, topsoil sampling sites that were not located in abandoned channels had much lower values on PC1 (e.g. 31, 43, 51 and 52).

On the positive axe of PC1 and negative axe of PC3, A layers at sites with year-round groundwater connection and good water retention are plotted (sites 16, 15 and 14 Figure 41c). However, these sites do not have higher soil organic matter content (positive PC1: high A2, A3, TOC), as values for sites 16 and 15 on PC1 are lower than those of sites 32, 42, 53, 54 and 55. In terms of position in the floodplain (Figure 43), sampling sites are located on a point bar (15), island (16) and in an abandoned channel (14). However, in general, few early biogeomorphic stages can be found close to the channel in the upwelling reach, as a great part of this floodplain has been encroached and thus stabilised (see chapter 5).

It follows that groundwater-depth along the reach influences soil organic matter content and composition, which can reach high values in groundwater distal zones, but only in abandoned channels. Conversely lower values are found in groundwater proximal sites (see arrow in Figure 41c).

PC4 represents the time since the last major destructive disturbance, as very high negative correlations with fluvial landform age could be found for this PC. However, this PC is also related to a lower extent to the biogeomorphic succession, as: (i) more negative values on PC4 indicate higher root density and reflect later phases in the biogeomorphic succession (e.g. Corenblit et al., 2009); and (ii) more positive values indicate higher values of HI, suggesting that the organic matter input is from early successional stages. Research has indicated that early successional litter is richer in hydrocarbons, thus higher in HI (Hodkinson, 1975; Isidorov and Jdanova, 2002; Sebag et al., accepted). The PC1/PC4 sample plot (Figure 42b) shows the relation between age since the last destructive disturbance and associated biogeomorphic succession with soil development.

However, again the topsoil layers located in abandoned channels mentioned above (54, 53, 32; Figure 43) but also site 42, have high values of PC1 (>4) and appear as a separate group. As before, these samples are characterised by very high values of PC1, thus high TOC mainly composed of A2 (lignin) and A3 (humified litter), and these do not considerably change in relation to their stability (towards negative values on PC4). However, samples not located in abandoned channels (51, 52, 43, 31, 16, 15, 14) show a similar relation to age/succession but generally plot at lower values on PC1 (2<s<4). This suggests that organic matter content and associated humification (higher A2 and A3) are higher at sites located in abandoned channels, than at sites not located in abandoned channels and that this does not change as a function of stability (age and biogeomorphic succession stage; see arrows in Figure 42b). Abandoned channels have sporadic access to the pulsing water flow, which may locally rise the organic matter and fine sediment content (e.g. Bureau, 1995; Pusch et al., 1998). Moreover, the ambient conditions (e.g. humidity) may also favour biological processes (e.g. earthworms, bacteria, algae) necessary for the organic matter decomposition (Bullinger-Weber et al., 2007; Bureau, 1995; Langhans et al., 2012; Pusch et al., 1998).

Combining the results above, it appears that present-day soil formation may drive, under certain circumstances, the biogeomorphic succession on the drier groundwater-distal sites. In these groundwater distal zones (with high values of PC3), general vegetation encroachment from aerial image interpretation has been shown to be slow (Chapter 5). However, for soil to be the driver, particular sedimentary environments are required such as abandoned channels (Figure 43), which allow supply of fine sediment and potentially particulate organic material (PC3; sites 32, 53, and 54) during flood pulses. A layers located in abandoned channels under groundwater distal conditions have much higher TOC, A2 and A3 content (high values of PC1) than comparable sites with similar age and succession stage (PC4) not located in abandoned channels (51, 52, 43, 31). This suggests that, in relation to their age/stability and groundwater access, soil formation is much more advanced in abandoned channels. The fine sediments and the high organic matter content ameliorate local edaphic conditions in such a way that poor access to groundwater can be compensated. More rapid biogeomorphic succession may follow, notwithstanding the disturbance frequency in this more dynamic part of the reach (Chapter 5). However, as shown by the presence of buried soils and organic matter enriched sandy deposits, pedogenesis can be interrupted by major sedimentation events.

Under groundwater proximal conditions, soil organic matter content is lower and is deemed to follow the progress of the biogeomorphic succession. Soil organic matter dynamics are thought to be mainly fed by the high vegetation establishment rates that are guaranteed by continuous access to groundwater (Chapter 5).

6.3.2 Soil profile development index and geomorphological setting

Use of the SPD index proposed by Birkeland et al. (1991) allows intercomparison of the complex structure of each pedon – the complex assemblage of Ai, Ah, Ab, M and C horizons – in relation to their specific geomorphic setting. The interpretation of the SPD index will be organised by following each biogeomorphic phase along the groundwater-depth gradient and by taking into account its geomorphological setting.

Four sites for the geomorphic phase were sampled, covering zones C and D. Water retention/access is highest for site 51 in zone C, a site located in a recently abandoned channel close to the actual main river channel (Figure 43). The high fresh organic matter accumulation rate may be due to fluvial input, as the point in succession is early (low stability Table 9). However, the proximity to the channel might also mean a higher magnitude and frequency of disturbance, hence showing the lowest total SPD index value. Site 53, shows the same geomorphic setting as site 51 in zone C, but with greater distance to the actual channel (Figure 43), and so possibly related to lower disturbance (high stability values; Table 9). In association with the deposition of fines (high values in distance to gravel), this site shows the highest total SPD value for the geomorphic phase within zone C. Fresh organic matter accumulation is highest at site 43 in zone C. This is attributed to the proximity of this site to the biogeomorphic site 42, which has a higher biomass productivity. However, the high gravel content in relation to poorer water retention and access, leads only to intermediate total SPD index values. In the upwelling zone D, site 14 formed after a channel shift due to gravel deposition during a major flood in 2004. The 2004 event also caused incision of the new channel (see Chapter 4.2). Although fresh organic matter is provided by the near terrace forest (high fresh organic matter accumulation rates; Table 9), this site shows very low rates of humification. Access to water is relatively low for zone D, although clay content is fairly high in relation to the other profiles. The deep gravel-coarse sand mix (14C samples in Figure 41c) in association with the higher elevation (formed due to abandoned channel infilling, and main channel incision), does not allow a capillary rise from the upwelling groundwater. River connection is hampered due to the higher position and the distance to the channel, reducing water, fine sediment and matter supply. Hence, although significant revegetation has been observed from aerial image interpretation for zone D (Chapter 5) the rate of succession locally remains low for this geomorphological setting.

Summarising, it appears that for the geomorphic phase, geomorphological setting matters, as it controls river connectivity and sediment supply: in the groundwater distal zones (C), abandoned channels at greater distance from the channel, had the best conditions for plant growth (site 53). In the groundwater proximal zone (zone D), high vegetation recolonization rates were observed (Chapter 5). However, locally this more rapid process can be hampered on sites that have been formed after channel abandonment in combination with coarse sediment infilling and without actual connection to the river flow (site 14). In fact, high values of the SPD index are mainly related to high clay content and fresh organic matter accumulation rates that increase the local water retention needed for propagule establishment. Humification plays a negative role for geomorphic sites, as it destroys the water retaining and surface mulching properties of fresh organic matter.

Pioneer sites were available for zone C and D. The lowest access / supply of water in zone C is shown for site 54, while for 55 it is highest (Table 9). Both sites are spatially very close, but differ in geomorphic setting. 54 is located on an ancient bar, while 55 in an old abandoned channel. The different geomorphological setting appears to impact the SPD index. Gravel depth and the initial elevation seam to reflect the aggradation of fines over the past years, which are higher in the abandoned channel (Ab layers defining buried soil; M layers defining organic matter enriched sandy alluvial deposits in profile 55) than on the bar (C layers defining alluvial gravel deposits in profile 54). Similarly, the humification rate shows a very high value for 55 and a very low value for 54. Overall this leads to a higher total SPD for site 55 than for 54. Site 52, a vegetated patch remnant after secondary channel formation in 2009, shows high humification rates and clay content. The proximity to the channel, in association with the engineering action of the willow growing on this site, allowed continuous sediment aggradation. The presence of buried soils (Ab layers), are witnesses to this process. However, due to disturbance, total SPD index value is intermediate.

In the upwelling zone D, site 15 was part of the main channel until 2004, where a large flood caused massive lateral erosion in association with incision. Humification and fresh organic matter accumulation have intermediate values. As detailed in Section 4.2, the first 13cm of the profile are characterised by alluvial organic matter enriched sandy deposits (M layers), which have been altered by pedogenesis (AhI and AhII defines layers altered by humification processes). Although, clay content is low and gravel content is high if compared to the other sites of the pioneer phase, this site has good access to water resources (river proximity, groundwater depth is low) to support plant growth.

In summary, the geomorphic setting appears again, under groundwater distal conditions, to be important, with abandoned channels having the highest values of total SPD index. However, the SPD index in the pioneer phase is mainly driven by the gravel content (lower values are best for plant and soil), humification (higher values imply higher organic matter turnover rates) and to geomorphic processes associated with fine sediment and possibly organic matter delivery. This suggests a higher dependency on soil forming processes for the pioneer than for the previously considered geomorphic phase (humification was negatively related to the total SPD).

For the biogeomorphic phase, samples cover a wider range of the groundwater-depth gradient, ranging from zone B through to zone D. In the groundwater distal zone B, site 31 (ancient bar) and 32 (abandoned channel) formed after a large avulsion in 1996. The humification index (Figure 43) is similar for both sites, although lower in comparison to the other two site at biogeomorphic succession phase (Table 9). Fresh litter accumulation rates show slightly higher values for site 32. Access and retention of water are similar for both sites due to the buried soil at site 31, which improves pedon water retention. In terms of stability, although both are high, site 32 shows slightly higher values, indicating that this site is more advanced in terms of plant succession. The higher clay content (Figure 43) which better supports plant growth, may have caused this difference. Although less pronounced, results are comparable to the finding for a similar geomorphic setting but at the pioneer phase of succession (sites 54 and 55), with a higher total SPD index value for the abandoned channel than for the bar. However, comparing site 31 and 32 to the other biogeomorphic sites with higher access to groundwater, total SPD perform with lower values.

In zone C, site 42 developed from a point bar and later, due to an avulsion, developed into an island. The perturbation history is reflected in the soil profile by the presence of a buried soil layer (Ab layer) and the deposition of alluvial organically enriched fine sand deposits (M layer). Humification shows intermediate values. However, fresh organic matter accumulation is low. Access to water is low and close to the values observed for zone B, as gravel is found at relatively shallow depths. Overall, the total SPD index has intermediate values.

In zone D, the biogeomorphic site 16, similar to site 42, has formed as an island since 2001. Its profile comprises three buried soil layers (Ab layers) and a series of alluvial organic matter enriched sandy deposits (M layers), which testify the aggradation rate of the past decade. Access to water is high, because of the proximity of this site to the river and because of upwelling groundwater. Moreover, the clay content is high and gravel content low, favouring water retention for plant growth. This leads to high humification rates, which do not allow organic matter to accumulate.

In summary, although the total SPD index values of the biogeomorphic phase have a wide range, it appears mainly driven by the groundwater gradient (water in Table 9).

Because this successional phase is not limited anymore by plant biomass production (biogeomorphic sites have already well-established willow shrubs; Corenblit et al., 2007, 2009, 2014), humification follows the trend of groundwater-depth, with enhanced rates as humidity increases.

From the analysis above, the geomorphic evolution and the actual setting of each site in respect to the river channel, creates a large mosaic of landform properties (PC indices; Table 9, Figure 43) at different biogeomorphic successional phases. However, ecological processes during the geomorphic phase appear to be mainly driven by water retention properties of the deposit (fine sediment and organic matter content). In the pioneer phase, higher gravel depth in relation to aggradation processes and humification ameliorate local ambient conditions for plant growth. Whilst in the biogeomorphic phase, access to water (via soil retention, groundwater and river water), the amount of fines and humification drive soil development. Humidity and fine sediments are thought to drive biological process such as earthworms, bacteria, algae and biofilm activity, which transform the fresh organic matter into plant available resources (humification - Bullinger-Weber et al., 2007; Bureau, 1995; Guenat et al., 1999; Langhans et al., 2012; Pusch et al., 1998).

As shown above, especially in groundwater distal sites where summer drought limits plant establishment, abandoned channels may guarantee fine sediment input, and possibly also fresh organic matter input, during smaller flood events, necessary to increase water retention to sustain propagule establishment in the geomorphic phase. During the pioneer phase, aggradation of fines continues and soil processes start transforming the accumulated organic matter into a young nutrient and water retaining soil. This sustains further plant growth and the associated root stabilisation effect, necessary for the transition into the biogeomorphic phase. The latter successional step is mainly driven by access to water, as the biological processes needed for humification are limited by humidity rather than by organic input, due to the higher biomass productivity of the site. Overall, this suggest that soil formation, linked to fine sediment and organic matter accumulation and successive humification, assists actively the succession on drier sites.

6.4 Conclusions

Integrating the results of Chapters 4 and 5 shows that the organic matter dynamics and sediment grain size remain of primary importance for explaining soil diversity in the Allondon floodplain. However, sites farther from the active channel and at higher altitude, indicate that, if located in groundwater distal reaches, the water demands of young vegetated fluvial landforms need to be compensated by fine sediment delivery (high silt and clay content) and humus development (high soil processing rates) so as to aid water retention. In dynamic gravelly environments, the best conditions are met in abandoned channels, as these may become channel connected during higher flows. Such connection may allow the aggradation of fines and allochthonous organic (woody) material. Although deposition of allochthonous organic (woody) material was not measured directly in this study, the presence of M layers (organic matter enriched sandy alluvial deposits) in the studied profiles suggests that some organic matter may be fluvial derived. However, in these cases, soil is thought to drive the biogeomorphic succession at plant and community level: the accumulation of organic material during the geomorphic phase and the later decomposition during the pioneer and biogeomorphic phase are thought to improve local ambient conditions (dashed orange line in Figure 40); in turn, locally more rapid biogeomorphic succession occurs and through the development of roots, this may increase landform resistance to erosion during floods. However, the fact that the groundwater distal zones remain more active suggests that this process does not occur sufficiently (either rapidly in time, or coherently in space) to counter the effects of disturbance (Chapter 5).

In the groundwater upwelling reach, where water is available all year round, vegetation does not rely on the water and nutrient retention capacity of the soil, as the ground water connectivity facilitates plant establishment (Boulton et al., 1998; Harner and Stanford, 2003; Mouw et al., 2009). Consequently, vegetation develops at higher rates, increasing fluvial landform stability via their attachment and leading to a more stable overall river morphology (Chapter 5).

Overall, this highlights the dependency of the first three phases of the biogeomorphic succession on the interplay between soil (organic matter) processes and (ground-) water availability to facilitate the progress of the biogeomorphic succession at higher rates than the disturbance frequency, thus allowing greater stability as a function of time.

7 Conclusions of the thesis

Recent research has fruitfully considered the short term and/or small spatial scale interactions between ecological processes and braided river morphodynamics (e.g. Corenblit et al., 2011; Gurnell, 2016; Gurnell et al., 2012). This ranged from studies addressing bar root reinforcement by vegetation (e.g. Pasquale et al., 2012, 2014; Pollen, 2007; Polvi et al., 2014; Sprackling and Read, 1979; Tron et al., 2015), to the recruitment and establishment of pioneer plants in braid-plains (e.g. Corenblit et al., 2014, 2016; Francis, 2007; Karrenberg et al., 2002; Mahoney and Rood, 1998; Moggridge and Gurnell, 2010; Picco et al., 2016). A second research field has focused on understanding feedbacks between vegetation dynamics and river morphodynamics at the decadal and river channel pattern scales. This was mainly achieved by tracing river channel change and river pattern evolution via remote sensing data (Beechie et al., 2006; Bertoldi et al., 2011; Kondolf and Curry, 1986; Picco et al., 2014; Zanoni et al., 2008) and/or flume model studies (e.g. Ashmore, 2013; Bertoldi et al., 2015; Hicks et al., 2007; Tal and Paola, 2010), and the subsequent correlation of these observation with changes in boundary conditions (sediment supply and hydrology).

The recent conceptual model of biogeomorphic succession proposed by Corenblit et al. (2007, 2014) has been a major contribution to the bridge between studies of braided river processes and studies of longer term morphodynamics and channel pattern changes. The validation of this model and the integration of further relevant ecosystem components is still in progress (e.g. Corenblit et al., 2014, 2016; Gurnell, 2016). Soils have been observed on vegetated patches in braided rivers, and these appear to form within a few decades (Bureau, 1995; Doering et al., 2011; Gerrard, 1987, 1995; Langhans et al., 2012; Mardhiah et al., 2014; Viereck et al., 1993). Similarly, access to groundwater has shown to influence vegetation growth rates (Boulton et al., 1998; Harner and Stanford, 2003; Mouw et al., 2009). This study aimed to consider the role and nature of soil development on biogeomorphic succession (at both plant community and population level; Corenblit et al., 2007, 2014) and how this relates to groundwater access.

7.1 Key research findings

After a review proposed in chapter 2, three research question were formulated and the summaries below responds to them

I) **To what extent is pedogenesis able to influence the rates of biogeomorphic succession? Is it actively involved in the succession process or is it a passively adaptive process that follows from stabilisation of the river deposits?**

The soil chronosequence approach in Chapter 4, showed the importance of considering alluvial soil organic matter and sedimentary environment as part of the biogeomorphic succession at both plant community and population level (Corenblit et al., 2007, 2014) in braided floodplains (Figure 18 page 73)."

Fine-grained deposits have higher water and nutrient retention, favouring plant establishment and thus local biomass production for initial soil formation, if not excessively disturbed. Here, we consider soil processes as passively involved in biogeomorphic succession. However, deposition process may also add organic matter-enriched material. This can be facilitated by plant induced sediment trapping. The humification of this material may add important resources (e.g. nutrients) and ameliorates local ambient conditions (e.g. water retention) for the first biogeomorphic phases. With fluvial supply of organic matter, initial soil processes, such as humification, can thus potentially act independently from in-situ biomass production. Consequently we argue that soil processes are proactive in biogeomorphic succession. However, the variability in soil states appears to be large and, as illustrated in Chapter 6, this variability is related to groundwater accessibility and to the geomorphological setting of deposits.

II) **To what extent does groundwater influence biogeomorphic succession performance and thus morphological stability at the reach scale?**

A dendroecological analysis of young willows growing on fluvial deposits was undertaken, making use of upstream to downstream variability in morphological change and the groundwater-depth gradient of the Allondon River (Chapter 5).

The analysis of tree ring derived willow growth rates showed that groundwater strongly influences moisture availability for plant growth. This can be attributed to: the location of the Allondon River in a temperate region, with important summer droughts; and the dominance of freely draining gravel substrates. Where the groundwater table is lower in altitude and more variable, plants can survive only along the main channel, where laterally river water reduces moisture stress. Away from the river channels, water stress was found to lead to lower willow establishment and slower biogeomorphic succession. The result is more patchy vegetation development, and this is likely to lead to spatially-variable rates of deposit stabilisation,explaining why the remotely sensed imagery suggested a more dynamic active channel.

Conversely for the groundwater proximal sites, water was not found to limit growth rates, suggesting that propagules can successfully establish on most undisturbed surfaces. A more rapidly-evolving plant cover leads to more spatially extensive vegetation development and this is likely also to lead to greater resistance to fluvial disturbance. The higher rate of biogeomorphic succession may explain why the groundwater proximal sites now contain much more stable zones, often in the latest phase of biogeomorphic succession.

III) How does the interplay between soil formation and groundwater availability influence biogeomorphic succession?

The interactions between soil development and access to groundwater were assessed in Chapter 6. Water access appears as a key control upon the biogeomorphic succession rate in gravelly environments. Hence, following results in Chapter 5, proximity to groundwater may alleviate potential water stress and guarantee a higher plant colonisation rate. Soil evolution appears in this case to follow the biogeomorphic succession. In groundwater distal sites, Chapter 6 suggested that water stress could be compensated for by soil forming processes, in conjunction with the deposition of riverine fine sediment and organic matter, to improve local water retention capacity. Soil forming processes improve local edaphic conditions allowing plant establishment rates that stabilise river deposits. In turn, if this stabilisation is sufficiently rapid, at a rate that is great enough to introduce additional stability before the next disturbance, then biogeomorphic succession may occur. However, these feedbacks are locally confined to abandoned channels, such as due to an avulsion upstream, even if they may become channel connected during higher flows.

7.2 Future research needs

Chapter 4 and 6, followed other authors (e.g. Cabezas and Comín, 2010; Doering et al., 2011; Naegeli, 1997; Tockner et al., 2006), in suggesting that fluvial processes can locally increase humification rates by delivering fine sediment and organic matter and thus facilitate plant establishment and growth under groundwater distal conditions. In this case, the presence of this process was inferred from some profiles having M layers rich in fine sediment and organic matter. However, organic matter supply during higher flow events was not measured directly. This needs to be addressed through multi-year monitoring. Doering et al. (2011) monitored soil and sediment respiration for different biogeomorphic succession stages at the braided Tagliamento River (IT). Soil respiration can be seen as a non-destructive method for measuring mineralisation activity. Combining a continuous soil respiration monitoring of different biogeomorphic succession stages in different geomorphic settings with the installation of, for instance, deposition pins (similar to erosion pins), a better quantification of the impact of geomorphic processes on soil evolution could be achieved. The fresh deposits could be directly analysed after deposition in terms of organic matter content and grain size distribution. Similarly, the set of different soil layers could be analysed at the end of the monitoring period. Additionally fresh aerial organic inputs from the surrounding vegetation could be monitored (trapped and quantified; Langhans et al., 2012). Measuring plant input in relation to the fresh organic matter content of the added deposits and the soil respiration data, may spatially and temporally differentiate between the importance of the different organic matter sources for local soil development. Additionally recent plant growth rates could be assessed via ring width and plant size measurement, and give an indication about the evolution of the local edaphic conditions. However, there will be a dependence of the experimental design upon high flow occurrence. Artificial “flooding” could be considered (e.g. adding fluvial organic enriched fine sediments manually) at least to allow evaluation of the soil processes that follow from fluvial, or other, inputs.

At a larger scale, the analysis of the organic matter sources and hydrological drivers of the locally deposited organic matter would be a step forward in understanding the catchment wide dependency of soil development. As suggested by Tabacchi et al. (1998) rivers are a downward link in the flux of matter, with the upper catchment acting as a resource while the lower braided sections act generally as sinks. Thus there is a dependency of vegetated landforms in braided sections on catchment scale processes (climate change, land use changes) that goes further than considering only its hydrology and sediment supply.

In Chapter 5 a hypothesis is advanced for the influence of groundwater-depth on the stabilising effect of roots. Resent research has suggested that roots affect fluvial landform stability (e.g. Pollen, 2007; Polvi et al., 2014). On the other hand a link between groundwater-depth and root distribution in soil/sediment has been reported (e.g. Imada et al., 2008; Pasquale et al., 2012; Tron et al., 2014). The northern groundwater distal reach of the Allondon River, provides a strong gradient in access to water, with easier access next to the channel and poorer access at more distal locations (deep groundwater). With increasing distance from the channel, lateral fluxes of water will have less impact, and roots are likely to have to extend to deeper layers. This may reduce fine root density in the upper reworkable layer, and so decrease the degree of additional bank cohesion, thus affecting erodibility. Henriod (2016) measured root-added (apparent) bank cohesion in this reach. Preliminary results along this water gradient, showed a decrease in apparent cohesion with increasing distance from the channel. However, further work is need to validate this relationship. Additionally a dendroecological analyses similar to the one propose in chapter 5, could be added and investigate the water dependency of plant growth with increasing distance to the channel. Such an approach closes the gap between long term morphological monitoring (e.g. Bertoldi et al., 2009; Gurnell and Petts, 2002; Zanoni et al., 2008) and short term studies on ecosystem feedbacks (e.g. reviews of Corenblit et al., 2011; Gurnell, 2014; Gurnell et al., 2012).

However, more sophisticated techniques could be explored to address the questions above. Electrical resistivity analysis (ERT) was only be used marginally in this study (Chapter 4.2), but could potentially add some valuable information. Amato et al. (2008) and Zenone et al. (2008), for instance, propose the use of ERT to characterize below ground root biomass and structure. Especially in low water retaining gravelly environments, this technique could be very valuable. As a second advantage, the ERT profiles allow assessment of the site specific groundwater-depth. Samouëlian et al. (2005), proposes the use of ERT for soil science. Its possible application here could be related in delineating the spatial distribution of the buried soil, thus ameliorating our understanding of past soil distribution, its fluvial landform specific spatial distribution and related aggradation rates.

The dendrochronological analysis presented in Chapter 5 is based on a large data set of trees, covering the entire range of biogeomorphic succession stages and floodplain gradients. This could potentially be used for a detailed dendrogeomorphological reconstruction of fluvial deposits. Although most samples did not show scars and wounding that could be used for dating disturbances, the buried soils testify site-specific aggradation rates. Thus, by re-examining the samples for the presence of tension wood, eccentricity and growth anomalies, in combination with information on changes plant exposure to riverine processes in time obtained from sequential aerial imagery, detailed dating of burial events might be achieved (e.g. Bayard and Schweingruber, 1991; Ruiz-Villanueva et al., 2010). This may potentially also allow dating of soil formation periods between two burying events.

In terms of geomorphological evolution, although, historical aerial images for photogrammetric use were available for the Allondon River, their resolution in relation to the relief of the Allondon river was not sufficient (Lane et al., 2010). Larger braided river systems such as the Maggia (Switzerland) or Tagliamento (Italy), with larger fluvial landforms and topographic changes would allow a better use of such historic information.

Finally, testing, comparing and combining the research findings presented here with other sites would allow the construction of a more generally validated model. Observations on the braided gravel bed rivers Maggia (Switzerland - Bayard and Schweingruber, 1991; Malaguerra, 2015; Molnar et al., 2008) and Tagliamento (Italy - Gurnell, 2016; Mardhiah et al., 2014) suggest a similar functioning to the Allondon River. In the large braided gravel bed river Tagliamento (Italy), Mardhiah et al. (2014) studied soil aggregate formation along the biogeomorphic succession. Generally, aggregate formation was reported to be very high if compared to other ecosystems which indicates high rates of soil formation in braided rivers, and thus shows the importance of considering soils in such dynamics systems. Moreover, for the same river, Gurnell (2016) suggests similar results on the groundwater-depth and pioneer plant-growth relationship found here, as vegetation growth rates appear to be related to upwelling or downwelling reaches.

For the Maggia River (Switzerland), a series of buried soils (Bayard and Schweingruber, 1991, Bureau, 1995) that developed under braided geomorphological dynamics (Malaguerra, 2015; Molnar et al., 2008) have been described. Dendroecological dating of scars, wounds, root exposure and tree ring eccentricity was used to reconstruct the aggradation/soil burial and disturbance history of different fluvial landforms (Bayard and Schweingruber, 1991), which indicate similar developmental time ranges as for the Allondon. However, in comparison to the Allondon, the Maggia River is located in a carbonate free catchment, and although the organic matter dynamics are suggested to be similar, physico-chemical processes linked especially to weathering and associated products are different for pedogenic processes (Bureau, 1995). Overall, this suggests a possible similar functioning (Figure 6 page 35) of the Allondon, Tagliamento and Maggia River. Applying comparable approaches to a wider selection of braided rivers in ideally a “braided river observatory” network, would enlarge our understanding of soil evolution and groundwater dynamics, and more generally of ecosystem processes, affecting the biogeomorphic succession.

Moreover, alluvial fans and proglacial braided sections show similar geomorphic dynamics to lowland braided rivers. A preliminary study on an alluvial fan in Alpine environment (Arolla, Switzerland), indicate a decoupling of soil and vegetating succession (Bätz and Lane, 2015). Abandoned channels allowed rapid colonisation by pioneer plants, due to the higher availability of water. In contrast, humification may be limited by temperature, but also by the nutrient poor snow and glacier meltwaters. Such approaches allow assessment of the overall validity of our understanding in similar systems (Corenblit et al., 2015), but also exploration of the range of limiting factors for certain feedbacks (e.g. climate, position along the river continuum).

The highly dynamic and complex character of braided rivers challenges the study of ecological processes involved in the biogeomorphic succession at the decadal scale. Many of these can be considered as “hidden” because they influence fluvial systems at lower rates than geomorphic processes (e.g. erosion and deposition) and/or are not as visually evident as geomorphic changes. However, these processes influence the biogeomorphic succession. Here we studied the influence of soil evolution and groundwater access on the biogeomorphic succession, by combining approaches from geomorphology, soil science and dendroecology to trace the coupled development of the river-floodplain system in terms of both physical and biogeochemical processes. More multidisciplinary approaches have the potential to unravel such “hidden” processes and create a better comprehensive process based understanding of fluvial system behaviour. This better understating will help in countering poor decision-making (Vaughan and Ormerod, 2010) by accounting for multiple environmental components and related feedbacks, and thus better support the management, protection and restoration of braided river sections within landscapes under increasing pressure due to growing multifunctional demands (e.g. Girel et al., 2003).

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Annex A

Depth, thickness and grain size distribution for each sampled horizon/sedimentary layer. Distance and elevation from the river (H-River) are also shown in this table.

Samples	Depth (cm)	Thickness (cm)	Clay (%Vol.)	Silt (%Vol.)	F. sand (%Vol.)	M. sand (%Vol.)	C. sand (%Vol.)	Stones (%Vol.)	Distance channel (m)	H-river (m)
21Ah1	3.00	6	14.6	38.2	24.6	14.1	8.6	0	48	2.18
21Ah2	21.00	18	12.9	34.8	26.7	18.3	7.4	40	48	2.06
21C1	27.00	6	7.1	21.2	22.2	27.6	21.9	50	48	1.94
21C2	38.00	17	9.7	30.3	15.9	19.8	24.2	40	48	1.83
21C3	52.00	11	6.3	22.7	16.6	28.1	26.3	80	48	1.69
21C4	63.00	10	7.4	24.1	13.8	23.1	31.6	40	48	1.58
21C5	75.00	18	13.2	44.7	19.5	10.7	11.8	30	48	1.44
21C6	92.00	14	9.8	29.7	14.0	17.0	29.5	80	48	1.28
21C7	103.00	10	10.3	31.6	19.3	22.7	16.1	40	48	1.11
22AhI	4.00	7	7.8	28.8	34.6	21.4	7.4	0	55	0.80
22AhII	14.00	13	8.5	21.8	32.7	27.8	9.1	0	55	0.69
22C	27.00	15	5.4	20.5	15.6	30.2	28.4	30	55	0.55
22Ahb	43.00	14	22.9	40.1	18.7	13.9	4.5	0	55	0.40
22C1	55.00	12	7.7	22.2	7.9	19.2	42.9	45	55	0.27
22C2	66.00	7	8.5	24.9	10.3	15.7	40.6	30	55	0.18
22C3	72.00	8	8.7	24.5	11.1	11.4	44.4	45	55	0.10
22C4	78.00	6	6.6	20.6	8.5	16.3	48.1	30	55	0.03
22C5	87.00	8	10.9	36.5	21.2	13.2	18.2	45	55	-0.04
22C6	95.00	10	6.8	19.0	7.9	20.6	45.6	30	55	-0.13
22C7	105.00	10	6.1	18.7	8.4	24.3	42.6	75	55	-0.23

22C8	110.00	10	8.5	25.9	11.8	14.4	39.4	75	55	-0.33
31Ah1	4.00	7	12.9	32.0	31.6	17.9	5.6	0	21	0.71
31Ah2	10.00	10	14.9	37.5	24.5	15.5	7.5	70	21	0.65
31C1	25.00	8	8.4	21.4	16.0	30.6	23.6	70	21	0.50
31C2	35.00	18	9.5	24.1	12.2	23.9	30.4	70	21	0.40
31Ahb(C)	55.00	8	12.5	27.1	14.8	25.9	19.9	50	21	0.20
31Ahb	40.00	8	10.2	23.7	33.1	26.2	6.8	50	21	0.35
32A	5.00	7	13.6	39.2	30.2	11.9	5.2	50	55	0.85
32C1	35.00	28	6.1	19.5	25.3	32.1	17.0	70	55	0.53
32C2	17.00	10	6.4	18.6	26.1	28.3	20.6	70	55	0.71
33A	5.00	10	14.6	39.2	24.7	15.4	5.9	5	84	1.26
33C1	26.00	24	11.2	32.3	27.1	19.8	9.7	80	84	1.05
33C2	56.00	12	8.1	26.3	16.7	27.1	21.7	70	84	0.75
34AhI	5.00	5	22.2	42.6	25.5	7.3	2.5	2	108	1.10
34AhII	15.00	15	15.7	41.3	27.1	10.9	5.1	2	108	1.00
34C	25.00	9	8.0	18.6	15.2	29.6	28.6	40	108	0.90
34Ab1	35.00	19	13.7	30.1	25.9	19.8	10.6	0	108	0.80
34Ab2	40.00	9	10.7	25.9	23.2	24.0	16.2	0	108	0.75
34C1	50.00	5	5.1	16.4	16.7	31.2	30.6	80	108	0.65
34C2	75.00	30	6.3	22.6	16.8	22.4	31.9	80	108	0.40
41A	3.00	5	20.0	41.1	20.0	11.2	7.6	70	52	1.07
41C1	15.00	21	9.4	22.9	11.5	14.9	41.2	70	52	0.95
41C/Go	32.00	18	9.7	24.7	21.0	26.3	18.3	90	52	0.75
41C/Gr	53.00	23	5.3	12.9	17.7	37.7	26.3	70	52	0.55
42Ai(M)	5.00	5	13.3	32.0	44.4	8.0	2.3	0	28	1.54
42M	16.00	22	11.2	27.7	50.9	9.1	1.1	0	28	1.43
42C1	32.00	14	11.1	24.6	9.2	16.7	38.5	30	28	1.28
42Ahb	40.00	4	16.2	35.5	27.9	11.9	8.5	30	28	1.19
42C2	49.00	17	16.4	36.5	12.4	7.0	27.7	50	28	1.10

42C/Ahb	67.00	14	12.0	24.0	29.6	24.5	9.9	70	28	0.92
42C3	77.00	15	13.8	24.8	12.9	22.7	25.9	70	28	0.82
43C1	3.00	5	10.8	26.7	14.9	16.5	31.1	70	13	0.96
43C2	15.00	15	10.1	22.8	12.6	19.5	35.0	70	13	0.83
51(Ai)	5.00	5	16.4	29.1	31.2	15.9	7.5	0	10	0.81
51C1	5.00	5	9.2	19.5	38.1	26.5	6.6	0	10	0.81
51C2	35.00	30	9.6	20.0	18.2	26.3	25.9	70	10	0.81
52C	10.00	20	13.8	28.8	26.7	19.6	11.0	40	34	1.35
52Ab	25.00	10	15.2	30.0	27.2	16.8	10.8	0	34	1.20
52C1	42.00	27	14.2	35.4	17.0	10.6	22.8	60	34	1.02
52C2/Ab	70.00	10	28.4	38.7	11.5	10.8	10.7	80	34	0.75
53A	3.00	5	17.2	33.1	41.2	6.2	2.2	0	45	1.74
53C2	30.00	23	15.8	33.0	14.2	16.2	20.7	80	45	1.46
53C3I	45.00	5	14.0	30.4	15.4	14.8	25.3	80	45	1.31
53C3II	82.00	40	8.9	21.7	18.6	23.1	27.6	80	45	0.94
54Ah	2.00	4	11.9	31.7	36.2	14.0	6.3	40	80	1.41
54CI	20.00	16	10.3	23.0	10.7	14.3	41.6	50	80	1.15
54CII	50.00	46	8.2	21.5	8.8	20.5	41.0	50	80	0.93
55Ai	3.00	6	11.8	28.7	33.5	16.5	9.4	0	96	1.20
55MI	17.00	11	13.1	27.2	28.6	21.6	9.5	5	96	1.06
55MII	27.00	21	16.5	31.0	28.3	16.4	7.8	5	96	0.96
55M/Ahb	38.00	6	19.4	33.5	26.7	12.8	7.5	0	96	0.85
55C/Go	47.00	9	18.5	38.5	13.9	8.0	21.0	50	96	0.76
55(Gr)Ab/C	53.00	8	16.8	32.9	25.8	16.2	8.3	60	96	0.70
16Ai	3.00	3	10.1	26.2	41.9	17.1	4.7	0	20	1.07
16M1I	14.00	14	12.6	30.1	36.9	15.4	5.0	0	20	0.96
16M1II	22.00	8	12.7	31.4	34.5	15.9	5.5	0	20	0.88
16M1III	36.00	14	12.4	27.7	46.1	12.0	1.8	0	20	0.74
16C1	52.00	16	7.3	19.0	21.7	25.3	26.7	10	20	0.58

16Ahb	60.00	8	11.3	24.1	41.0	19.4	4.2	0	20	0.50
16C2/M2	62.00	2	6.3	17.1	39.9	25.2	11.5	2	20	0.48
16Ahb	75.00	13	11.3	24.8	39.1	17.9	6.9	0	20	0.35
16C3/M3	82.00	7	6.9	18.3	29.5	21.9	23.3	0	20	0.28
16C4I	92.00	10	13.6	31.5	36.0	10.3	8.6	40	20	0.18
16C4II	106.00	14	10.5	26.8	35.4	16.4	10.9	40	20	0.04
16C6/Ahb	120.00	14	8.2	19.6	40.9	24.6	6.7	80	20	-0.10
15AhI	5.00	5	18.4	35.8	31.7	8.1	5.9	0	11	0.25
15AhII	9.00	4	19.9	37.4	24.6	10.3	7.8	0	11	0.21
15M	13.00	4	5.8	15.3	19.7	32.1	27.2	0	11	0.17
15C1	23.00	10	6.9	18.0	28.3	31.4	15.3	50	11	0.07
15C2	30.00	7	6.8	17.1	13.1	29.5	33.5	80	11	0.00
15C3	47.00	17	7.4	19.8	26.9	28.9	17.0	80	11	-0.17
15C4	70.00	23	6.5	18.4	11.6	21.9	41.5	60	11	-0.40
11Ah	5.00	5	19.0	46.2	18.8	7.1	8.8	20	124	2.45
11Ah	17.00	12	21.6	46.5	18.6	6.7	6.6	20	124	2.33
11CI	35.00	18	9.2	22.9	22.9	23.0	22.0	40	124	2.15
11CII	60.00	25	5.5	15.6	28.5	31.6	18.8	40	124	1.90
12Ah1	5.00	5	20.4	41.3	26.6	5.4	6.3	5	66	2.25
12Ah2	22.00	17	17.9	42.2	29.4	5.4	5.1	15	66	2.08
12M	53.00	31	8.1	25.4	51.0	12.2	3.3	5	66	1.77
12C1I	80.00	27	7.2	17.3	30.7	27.0	17.8	50	66	1.50
12C1II	107.00	27	11.2	25.7	34.8	18.2	10.0	50	66	1.23
12AhbI	125.00	18	21.5	41.0	24.4	7.4	5.7	50	66	1.05
12AhbII	130.00	5	21.6	41.0	21.5	7.7	8.1	50	66	1.00
12C2I	137.00	7	17.8	34.8	18.2	14.5	14.7	50	66	0.93
12C2II	170.00	33	22.2	34.7	11.8	12.2	19.0	50	66	0.60
13AhI	5.00	5	18.7	36.8	21.9	12.9	9.7	20	178	3.65
13AhII	15.00	10	18.3	36.0	20.9	13.4	11.4	20	178	3.55

13AhC1	24.00	9	8.8	22.6	20.6	22.8	25.2	30	178	3.46
13C2I	45.00	21	6.7	19.6	15.6	26.0	32.1	90	178	3.25
13C2II	63.00	18	7.8	21.9	38.8	18.7	12.9	50	178	3.07
14(Ai)C1	4.00	4	10.9	34.5	20.1	18.8	15.8	0	62	0.36
14C1	18.00	14	6.3	17.5	11.1	26.5	38.5	40	62	0.22
14C2	28.00	10	5.7	15.3	9.9	25.4	43.7	40	62	0.12
14C3	55.00	27	8.2	17.2	8.3	20.6	45.7	70	62	-0.15
14C4	72.00	17	7.0	18.4	9.8	21.1	43.8	30	62	-0.32
14C5	82.00	10	5.7	18.3	12.3	20.1	43.6	70	62	-0.42

Annex B

Organic matter quality for each sampled horizon/sedimentary layer based on the Rock-Eval method and related root density.

Samples	TOC (%mass)	MINC (%mass)	HI (mgHC/ g TOC)	OI (mgCO^2/ g TOC)	TpS2 (°C)	A1 (%TOC)	A2 (%TOC)	A3 (%TOC)	A4 (%TOC)	A5 (%TOC)	R-Index	I-Index	Root density (n/dm^2)
21Ah1	6.70	2.70	202	242	367	19.57	26.44	25.85	23.13	4.69	0.54	0.25	4
21Ah2	3.83	3.50	175	259	458	17.66	24.45	26.80	25.20	5.35	0.57	0.20	12
21C1	0.11	4.16	140	422	468	17.53	13.35	16.28	23.03	20.35	0.60	0.28	7
21C2	0.14	4.37	99	413	470	16.38	14.35	17.85	24.22	19.05	0.61	0.24	2
21C3	0.13	4.42	117	550	467	18.48	12.69	15.31	22.04	21.41	0.59	0.31	2
21C4	0.22	4.12	94	321	421	15.97	14.56	20.25	23.62	17.93	0.62	0.18	0
21C5	0.06	4.58	134	579	519	19.10	11.78	13.19	21.29	23.27	0.58	0.37	1
21C6	0.10	4.61	114	422	430	17.59	13.28	15.49	22.65	21.31	0.59	0.30	0
21C7	0.14	5.07	114	430	474	16.71	14.12	16.97	24.30	19.36	0.61	0.26	0
22AhI	8.33	3.61	238	214	363	18.96	30.99	24.94	20.17	4.65	0.50	0.30	8
22AhII	0.75	3.93	139	269	459	12.70	21.34	27.49	27.83	8.70	0.64	0.09	3
22C	0.17	4.38	118	325	466	16.73	13.21	16.56	24.04	20.10	0.61	0.26	1
22Ahb	1.26	3.60	151	237	456	13.40	21.53	28.84	28.02	7.13	0.64	0.08	4
22C1	0.05	4.77	162	532	423	20.67	10.96	12.18	18.20	25.30	0.56	0.41	0
22C2	0.07	4.72	133	418	421	19.99	11.69	13.00	19.33	24.19	0.57	0.39	0
22C3	0.06	4.63	106	469	427	18.05	12.33	15.75	21.40	22.36	0.59	0.29	0
22C4	0.06	4.71	124	498	428	19.21	12.35	15.48	19.00	22.33	0.57	0.31	0
22C5	0.06	4.67	133	537	515	21.13	12.24	12.21	18.52	23.64	0.54	0.44	0
22C6	0.07	4.73	124	340	526	20.82	11.11	11.32	18.99	25.39	0.56	0.45	0
22C7	0.06	4.99	132	410	514	19.58	11.15	12.42	20.30	24.77	0.57	0.39	0
22C8	0.12	4.65	109	446	419	18.12	13.35	15.45	21.52	22.11	0.59	0.31	0
31Ah1	2.47	3.41	171	238	453	16.51	25.26	27.94	23.98	5.55	0.57	0.17	6
31Ah2	1.15	3.91	162	244	445	14.80	22.71	27.83	25.64	7.33	0.61	0.13	5

31C1	0.13	4.92	120	394	444	16.26	13.91	18.48	23.78	19.45	0.62	0.21	0
31C2	0.07	4.74	124	531	477	18.08	13.95	15.60	22.50	20.79	0.59	0.31	0
31Ahb(C)	0.36	4.76	123	273	463	13.54	18.31	23.95	27.28	12.77	0.64	0.12	4
31Ahb	0.51	3.70	114	292	446	12.34	20.89	28.38	26.58	9.71	0.65	0.07	5
32A	5.06	2.99	240	222	366	20.12	30.50	24.69	20.07	4.37	0.49	0.31	18
32C1	0.15	4.77	112	359	445	16.65	15.72	19.27	22.85	17.78	0.60	0.23	5
32C2	0.25	4.56	101	335	468	14.27	16.54	22.42	26.33	14.92	0.64	0.14	5
33A	8.80	3.47	218	224	373	16.66	28.69	26.03	23.23	5.15	0.54	0.24	9
33C1	0.46	4.53	125	301	458	13.81	19.23	25.83	26.82	11.06	0.64	0.11	0
33C2	0.10	4.63	105	585	443	17.98	12.55	15.15	22.45	21.71	0.59	0.30	2
34AhI	3.57	3.41	189	226	454	15.88	24.81	28.11	25.30	5.42	0.59	0.16	6
34AhII	2.16	3.68	163	245	454	15.79	23.76	28.19	25.22	6.15	0.60	0.15	6
34C	0.26	4.53	95	284	463	13.45	15.11	22.24	27.58	16.17	0.66	0.11	1
34Ab1	0.81	3.84	159	278	456	13.26	20.43	28.32	28.21	8.16	0.65	0.08	4
34Ab2	0.54	4.22	141	268	459	13.87	20.05	27.10	26.99	9.38	0.63	0.10	4
34C1	0.09	4.74	150	404	429	17.05	13.09	16.70	23.64	20.33	0.61	0.26	0
34C2	0.16	4.58	70	465	473	18.92	13.10	14.41	21.10	21.69	0.57	0.35	0
41A	1.99	4.05	181	242	464	14.40	24.24	28.53	26.84	5.42	0.61	0.13	10
41C1	0.12	4.56	121	473	465	16.20	14.39	18.09	24.75	18.59	0.61	0.23	0
41C/Go	0.10	4.96	74	456	499	19.07	12.19	13.36	21.35	22.84	0.58	0.37	0
41C/Gr	0.16	4.38	96	453	474	17.06	13.42	16.63	23.74	20.18	0.61	0.26	2
42Ai(M)	2.22	3.70	174	242	421	16.66	25.03	27.25	23.56	6.64	0.57	0.18	15
42M	1.14	3.18	150	266	448	14.31	23.31	26.74	25.02	8.86	0.61	0.15	12
42C1	0.06	4.97	159	507	501	19.75	11.22	12.47	20.29	24.57	0.57	0.40	5
42Ahb	1.11	2.91	159	250	459	15.15	22.62	26.98	26.78	7.11	0.61	0.15	2
42C2	0.18	4.72	83	375	461	16.13	14.81	18.99	24.21	18.07	0.61	0.21	0
42C/Ahb	0.65	3.99	138	280	452	14.60	21.88	27.45	24.13	9.13	0.61	0.12	3
42C3	0.15	4.53	115	423	443	15.33	15.14	20.76	25.18	16.75	0.63	0.17	0
43C1	0.14	4.40	132	324	468	15.28	15.62	20.60	24.52	17.07	0.62	0.18	0

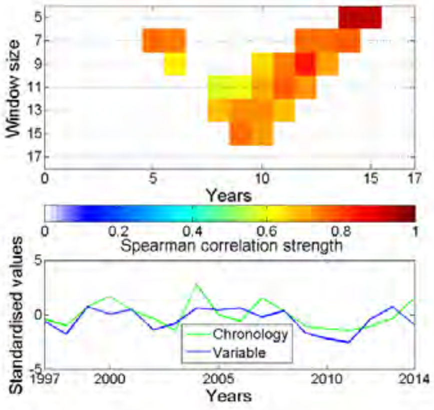
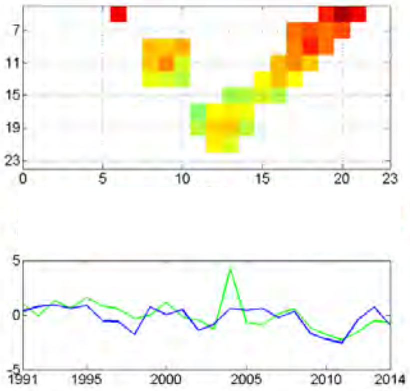
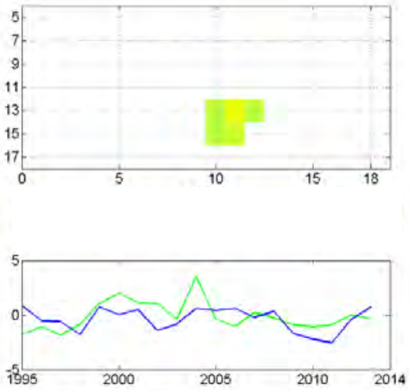
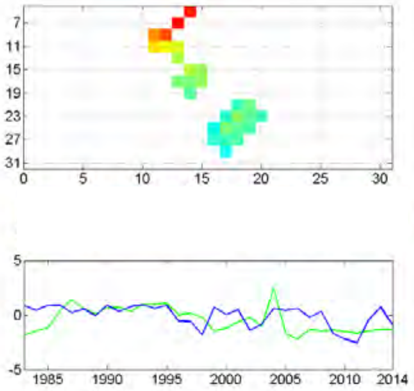
43C2	0.11	4.42	120	484	429	16.31	13.72	18.34	23.46	19.63	0.61	0.21	0
51(Ai)	1.45	3.62	165	272	461	14.32	22.88	28.89	26.99	6.03	0.62	0.11	2
51C1	0.44	3.79	127	281	460	13.04	18.59	26.55	27.31	11.24	0.65	0.08	0
51C2	0.14	4.52	138	407	423	14.37	15.75	21.68	25.80	16.22	0.64	0.14	0
52C	0.71	4.04	155	255	460	12.80	21.69	27.44	27.86	8.24	0.64	0.10	6
52Ab	1.65	3.99	184	229	451	15.76	24.97	26.82	24.77	6.57	0.58	0.18	11
52C1	0.31	5.07	147	331	468	11.54	17.39	26.84	30.70	10.33	0.68	0.03	3
52C2/Ab	1.82	4.39	213	221	454	16.03	22.62	29.60	26.24	4.89	0.61	0.12	4
53A	1.90	3.36	217	248	458	17.04	24.51	27.41	24.71	5.68	0.58	0.18	10
53C2	0.24	5.03	125	340	459	14.69	16.45	22.21	26.45	14.46	0.63	0.15	14
53C3I	0.08	5.00	133	365	417	17.85	12.67	15.29	21.91	22.29	0.59	0.30	5
53C3II	0.21	4.27	134	308	464	15.06	15.70	20.80	25.38	16.19	0.62	0.17	1
54Ah	10.25	2.90	268	190	369	18.50	29.24	25.94	21.84	4.19	0.52	0.26	12
54CI	0.06	4.94	161	724	425	19.44	11.33	14.34	19.04	24.18	0.58	0.33	0
54CII	0.05	4.28	162	555	515	19.20	11.62	12.39	20.52	24.54	0.57	0.40	0
55Ai	3.41	3.45	216	224	373	17.66	27.29	26.87	22.81	4.97	0.55	0.22	4
55MI	1.91	3.92	169	255	449	15.75	25.44	28.60	24.24	5.32	0.58	0.16	1
55MII	2.29	3.60	172	228	456	15.30	24.77	28.42	25.45	5.48	0.59	0.15	1
55M/Ahb	6.72	3.73	198	212	450	17.29	25.48	28.35	24.10	4.23	0.57	0.18	1
55C/Go	0.20	4.45	96	327	449	14.79	16.75	22.15	25.14	15.28	0.63	0.15	0
55(Gr)Ab/C	1.54	3.91	168	220	460	13.25	23.05	29.32	27.48	6.13	0.63	0.09	4
16Ai	5.02	3.19	202	213	369	22.03	29.17	26.60	21.58	4.91	0.53	0.28	2
16M1I	1.73	3.47	141	288	449	18.52	24.11	26.87	23.86	6.64	0.57	0.20	10
16M1II	1.28	3.39	124	299	449	17.42	21.95	26.94	25.36	8.32	0.61	0.16	10
16M1III	1.05	3.30	128	270	450	15.45	20.80	27.69	27.15	8.92	0.64	0.12	10
16C1	0.21	4.48	102	296	438	17.02	14.55	25.42	24.66	18.35	0.68	0.09	2
16Ahb	2.04	3.66	126	275	449	18.59	23.29	27.01	24.47	6.64	0.58	0.19	7
16C2/M2	0.40	3.93	99	317	440	18.15	17.40	23.86	25.52	15.07	0.64	0.17	7
16Ahb	2.75	3.82	133	275	439	18.77	24.05	27.52	23.73	5.93	0.57	0.19	4

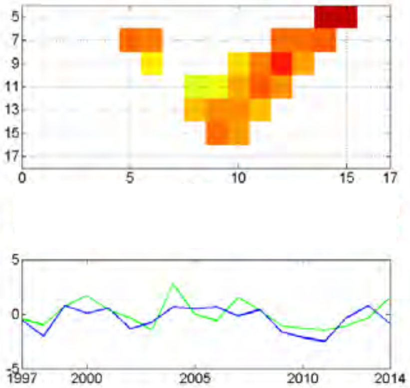
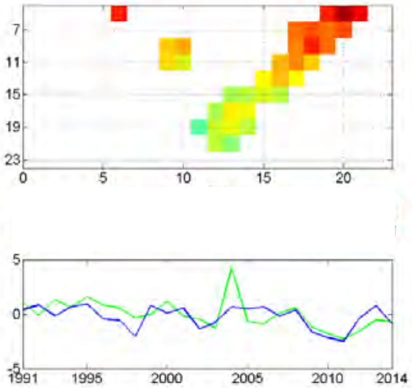
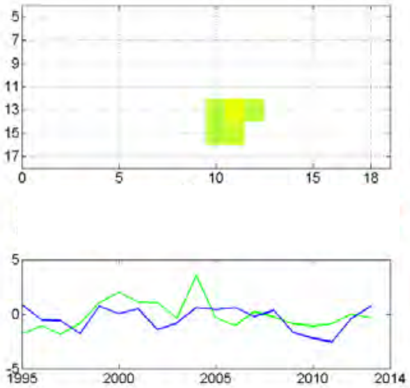
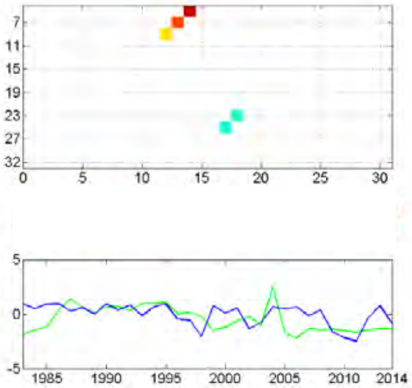
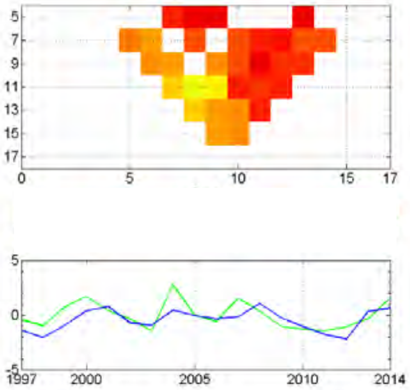
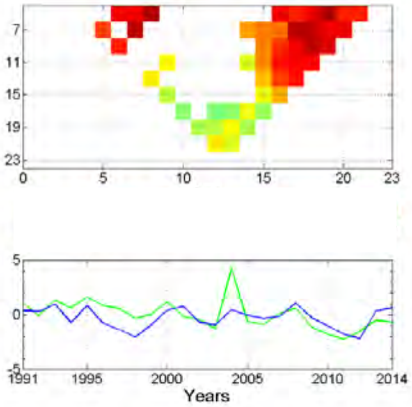
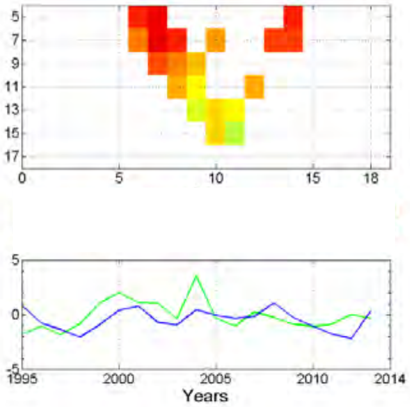
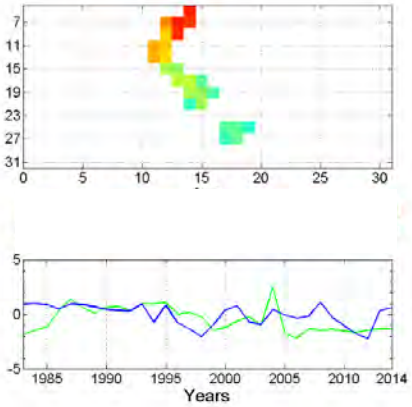
16C3/M3	0.13	4.64	91	395	444	21.47	14.45	18.50	21.88	23.70	0.64	0.29	4
16C4I	0.27	4.63	135	410	446	18.29	14.37	26.86	22.02	18.47	0.67	0.08	1
16C4II	0.30	4.45	114	351	442	18.65	16.16	22.41	25.82	16.96	0.65	0.19	0
16C6/Ahb	0.68	3.78	119	292	444	16.30	21.24	27.23	26.01	9.22	0.62	0.14	4
15AhI	1.86	3.51	176	297	453	18.21	24.02	27.19	24.18	6.41	0.58	0.19	10
15AhII	1.81	3.52	161	299	451	19.71	24.32	26.51	23.22	6.24	0.56	0.22	10
15M	0.10	4.03	145	490	446	19.67	15.76	19.13	24.40	21.04	0.65	0.27	4
15C1	0.22	3.84	121	392	449	19.56	16.58	21.31	25.32	17.23	0.64	0.23	0
15C2	0.07	4.25	214	721	429	19.75	12.81	20.99	22.87	23.58	0.67	0.19	0
15C3	0.28	3.73	117	378	439	19.61	17.37	23.95	23.65	15.41	0.63	0.19	3
15C4	0.04	4.36	230	807	428	23.26	12.66	16.38	21.34	26.36	0.64	0.34	0
11Ah	9.69	2.19	197	245	375	22.31	25.77	25.25	22.57	4.11	0.52	0.28	18
11Ah	3.99	2.34	216	307	463	21.62	24.11	25.77	23.86	4.65	0.54	0.25	18
11CI	0.09	4.56	107	575	435	20.94	13.46	18.46	22.73	24.41	0.66	0.27	1
11CII	0.06	4.21	130	610	424	21.56	12.98	16.86	22.00	26.59	0.65	0.31	1
12Ah1	4.29	2.94	171	341	453	22.07	23.25	26.14	23.36	5.18	0.55	0.24	18
12Ah2	3.21	3.22	157	354	457	20.42	22.40	26.38	25.21	5.58	0.57	0.21	7
12M	0.24	3.19	130	564	430	19.44	16.40	22.66	24.22	17.28	0.64	0.20	16
12C1I	0.14	4.05	126	593	430	20.28	14.58	22.06	22.76	20.32	0.65	0.20	7
12C1II	0.25	4.49	109	531	438	21.15	13.88	20.89	23.39	20.69	0.65	0.22	3
12AhbI	2.17	3.49	136	356	452	19.29	21.38	27.44	25.60	6.30	0.59	0.17	4
12AhbII	1.46	3.77	124	377	448	19.17	19.70	26.78	25.53	8.82	0.61	0.16	4
12C2I	0.18	4.65	159	532	432	21.85	14.49	22.45	22.40	18.82	0.64	0.21	0
12C2II	0.31	4.46	100	445	435	21.08	15.72	20.83	23.87	18.50	0.63	0.25	0
13AhI	13.09	0.87	213	223	374	22.87	25.15	24.23	23.17	4.59	0.52	0.30	9
13AhII	8.28	1.48	202	216	465	23.32	24.36	24.55	23.53	4.24	0.52	0.29	9
13AhC1	0.50	3.96	140	320	454	18.89	19.97	25.08	25.93	10.13	0.61	0.19	8
13C2I	0.14	4.16	99	421	439	18.71	15.60	21.03	25.31	19.36	0.66	0.21	2
13C2II	0.18	4.07	141	466	435	23.87	17.85	22.39	21.36	14.53	0.58	0.27	2

14(Ai)C1	0.32	4.17	137	351	453	16.72	18.35	26.09	27.23	11.61	0.65	0.13	0
14C1	0.08	4.24	236	965	426	26.49	15.84	18.76	19.26	19.65	0.58	0.35	0
14C2	0.08	4.42	138	430	434	22.25	12.31	16.75	20.36	28.34	0.65	0.31	0
14C3	0.12	4.32	126	577	403	34.34	14.73	14.33	17.44	19.16	0.51	0.53	0
14C4	0.04	4.06	204	664	429	22.03	12.45	18.88	21.72	24.92	0.66	0.26	0
14C5	0.06	3.99	145	404	430	22.79	12.48	16.41	20.68	27.64	0.65	0.33	0

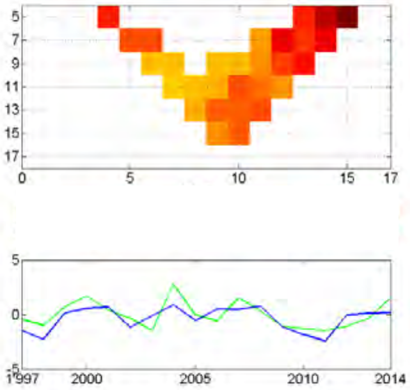
Annex C

Multi scale Spearman rank correlation approach for three variables (lines) and the four willow chronologies/units (columns). For each combination, a colored-square plot shows the strength of significant (α=0.05) correlations with varying window size along the chronology. Additionally, a line plot shows the evolution in time of the chronology and the related variable. Below the correlation indices (CorInd) and weighted correlation indices (CorInd^{w}) are plotted. Note the decline in correlation along the reach.

A	B	C	D
Max groundwater level during growing season	Max groundwater level during growing season	Max groundwater level during growing season	Max groundwater level during growing season
			
CorInd = 58.9 CorInd^{w} = 42.5	CorInd = 51.7 CorInd^{w} = 33.0	CorInd = 14.3 CorInd^{w} = 8.0	CorInd = 24.4 CorInd^{w} = 11.4

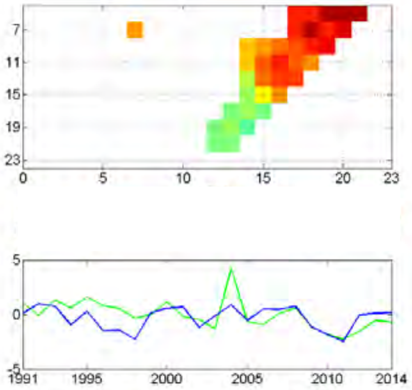
Max groundwater level during summer	Max groundwater level during summer	Max groundwater level during summer	Max groundwater level during summer
			
CorInd = 58.9 CorInd^{w} = 42.5	CorInd = 45.5 CorInd^{w} = 27.7	CorInd = 14.3 CorInd^{w} = 8.0	CorInd = 3.0 CorInd^{w} = 1.5
Min groundwater level during hydrological year	Min groundwater level during hydrological year	Min groundwater level during hydrological year	Min groundwater level during hydrological year
			
CorInd = 71.5 CorInd^{w} = 57.2	CorInd = 56.0 CorInd^{w} = 37.9	CorInd = 34.1 CorInd^{w} = 23.8	CorInd = 16.1 CorInd^{w} = 8.5

Min groundwater level during growing season



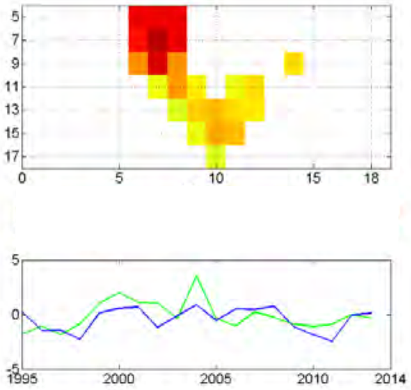
CorInd = 68.7 CorInd^w = 52.1

Min groundwater level during growing season



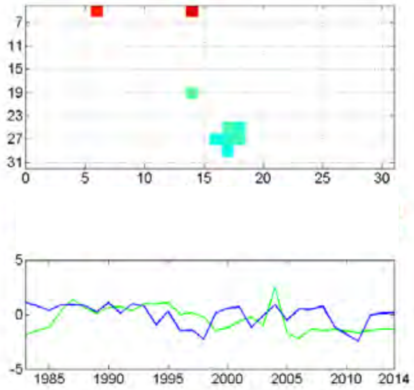
CorInd = 44.6 CorInd^w = 27.9

Min groundwater level during growing season



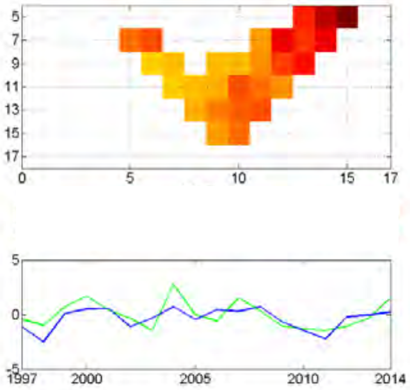
CorInd = 43.9 CorInd^w = 30.6

Min groundwater level during growing season



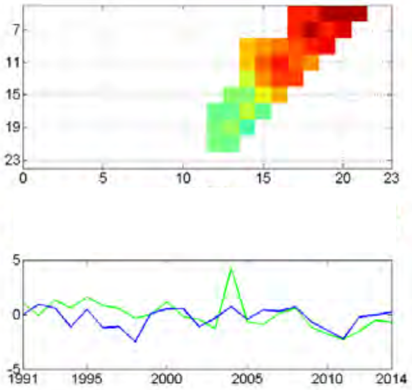
CorInd = 12.5 CorInd^w = 5.3

Min groundwater level during summer



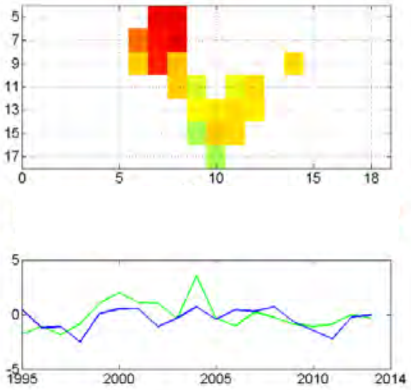
CorInd = 67.5 CorInd^w = 50.7

Min groundwater level during summer



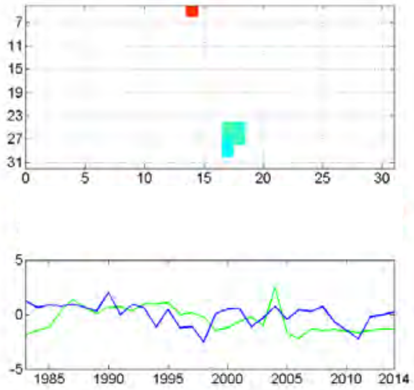
CorInd = 46.9 CorInd^w = 28.8

Min groundwater level during summer

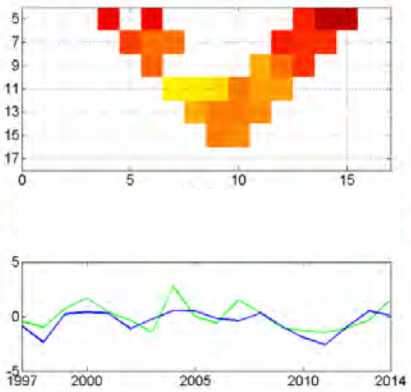
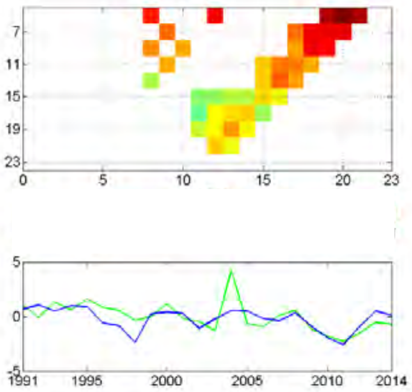
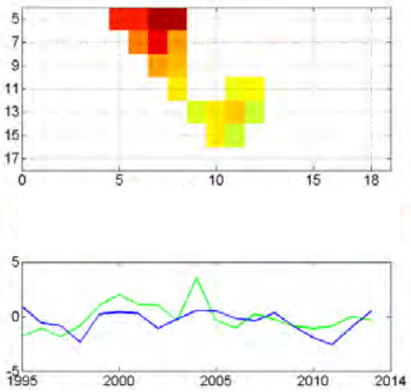
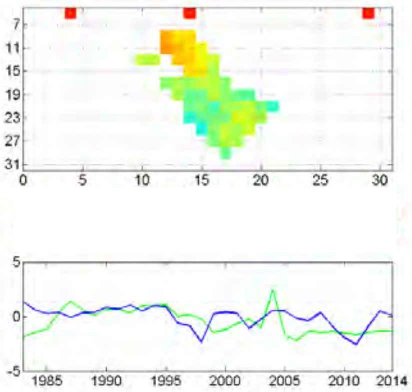
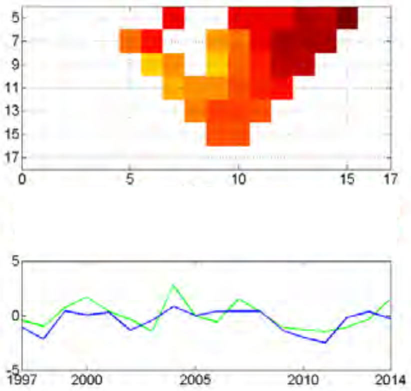
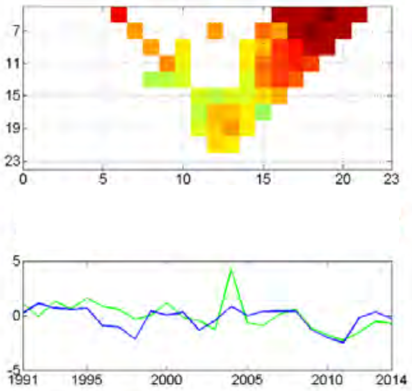
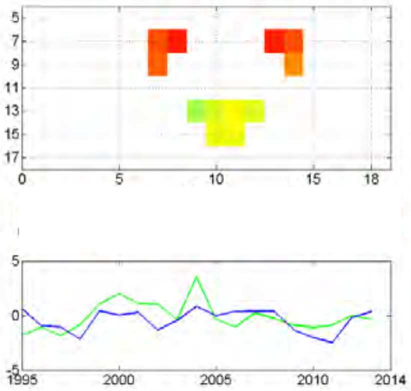
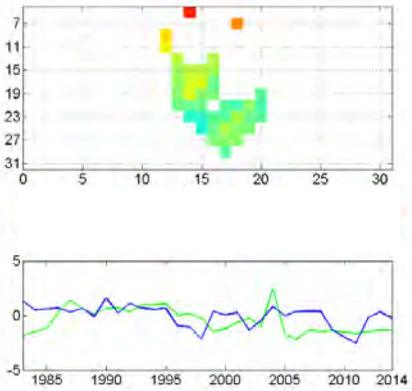


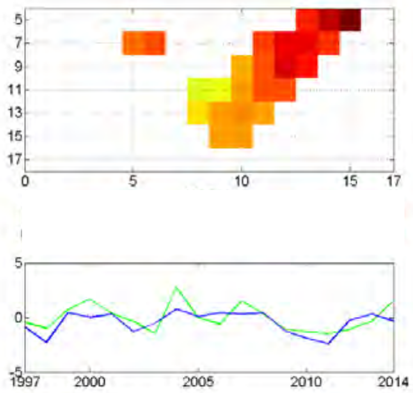
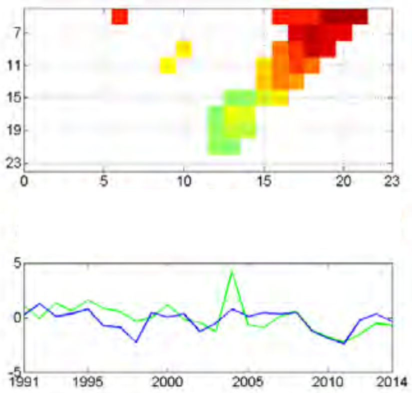
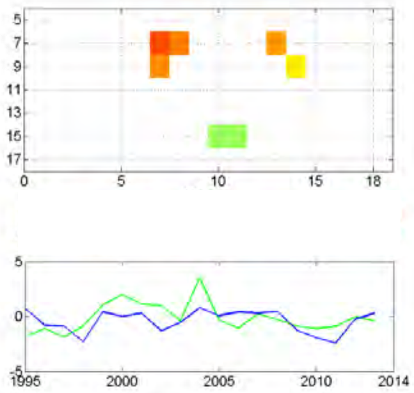
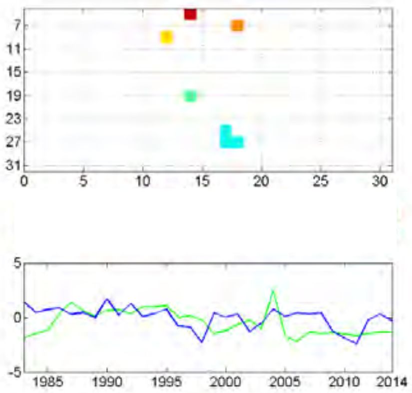
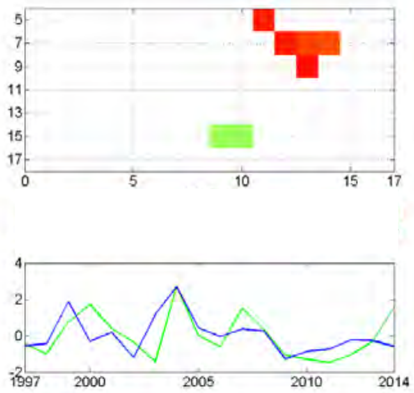
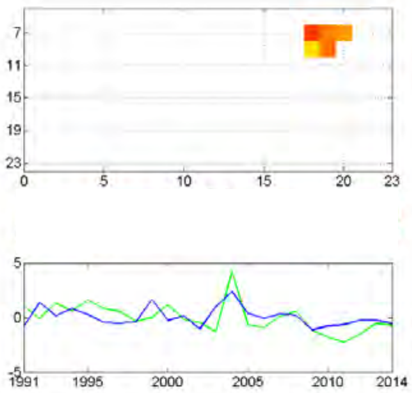
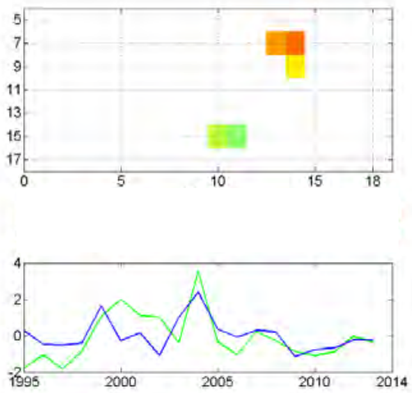
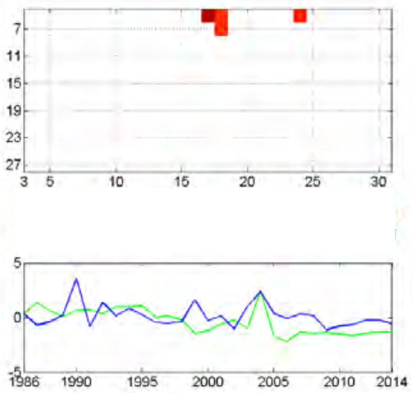
CorInd = 38.7 CorInd^w = 25.9

Min groundwater level during summer

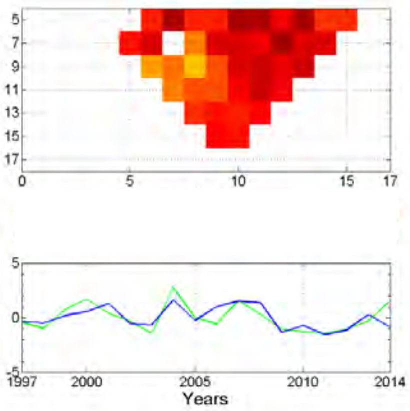


CorInd = 9.8 CorInd^w = 4.0

Mean groundwater level during hydrological year	Mean groundwater level during hydrological year	Mean groundwater level during hydrological year	Mean groundwater level during hydrological year
			
CorInd = 64.5 CorInd^w = 48.2	CorInd = 53.5 CorInd^w = 35.3	CorInd = 32.5 CorInd^w = 21.8	CorInd = 41.0 CorInd^w = 21.8
Mean groundwater level during growing season	Mean groundwater level during growing season	Mean groundwater level during growing season	Mean groundwater level during growing season
			
CorInd = 75.1 CorInd^w = 60.6	CorInd = 63.3 CorInd^w = 43.8	CorInd = 24.3 CorInd^w = 15.8	CorInd = 35.0 CorInd^w = 17.3

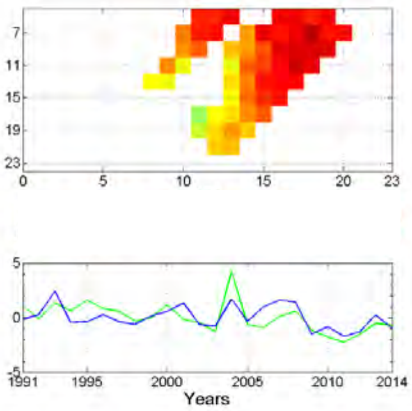
Mean groundwater level during summer	Mean groundwater level during summer	Mean groundwater level during summer	Mean groundwater level during summer
			
CorInd = 59.8 CorInd^w = 44.6	CorInd = 44.6 CorInd^w = 28.6	CorInd = 13.6 CorInd^w = 8.4	CorInd = 6.3 CorInd^w = 2.8
Max discharge during hydrological year	Max discharge during hydrological year	Max discharge during hydrological year	Max discharge during hydrological year
			
CorInd = 21.5 CorInd^w = 13.5	CorInd = 3.3 CorInd^w = 2.4	CorInd = 11.0 CorInd^w = 6.5	CorInd = 1.4 CorInd^w = 1.2

Max discharge during growing season



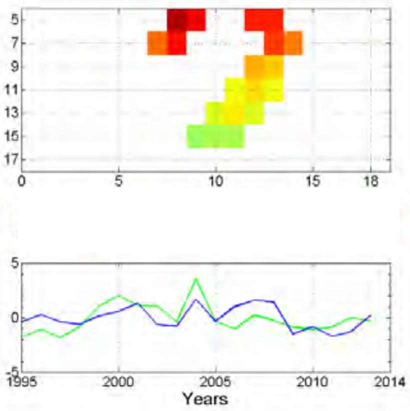
CorInd = 81.9 CorInd^{w} = 69.7

Max discharge during growing season



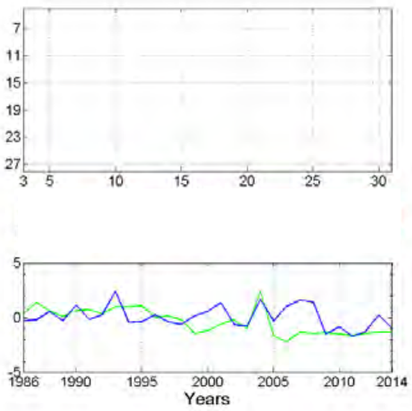
CorInd = 63.6 CorInd^{w} = 46.6

Max discharge during growing season



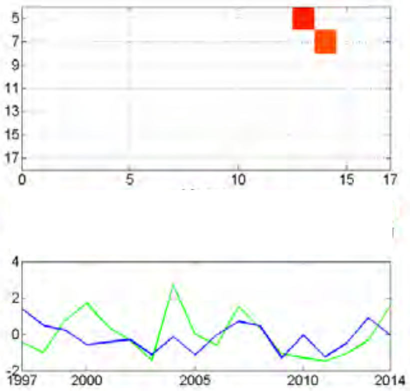
CorInd = 34.9 CorInd^{w} = 22.6

Max discharge during growing season



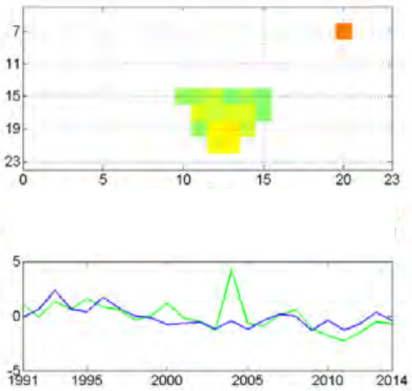
CorInd = 0.0 CorInd^{w} = 0.0

Max discharge during summer



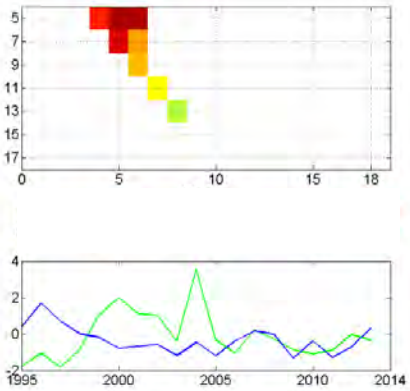
CorInd = 2.6 CorInd^{w} = 2.1

Max discharge during summer



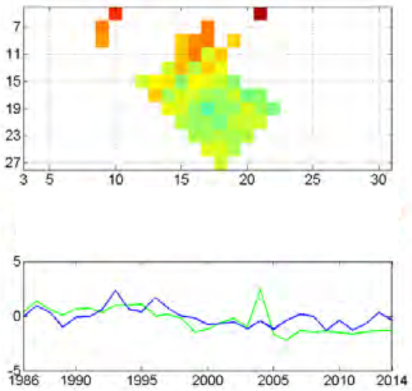
CorInd = 36.5 CorInd^{w} = 21.1

Max discharge during summer



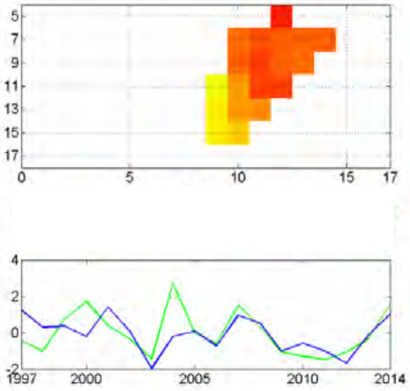
CorInd = 11.0 CorInd^{w} = 8.1

Max discharge during summer



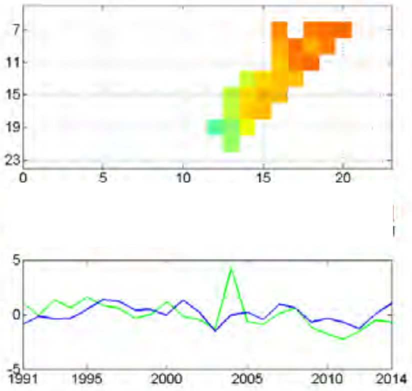
CorInd = 47.0 CorInd^{w} = 27.0

Min discharge during hydrological year



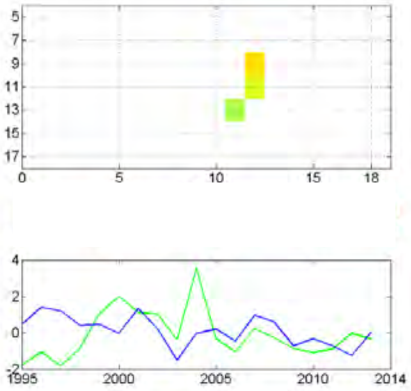
CorInd = 50.0   CorInd^w = 35.7

Min discharge during hydrological year



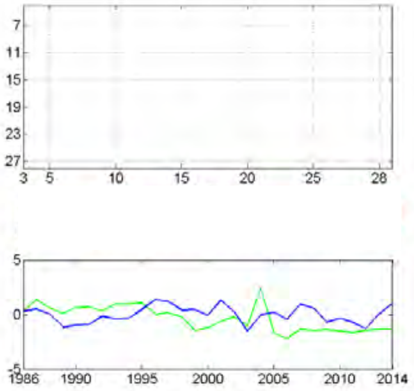
CorInd = 31.4   CorInd^w = 21.2

Min discharge during hydrological year



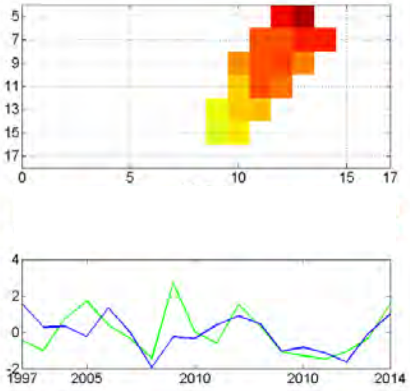
CorInd = 5.6   CorInd^w = 3.2

Min discharge during hydrological year



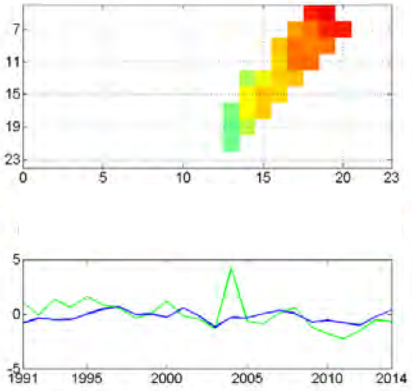
CorInd = 0.0   CorInd^w = 0.0

Min discharge during growing season



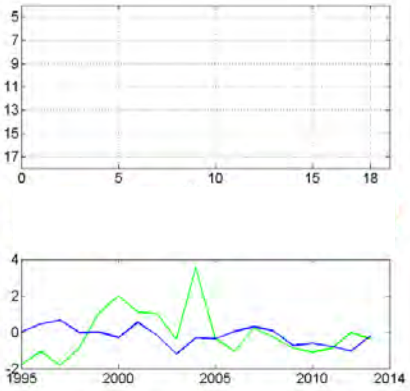
CorInd = 47.4   CorInd^w = 33.1

Min discharge during growing season



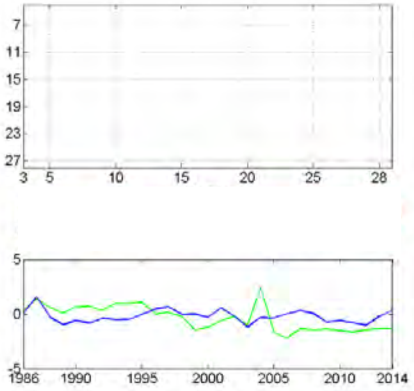
CorInd = 31.7   CorInd^w = 19.6

Min discharge during growing season



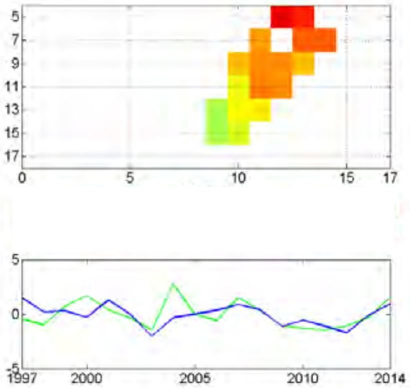
CorInd = 0.0   CorInd^w = 0.0

Min discharge during growing season



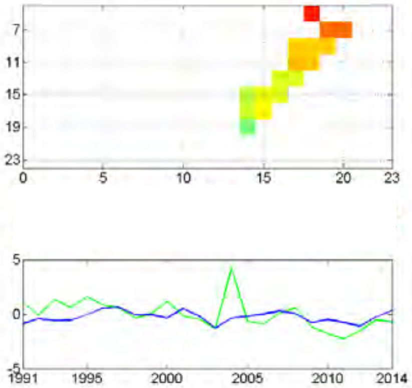
CorInd = 0.0   CorInd^w = 0.0

Min discharge during summer



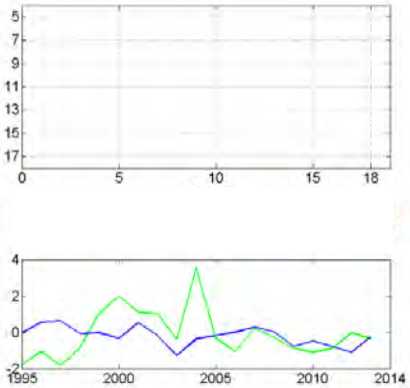
CorInd = 46.0 CorInd^w = 29.8

Min discharge during summer



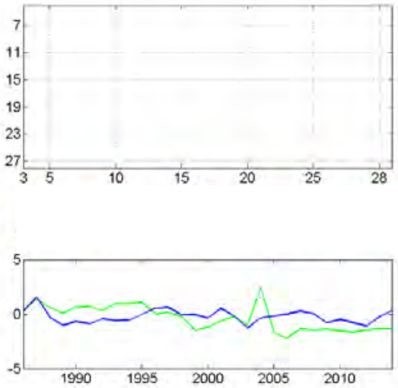
CorInd = 17.2 CorInd^w = 10.5

Min discharge during summer



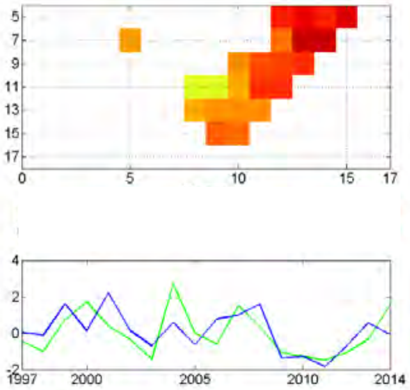
CorInd = 0.0 CorInd^w = 0.0

Min discharge during summer



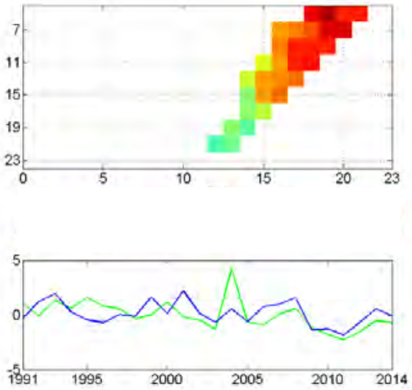
CorInd = 0.0 CorInd^w = 0.0

Total precipitations during growing season



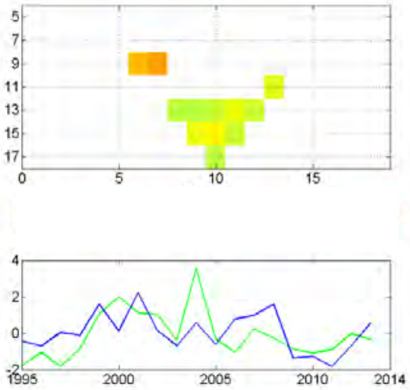
CorInd = 58.1 CorInd^w = 43.9

Total precipitations during growing season



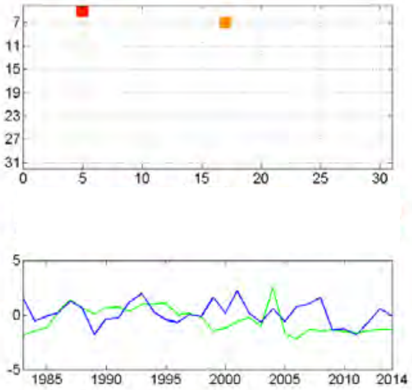
CorInd = 37.6 CorInd^w = 23.3

Total precipitations during growing season

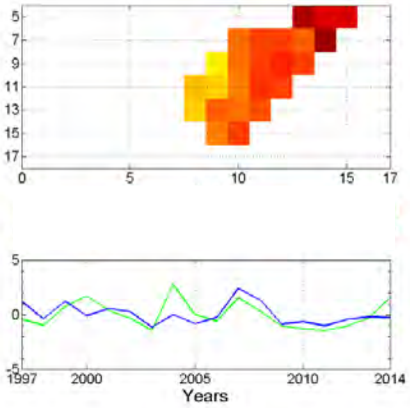
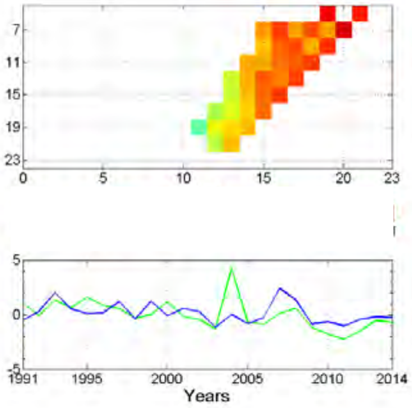
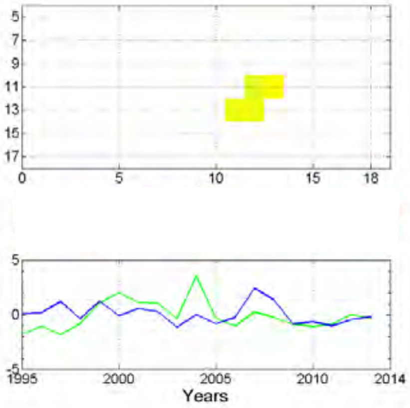
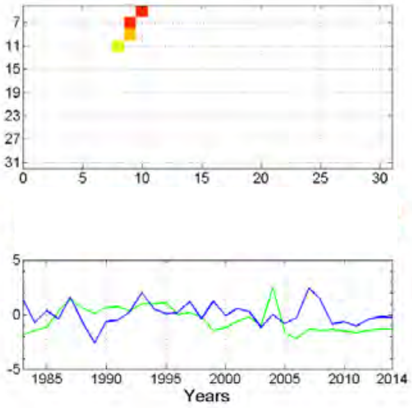
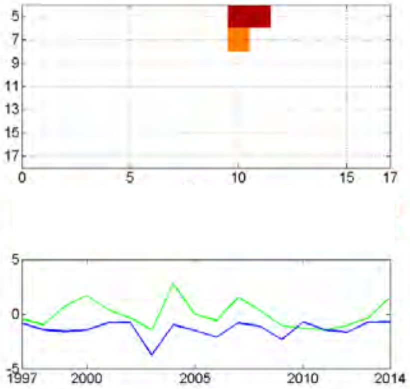
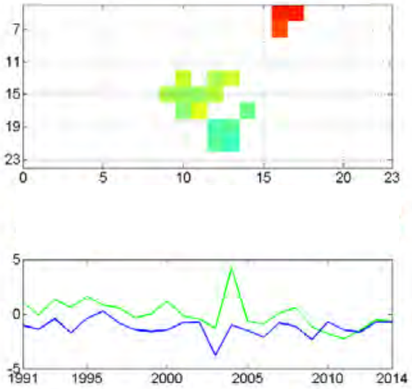
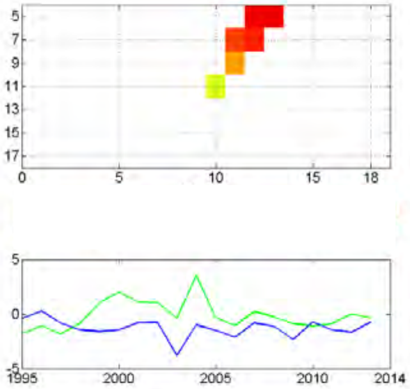
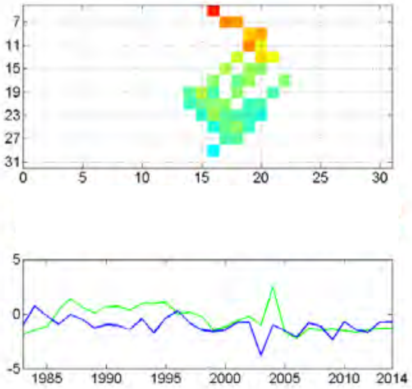


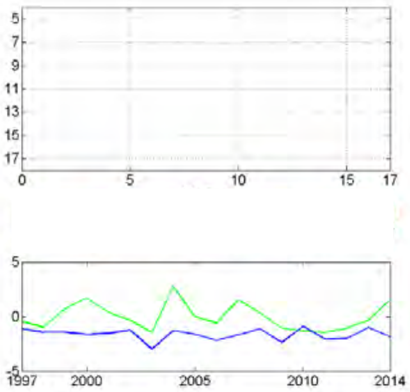
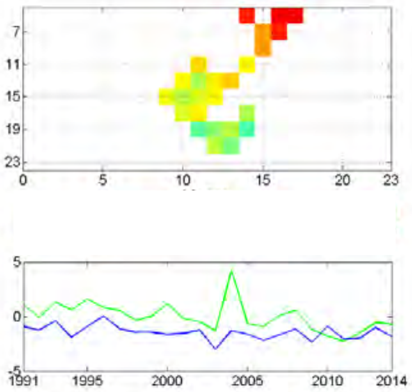
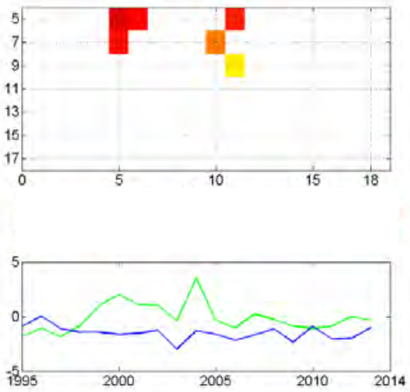
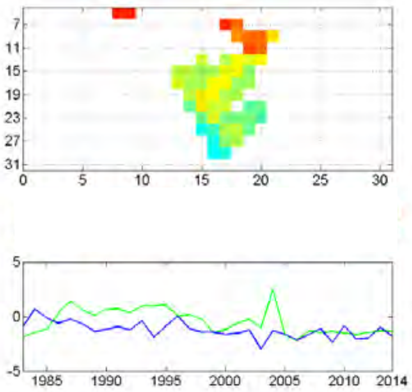
CorInd = 27.3 CorInd^w = 16.2

Total precipitations during growing season



CorInd = 0.6 CorInd^w = 0.4

Total precipitations during summer	Total precipitations during summer	Total preciitations during summer	Total precipitations during summer
			
CorInd = 60.1 CorInd^{w} = 46.5	CorInd = 49.3 CorInd^{w} = 33.1	CorInd = 8.3 CorInd^{w} = 5.0	CorInd = 1.3 CorInd^{w} = 0.9
Average temperature during summer	Average temperature during summer	Average temperature during summer	Average temperature during summer
			
CorInd = 3.8 CorInd^{w} = 3.3	CorInd = 29.7 CorInd^{w} = 15.1	CorInd = 7.6 CorInd^{w} = 5.8	CorInd = 31.3 CorInd^{w} = 15.0

Average temperature during growing season	Average temperature during growing season	Average temperature during growing season	Average temperature during growing season
			
CorInd = 0.0 CorInd^{w} = 0.0	CorInd = 39.3 CorInd^{w} = 22.5	CorInd = 6.9 CorInd^{w} = 5.5	CorInd = 42.9 CorInd^{w} = 22.1