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Key Points:

- The groundwater-depth gradient in a gravel braided systems affects the intensity and efficiency of biogeomorphic succession
- Differences in biogeomorphic succession intensity along the reach create a spatially diverse morphodynamic response
- Groundwater has the potential to drive indirectly long-term changes in river morphodynamics and so the success of river restoration

Supporting Information:

- Supporting Information S1

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Groundwater controls on biogeomorphic succession and river channel morphodynamics

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Abstract Biogeomorphic succession describes feedbacks between vegetation succession and fluvial processes that, at the decadal timescale, 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 the following: 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.

1. 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 [Schumm and Khan, 1971; Murray and Paola, 1994; Ashmore, 2013]. 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 [Surian and Rinaldi, 2003; Piégay et al., 2009]. Second, research has shown that vegetation has the capacity to “engineer” river systems, notably by constraining active channel width, over both short and long timescales [e.g., Hicks et al., 2007; Tal and Paola, 2007; Zanoni et al., 2008; Bertoldi et al., 2009; Corenblit et al., 2011; Gurnell et al., 2012; Gurnell, 2014; Picco et al., 2014]. Crucial here is the stabilizing effect of rooting vegetation [e.g., Karrenberg et al., 2003; Pollen, 2007; Scippa et al., 2008; Edmaier et al., 2011, 2015; Van Dijk et al., 2013; Polvi et al., 2014; Mannes et al., 2015] and the influence of vegetation on flow and sediment transport around the vegetation [e.g., Edmaier et al., 2015; Mannes et al., 2015].

Vegetation development in rivers involves a process of succession [Gurnell et al., 2001; 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” (in the sense of Corenblit et al. [2007, 2009, 2014]). Following Corenblit et al.’s definition, 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 propagules establishment); 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, 2016b]. 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 [*Hicks et al.*, 2007; *Tal and Paola*, 2007; *Gurnell et al.*, 2009].

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., *Busch et al.*, 1992; *Busch and Smith*, 1995; *Amlin and Rood*, 2003; *Perucca et al.*, 2007; *Gurnell*, 2014, 2016; *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.*, 2001], the rate of biogeomorphic succession may change as a function of access to groundwater. Such shifts may be driven by long-term climate change [*Lamb et al.*, 1995; *Rinaldo et al.*, 1995; *Betancourt et al.*, 2000; *Maxwell and Kollet*, 2008; *Rodell et al.*, 2009; *Foreman et al.*, 2012] 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., *Busch and Smith*, 1995; *Scott et al.*, 1999, 2000; *Amlin and Rood*, 2003; *Cooper et al.*, 2003; *Sargeant and Singer*, 2016].

Studies have considered the relationship between groundwater dynamics and vegetation growth rates in riparian forests [e.g., *Rains et al.*, 2004; *Singer et al.*, 2014; *Sargeant and Singer*, 2016]. *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 [*Stanford and Ward*, 1988; *Boulton et al.*, 1998; *Harner and Stanford*, 2003; *Mouw et al.*, 2009]. 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., *Snyder and Williams*, 2000; *Rains et al.*, 2004; *Amoros et al.*, 2005; *Singer et al.*, 2014; *Sargeant and Singer*, 2016]. Further work has suggested that vegetation degradation can follow from changes in groundwater dynamics [*Scott et al.*, 1999, 2000; *Amlin and Rood*, 2003; *Cooper et al.*, 2003; *Stella et al.*, 2013].

Aside this research, 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.

2. Study Site

The Allondon River system is located west of Geneva (Switzerland), and its characteristics are described [*Bätz et al.*, 2016] and summarized briefly below. The ~145 km² catchment is mainly located in the French karstic Jura Mountains and ranges from 1705 m above sea level (asl) (Crêt de la Neige) to 349 m asl 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 3 km long, 200–300 m wide and 50–80 m deep floodplain valley with 1.02% slope. This section is the reach generally referred to

Figure 1. Aerial image showing the study reach of the Allondon River (canton Geneva, Switzerland— $46^{\circ}12'5.08''\text{N}$; $5^{\circ}59'56.59''\text{E}$). Flow is from north to south. The blue lines bound the four morphologic evolutionary zones observed from historic aerial images (Figure 10). The dots show the location of dendroecological sampling. The color code of willow corresponds to the chronologies shown in Figure 5.

as the Allondon River (Figure 1). 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 cutoffs, 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 $\sim 0.5 \text{ m}^3/\text{s}$ and extreme flows (with return periods) of $43.2 \text{ m}^3/\text{s}$ (2 years), $79.9 \text{ m}^3/\text{s}$ (10 years), $117 \text{ m}^3/\text{s}$ (30 years), and $176 \text{ m}^3/\text{s}$ (100 years) (period 1986–2014 [Federal Office for the Environment (FOEN), 2014]).

Historical maps and aerial images show the morphological evolution of the studied river reach over the last decade [Bätz *et al.*, 2016]. They suggest a braided pattern before the 1960s (the earliest map dates to 1836) and a recent change toward 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 2. Groundwater table depths along the studied river reach (based on *GESDEC* [2015] and *Hottinger* [1998]). The dotted line indicates the range of fluctuations of about 3.2 m (2σ) around the mean stage. Moreover, the letters indicate the location of the dendroecological sampled along the morphologic evolutionary zones (Figures 1 and 5).

(Figure 2). The upper northern reach has deep groundwater levels (2–7 m deep), while the southern lower reach has shallow upwelling groundwater. It is the relation between spatial and temporal variabilities in channel morphodynamics and the groundwater-depth gradient that we aim to quantify in this study.

3. 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 morphodynamic evolution, focusing in particular on the spatial and temporal variabilities 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 (in the sense of *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., *Karrenberg et al.*, 2002; *Corenblit et al.*, 2009] and because willows are observed to have an engineering function [e.g., *Gurnell*, 2014, 2016], responsible for stabilizing channel and floodplain morphology [e.g., *Hicks et al.*, 2007; *Tal and Paola*, 2010; *Van Dijk et al.*, 2013]. 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 nonparametric multitimescale dendroecological analysis was performed to quantify the level of dependence of the tree growth rates upon climatological and hydrological variables (e.g., groundwater).

3.1. 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 500 m upstream of the study reach [FOEN, 2014] and were used not only 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.

Groundwater data were available for the period 1998–2014 at two sites, labeled P218 (upstream, Figure 1) and P219 (downstream, Figure 1) [Service de géologie, sols et déchets (GESDEC), 2015] and were used to

Figure 3. Groundwater levels in relation to the Allondon floodplain surface level (the elevation difference between piezometer reference level and river level has been removed).

represent the groundwater fluctuations along the gradient observed by Hottinger [1998] (Figure 2). Hottinger [1998] reconstructed the groundwater levels and subsurface permeability of the study area based on 17 radio magnetotelluric profiles. The comparison of his results with the piezometer records (Figure 3) showed that while 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 modeled groundwater stages for a longer period, based on a third piezometer located 1800 m upstream (site P62 is not shown in Figure 1) which had continuous data available from 1972 [GESDEC, 2015]. First, the respective minima were moved from the two measured data sets. 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 while 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 R^2 of 88.9% (Figure 3). This relationship was then applied to the full P62 data set, 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 overestimated 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 modeling was undertaken for P219.

3.2. 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 [Swiss Federal Office of Topography, 2012; *Système d'information du Territoire à Genève*, 2014]. 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.

Figure 4. 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 in Figures 1, 2, 8, and 10.

After classification, we merged the classes shrub and forest (woody vegetation), representing those land covers that required channel stability, and water, bare sediment, and nonwoody plants (e.g., sparse herbaceous grasses), representing the morphodynamically active zone. Nonwoody plants are included in the definition morphodynamically 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; Hey and Thorne, 1986; Micheli and Kirchner, 2002; Corenblit et al., 2007*].

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 4 shows three examples of classified historic images, while Table 1 summarizes the overall historical images classification performance. Active width and wooded vegetation cover identification were 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 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

Table 1. Kappa Values for the Historic Aerial Images Classification of Woody Vegetation (Shrub + Forest) and Active Width (Water + Sediments + Grass Covered)

Image year	Conditional Kappa Value (Strength of Agreement) ^a	
	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)

^aStrength of agreement following *Altman [1990]* classification <0.20 poor, 0.21–0.40 fair, 0.41–0.60 moderate, 0.61–0.80 Good, and 0.81–1.00 very good.

approaching this problem is to focus directly on morphological activity, using parameters like the active width [e.g., Zah *et al.*, 2001; Boruah *et al.*, 2008; Zaroni *et al.*, 2008; Ashmore *et al.*, 2011; Bertoldi *et al.*, 2011; Belletti *et al.*, 2015]. 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 toward 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 4), 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 1) 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 Figures 1 and 4. 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 were determined for 5 m sections perpendicular to the main river slope (parallel to the blue lines in Figure 4). A 50 m moving average was then applied to remove small-scale classification errors/variability (e.g., tree 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.

3.3. Dendrochronological Methodology

Standard dendrochronological methods [Schweingruber, 1988; Wilford *et al.*, 2005; Cook and Kairiukstis, 1992] were applied to reconstruct yearly vegetation growth rates (tree ring width) for pioneer fluvial and biogeomorphic landforms (in the sense of Corenblit *et al.* [2007]) colonized by willows (*Salix elaeagnos* Scop., *S. nigricans* Sm., and *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, and 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 [Schweingruber, 1988; Cook and Kairiukstis, 1992]. 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 characterization 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 compare with the average chronologies of other species, in this case, species associated with later biogeomorphic succession stages on the stable terraces (e.g., ash and oak). This allowed insertion of very narrow rings where a ring was identified as missing (1/100 mm) 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 [Schweingruber, 1988; Cook and Kairiukstis, 1992]. Each of these four steps is explained in detail below.

3.3.1. Dendrochronological Methods: Field Sampling

Willows, both shrubs and trees, located on pioneer and biogeomorphic stages of the biogeomorphic succession were sampled and spatially referenced (in the sense of 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., and *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, 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 [Theurillat and Matthey, 1987; Bätz *et al.*, 2015a, 2015b], 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.

3.3.2. 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 and thus identification of ring boundaries [Gärtner and Nievergelt, 2010]. After core/disk preparation, yearly ring widths were measured using a digital position table, with 1/100 mm 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 [see also Briffa *et al.*, 1996; Tognetti *et al.*, 2000; Cook and Kairiukstis, 1992]. 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.

3.3.3. Dendrochronological Methods: Crossdating

Each ring-width series was crossdated against other series of the same species. This involved a two-stage process as follows: (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.

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., Schweingruber, 1988; Cherubini *et al.*, 2002; Bernard, 2003; Trouet *et al.*, 2006, 2010; Malik and Owczarek, 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

Table 2. List of Extreme Events for the Considered Environmental Variables to Which Chronologies Should Have Produced Pointer Years

Year	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

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 were used to identify series measurement errors, displacements, and 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 were checked using not only the GLK but also the COFECHA software [Holmes, 1983; Grissino-Mayer, 2001]. 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 2), 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 3). 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 total average willow chronology (Table 3). This comparison confirmed the conclusion that double rings were likely in the willow series in 1988, 1998, and 2004 (Figure 5). 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 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 tree/shrub samples could be used to build the final chronologies (Figure 1): 30 cores from 19 oak trees, 26 cores from 18 ash trees, and 78 cores from 57 willow trees/shrubs. Comparison

Table 3. GLK Index (Gleichläufigkeit) Calculated Between Two Chronologies

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	-

level of significance.

* $\alpha = 0.05$.

** $\alpha = 0.01$.

*** $\alpha = 0.001$.

Figure 5. (a) Colored lines show the willow chronologies for the zones A, B, C, and D (color coded as for Figures 1 and 10). In black, the overall willow chronology used for crossdating with (b) ash (continuous gray) and oak (dashed gray) chronologies. The triangles in both figures show pointer years (Table 2), while the boxes show corrected years (double/missing rings).

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 broadscale 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 3). 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.

3.4. 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 multiscale 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, nonparametric Spearman correlations were calculated

of the willow chronologies with the ash and oak average chronologies gave GLK values of 64% and 65%, respectively (Table 3). The last two also significantly correlate (GLK) with the oak reference site.

3.3.4. Dendrochronological Method: Zone-Specific Ring-Width Indices

From the total willow chronology (Table 3), samples of the trees/shrubs growing on the pioneer and biogeomorphic landforms were identified to create zone-specific (Figure 1) 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–D) were then defined (Figures 1 and 2). 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 5a). The growth rate index of zone B is determined from 14 samples taken from 10 plants with a mean standard error of ± 15.1 . The maximum age is 1990. The zone C ring-width index was derived from 15 samples taken from 8 plants.

Figure 6. Minimum, average, and maximum monthly mean (a) temperatures and (b) precipitations per hydrological year for Geneva Cointrin 10 km east of the study site [MeteoSwiss, 2014].

length by their mean significant correlation at that length. This allows particularly strong correlations to be taken into account.

4. Results

4.1. Climate, Discharge, and Groundwater Variability

Figure 6 shows the development of the temperature and precipitation for each hydrological year over the last century. Generally, an increase of about 2°C in the average temperature can be observed, the trend increasing from the 1980s. Precipitation follows this trend notably with an increase in the magnitude of extreme events (alternation of years with high and low maximum precipitation, Figure 6). Only the last decade shows a reduction in maximum precipitation, but also in average and minima, indicating dryer conditions.

Figure 7. Maximum annual flow occurrence for two periods, showing the change in flood seasonality (© Ion Iorgulescu). The mesh scale indicates the monthly probability.

for moving windows with a range of window lengths, ranging from a minimum length of 5 years, through 2 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

The observed long-term climatic change was associated with a regime shift from pluvio-nival to pluvial. Figure 7 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 (1986–2013; Figure 7), 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

Figure 8. Floodplain age map derived from aerial image classification (see section 3.2).

higher magnitude of extreme precipitation events, flood magnitude increased by about 30% during the last 50 years [Bätz *et al.*, 2016].

Figure 2 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 Figures 1 and 2) and, from 700 m downstream, the onset of upwelling (zones B, C, and D in Figures 1 and 2). The partly modeled piezometer data (Figure 3) were located in zone A (P218) and in zone D (P219) in Figure 2. In the downwelling upstream reach (represented by P218, Figures 1 and 3), the average groundwater depth from the river level was 4.4 m (standard deviation $\sigma = \pm 1.6$ m) with median lowering rates during recession periods of 0.02 m/d (first interquartile = 0.01 m/d and third = 0.04 m/d). Downstream, in the groundwater upwelling zones (represented by P219, Figure 1), mean groundwater depth from the river level was 0.7 m with little change around this value ($\sigma = \pm 0.2$ m, Figure 3).

4.2. Reach-Scale Fluvial Morphodynamics

Figure 8 shows the morphological ages of the reach as of 2012 (see also Figure 4). 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 toward 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 toward 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 9 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 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 9). 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 9), reflecting a more binary distribution (most of the zone is either old or active) zone C has an age distribution intermediate between zone 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 in Figure 10. 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 9. In the upstream most zone (A), from 500 to 950 m along the studied reach (Figure 10), width

Figure 9. Floodplain age distribution for the study zones A, B, C, and D extracted from Figure 8.

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 10). 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 1250 m upstream (Figure 10), 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 9. 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 9) and the intermediate active width ratio (Figure 10).

Zone C also has a major increase in encroachment and reduction in active width, but earlier than in zones A and B, notably between 1972 and 1980 (Figure 10). 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. While the active zone generally comprises a smaller percentage of the reworkable floodplain by 2012 (Figure 10), 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 chute cutoff when the sinuosity becomes locally very high. This is reflected in Figure 4, 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 10), 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%, Figures 9 and 10), and it is maintained as such. Sudden channel shifts and associated meander cutoff are apparent, as per zone C.

The results exposed above for the different zone are summarized in Table 4. Data on the morphological age of the reach, combined with analysis of active width/woody vegetation encroachment, suggest 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.

4.3. Dendroecological Analysis

Figure 11 shows an example of the multiscale 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 10 years due to the hotter and drier climate conditions (see above; Figure 6). However, moving from zone A to zone D, that is following the downstream groundwater-depth gradient, willow growth rates show progressively reduced

Figure 10. (a) 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 section 3.2) 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 $\alpha = 0.05$). The blue lines indicate the different morphologic evolutionary zones (see section 4.2). 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; and dark green = willow of the chronology D.

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 ($\text{CorInd}^w = 69.7$) 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 11), but the level of correlation is much reduced. Precipitation correlations with growth rates also decrease markedly from zones A to D, suggesting that downstream growth rates are independent of precipitation. Taken together, a general trend appears toward zone D, in which the correlation with the hydrological variables decreases with the groundwater depth. It also suggests that the CorInd and CorInd^w variables provide a picture of the spatial variability in the association of hydrological and climate variables with willow growth rates.

Table 4. Table Summarizing the Main Geomorphic Properties of the Four Analyzed Zones

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

Figure 11. Examples of the multiscale 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 ($\alpha = 0.05$) 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.

Figure 12 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 toward 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 (Figures 11 and 12). 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 among the lowest found in Figure 12. Indeed, only exceptional flooding events (e.g., the 2004 event—Table 2) 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

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

Figure 12. Summary of the correlation indices (CorInd) and weighted correlation indices (CorInd^w) for different environmental variables (e.g., Figure 11) along the four dendroecological sampled zones (A–D, Figures 1 and 5). 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 2).

hydrological year, growing season and summer, shows 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 has 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.

Summarizing the dendroecological analysis (Figure 12), 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. Discussion

5.1. 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 10). Upstream sites remained morphologically more active (younger age, Figures 8 and 9) 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 10). This evolution initially appears to be due to a regime shift from bimodal pluvio-nival to unimodal pluvial (Figure 7), 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., Hicks *et al.*, 2007; Francis *et al.*, 2009]. 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 (Figures 2 and 3), with mean groundwater levels lower (4.4 m deep) and more variable ($\sigma = \pm 1.6$ 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 (Figures 11 and 12) 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/d (first interquartile = 10 mm/d and third interquartile = 40 mm/d) in the gravelly aquifer were greater than the maximum root growth rates of 1–13 mm/d typically reported for willow propagules [Naumburg *et al.*, 2005]. Moreover, the minimum groundwater depths of about 5 m, and recently up to 7 m, during summer (Figure 3) may not be accessible by young roots during the first year of establishment [Mahoney and Rood, 1998; Guillois *et al.*, 2011]. This reduces the rate of success of propagules establishment [e.g., Gurnell *et al.*, 2012]. Likewise for established willows, while it is likely that the deep taproots may be able to develop access to groundwater during times of extended drawdown [Pockman *et al.*, 1995; Rood *et al.*, 2000; Francis *et al.*, 2005; Naumburg *et al.*, 2005], 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 (Figure 12) confirmed the importance of water as a limit on growth rates, with discharge and precipitation becoming alternative water sources during periods of water table drawdown.

The aerial imagery (e.g., Figure 1) suggests in zone A that only propagules 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 (Figure 12), 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 propagules 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 (Figure 12) follows the increase in the mean groundwater level with respect to the surface (Figure 2), 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 riverbed (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.

5.2. Groundwater as a Driver of Biogeomorphic Succession

Changes in channel morphology due to pioneer vegetation dynamics have been documented in flume experiments [e.g., Hicks *et al.*, 2007; Tal and Paola, 2007, 2010; Van Dijk *et al.*, 2013; Bertoldi *et al.*, 2015] and historical image analysis [e.g., Kondolf and Curry, 1986; Beechie *et al.*, 2006; Zanoni *et al.*, 2008; Bertoldi *et al.*, 2011; Picco *et al.*, 2014]. Links to field experiments and observations suggest that roots reinforce river sediment stability [e.g., Karrenberg *et al.*, 2003; Pollen, 2007; Edmaier *et al.*, 2011; 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, 2012, 2014; Gurnell *et al.*, 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 coevolve 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.*, 2014, 2016a; Mahoney and Rood, 1998; Shafroth *et al.*, 1998; Karrenberg *et al.*, 2002; Francis, 2006; Moggridge and Gurnell, 2010; Hervouet *et al.*, 2011], 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 [Gurnell *et al.*, 2008; Crouzy and Perona, 2012; Perona *et al.*, 2012]. These vary in terms of propagule availability (species and quantity) and ambient conditions (elevation and 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 timescale of variability (i.e., a function of long-term aquifer recharge and drawdown) than streamflow (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/d, a maximum groundwater decline of 0.02 m/d (first interquartile = 0.01 m/d and third interquartile = 0.04 m/d) is likely to be tolerable but may still lead to potential water stress symptoms [Naumburg *et al.*, 2005; Guilloit *et al.*, 2011] 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 3), and the drier climate of the last decade (Figure 6), plant water

stress has increased in the upstream part of the study reach. Downstream, in the groundwater upwelling zones (represented by P219, Figure 1), groundwater levels change insignificantly ($\sigma = 0.2$ m, Figure 3) 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 [Mahoney and Rood, 1998; Shafroth et al., 1998; Guillo et al., 2011]. 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., Sprackling and Read, 1979; Shafroth et al., 2000; Naumburg et al., 2005; Pasquale et al., 2012; 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 [Perucca et al., 2007; Pollen, 2007; Imada et al., 2008; Pasquale et al., 2012; 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; Pollen, 2007; Pasquale et al., 2012; 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].

6. 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, and 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 and river flow). Active width was narrower,

and morphodynamics were more associated with the progressive development of sinuosity followed by a chute cutoff.

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 their 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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Erratum

In the originally published version of this article, the supporting information file was inadvertently omitted. The file has since been added and this version may be considered the authoritative version of record.