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Morphodynamic effects of riparian vegetation growth after stream restoration

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ABSTRACT: The prediction of the morphological evolution of renaturalized streams is important for the success of restoration projects. Riparian vegetation is a key component of the riverine landscape and is therefore essential for the natural rehabilitation of rivers. This complicates the design of morphological interventions, since riparian vegetation is influenced by and influences the river dynamics. Morphodynamic models, useful tools for project planning, should therefore include the interaction between vegetation, water flow and sediment processes. Most restoration projects are carried out in USA and Europe, where rivers are highly intervened and where the climate is temperate and vegetation shows a clear seasonal cycle. Taking into account seasonal variations might therefore be relevant for the prediction of the river morphological adaptation. This study investigates the morphodynamic effects of riparian vegetation on a re-meandered lowland stream in the Netherlands, the Lunterse Beek. The work includes the analysis of field data covering 5 years and numerical modelling. The results allow assessment of the performance of a modelling tool in predicting the morphological evolution of the stream and the relevance of including the seasonal variations of vegetation in the computations. After the establishment of herbaceous plants on its banks, the Lunterse Beek did not show any further changes in channel alignment. This is here attributed to the stabilizing effects of plant roots together with the small size of the stream. It is expected that the morphological restoration of similarly small streams may result in important initial morphological adaptation followed by negligible changes after full vegetation establishment. Copyright © 2018 John Wiley & Sons, Ltd.

KEYWORDS: stream restoration; stream dynamics; vegetation modelling; seasonal variation; Lunterse Beek; Delft3D

Introduction

A large number of lowland rivers has been severely altered by humans to lower flood levels, reduce natural channel migration, increase land drainage and improve navigation (Brookes, 1988; Gleick, 2003). Channelization is one of the most common interventions, leading to a considerable number of unnatural rivers around the world. Channelized rivers are often also straightened, with long-term consequences that include: increased flood risk downstream, channel incision, decreased connectivity between main channel and floodplains, lowered groundwater tables and bar alteration. The result is a general loss of morphological complexity, as well as biodiversity and productivity in both main channel and floodplains (Goodwin *et al*., 1997; Van Ruijven and Berendse, 2005; Richardson *et al*., 2007; Gross *et al*., 2014).

Considering the importance of preserving riverine ecosystems (Brachet *et al*., 2015), there has been an increasing awareness of the need to halt degradation and rehabilitate rivers through restoration programs since the early 1980s (Buijse *et al*., 2002; Bernhardt *et al*., 2007). Currently, most river restoration projects are found in USA (Kondolf *et al*., 2013) and Europe (Mohl, 2004; Madsen and Debois, 2006; Nones and Gerstgraser, 2016; European Centre for River Restoration, www.ecrr.org; the River Restoration Centre, http://www.therrc.co.uk/), particularly in the most populated areas, characterized by temperate climates. In these regions, vegetation shows a clear seasonal cycle (Peel *et al*., 2007), exhibiting important variations of its characteristics and coverage through the year.

River restoration projects can be divided into two categories (Parker, 2004): landscape-design-based and process-based. The first category includes the projects aiming at increasing the aesthetical value of the riverine area, restricting or impeding any morphological adaptation. Projects of this type are based on primarily channel re-meandering and are often carried out in urban contexts to create recreational areas (e.g. PUB Singapore’s National Water Agency, 2014). The second category comprehends all projects aiming at restoring a certain degree of natural river dynamics, including some morphodynamic processes (Beechie *et al.*, 2010). A large part of these projects include only channel re-meandering (Kondolf, 2006), but in most cases the freedom of the river to migrate laterally remains limited to avoid damage to agricultural land and private property (Piégay *et al.*, 2005). This means that some morphological processes that allow for ongoing channel movement, such as bank erosion, bank accretion and channel widening, are often seen as undesirable (Kondolf *et al.*, 2001). Moreover, in many cases floodplain vegetation is regularly cut to limit flood levels (Nienhuis and Leuven, 2001).

In general, the quantification of the effects of restoration projects remains a difficult task for practitioners, scientists and managers (Walker *et al.*, 2007; González *et al.*, 2015) because, despite their increasingly large number, only few projects include post-restoration monitoring activities (Kondolf and Micheli, 1995; Ormerod, 2004; Roni *et al.*, 2005; Bernhardt *et al.*, 2005, 2007). In addition to scarcity of data, there is no consensus on the criteria to be adopted to evaluate the effectiveness of restoration measures (Palmer *et al.*, 2005).

The experience gained from the past has always been important for future projects (Kondolf and Micheli, 1995), as it enables professionals in river restoration to set more realistic goals and improve design procedures and standards, as well as reduce maintenance costs (van Breen *et al.*, 2003; Dufour and Piégay, 2009; Nones and Gerstgraser, 2016). The proper setting of achievable and measurable goals in stream restoration programs is, therefore, an important activity, which in turn requires a clear understanding of the physical, chemical, biological and eco-morphological processes of these systems (Hobbs, 2005; Kondolf, 2011; Schirmer *et al.*, 2014). Such knowledge would allow assessing the geomorphological and ecological conditions that can be obtained after restoration measures and avoiding unwanted morphodynamic responses.

In recent years, the collaboration among different scientific communities has advanced our understanding of the linkages between vegetation dynamics and river morphodynamics to reveal the underlying processes that control the fluvial system. The contributions of, among others, Simon *et al.* (2004), Corenblit *et al.* (2007, 2009, 2011) and Gurnell *et al.* (2012) have advanced our knowledge on how plants alter water flow, soil resistance and sediment processes, and how these in turn determine plant settlement, establishment and survival (Gurnell, 2014). The effects of vegetation on flow and sediment transport in aquatic environments have been analysed by combining laboratory experiments and field data (see Nepf, 2012 for a review). Augustijn *et al.* (2008) and Vargas-Luna *et al.* (2015), among others, focused on flow resistance; Neary *et al.* (2012), Yager and Schmeeckle (2013) and Ortiz *et al.* (2013) on turbulent structures; Poggi *et al.* (2007) and Poggi and Katul (2007) on bedforms, whereas Gran and Paola (2001) Braudrick *et al.* (2009) and Tal and Paola (2007, 2010) studied the effects of riparian vegetation on the river planform formation.

Riparian vegetation decreases soil and bank erosion and increases sediment deposition by locally reducing flow velocity (Owens *et al.*, 2005; Keesstra, 2007; Facchini *et al.*, 2009; Montes Arboleda *et al.*, 2010; Keesstra *et al.*, 2012) and through the additional soil-binding action of roots. Similarly, riparian vegetation increases also bank stability (Hickin, 1984; Thorne, 1990; Gyssels *et al.* 2005; Pollen-Bankhead and Simon, 2010; Berendse *et al.*, 2015).

The establishment of vegetation in riverine environments, such as river bars, banks and islands is governed by the river flow and sediment regime (Gorla *et al.*, 2015a, b). Soil erosion in vegetated bars and islands has been studied to estimate the survival of vegetation to uprooting (Edmaier *et al.*, 2011, 2015).

Considering the importance of these feedbacks, including vegetation in morphodynamic models is now considered essential to predict the evolution of river systems, in particular after important interventions, such as morphological restoration. Modelling of these interactions has substantially advanced in recent decades (Marion *et al.*, 2014). Most efforts focused on better describing the effects of vegetation on flow and sediment processes (Baptist 2005; Baptist *et al.*, 2007; Camporeale *et al.*, 2013; Solari *et al.*,2015) and on fluvial planform formation (Murray and Paola, 2003; Crosato and Samir Saleh, 2011; Nicholas, 2013; Crouzy *et al.* 2016; van Oorschot *et al.*, 2016). Many contributions describe the morphological effects of plants colonizing river cross-sections (Perona *et al.*, 2014), banks (Eke *et al.*, 2014), bars (Bertoldi *et al.*, 2014; Bärenbold *et al.*, 2016) and point bars (Perucca *et al.*, 2007; Asahi *et al.*, 2013). However, current morphodynamic models only consider plants in a strongly simplified way, disregarding seasonal variations of vegetation. Instead, considering the important feedbacks described above, seasonal variations of vegetation might be relevant for the dynamics of rivers in temperate climates, especially small streams (Champion and Tanner, 2000; Cotton *et al.*, 2006; Jankowska *et al.*, 2014), but this issue has not been quantitatively addressed yet.

Monitoring of streams after restoration is not common (Kondolf and Micheli, 1995; Hauer *et al.*, 2008; Schirmer *et al.*, 2014; Nones, 2016). Some contributions regarding lowland streams in UK (Gurnell *et al.*, 2006a, b), Austria (Hauer *et al.*, 2008) and USA (Kondolf *et al.* 2001) report rapid initial morphological responses of these systems in relation to bedform and sediment deposits formation, with subsequent vegetation development. Australian experiences (O'Donnell et al., 2016) show the potential of floodplain vegetation in stabilizing river banks. The study of river–soil–groundwater interactions in the restored reach of the Thur River, Switzerland (Schirmer *et al.*, 2014) illustrates the need to include hydrological and biochemical dynamics in future monitoring plans.

This study analyses the morphological evolution of a small lowland river located in the Netherlands, the Lunterse Beek. Re-meandered in 2011, this stream is assumed to be a representative of small restored rivers in temperate climates. The goal is to investigate the morphodynamic effects of riparian vegetation, and in particular the need to include its seasonality, on predicting the morphological developments of small water courses with numerical models. The work is made possible by the availability of detailed data covering the first 5 years of development after restoration, a period in which the river floodplains evolved from completely bare to richly vegetated (Eekhout *et al.*, 2014). To study the applicability of numerical tools for predicting the evolution of restored streams, a 2D morphodynamic model is setup and applied to reproduce the observed behaviour. The model is then used as a tool to assess the relevance of considering seasonal variations of vegetation to study the morphological evolution of this type of stream.

Study Area

The Lunterse Beek is a lowland stream located in the central part of the Netherlands (Figure 1(a)). The stream has a catchment area of 63.6 km^2, of which 80% is used for agriculture, and a mean daily discharge of 0.36 m^3/s. The flow regime is characterized by a wide range of discharges, ranging from 0.002 m^3/s to 4.258 m^3/s during the study period. Flows exceeding the mean daily discharge of 0.36 m^3/s are only present during 35% of the time. On the basis of a 5-year monitoring period, high flow events with probability of exceedance of 1%

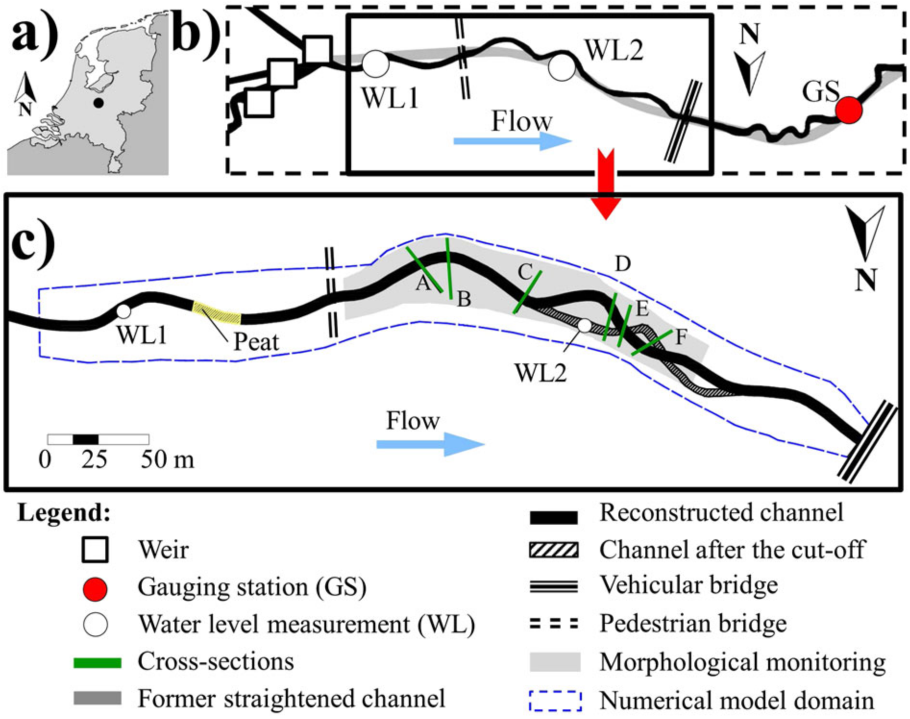

Figure 1. Study area: (a) location in the Netherlands; (b) location of model domain; and (c) sketch of the stream employed in this study. [Colour figure can be viewed at wileyonlinelibrary.com]

(2.1 m^3/s) have an average recurrence interval of 3 months. The relevant catchment characteristics are listed in Table I.

In October 2011, a restoration project was conducted on this stream over a reach of 1.6 km near Renswoude, a municipality of the province of Utrecht. A bare soil channel (6.5 m wide and 0.4 m deep) with a longitudinal slope of 0.96 m/km, lowered floodplains and a sinuous planform was excavated to replace the former straightened channel, see Figure 1(a). The overall restoration was meant to improve the ecological conditions of the riverine area while maintaining flood safety and appropriate groundwater levels for agriculture. The study area is a 200 m long reach where detailed field work has been undertaken since restoration. The reach was selected out of the restored 1.6 km because the other areas included different types of bed fixing structures, which were not meeting the interests of this research. A series of weirs, and a bridge and a gauging station are located upstream and downstream of the study area, respectively, defining well marked boundary conditions (Figure 1(a)). The river bed material is composed of medium to fine sand with median diameter, D_{50}, equal to 258 µm, with the exception of a 20-m-long reach in which the channel bed is excavated in a deposit of peat (Figure 1(b)). Previous studies on this restored stream have shown that there are no noticeable temporal variations in the bed material composition (Eekhout *et al.*, 2015; Eekhout and Hoitink, 2015) in the period following the restoration project.

Three months after re-meandering, in January 2012 the channel bifurcated at the river bend that coincides with cross-section C, indicated in Figure 1(b), to meet more downstream again. This initial adaptation, a chute cutoff, took place when vegetation was still absent as a result of the first high-flow season. High discharges induced sediment deposition, which caused the blockage of the main channel so that the flow took another course (Eekhout and Hoitink, 2015).

Table I. Catchment characteristics in the study area for the Lunterse Beek

Attribute	Value
Latitude	52° 4′ 46″ N
Longitude	5° 32′ 37″ E
Altitude (masl)	5.2
Catchment area (km^2)	63.6
Annual average rainfall (mm)[a]	820.4
Annual average temperature (°C)[a]	9.8
Mean daily discharge (m^3/s)[b]	0.36
Maximum daily discharge (m^3/s)[b]	4.26
Sediment size (µm)[c]	258

[a]Calculated from data recorded at Wageningen-Veenkampen in 1971-2015.
[b]Calculated from data recorded at Barneveldsestraat between January 2011 and April 2016.
[c]As reported by Eekhout *et al.* (2014).

Materials and Methods

This study combines the analysis of detailed field observations and 2D morphodynamic modelling, based on the Delft3D code, covering the first 5 years after restoration. Field data include hydrological time-series, high-resolution bathymetric data, photos acquired with an unmanned aerial vehicle and standard aerial photographs. The analysis of field data allows description of the processes that occurred in the study area. The comparison between modelled and observed evolution allows establishing whether a numerical tool including the effects of vegetation can be used to optimize stream restoration projects by predicting the channel response beforehand. The comparison of different modelled scenarios, in which vegetation properties are either kept constant or changed over time and space according to observations, allows assessment of the importance of including seasonality and/or other vegetation dynamics for this type of model investigations.

Data sources, data collection and processing

Time-series of discharges and water levels, measured at Barneveldsestraat, downstream of the study reach (GS in Figure 1(a)), were provided by the Waterboard (Waterschap Vallei en Veluwe) who supplied also water level time series at two other locations along the study reach (WL1 and WL2 in Figure 1(a)). Daily mean air temperature and precipitation time-series were provided by the Royal Netherlands Meteorological Institute (KNMI) (Klein Tank *et al.*, 2002). The Wageningen-Veenkampen station was selected due to its closeness to the study reach (51° 58′ 53″ N, 5° 37′ 18″ E).

Stream bed topography, including channel and floodplains, was measured in the framework of this study over a length of almost 200 m every 2 months on average. The information about the surveys is listed in Table II and the monitored area is indicated in light grey in Figure 1(b). Real Time Kinematic (RTK) GPS equipment (Leica 1200+ for surveys 1 to 13 and Leica Viva GS10 for surveys 14 to 26, see Table II) was used to measure channel-bed and floodplain surface elevations with an accuracy of 1–2 cm. Longitudinal water surface profiles were measured during the surveys with the RTK-GPS equipment. In each survey, the repeated measurement of fixed points located in the study area was used to control the precision of the equipment.

Digital Elevation Models (DEMs) were constructed using the data set obtained with the RTK-GPS equipment, following the method proposed by Milan *et al.* (2011), as described by Eekhout *et al.* (2014). The DEMS were then used to study the morphological evolution of the stream. DEMs of difference (DoDs) (Lane *et al.*, 2003) were produced for the analyses of deposition and erosion patterns and seasonal changes.

As instrumental errors or errors that arise from the interpolation method may generate uncertainties in the individual DEMs or the constructed DoDs, apparent morphological changes can slightly differ from real morphological changes. Uncertainty was estimated using the method of Milan *et al.* (2011), which establishes uncertainties by determining the threshold level of detection (Eekhout *et al.*, 2014).

Vegetation coverage was monitored with several approaches, at different spatial scales and from different sources. Dominant vegetation species were identified for the first 2 years after restoration during two independent field campaigns (September 2012 and July 2013) by Eekhout *et al.* (2014). In this study, the seasonal changes and colonization processes were tracked with oblique and in-stream terrestrial photographs that were correlated with the riparian vegetation patterns obtained from aerial photographs. Table III lists the characteristics of the aerial photographs that were used to establish the vegetation development and its spatial distribution over a length of 300 m.

In order to record the development of vegetation after restoration, two types of aerial photographs were used: standard (spatial resolution larger than 10 cm) and detailed (spatial resolution smaller than 10 cm). The standard aerial photographs were collected from different sources, whereas the detailed ones were taken during the execution of this study, see Table III.

Land cover maps were created from the aerial photographs acquired in 2015 (May 11, June 16 and September 9) and in 2016 (January 21) using an unmanned MAVinci fixed-wing aircraft with an on-board Panasonic Lumix GX1 camera. The raw images were processed with Structure-from-Motion photogrammetry (Westoby *et al.*, 2012) using Agisoft Photoscan Professional to create Digital Surface Models (DSM) and orthophotos. The DSM and orthophotos were subsequently used as input for a stratified object-based image classification procedure (Anders *et al.*, 2011) in the software eCognition Developer 9. Here, objects were formed on the basis of

Table II. Summary of the field campaigns carried out

No.	Q (m^3/s)	Date (Y-M-D)	Days after restoration	Point density (points/m^2)
1	1.19	2011-10-12	0	0.16
2	0.48	2012-01-13	93	0.32
3	0.40	2012-02-22	133	0.27
4	0.16	2012-04-20	191	0.20
5	0.10	2012-05-30	231	0.31
6	0.11	2012-07-26	288	0.35
7	0.03	2012-09-17	341	0.33
8	0.24	2012-10-23	377	0.43
9	0.77	2012-12-11	426	0.39
10	0.46	2013-01-08	454	0.37
11	0.44	2013-02-12	489	0.35
12	0.28	2013-03-20	525	0.38
13	0.11	2013-04-22	558	0.31
14	0.01	2013-06-19	616	0.34
15	0.02	2013-08-14	672	0.45
16	0.05	2013-10-09	728	0.43
17	0.26	2013-11-27	777	0.43
18	0.57	2014-01-29	840	0.28
19	0.16	2014-04-09	910	0.39
20	0.19	2014-07-09	1001	0.32
21	0.17	2014-11-12	1127	0.34
22	0.26	2015-02-12	1219	0.45
23	0.23	2015-04-09	1275	0.49
24	0.02	2015-06-09	1336	0.45
25	0.06	2015-08-12	1400	0.39
26	0.29	2015-10-22	1471	0.45
27	0.28	2015-12-29	1539	0.40
28	0.23	2016-04-05	1637	0.38

Table III. Summary of the aerial photographs used in the study

No.	Date (Y-M-D)	Days after restoration	Source	Pixel size (cm)	Season
1	2012-01-17	97	Slagboom & Peters	10×10	Winter
2	2012-07-26	288	Slagboom & Peters	10×10	Summer
3	2013-02-02	479	Cyclomedia	23×23	Winter
4	2013-07-09	636	Slagboom & Peters	10×10	Summer
5	2014-02-25	867	Cyclomedia	23×23	Winter
6	2014-07-04	996	Dutch cadastre office	60×60	Summer
7	2015-05-11	1307	WUR-UARSF[a]	2×2	Spring
8	2015-06-16	1343	WUR-UARSF	2×2	Summer
9	2015-09-09	1428	WUR-UARSF	2×2	Autumn
10	2016-01-21	1562	WUR-UARSF	2×2	Winter

[a]The Unmanned Aerial Remote Sensing Facility of the Wageningen University.

clustering DSM and orthophoto image pixels using the multi-resolution image segmentation algorithm (MRS, Baatz and Schäpe, 2000) to distinguish 'water', 'trees', 'bare ground', 'grass' and 'herbaceous plants'. Obvious errors of land cover classifications were corrected manually. Lastly, the same vegetation classes were manually identified in the standard aerial photographs (Photos 1 to 6 in Table III) by using a Geographical Information System (GIS). Vegetation height was assigned on the basis of the information gathered from the field and vegetation density was derived from calibrated values on real-river applications of similar models from the literature. The detailed description of vegetation properties is presented in the following sections.

Morphodynamic modelling

The objectives of the numerical investigation were to (1) identify the level of performance of a 2D morphodynamic model in reproducing the morphological evolution of a small restored stream, and (2) assess the importance of including seasonal variations of vegetation in this type of studies. To achieve this, a model was constructed and used to simulate the morphological developments of the Lunterse Beek in the 4-year-long period between Campaign 5 and Campaign 28 (Table II). Four different scenarios were considered: (1) complete absence of vegetation; (2) considering only vegetation of grass type, with characteristics invariant over time and uniformly distributed on colonized banks and floodplains; (3) considering only herbaceous vegetation, with characteristics invariant over time and uniformly distributed; (4) considering the observed seasonal variations of vegetation (type, properties and spatial distribution). Two vegetation types were considered: grass and herbaceous. Although a few trees were present in the field, they were not included in the model due to limitations of the Baptist method in describing this type of vegetation found in previous studies (Vargas-Luna *et al*., 2016). Since information on vegetation cover was available only at specific times (Tables III and IV), in scenario 4 vegetation characteristics were updated at the time corresponding to the field observations and maintained constant in the period between two successive observations.

The numerical tool was constructed using the open-source Delft3D software package (http://oss.deltares.nl/web/delft3d/source-code), which allows simulation of flow, sediment transport and bed level changes in vegetated streams with a simplified representation of bank erosion. The hydrodynamic equations are based on the Reynolds equations for incompressible fluid and shallow water (de Saint Venant equations) with a parameterization of the 3D effects that become relevant for curved flow (Struiksma *et al*., 1985). The effects of transverse flow convection causing a redistribution of the main flow velocity are accounted for by a correction in the bed friction term. The direction of sediment transport is corrected by a modification in the direction of the bed shear stress. The model includes the effects of gravity on bed load direction (Bagnold, 1966; Ikeda, 1982). The adopted turbulence closure scheme is a k-ε model, in which k is the turbulent kinetic energy and ε is the turbulent dissipation.

The local bed level changes are derived by means of sediment balance equations. Delft3D adopts Exner's approach, valid for immediate adaptation of sediment transport to local flow characteristics, for bed load and 2D advection–diffusion equations for suspended load, forced by sediment entrainment and deposition.

Bank erosion is computed in a strongly simplified way relating bank retreat to bed degradation at the toe of the bank. In practice, the shift of the river bank is obtained by assigning a part of the bed erosion occurring inside the wet cells at the margin of the wet area to their adjacent dry cells, which are then converted to wet cells and become a part of the conveying river channel (van der Wegen and Roelvink, 2008).

The effects of vegetation on bed roughness and sediment transport are accounted for according to Baptist's method (2005), which is one of the most complete vegetation models (see Vargas-Luna *et al*., 2015, 2016 for an analysis of the applicability of this method). This method derives the Chézy resistance coefficient for flow over submerged vegetation, C_r, as

$$C_{r\ Submerged} = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{C_D a h_v}{2g}}} + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{h_v}\right) \quad \text{with} : h/h_v > 1 \quad (1)$$

where C_b is the Chézy coefficient for the bare soil, C_D is the drag coefficient of plants assumed as rigid cylinders (assumed

Table IV. Vegetation properties used in the numerical model

Scenario	Period	Dates	Grass a (m^{-1})	Grass h_v (m)	Herbaceous plants a (m^{-1})	Herbaceous plants h_v (m)
1	1	2012/02/22 – 2016/04/05	-	-	-	-
2	1	2012/02/22 – 2012/05/30	-	-	-	-
	2	2012/05/30 – 2016/04/05	0.15	0.15	-	-
3	1	2012/02/22 – 2012/05/30	-	-	-	-
	2	2012/05/30 – 2016/04/05	-	-	2.00	0.60
4	1	2012/02/22 – 2012/05/30	-	-	-	-
	2	2012/05/30 – 2012/10/23	0.15	0.15	-	-
	3	2012/10/23 – 2013/04/22	0.15	0.15	2.00	0.30
	4	2013/04/22 – 2013/11/27	0.15	0.35	2.00	0.60
	5	2013/11/27 – 2014/07/09	0.15	0.15	2.00	0.50
	6	2014/07/09 – 2015/02/12	0.15	0.60	2.00	1.20
	7	2015/02/12 – 2015/06/09	0.15	0.15	2.00	0.30
	8	2015/06/09 – 2015/08/12	0.15	0.35	2.00	0.80
	9	2015/08/12 – 2015/12/29	0.15	0.15	2.00	0.60
	10	2015/12/29 – 2016/04/05	0.15	0.15	2.00	0.15

equal to 1 as recommended by Vargas-Luna *et al.*, 2016), a is the projected plant area per unit volume (Nepf, 2012), h_v is the vegetation height, h is the water depth, g is the acceleration due to gravity and κ (= 0.41) is Von Kármán's constant. The bed-shear stress is estimated as

$$\tau_{bv} = \frac{\rho g}{C_b^{'2}} \overline{u}^2 \tag{2}$$

where $\overline{u} = C_{rSubmerged}\sqrt{hi}$, ρ is the density of the fluid and $\overline{u}$ is the mean flow velocity and

$$C_b^{'} = C_b + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{h_v}\right)\sqrt{1 + \frac{C_D a h_v C_b^2}{2g}} \quad \text{with: } h/h_v > 1 \tag{3}$$

Submerged vegetation reduces the bed shear stress in two ways: 1) by reducing the flow velocity (Equations (1) and (2)) and by reducing the bed resistance (with vegetation $C_b^{'} > C_b$ in Equation (3)).

The effects of emergent plants ($h/h_v \leq 1$) are obtained by assuming $h_v = h$, so for this condition $C_b^{'} = C_b$. In this case, Equation (1) takes the form

$$C_{r\,Emergent} = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{C_D a h}{2g}}} \quad \text{with: } h/h_v \leq 1 \tag{4}$$

For emergent vegetation

$$\overline{u} = C_{rEmergent}\sqrt{hi} \tag{5}$$

Baptist's approach has been applied to rivers with floodplain vegetation by Montes Arboleda *et al.* (2010), Villada Arroyave and Crosato (2010) and Crosato and Samir Saleh (2011), among others. The performance of the approach implemented in the Delft3D software has been analysed by Vargas-Luna *et al.* (2016) who found that the model performs well for dense grass and herbaceous vegetation, as the one on the Lunterse Beek floodplains. Soil reinforcement due to the root systems of plants is not considered. Also vegetation uprooting as a response to flow disturbances is not considered. However, if spatial distribution and properties of vegetation are manually updated, natural and artificial (due to cutting) plant removal is taken into account.

All mathematical equations and their numerical representation are described more in detail in the manuals, which can be downloaded from http://oss.deltares.nl/web/delft3d/manuals.

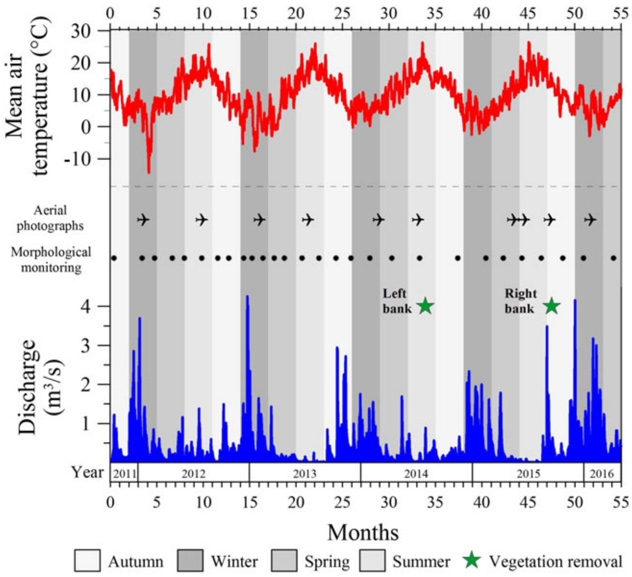

Figure 2. Time series of the information available after stream restoration: discharge (m^3/s), mean air temperature (°C), morphological campaigns and aerial photos. Month 0 represents the beginning of October 2011. Information about the dates of morphological campaigns and aerial photos can be found in Tables II and III, respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

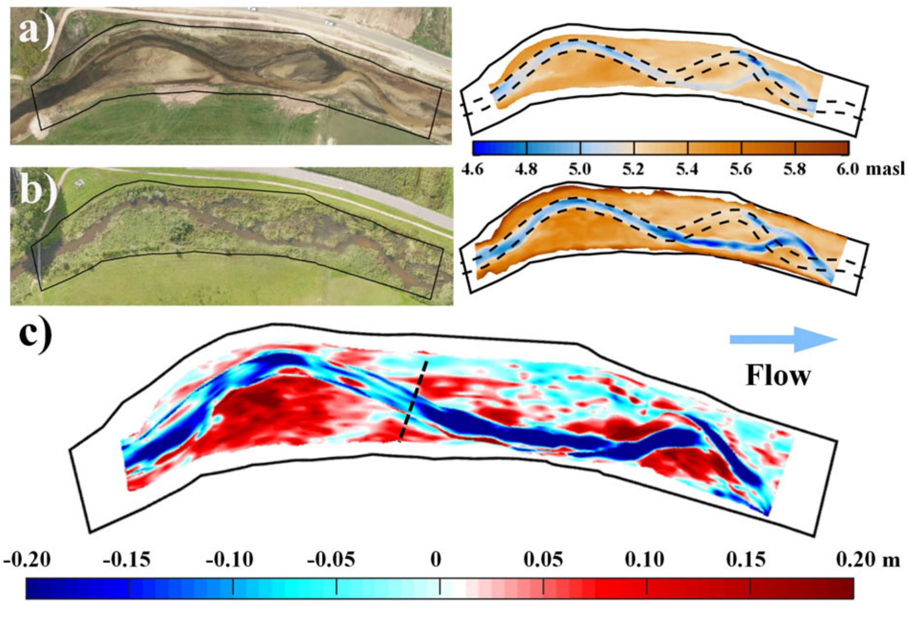

Figure 3. Evolution of the Lunterse Beek from (a) January 2012 to (b) September 2015. Left panel: Aerial pictures, Right panel: DEMs with legend indicating the bed level (masl), the initially reconstructed channel is shown in dashed lines. (c) Difference between the campaigns shown in (a) and (b), erosion is indicated in blue and sedimentation in red. The cross-section indicated in (c) is used for further analyses. Monitoring area enclosed with a black contour. [Colour figure can be viewed at wileyonlinelibrary.com]

Model setup and calibration

A curvilinear grid following the alignment of the main channel was constructed covering an area 430 m long and 45 m wide, see Figure 1(b). To minimize the influence of the boundary the model domain covered an area that is larger than the area of interest (Figure 1). The mean grid cell size was 1.5 m with an average aspect ratio of 2.7. The initial bed topography was generated from the elevations measured on 22/02/2012 (campaign 2, Table II), just after the initial cutoff. Daily flow discharge and water level series constituted the upstream and downstream boundary conditions, respectively. The sediment was assumed as uniform, with grain size of 258 µm as observed in the field (Eekhout *et al.*, 2014). The area with the peat bed was not distinguished from the rest.

The morphological evolution and the water level series of the period between Campaign 3 and 5 (see Table II), in which vegetation was not present, were used to calibrate the roughness of the bare bed, to select the sediment transport formula and to optimize the value of the coefficients weighing the effects of transverse slopes. The outcomes of this calibration procedure were: a Chézy coefficient, C_b = 45 $m^{1/2}/s$ for the areas not covered by vegetation; the Engelund and Hansen (1967) sediment transport formula; and the application of Koch and Flokstra's (1980) approach, extended by Talmon *et al.* (1995), for the adjustment of the bed load transport direction on sloping beds.

The adopted density and diameter of the cylinder arrays used in the Baptist method to represent vegetation were derived from calibrated values on real river applications from the literature (Van Velzen *et al.*, 2003; Baptist, 2005; de Jong, 2005). The height of plants was assigned according to the conditions observed in the field during the morphological campaigns, imposing a drag coefficient of 1.0, as suggested by Vargas-Luna *et al.* (2016). Table IV summarizes the properties of the cylinder arrays used in the model for the four scenarios considered.

Results of Data Analysis

Seasonal variations

The seasonal variations of climate were identified by analysing the annual and intra-annual variability in precipitation, mean air temperature and flow discharge. Seasonal

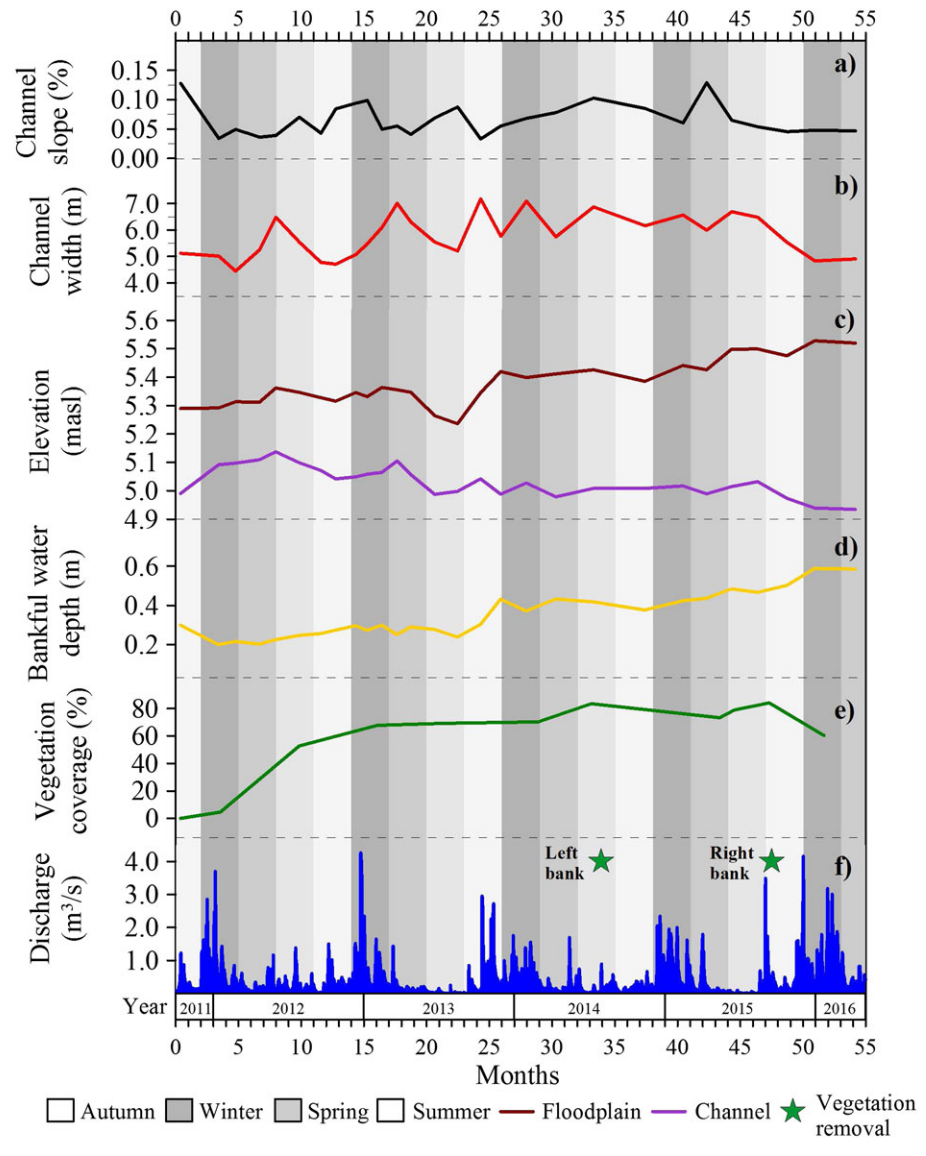

Figure 4. Temporal evolution of reach averaged (a) channel slope (%), (b) channel width (m), (c) elevation of bed channel and floodplains (masl), (d) bankfull water depth (m), and (e) vegetation coverage (%), as well as (f) discharge (m^3/s) in the Lunterse Beek. Month 0 represents the beginning of October 2011. [Colour figure can be viewed at wileyonlinelibrary.com]

variations of vegetation characteristics were identified by analysing the aerial photos and the data collected in the field.

Monthly mean air temperature, recorded at Wageningen-Veenkampen in the period 1971–2015, exhibits periods of high (June–August, 16.8°C on average), mean (March–May, 9.1°C on average, and September–November, 10.4°C on average) and low (December–February, 3.1°C on average) values. Instead, monthly mean precipitation for the period 1971–2015 exhibits small variations throughout the year, ranging from 45 mm (in April) to 82 mm (in December). This means that seasonal changes of vegetation are mainly driven by temperature variation and flow disturbances. The annual average of monthly air temperature is 9.8°C and the yearly precipitation is 820.4 mm. As in most temperate streams, the seasonal variation of vegetation observed along the Lunterse Beek comprises increasing coverage starting in spring and reaching maximum density in the late summer, while foliage and root biomass reduction is observed from autumn through winter.

Figure 2 shows the daily air temperature and discharge time series indicating also the dates in which the aerial photographs were taken and when the morphological campaigns were carried out. The highest discharges occur in winter, when the mean air temperature is at its minimum. It is important to mention here that the natural variability of flow discharge and water levels have been reduced in the study area by weirs located upstream and by the downstream gauging station. Flow control is believed to have affected some vegetation processes, such as colonization and growth. It is not possible to quantify these effects from the available data.

Morphological evolution

The DEMs and DEMs of difference (DoDs) are given as Supporting information Data S1 and S2, respectively. Following Milan *et al.* (2011) and assuming a confidence limit equal to 95% and a lower bound for the critical threshold error of two times the maximum error of the RTK-GPS equipment (0.04 m), the elevation differences between subsequent surveys at a particular grid cell were found insignificant, establishing that the uncertainty levels in the calculated DoDs were low.

The first high-flow period that occurred immediately after restoration changed substantially the planform of the Lunterse Beek. No other substantial planform changes were observed in the study period. Figure 3 shows the changes between January 2012 and September 2015 (three and a half years). Differences in bed level (Figure 3(c)) emphasize the processes of channel deepening and floodplain rising. Some floodplain soil erosion (lower than 5 cm) occurred far from the channel.

Figure 4 shows the temporal evolution of the reach-averaged values of reach-averaged longitudinal channel slope, width and bed elevation, floodplain elevation, bankfull water depth and vegetation coverage, to be compared to the daily discharge time-series. Figure 5 shows the percentage change of the same variables with respect to their initial values. In the study period, the channel slope oscillated between the values of 0.04 and 0.12 (Figure 4(a)) to stabilize around the lowest value. It suddenly decreased in 2011 due to the initial chute cutoff and later reacted dynamically to deposition and erosion processes as a response to pool migration in the downstream part of the monitored reach. Figure 4(b) shows that the channel width has exhibited different trends during the study period. In the first year, the width remained almost constant in autumn

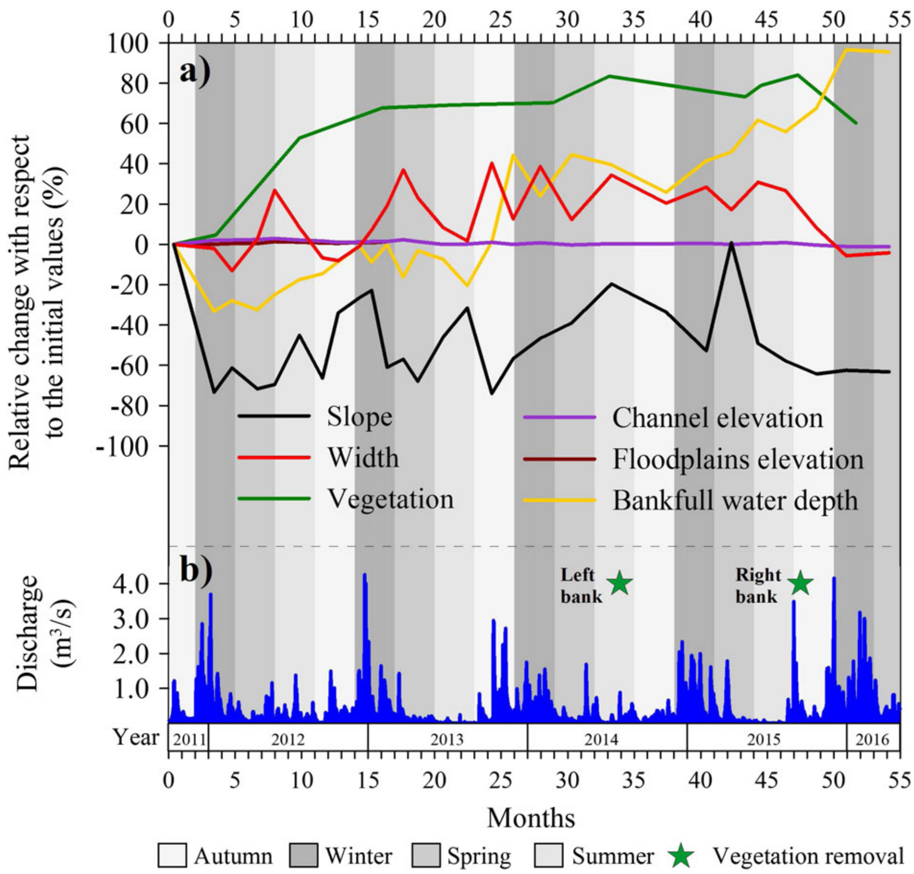

Figure 5. Temporal evolution of (a) reach averaged channel properties with respect to the initial values (%), and (b) discharge (m^3/s) in the Lunterse Beek. Month 0 corresponds to October 2011. [Colour figure can be viewed at wileyonlinelibrary.com]

and decreased by 10% with respect to the initial value during the winter, characterized by high flow. The opposite trend can be observed in the following spring, when the channel width increased to become 30% larger than the initial width. Channel widening occurred at low flow, see Figures 4 and 5. This behaviour is here attributed to the exceptionally cold temperatures in the first months of 2012 (see Figure 2), resulting in bank freezing and freezing of slack water, mainly near the banks. Ice forming and then melting resulted in bank failure, which caused the observed channel widening in spring. Later in 2012 the channel width decreased again to reach a value smaller than the initial one in autumn. In the summer period the bed started to degrade (incision) and due to vegetation growth on banks. This shows the interaction between bed and bank dynamics and vegetation growth. Channel slope and channel width changes seem slightly correlated after the second year. Longitudinal slope changes are related to bed dynamics: the slope increases if sediment is deposited in the upstream part of the reach, and vice-versa the slope decreases if sediment is deposited in the downstream part of the reach or if the bed is eroded in the upstream part. Bed erosion leads to channel narrowing and deposition leads to channel widening. It is important to note that even though the flow disturbances remained of the same order of magnitude (Figure 4(f)), the

Table V. Measured erosion and accretion rates between spring seasons. The localization of the selected cross-sections can be seen in Figure 1

Cross-section	Year 1-2			Year 2-3			Year 3-4			Year 4-5		
	BE[a]	VA_{rb}[b]	VA_{lb}[c]	BE[a]	VA_{rb}[b]	VA_{lb}[c]	BE[a]	VA_{rb}[b]	VA_{lb}[c]	BE[a]	VA_{rb}[b]	VA_{lb}[c]
A	5.1	-0.3	-1.5	3.0	2.2	5.6	5.5	-1.3	7.9	4.2	4.1	-4.7
C	13.0	-6.5	-1.3	25.6	2.7	5.5	-8.7	6.6	0.9	0.8	-6.2	7.3
F	25.4	6.2	0.5	14.9	1.2	4.8	9.6	2.1	-2.0	9.4	3.3	8.6

[a]BE = Mean bed erosion rate, in centimetres per year.
[b]VA_{rb} = Mean vertical accretion rate on the right bank, in centimetres per year.
[c]VA_{lb} = Mean vertical accretion rate on the left bank, in centimetres per year.

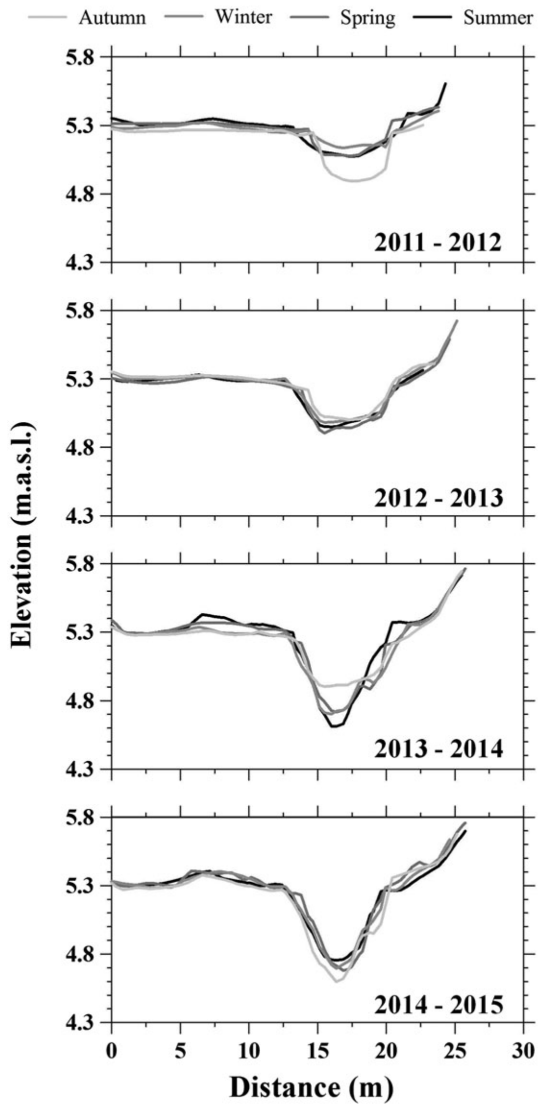

Figure 6. Seasonal variation observed on cross-section C, see Figure 1.

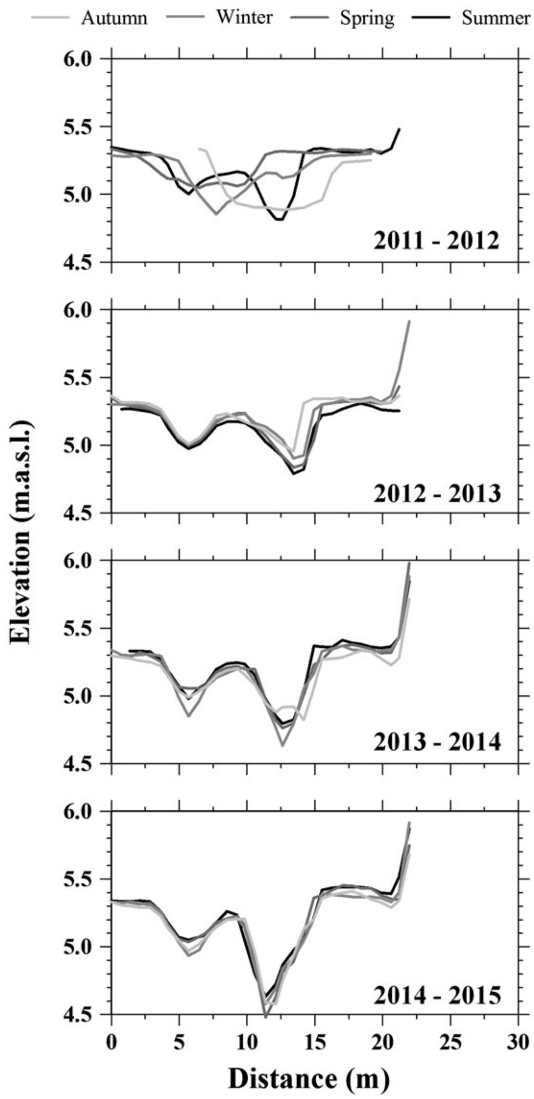

Figure 7. Seasonal variation observed on cross-section E, see Figure 1.

channel width presented lower variations after the establishment of vegetation, which occurred in the second spring after restoration (May 2013). The analysis of channel width evolution indicates that plants and in particular roots had the major role in bank stabilization. This is deduced from the progressive decrease of channel widening even if high flows systematically occurred in winter when plant foliage was drastically reduced.

The bankfull water depth, derived here as the difference in elevation between mean floodplain and channel bed (Figure 4(c)), progressively increased as a result of channel incision and sediment deposition on the floodplains. It can be observed from Figure 5(a) that the bankfull water depth doubled its initial value. The decrease of reach-averaged floodplain elevation in summer 2013 is a result of dewatering due to the maintained low flows; its subsequent increase reflects the re-watering and sedimentation processes caused by the high flows that occurred later in autumn, see Figure 4(f). Floodplain vegetation was cut by the Water Board at the end of the summer in 2014 and 2015 as a flood-safety measure (Figure 3). The reduction in the coverage of vegetation due to the vegetation cutting can be identified in Figure 4(e).

Erosion and deposition processes can be analysed by using the DoDs that are given as Supplementary material B. Bed erosion and vertical accretion rates were calculated from three selected cross-sections (see Figure 1) and presented in Table V. The relatively high erosion and deposition rates observed in the first DoDs are related to the initial chute cutoff. After this,

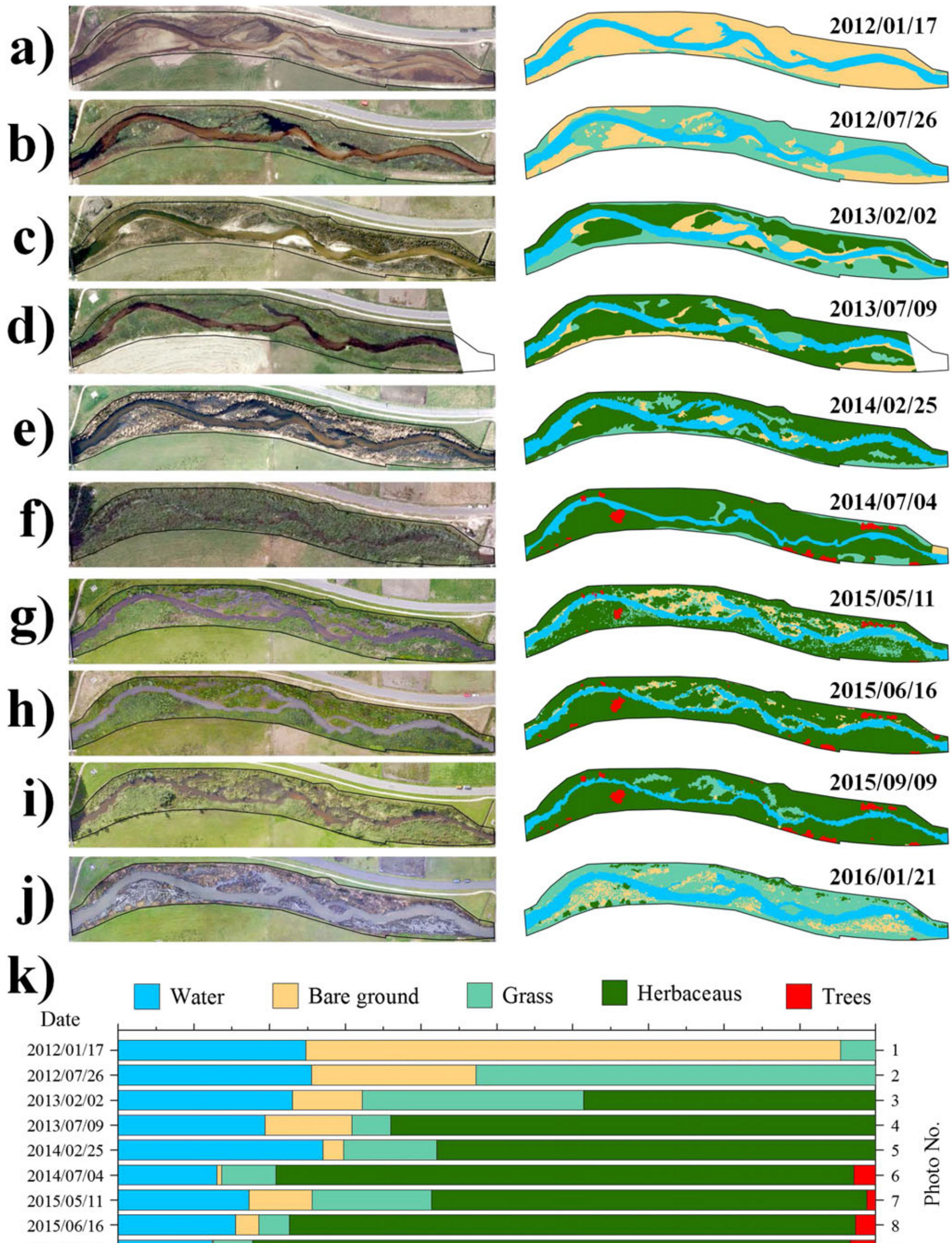

Figure 8. (a-j) Aerial photographs and vegetation classification maps of the Lunterse Beek and (k) spatial distribution in percentage. Aerial photos information is presented in Table IV. [Colour figure can be viewed at wileyonlinelibrary.com]

erosion and deposition processes occurred at lower rates. During the first year, the sediment that settled during the high-flow season on the bank edges, forming natural levees, was washed away during the next winter. This can also be seen in the negative rates of vertical accretion reported in Table V for cross-sections A and C during the first year. However, after the high-flow period of the second year vegetation was able to establish on levees, reinforcing them and increasing local sediment capture. Consequently, vertical accretion in these areas started to occur after the second year (see Table V). Levee formation enhanced channel bed erosion due to flow concentration (i.e. channel incision), and floodplain rising. Two episodes of reduction in floodplain levels can be identified from the DoDs. These were most probably caused by the cutting of vegetation carried out by the Water Board, as a flood-risk reduction measure, which occurred in 2014 and 2015. This is also shown by the negative values of vertical accretion reported in Table V for the last period (Year 4–5), highlighting the importance of the vegetation maintenance in restored streams.

The seasonal variation of the six selected cross-sections (see Figure 1(b)) is given as Supporting information Data S3. The evolution of cross-sections C and E is shown in Figures 6 and 7, respectively. Cross-section E corresponds to the area in which the initial chute cutoff occurred.

Evolution of vegetation

The spatial distribution of vegetation at different times is presented in Figure 8. The seasonal evolution of vegetation has been documented through the photographic annex given as Supporting information Data S4.

Riparian vegetation started to appear in this stream during the first spring after restoration (Figure 4 shows the evolution of vegetation coverage with time). However, the shoots that emerged in the lower areas did not survive the winter due to flow disturbance: the lower areas covered by vegetation in Figure 8(b) (first summer after restoration) become bare ground in Figure 8(c) (second winter after restoration). A higher

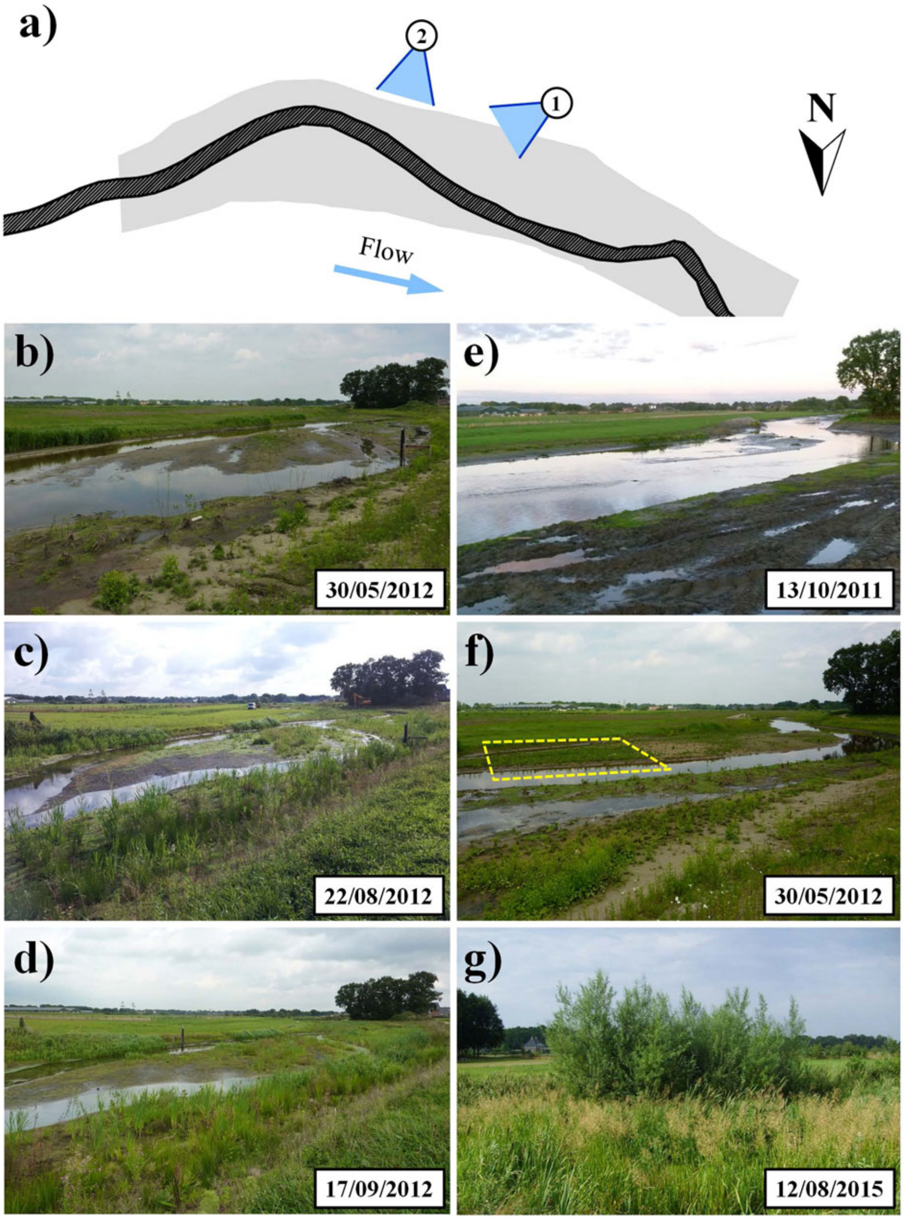

Figure 9. Terrestrial photographs highlighting vegetation succession. (a) Scheme indicating the position and direction of the photographs, vegetation stages from (b) to (g) explained in the text. Photographs (b) to (f) taken from position 1; photograph (g) taken from position 2. [Colour figure can be viewed at wileyonlinelibrary.com]

coverage was observed in the lower areas of the floodplains in the second annual growth cycle, see Figures 4(e), 8(d) and 8(e).

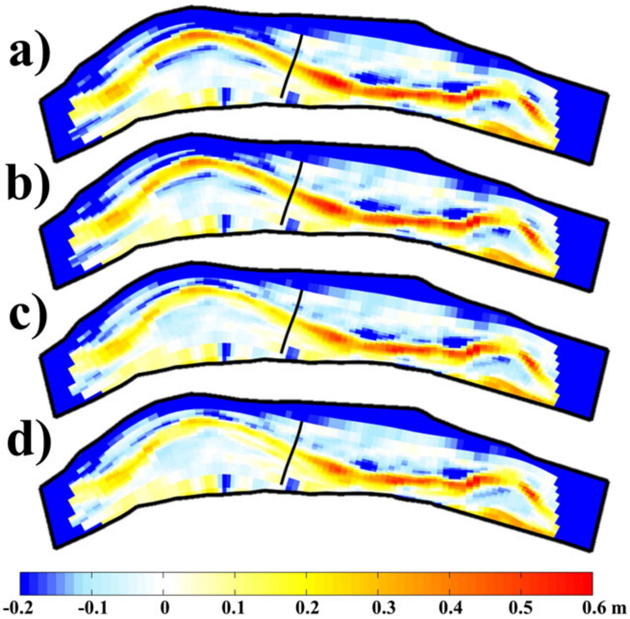

Figure 10. DEMs of difference (DoDs) in bed topography at the end of the study between the estimations with the model and the observations for (a) Scenario 1, without vegetation; (b) Scenario 2, uniform low-density grass; (c) Scenario 3, uniform high-density herbaceous vegetation; and (d) Scenario 4, with the observed seasonal vegetation variations. [Colour figure can be viewed at wileyonlinelibrary.com]

By comparing the photos and vegetation classification maps in winter after the first colonization (Figures 8(c) and 8(e)), it is possible to observe that the areas close to the stream from which vegetation was uprooted were successfully colonized during the second colonization cycle, showing the effectiveness of the re-colonization process and the quick adaptation of pioneer plants. Little organic residuals were observed to remain in these sediment deposits. These residuals are believed to enhance the establishment of new vegetation during the following colonization cycles.

The amount of grassy and bushy species steadily increased, as did also softwood trees, but to a much lesser extent. Species variety increased every year. Spontaneous regeneration of softwood species in restored streams was found also in previous investigations (Friedman *et al.*, 1995; Geerling *et al.*, 2008).

The first stages of ecological succession from grass to shrubs and from grass to woody vegetation (*Salix alba*) could be observed already in the first 5 years after restoration. In Figure 9, two locations (see Figure 9(a)) have been selected to show this process. Figure 9(b) shows the establishment of grassy vegetation on the highest areas, the ones that were first colonized. Figures 9(c) and 9(d) emphasize further developments, i.e. succession of the first colonized patches and vegetation growth in other areas after only 4 months. Figure 8 (g) shows a patch of Willows (*Salix alba*), which succeeded the plants that first colonized this area (shown in Figure 9(f)). The first well-developed tree stands with low-dense foliage were observed after 3.5 years, approximately, on the fourth summer after restoration. These young trees started to develop more intensively during the last year, reaching a height of more than

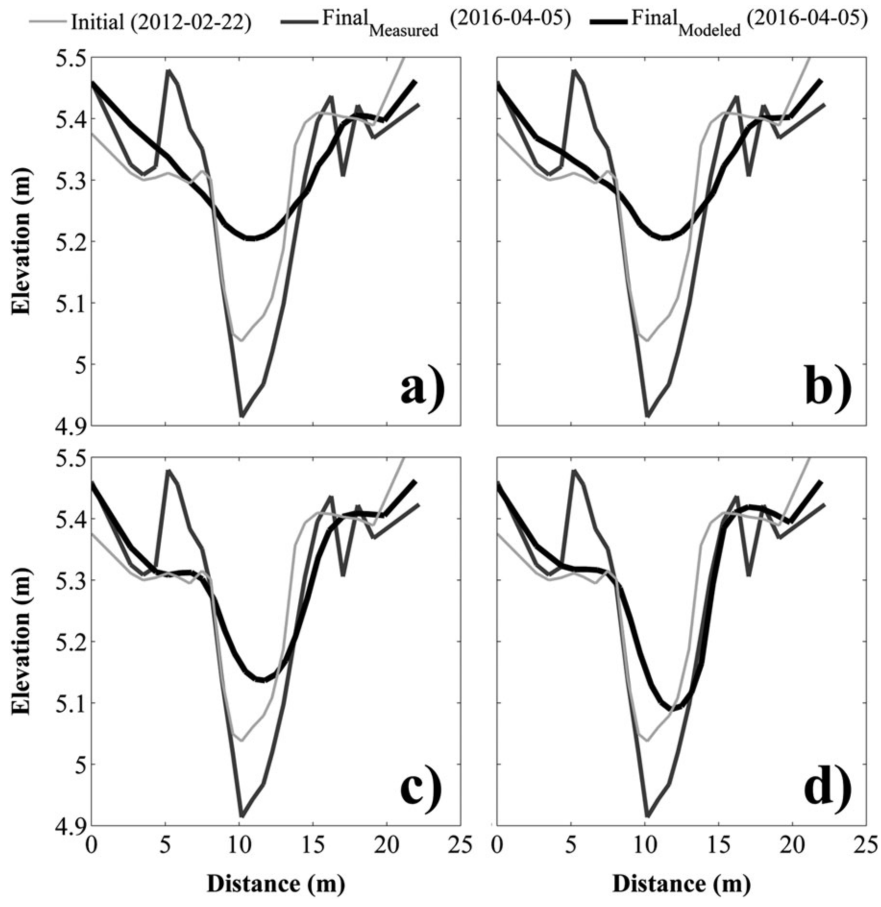

Figure 11. Comparison between the initial conditions, and the observed and modelled bed levels at the end of the study for the cross-section indicated in Figures 3 and 9 for (a) Scenario 1, without vegetation; (b) Scenario 2, uniform low-density grass; (c) Scenario 3, uniform high-density herbaceous vegetation; and (d) Scenario 4, with the observed seasonal vegetation variations.

2 m and a mean diameter of the main branch of 2.0 cm. The described areal expansion of these trees and the location of other patches of smaller willows that were developed during the same period can be identified in Figures 8(g) to 8(i). Figure 8(k) shows that the area covered by trees increased considerably (0 to 3%) during a period of 4 months (2014/02/25–2014/07/04). The dynamics described in the examples presented in Figure 9 was observed also in other high floodplain areas. However, the condition of vegetation and trees shown in Figure 9 drastically changed at the end of the monitoring campaigns, because of vegetation removal by the Water Board, as can be seen in Figures 8(j) and 8(k).

Results of Numerical Modelling

The DEMs of difference obtained between the bed levels calculated with the model and the ones measured during Campaign 28 are presented in Figure 10 for the four scenarios: (1) without vegetation; (2) uniform low-density grass, constant with time, on banks and floodplains; (3) uniform high-density herbaceous vegetation, constant with time; (4) with the observed seasonal variations of vegetation. Positive values in red indicate model overestimation whereas negative values in blue indicate model sub-estimation. The cross-section indicated in Figures 3 and 10 is used to show the cross-sectional developments. The comparison between the bed levels obtained with the model for the different scenarios and the ones observed in the field at the selected cross-section is presented in Figure 11. This cross-section was chosen because of it presented high dynamics. In general, the model reproduced well the morphological development of the floodplains, whereas poor results were obtained for the main channel. The best results were obtained for scenario 4 (with seasonal variations of vegetation). The reasons for this outcome are explained below.

From the four simulated scenarios, two different trends can be identified. The first one was obtained for the scenario without vegetation and for the scenario with low-density grass (1 and 2, respectively). The second trend was obtained for the scenario with herbaceous vegetation and with the observed vegetation coverage (scenarios 3 and 4). When vegetation is not included in the model (scenario 1), a wider and shallower channel than the one observed in the field is obtained. For scenario 2, with uniformly distributed low-density grass, there is little contribution from the increased roughness due to the plants, resulting in a situation similar to the one obtained for scenario 1.

Herbaceous vegetation produces a much higher flow resistance concentrating the flow in the main channel which results in channel incision. In general, the modelled width is larger than the observed one and in some areas the modelled bed level is considerably higher than the observed one, see Figures 10 and 11. This is due to not including the effects of plant roots on the stability of the banks so that bank erosion is overestimated. Another shortcoming arises from the strongly simplified bank erosion formulation, assigning part of the bed erosion occurring in the wet cells at the channel margin to the adjacent dry cell, so that channel incision always results in widening.

Scenario 4 resulted in the best predictions (6% reduction of calculated error for the floodplain areas and almost 20% reduction for the main channel bed), confirming the ability of Baptist's method in reproducing the effects of vegetation on local sedimentation (Montes Arboleda *et al.*, 2010). However, the model does not completely capture the flow concentration in the main channel and levee formation as in the other scenarios and, therefore, excessive sedimentation is also obtained in the main channel.

Regarding the relevance of considering the seasonal variations of vegetation in this type of streams, the results of the model show that including seasonal variations is important for the simulation of the evolution of small streams in temperate climates, like the Lunterse Beek.

Conclusions

The combined analysis of climatic and hydrological time-series, bathymetric data, vegetation dynamics and numerical modelling allowed studying the morphological adaptation of a lowland temperate-climate stream, the Lunterse Beek, during the first 5 years after channel re-meandering, starting from unvegetated floodplains. The results highlight the relevance of vegetation establishment for channel width stabilization and for the vertical accretion of both levees and floodplains. In the first period without vegetation, the levees that formed during overbank flows were later washed away. After soil stabilization by vegetation, the formed levees remained and the channel started incising.

A 2D morphodynamic model including vegetation was used to study different scenarios: (1) absence of vegetation; uniform and constant coverage by low-density grass (2) or high-density herbaceous vegetation (3); vegetation following the observed seasonal and inter-annual dynamics (4). The model reproduced the morphodynamic trends of floodplains well, but did not fully reproduce the observed bed and bank dynamics. This has been attributed to not including the stabilizing effects of roots and to the strongly simplified bank erosion formulation.

The results show that the seasonal variations of vegetation are relevant for the morphodynamic adaptation of small streams. This is especially true if vegetation is not well developed. Sparse plants tend to disappear in winter due to uprooting, which makes seasonal variations more relevant. With well-developed vegetation the small stream was unable to rework its banks even in the winter season, characterized by the highest flows and the least dense vegetation cover. This means that the establishment of floodplain vegetation is enough to fix the channel alignment of small streams, like the Lunterse Beek (averaged width of 5 m; averaged discharge of 0.36 m^3/s). We attribute this to root systems which were effective in protecting the soil also in winter. Yet, exceptionally high flows, not observed in the 5-year monitoring period, might still be able to eradicate riparian plants, causing changes that are larger than the observed ones. We believe that this conclusion is only valid for small streams characterized by flows with relatively low stream power (0.01–20.9 N/s). Our work, together with observations on other restored streams, indicates that re-meandering of small streams is often followed by an important initial morphological adaptation and that the establishment of riparian vegetation decreases the degree of subsequent morphological evolution.

Quantifying the effects of plant roots on soil reinforcement and on bank accretion is an important issue that should be addressed in future investigations to accurately predict the morphological evolution of river systems. Considering the limitations exhibited by the available estimators in reproducing the effects of trees, the representation of the morphological effects of isolated plants should be another issue of future investigations.

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Data S1. Supporting information

Data S2. Supporting information

Data S3. Supporting information

Data S4. Supporting information