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Morphological assessment of reconstructed lowland streams in the Netherlands

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ABSTRACT

Channelisation measures taken halfway the 20th century have had destructive consequences for the diversity of the ecology in the majority of the lowland streams in countries such as the Netherlands. Re-meandering is the common practice in restoring these lowland streams. Three reconstructed streams were monitored during the initial two years after construction of a new channel. The monitoring program included morphological surveys, sediment sampling, habitat pattern surveys, and discharge and water level measurements. Adjustments of the longitudinal bed profile formed the main morphological response. These adjustments were most likely caused by a lack of longitudinal connectivity of the streams as a whole, interrupting transport of sediment at locations of weirs and culverts. Bank erosion was observed only in a limited number of channel bends, and was often related to floodplain heterogeneity. Longitudinal channel bed adjustments and bank erosion were mainly caused by exogenous influences. In channel bends, the cross-sectional shape transformed from trapezoidal to the typical asymmetrical shape as found in meandering rivers. This behaviour can be attributed to an autogenous response to the prevailing flow conditions. Due to the prevailing fine sediment characteristics, bed material is readily set in motion and is being transported during the entire year. The existing design principles fail to address the initial morphological development after reconstruction. An evaluation of pre-set targets to realise water depth and flow velocity ranges shows the current procedures to be deficient. Based on this unfavourable evaluation, and the two-dimensional nature of habitat patterns needed to improve the conditions for stream organisms, we recommend to predict morphological developments as part of the design procedures for lowland stream restoration in the Netherlands.

1. Introduction

1.1. Lowland stream degradation

Halfway the 20th century, groundwater management in agricultural areas led to channelisation of a vast number of lowland streams in densely populated agricultural areas. The design of the straightened streams aimed at reducing flood risk and meeting the hydrological requirements for the adjacent agricultural fields. To achieve these requirements, the straightened streams were redesigned to obtain an increased cross-sectional area and to become controlled by weirs. During this period, the drainage density within lowland catchments also increased through the construction of ditches. All these measures were aimed at a fast discharge response during high flows, whereas weirs were in control of groundwater levels during low flows. These measures have seriously affected the hydrological conditions in catchments in The Netherlands [1]. Similar channelisation measures of lowland streams were implemented in Denmark [2–4], Germany [5], Japan [6], and the UK [7].

The channel modifications of lowland streams in the Netherlands had destructive consequences for the abiotic conditions within the stream and for the stream valley ecosystems [8]. The construction of straight channelised streams resulted in homogeneous in-channel habitat patterns, often solely consisting of bare sand. In an extensive survey, Verdonschot et al. [9] conclude that the measures (channelisation, increase of channel dimensions and increase of drainage density) had major consequences for flow velocity, being the key variable of the abiotic environment relevant in running water ecosystems [10]. During low flows, weirs were closed to increase groundwater levels. This caused flow velocities to drop to nearly zero and fine sediment (e.g. silt) to be deposited on the channel bed. During high flows, weirs were lowered and

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flow velocities increased dramatically. Eventually, this has caused channel incision and the disappearance of heterogeneous in-stream habitat patterns. In particular, coarse substrates, such as large woody debris and gravel, were lost [11]. The homogeneous channel beds consisting of fine sediment in combination with high flow velocities during high discharge events were detrimental for the existing stream organisms. Furthermore, the groundwater management had detrimental effects on the terrestrial stream valley ecosystems.

1.2. Morphological processes in lowland streams

Only a few studies have been presented in the literature focussing on morphological processes in lowland streams. These studies mainly focus on the morphological development after stream restoration measures were implemented in lowland streams. Wolfert [12] presented the most extensive morphological study on lowland stream restoration in the Netherlands to date. Three reconstructed streams, located in the southern part of the Netherlands, were monitored over a period of two years. Wolfert [12] showed that the largest sediment production rates were associated with the first bankfull discharge event, which occurred in the first year after construction. Adjustment of the channel bed included local scouring of pools, undercutting of banks, coarsening of bed material and the formation of depositional bedforms. Following the initial morphological response, rates of sediment production declined and the balance of sediment input and output was restored. Similar observations have been made in lowland stream restoration projects in the UK [13] and the US [14]. These findings confirm the results by Kuenen [15], who studied the meandering dynamics of several lowland streams in the northern part of the Netherlands. Kuenen [15] concluded that the majority of streams did not show signs of lateral migration.

The channel bed of lowland streams mainly consists of sand. In natural streams, a mosaic of substrate patterns has been observed covering the sand bed [16]. The variety of substrates include gravel, leaves, branches, large woody debris and coarse and fine organic detritus. Tolkamp [16] showed that the substrate pattern is dynamic over time, with distinct differences between the four seasons. Macrophytes are frequently observed in non-shaded lowland streams [17]. When macrophytes are present, they can have a strong control over the dynamics of the substrate pattern, by capturing fine sediments [5,12] and by reducing the active channel width [14].

1.3. Stream restoration in the Netherlands

The vast majority (96%) of lowland streams in the Netherlands are severely impacted by anthropogenic influences [8,18], reflecting the need for stream restoration. Wohl et al. [19] defines stream restoration as: "assisting the establishment of improved hydrologic, geomorphic, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the natural system". An important element of this definition is the focus on the catchment scale. Recently, several stream restoration concepts have been presented focussing on catchment scale measures, such as the '*erodible corridor*' [20] and '*espace de liberté*' [21]. Until now, stream restoration has mainly taken place adopting reach scale measures [22,23]. The common practice in the Netherlands is no exception to this.

Stream restoration in the Netherlands has largely been triggered by the Water Framework Directive [WFD; 24], in which it is stated that all water bodies should achieve a good quality ecological status by 2015, with extensions until 2027. The main objective of stream restoration in the Netherlands is to improve the ecological status. The second objective is to increase the retention of water within the catchment, which follows from the National Water Act [WB21; 25]. Other objectives are related to hydrological conditions, to prevent groundwater damage to crops on agricultural fields and to assure wetland conditions of natural areas, and recreation, to combine measures with an increase of recreational facilities.

Most often, stream restoration in the Netherlands involves the construction of sinuous channels (re-meandering), mimicking the channel planform characteristics before channelisation. The sinuous planform is often based on historical sources. Re-meandering has been widely adopted as a stream restoration measure (e.g., [5,13,26]). Positive effects on the habitat diversity have been reported after re-meandering measures were implemented [5]. Re-meandering or other channel reconfiguration measures are often applied at a local scale, in isolated channel reaches. Locally, these measures may be successful in improving the habitat conditions, but recovering the typical stream assemblages may only be successful when taking measures at a larger scale, i.e. the catchment [27].

The design procedure, adopted by the Dutch water authorities, mainly focusses on the design of the cross-sectional shape of the reconstructed streams. The design procedure involves three main requirements of the new channel design: (1) flood risk reduction, (2) optimal groundwater conditions for adjacent agricultural fields and (3) improvement of the conditions beneficial for benthic ecology. Table 1 shows details of the design principles, that served as a basis for the three stream restoration projects here subjected to study. When designing the new cross-sectional shape, the following steps are commonly followed. The channel bed level is adjusted such that existing groundwater levels are maintained. Often a groundwater model is used to predict the future groundwater levels. The cross-sectional shape is adjusted to achieve conditions of water depth and flow velocity that best suit the needs of specific lowland ecosystems [9]. A 1D-flow model [e.g. SOBEK Channel flow; 28] is typically used in this step. Finally, the floodplain level is adjusted to meet the legal requirements of flood risk. The flooding occurrence is related to the bankfull discharge. The bankfull discharge is obtained from a flow duration curve, in which the expected frequency corresponds to the total inundation period. The measures taken to improve the abiotic conditions for benthic ecology and the construction of a floodplain aims at restoring the natural processes in the streams. Although it has been widely used in stream restoration design, 1D-flow modelling may not capture small scale processes related to the benthic ecology appearing in natural lowland streams.

In the design process of lowland stream restoration in the Netherlands, little attention has been paid to the morphological developments that may occur after channel reconstruction. Nevertheless, the Dutch water authorities are concerned with sediment

Table 1
Hydrological and ecological constraints for the design of the three stream restoration projects. Not all constraints were used in each stream restoration project. The constraints that were not used are denoted with n/a (not available).

	Period	Hagmolenbeek	Lunterse beek	Tungelroyse beek
Hydrological constraints				
Inundation frequency (days yr^{-1})		10–20	160–200	>100
Groundwater level	Summer	n/a	1	n/a
(m – Surface elevation)	Spring	n/a	n/a	0.50–0.80
	Winter	n/a	n/a	0.30–0.50
Ecological constraints				
Flow velocity (m s^{-1})	Summer	>0.10	>0.10	>0.20
	Spring	0.20–0.40	n/a	0.10–0.50
	Winter	n/a	0.60–0.80	<1.00
Water depth (m)	Summer	n/a	>0.20	0.20–0.70

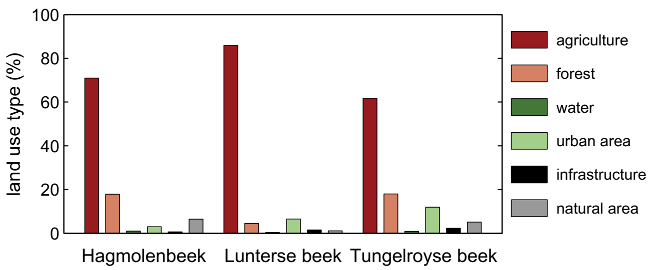

Fig. 1. Land use type (%) in each of the three catchments [31].

transport and the associated morphological changes after channel reconstruction. These concerns mainly address bed slope developments and lateral channel bed adjustments. The objective of this study is to characterise and understand the channel bed adjustments in the three selected lowland streams subject to a stream reconstruction. The selected streams all represent conditions typical for the Netherlands, but are different in bed slope, sediment grain size and channel width.

2. Study areas

The three streams under study are located in three different provinces of the Netherlands (Fig. 2). The catchments are located in aeolian-sand deposits and land use is dominated by agriculture (Fig. 1). Climatological conditions can be considered constant throughout the Netherlands, with the average yearly precipitation amounting to 793 mm [29]. Channel reconstruction in all three streams ended between June 2010 and October 2011. The overall stream restoration strategy included the construction of a sinuous channel planform, removal of weirs, and lowering of the floodplains. Table 2 shows characteristics of the three projects. Although the same restoration strategy was used in all three projects, the resulting channel characteristics differ. Constructed channel widths range from 2.0 m to 12.9 m, and constructed channel slopes from 0.08 m km^{-1} to 0.96 m km^{-1}.

Several site specific characteristics can be observed from the sketches of the study areas (Fig. 2). In the Lunterse beek (panel a), the reconstructed channel crosses the former straightened channel at several locations. A weir is located upstream from the study reach. A peat deposit is located in the upstream part of the study reach. The Lunterse beek was also subject to extensive analyses in [32]. The study reach of the Lunterse beek analysed in the current manuscript includes the reconstructed channel reach upstream from the bend where a cutoff event occurred [32]. This choice was made to facilitate comparison with the morphological processes that occurred in the two other study reaches discussed here. In the Hagmolenbeek (panel b), the reconstructed channel partly follows the former straightened channel, at the location where a bridge was maintained. Here, the channel dimensions increased, compared to the rest of the study reach. The study reach of the Tungelroyse beek (panel c) is located upstream from an area where a straightened channel was maintained, causing an increase of the channel dimensions at the downstream end of this study reach.

3. Material & methods

A standardised monitoring scheme was implemented for all three projects. The monitoring focused on morphological and hydrological parameters. Monitoring activities were performed for study reaches with a length between 250 and 380 m. The lengths of the study reaches were chosen such that they captured at least two complete meander wavelengths. Morphological data were collected using Real Time Kinematic (RTK) GPS-equipment (Leica GPS 1200+), with a one-year interval between the surveys. The RTK-GPS equipment allows to measure a point in space with an accuracy of 1 to 2 cm. Morphological data were collected along 30 to 69 cross-sections during each survey. The water level was recorded at each cross-section, from which the water surface slope was determined.

Table 2
Characteristics of the study areas, the stream restoration design and the field surveys.

	Hagmolenbeek	Lunterse beek	Tungelroyse beek
Study area			
Longitude	52°12′59″ N	52°4′46″ N	51°14′42″ N
Latitude	6°43′22″ E	5°32′37″ E	5°53′10″ E
Altitude (m a.m.s.l.)	17.8	5.2	23.3
Catchment area (km^2)	59.5	63.6	116.1
Mean daily discharge (m^3 s^{-1})	0.15	0.31	1.01
Yearly peak discharge (m^3 s^{-1})	1.00	3.55	4.77
Annual coeff. of flow variation[a] (–)	123.2[b]	138.5[b]	77.4[c]
Sediment size (μm)	188	258	141
Stream restoration design			
Total channel length (km)	1.7	1.6	9
Channel width (m)	2.0	6.5	12.9
Channel depth (m)	0.4	0.4	1.4
Channel slope (m km^{-1})	0.50	0.96	0.08
Sinuosity (–)	1.20	1.24	1.32
Floodplain width (m)	20–40	15–25	60–100
Floodplain depth (m)	0.3	0.7	1.4
Vegetation management (floodplain)	Sowed[d]	Trees planted[e]	Trees planted[f]
Field surveys			
Length of study reach (m)	385	250	380
Surveying period (from–to)	September 2010–July 2012	October 2011–August 2013	June 2011–August 2013

[a] Standard deviation divided by average discharge [30].
[b] Between harsh intermittent and intermittent flashy [30].
[c] Between intermittent flashy and intermittent runoff [30].
[d] With a seed mixture of Perennial ryegrass (*Lolium perenne*), White Clover (*Trifolium repens*), and Timothy (*Phleum pratensis subsp. pratensis*).
[e] Alder saplings (*Alnus glutinosa*) and Willow saplings (*Salix alba*, *Salix cinerea*, *Salix repens*).
[f] Alder saplings (*Alnus glutinosa*).

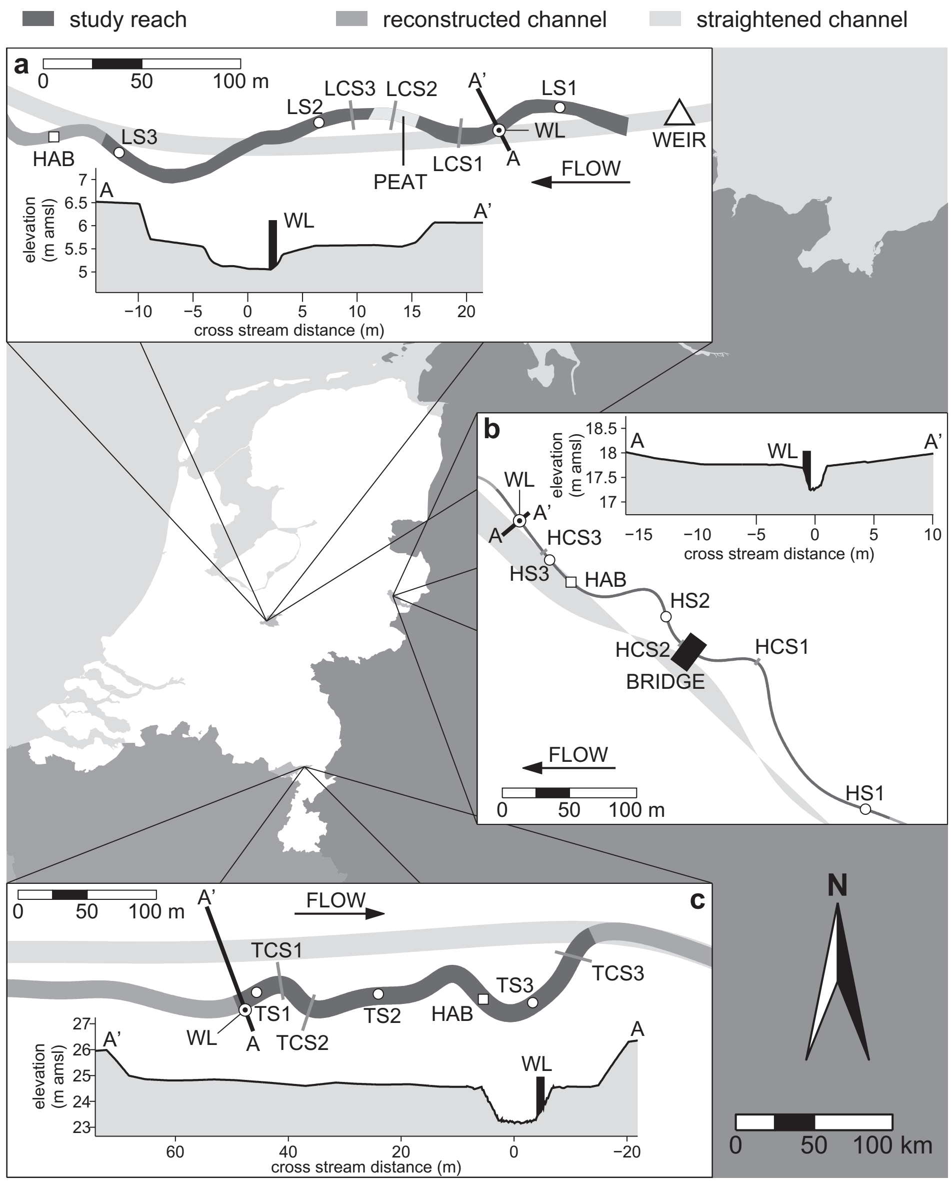

Fig. 2. Location and sketches of the study areas in the Netherlands of Lunterse beek (a), Hagmolenbeek (b), and Tungelroyse beek (c). The sketches include the study reach (dark grey), reconstructed channel (grey) and former straightened channel (light grey), the sediment sample locations (S1, S2, S3), the locations of the cross-sections (CS1, CS2, CS3), the location of the habitat survey (HAB), and the location of the water level gauge (WL), including a cross-section (A–A′). The sketches also include the location of a weir and a peat deposit in the Lunterse beek (panel a) and the location of a bridge in the Hagmolenbeek (panel b).

The channel width and channel bed elevation were determined at each individual cross-section. The channel width is defined as the distance between the two channel bank tops. The location of the channel bank tops in each cross-section were marked during the field surveys. The channel bed elevation was obtained by subtracting the hydraulic radius from the average elevation of the two opposing channel bank tops. The hydraulic radius is defined as the cross-sectional area divided by the wetted perimeter. The average channel slope over the total length of the study reach was determined by fitting a straight line through the channel bed elevations.

The in-channel habitat patterns were obtained at 20-m subsections of the three study reaches (HAB; Fig. 2). Each year, three pattern sketches were made of the channel bed, distinguishing substrate (sand, gravel and silt), macrophytes and algae. The in-channel habitat surveys were performed independent from the morphological surveys. In the Lunterse beek, the habitat pattern was obtained at a location downstream of the main study reach (see Fig. 2a), which overlaps with the area where the chute cutoff occurred.

Sediment samples were taken at three locations along the channel, i.e. upstream, half way, and downstream of the study reaches (S1,S2,S3; Fig. 2). Samples were taken during the first and last morphological surveys. Sediment samples were taken with a sediment core sampler (KC Denmark Kajak Model A). At each location, three sediment samples were taken from the top 5 cm of the channel bed. The three samples were combined to obtain the sediment distribution at each location. The sediment samples were dried for 24 h in an oven at 105 °C. The dried samples were sieved using a stack of eight sieves, with mesh sizes ranging from 63 to 2000 μm. The weight of each subsample was determined and the cumulative grain size distribution was established. The median grain size was derived from the cumulative grain size distributions.

Table 3
Average water surface slope and critical Shields stress for each stream.

	Hagmolenbeek	Lunterse beek	Tungelroyse beek
Water surface slope (m^{-1})	0.69	0.43	0.08
Critical Shields stress (–)	0.052	0.042	0.067

Discharge was measured continuously at a measurement weir, located outside the study areas. Discharge was sampled at a one-hour frequency for the Hagmolenbeek and Lunterse beek and at a 15-min frequency for the Tungelroyse beek. Water level was measured continuously using a water level gauge inside the study reach (WL; Fig. 2). Water level was sampled at a one-hour frequency. Since short-term water level variation may relate to local effects at the water surface, further analysis focusses on the daily-averaged time-series for discharge and water level.

Discharge and water level time-series were combined to determine the cross-sectional averaged flow velocity $\bar{u}$ and dimensionless bed shear stress (Shields stress) θ. The cross-sectional flow area was determined based on the water level and cross-sectional shape at the water level gauge (Fig. 2). Values of $\bar{u}$ were obtained by dividing the discharge by the cross-sectional flow area.

Assuming near-uniform flow conditions, Shields stress θ was estimated according to:

$$\theta = \frac{R\frac{\Delta\zeta}{\Delta x}}{d_{50}s} \quad (1)$$

where R is the hydraulic radius (m), $\frac{\Delta\zeta}{\Delta x}$ is the longitudinal water surface slope (–), d_{50} is the median grain size (m), and $s = (\rho_s - \rho)/\rho$ is the relative submerged specific gravity of the sediment (–), with $\rho = 1000$ kg m^{-3} the density of water and $\rho_s = 2650$ kg m^{-3} the density of sediment. The longitudinal water surface slope $\frac{\Delta\zeta}{\Delta x}$ was based on the average measured longitudinal water level (Table 3). The median grain size d_{50} was obtained from the average of the sediment samples from the first survey.

The cross-sectional averaged Shields stress time-series were used to determine the time windows when the Shields stress exceeds the critical Shields stress, corresponding to the periods when sediment may have been actively transported. The critical Shields stress depends on the grain size and is defined as [33]:

$$\theta_{cr} = 0.24D_*^{-1} \quad \text{for } 1 < D_* \leqslant 4 \quad (2)$$

$$\theta_{cr} = 0.14D_*^{-0.64} \quad \text{for } 4 < D_* \leqslant 10 \quad (3)$$

where D_* is the particle parameter:

$$D_* = \left[\frac{(s-1)g}{\nu^2}\right]^{1/3} d_{50} \quad (4)$$

where $g = 9.81$ m s^{-2} is the gravitational acceleration and $\nu = 10^{-6}$ m^2 s^{-1} is the kinematic viscosity of water.

4. Results

4.1. Morphological surveys

Fig. 3 shows the temporal changes of the channel width (upper panels) and channel bed elevation (lower panels) along the channel centerline. The figure indicates the location where the reconstructed channel crosses the former straightened channel (Hagmolenbeek and Lunterse beek) and the location of the peat deposit (Lunterse beek).

At two locations in the Hagmolenbeek, changes in channel width and channel bed elevation were observed. One location is situated where the reconstructed channel partly follows the former straightened channel, which coincides with the location of a bridge. The channel bed elevation before reconstruction was partly maintained. During the two-year monitoring period, this section of the channel was filled with sediment. The other location showing pronounced changes is in the bend just upstream from the bridge. Here, a channel width increase and channel incision were observed from year 0 to year 2. A minor form of channel incision is observed in the downstream half of the study reach.

Most variation in channel width and bed elevation was observed in the Lunterse beek. The channel width increased by 1 to 3 m at two sections of the channel. At these two sections, the reconstructed channel crossed the former straightened channel. Channel incision occurred at two locations along the channel centerline: upstream and downstream from the peat deposit. Sediment was deposited downstream of the streamwise coordinate 175 m. Most of the changes in channel width and bed elevation occurred during the first year after construction of the reconstructed new channel. In the second year, only minor changes occurred.

During the two-year survey period, hardly any changes in channel width were observed in the Tungelroyse beek. Changes were more apparent in the temporal evolution of the bed elevation. Channel incision occurred between streamwise coordinates 125 and 150 m. Deposition of sediment occurred around streamwise

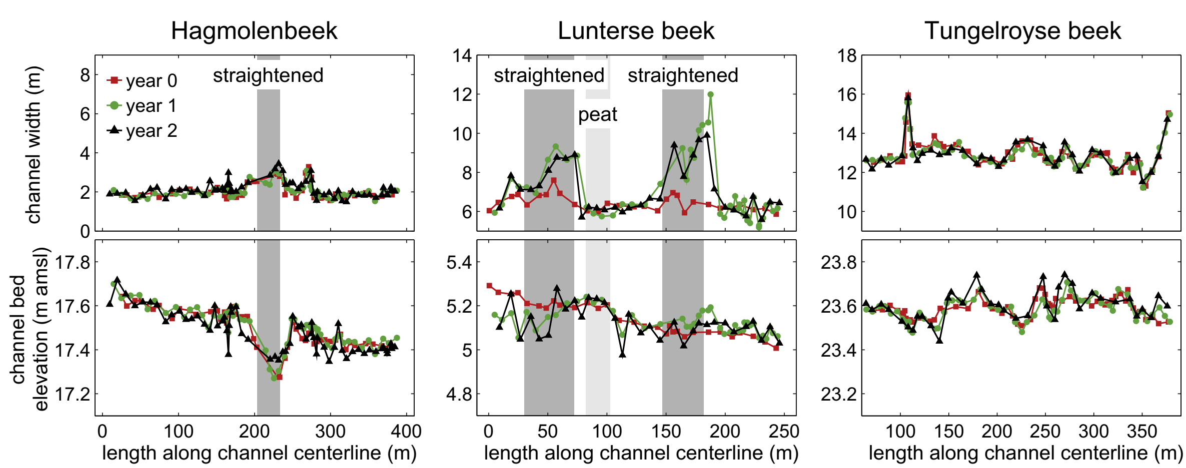

Fig. 3. Channel width and channel bed elevation along the channel centerline at year 0 (red squares), year 1 (green circles) and year 2 (black triangles). The location where the reconstructed channels cross the straightened channels are indicated with dark grey (Hagmolenbeek and Lunterse beek). The location of the peat deposit in the Lunterse beek is indicated with light grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

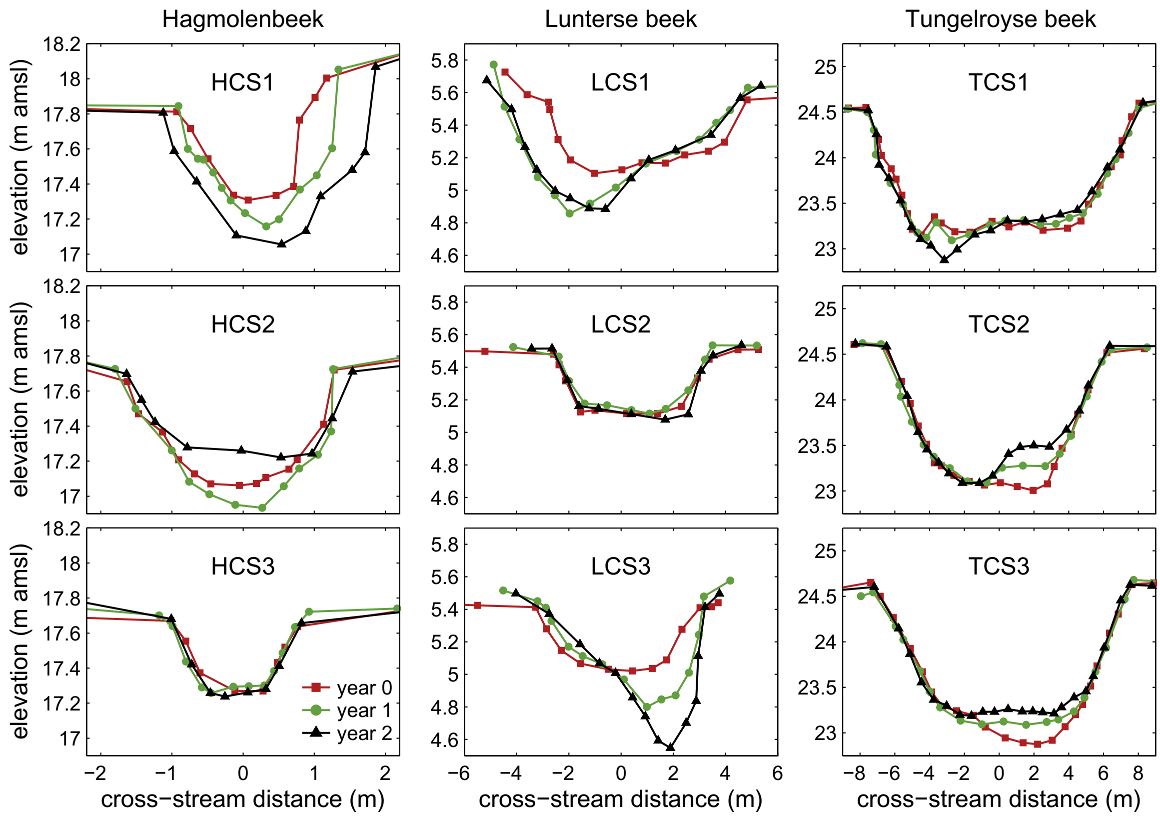

Fig. 4. Three examples of the temporal evolution of cross-sections in the three streams at year 0 (red squares), year 1 (green circles), and year 2 (black triangles). The location of the cross-sections correspond to the locations as shown in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

coordinates 175 m and 250 m, and downstream from streamwise coordinate 350 m. The latter is most evident for cross-section TCS3 (Fig. 4).

Fig. 4 shows three examples of cross-sections for each study reach and emphasises some of the observations from Fig. 3. HCS1 from the Hagmolenbeek shows the bend where both channel widening and channel bed incision occurred. Channel widening is mainly related to bank erosion. Here, bank erosion occurred gradually, from year 0 to year 2, and amounts up to 1.05 m (62% of the channel width). Channel bed incision also occurred gradually and amounted up to 0.25 m (44% of the channel depth). HCS2 shows the rate of sedimentation of the channel near the bridge. Here, the constructed channel width (3.0 m) exceeded the channel width of the rest of the channel. Deposition of sediment locally exceeded 0.29 m (37% of the channel depth). HCS3 shows an example of a cross-section from the downstream half of the study area. Only minor changes occurred here, even though Fig. 3 suggests channel incision in this part of the study reach.

In the Lunterse beek, channel widening and incision occurred at a larger scale. LCS1 shows a location along the channel where the reconstructed channel crosses the former straightened channel. It shows a cross-section where bank erosion occurred next to incision of the channel bed near the eroding bank. This resulted in an asymmetric cross-sectional shape, as typically found in meandering rivers. The upstream cross-section also shows that morphological adjustments mainly occurred in the first year. At this location, bank erosion amounted to 1.4 m (19% of the channel width). Channel incision amounted to 0.22 m (55% of the channel depth). LCS2 shows a cross-section within the peat deposit. Few morphological adjustments occurred in this section of the channel. LCS3 shows that just downstream of the peat deposits, channel incision occurred. As opposed to other locations along the channel, here the morphological development took place gradually. In the first year, incision amounted up to 0.22 m and in the second year up to 0.25 m, reaching 130% of the channel depth in total.

Fig. 3 shows that few changes in channel width were observed in the Tungelroyse beek. TCS1 shows the cross-section where the channel was constructed, with a channel width exceeding the rest of the channel, viz. 15.7 m against an average of 12.9 m. At this location, located in a bend, channel incision of the outer bank and aggradation of the inner bank occurred. TCS2 shows point bar development in the inner bend. Here, sediment was deposited in the inner bend, resulting in a gradual increase amounting to 0.27 m in the first year and 0.22 m in the second year. TCS3 is located at the downstream end of the study reach and shows the channel bed gradually aggregated over the two-year period, by 0.23 m in the first year and 0.13 m in the second year.

Fig. 5 shows the channel slopes for each of the three surveys per stream. The channel slope in the Hagmolenbeek hardly changed

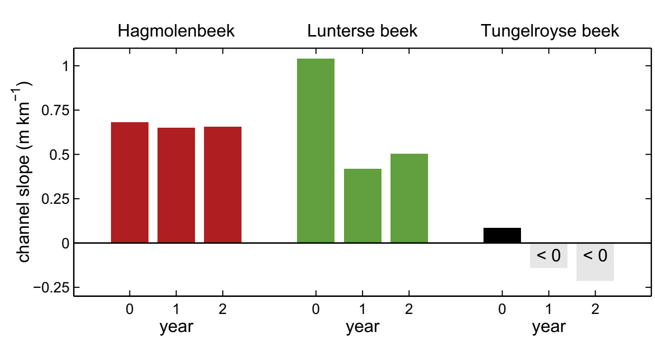

Fig. 5. Channel bed slope (m km^{-1}) derived from the lower panels of Fig. 3.

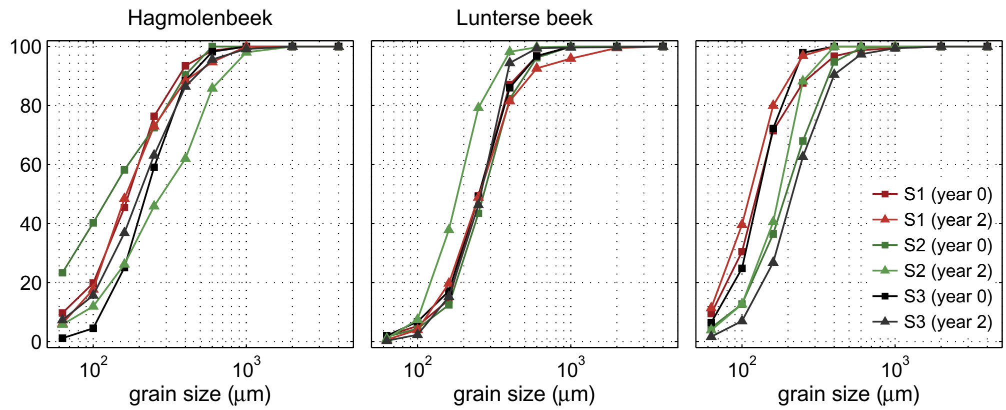

Fig. 6. Grain size distributions taken during year 0 (squares) and year 2 (triangles). Samples were taken at three locations along the channel centerline: S1 (red), S2 (green) and S3 (black). The sample locations are shown in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Median grain size (µm) of each sediment sample, derived from the grain size distributions (Fig. 6). The sample locations are shown in Fig. 2.

	Hagmolenbeek		Lunterse beek		Tungelryse beek	
	Year 0	Year 2	Year 0	Year 2	Year 0	Year 2
S1	171	165	252	254	125	113
S2	129	282	271	182	194	175
S3	222	200	253	259	128	214
Average	188	203	258	227	141	179
σ_g [a]	1.88	2.11	1.53	1.49	1.50	1.46

[a] Geometric standard deviation, $\sigma_g = \sqrt{d_{84}/d_{16}}$ [34].

over the two-year period. Both the Lunterse beek and the Tungelroyse beek show decreasing channel slopes over time. The decrease of channel slope in the Lunterse beek was most dramatic in the first year. This was mainly caused by channel incision at the upstream end of the study reach. In the second year, a slight increase of the channel slope was observed. The Tungelroyse beek featured negative channel slopes at the time of the surveys that took place one and two years after construction, which can be attributed to local sedimentation in the downstream half of the study area.

4.2. Grain size analysis

Fig. 6 shows the grain size distributions for the three sample locations in each of the three streams, both at the start and at the end of the monitoring period. Table 4 lists the median grain sizes established from the sediment samples. Only small changes in bed material composition have occurred during the two-year study period. In each of the three streams, two out of three sample locations show negligible changes. Especially in the Lunterse beek, all except one of the grain size distributions remain nearly identical. In each stream, one sample location differs from this observation, i.e. location HS2, LS2, and TS3. Eventually, this caused a change in average median grain size, with an increase in the Hagmolenbeek and Tungelroyse beek and a decrease the Lunterse beek.

4.3. Habitat patterns

Fig. 7 shows the evolution of the in-channel habitat patterns. All three study reaches were constructed in bare sand. Within the first year several habitat types developed in the Hagmolenbeek and in the Lunterse beek. In the Tungelroyse beek the channel bed still consisted of bare sand after the first year. In each study reach, macrophytes emerged, mainly near the channel banks. Also other habitat types were observed: algae in the Hagmolenbeek and in the cutoff channel of the Lunterse beek, gravel in the Lunterse beek and silt in the Tungelroyse beek. Since the habitat surveys were mainly performed in the summer period in the Hagmolenbeek, the dense cover of algae cover as observed from the figure may not represent the habitat conditions during the entire year.

4.4. Hydrological results

Fig. 8 shows Box-and-whiskers plots of the cross-sectional averaged flow velocity and Shields stress. The lowest cross-sectional averaged flow velocities occurred in the Hagmolenbeek, where the median value amounts to 0.08 m s^{-1}. The cross-sectional averaged flow velocities in the Lunterse beek and Tungelroyse beek were similar, with median values amounting to 0.13 m s^{-1}. Most variation in cross-sectional averaged flow velocity is observed in the Lunterse beek. Here, values reach up to 0.41 m s^{-1}. The least variation is observed in the Hagmolenbeek.

The highest values for the Shields stress are observed in the Hagmolenbeek, where the median Shields stress amounts to 0.34. The median values for the Shields stress in the Lunterse beek and Tungelroyse beek are slightly lower, both amounting to 0.22. The variation of the Shields stress differs among the three streams. Most variation is observed in the Hagmolenbeek and the least in the Tungelroyse beek. Apart from these differences, the fraction of time for which the threshold for sediment motion is exceeded is similar for all three study reaches, amounting to 87%, 84%, and 81% of the time for the Hagmolenbeek, Lunterse beek and Tungelroyse beek, respectively.

5. Discussion

5.1. Longitudinal adjustments

Longitudinal channel bed adjustments were observed at channel sections where the reconstructed channel either crossed the former straightened channel (Hagmolenbeek), downstream from a weir and a peat deposit (Lunterse beek) or upstream from a straight channel section (Tungelroyse beek). In the Hagmolenbeek, longitudinal channel bed adjustments mainly occurred at a location where the reconstructed channel crosses the former straightened channel. At this location, where a bridge was located, the cross-section was initially both deeper (59%) and wider (34%) than the average values for the rest of the study reach. It is likely that the increase of channel dimensions caused flow velocities to decrease in this area,

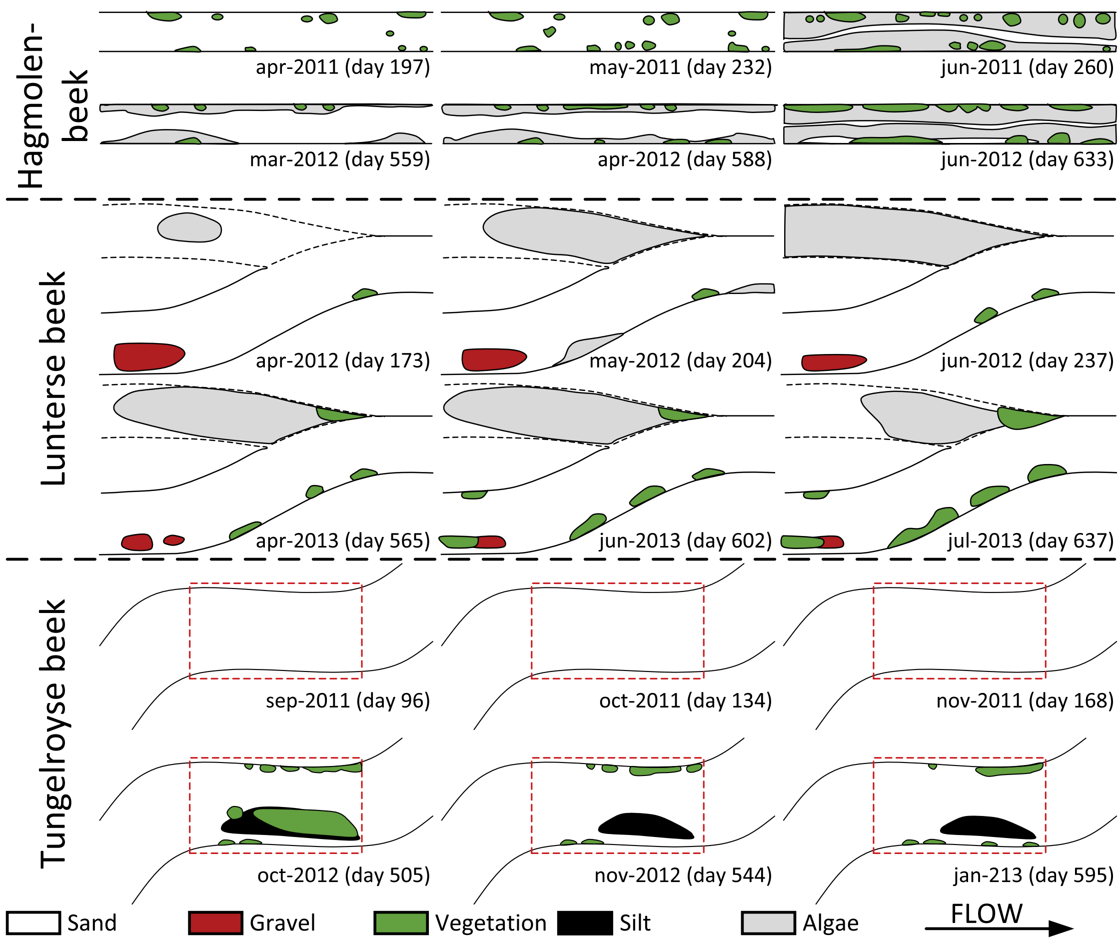

Fig. 7. Temporal evolution of the in-channel habitat pattern in a 20-m study reach. The location of the following habitat types were observed: sand (white), gravel (red), vegetation (green), silt (black), and algae (grey). The sample locations are shown in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

eventually leading to channel bed aggradation. Geometrical effects may have been responsible for the aggradation of the channel bed at the downstream end of the Tungelroyse beek. Here, the reconstructed channel eventually flows into the straightened channel, resulting in an increase of channel width.

In the Lunterse beek, a weir was maintained upstream from the study reach. At the upstream end of the study reach, channel incision was observed. It is likely that a lack of sediment transport past the weir resulted in an imbalance in sediment transport downstream of the weir. Consequently, more sediment may have been entrained because of the difference between the actual sediment transport and the transport capacity in this section, resulting in channel incision. A similar situation may have occurred downstream of the peat deposit. The peat area may trap sediment from upstream, interrupting the along channel sediment transport. Downstream of the peat deposit, sediment was available and must have been entrained to increase the sediment transport towards the transport capacity of the flow, causing channel bed incision.

It has been recognised that successful stream restoration requires an increase of connectivity [8,19,35]. Most restoration projects focus on single, isolated channel reaches and therefore lack connectivity, which is vital for improving the ecosystem. From the three stream restoration projects evaluated in this study, only one project (Tungelroyse beek) involved restoration of the whole stream. The other projects were constructed in isolated channel reaches. This has caused a lack of longitudinal connectivity, affecting the temporal evolution of the longitudinal channel bed profile. The longitudinal channel bed profile was influenced by backwater effects, caused by widening of the channel width where the reconstructed channel follows the maintained straightened channel (Hagmolenbeek and Tungelroyse beek), and by a lack of upstream sediment input (Lunterse beek). All these influences can be classified as exogenous. Eventually, these exogenous influences caused a decrease of channel slope in two of the studied streams (viz. Lunterse beek and Tungelroyse beek). Similar morphological adjustments have been observed in isolated reconstructed channel reaches of lowland streams in the UK [13]. The discontinuity of sediment transport hampers the use of concepts known from geomorphology such as described by [36,37], which would allow to predict developments in bed material size, channel gradients and stream flow. To better understand the long-term morphological response to local stream restoration efforts like the ones undertaken, more theoretical knowledge is warranted about the developments under supply limited conditions. In future stream restoration projects it may be worthwhile to aim at increasing the longitudinal connectivity by removing weirs and to anticipate the causes of backwater effects.

5.2. Lateral adjustments

Lateral channel bed adjustments occurred in each of the three streams. The cross-sections were constructed with a trapezoidal shape. The temporal evolution of the cross-sections shows that after two years an asymmetrical profile emerged, especially in

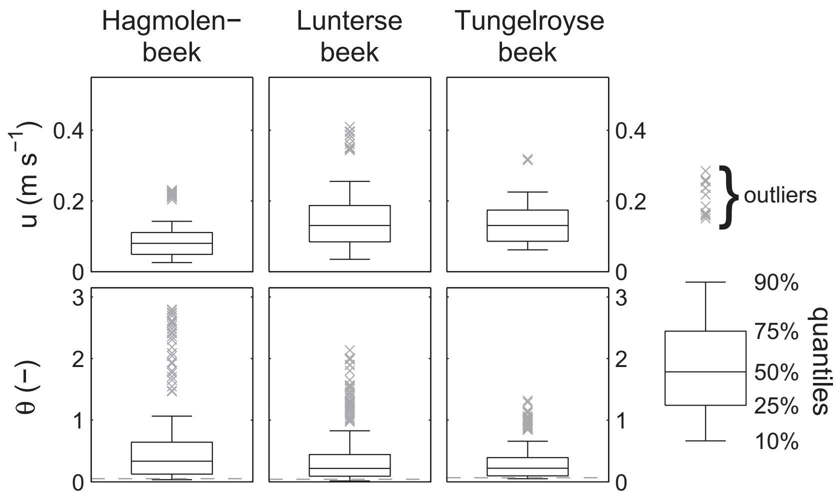

Fig. 8. Box-and-whiskers plots (median, 25th and 75th percentiles within the box and 10th and 90th percentiles as whiskers) of the cross-sectional averaged flow velocity $\bar{u}$ (m s^{-1}) and cross-sectional averaged Shields stress θ (–). The dashed lines in the lower plots indicate the critical Shields stress. A value X is considered to be an outlier when the value is outside the range between $Q_{25} - w(Q_{75} - Q_{25})$ and $Q_{75} + w(Q_{75} - Q_{25})$, with $w = 1.5$. Outliers are plotted with grey crosses.

the channel bends. Asymmetrical cross-sectional profiles are typical for meandering rivers and originate from secondary circulation, causing transfer of longitudinal momentum leading to higher flow velocities near the outer bank of a bend. The observations of erosion at the outer bank and deposition at the inner bend, may thus be attributed to an autogenous process.

Not all lateral channel adjustments are autogenous. In the Lunterse beek, bank erosion was observed in areas where the reconstructed channel crosses the former straightened channel. At these locations, the former channel was filled with sediment prior to channel reconstruction. It is very likely that this resulted in a less consolidated floodplain, which was prone to erosion. In the Hagmolenbeek, bank erosion was observed at a location where a non-cohesive sandy layer was overlain by a vegetated upper layer. Erosion of the sandy layer undermined the upper cohesive layer, causing failure of the overhanging upper layer. Furthermore, vegetation may also have played a role in stabilizing the channel banks. Fig. 7 shows that macrophytes emerged mainly near the channel banks. Vegetation can have a significant effect on bank stability [38,39]. Our standardised monitoring plan did not include an in-depth analysis on the role of vegetation on bank stability. For future stream restoration analysis, it may be worthwhile to monitor bank stability, since it may have a significant effect on lateral channel development.

Bank erosion, as observed in the Hagmolenbeek and Lunterse beek, was related to spatial variation of the bank material. Recently, the importance of floodplain heterogeneity to meander planform dynamics has been recognised and studied using meander models [40,41]. In the Hagmolenbeek and Lunterse beek, the channel bank composition (former channel fills, peat deposit and vegetated upper layer) was a cause of floodplain heterogeneity, and, hence, resulted in spatial variation of the observed lateral development. In future stream restoration projects causes of floodplain heterogeneity can readily be mapped in a field reconnaissance, establishing local seepage and the occurrence of gravel and peat deposits, and former channel fills. Such field reconnaissances may assist in assessing the causes of lateral channel development, and may help to prevent unwanted changes to the new channel topography.

5.3. In-stream ecology

Table 1 lists the principles used by the water authorities involved in the design of the three streams subjected to study. The ecological constraints include minimum and maximum flow velocity and water depth values, which reflect the abiotic conditions relevant for improving the ecological status of the streams. The ecological constraints differ between the seasons. The time-averaged values for the cross-sectional averaged flow velocity and water depth were estimated based on the discharge and water level time-series. In nearly all cases, the flow velocity conditions in spring and in summer are lower than the design values, with cross-sectional averaged flow velocities around 0.07 m s^{-1} in the Hagmolenbeek and around 0.10 m s^{-1} in the Lunterse beek and Tungelroyse beek. For winter conditions, these values increase to around 0.10 m s^{-1} in the Hagmolenbeek, 0.18 m s^{-1} in the Lunterse beek, and 0.15 m s^{-1} in Tungelroyse beek. The Tungelroyse beek is the only stream meeting the design criterion for flow velocity in winter conditions. The water depths are evaluated for summer conditions only, averaging 0.34 m in the Hagmolenbeek, 0.25 m in the Lunterse beek, and 0.79 m in the Tungelroyse beek. The Lunterse beek is the only stream that meets the design criterion for water depth in summer conditions.

It is likely that these constraints are too much of a simplification of the conditions that best suit the ecology in lowland streams. The habitat of stream organisms mainly occurs just above and below the channel bed and within channel structures, such as patches of leaves, woody debris and macrophytes. At this scale their habitat and mobility can be explained in relation to life resources, including oxygen, food and protection against forces of shear stress [42]. At larger spatial scales, the distribution of stream organisms relates to habitat patchiness [10], where each habitat (e.g. sand, gravel, leaves, woody debris) forms under different abiotic conditions. Hydraulic conditions play an important role in the formation of each habitat type. Due to their physical characteristics, each habitat type forms under different hydraulic conditions.

Analysis of habitat patterns in the three reconstructed streams show that a gravel bar and a silt bar formed in the Lunterse beek and in the Tungelroyse beek, respectively. These habitat types may be related to the prevailing flow regime. Fig. 8 shows that the highest values for the Shields stress were observed in the Hagmolenbeek and the lowest values for the Shields stress in the Lunterse beek and Tungelroyse beek, although the Lunterse beek shows more variation. The low values for the Shields stress in the Tungelroyse beek may explain the formation of a silt bar. Similar habitat dynamics have been observed in other lowland streams, but under different flow conditions [12,16]. Local variation in hydraulic conditions may result in a mosaic of habitat types, such as the gravel bar in the Lunterse beek. The presence of algae (Hagmolenbeek) and macrophytes (all three streams) may also be related to the flow conditions, although it is likely that nutrient availability and other physical conditions (e.g. temperature, shading) also play an important role in the distribution of these habitat types.

The evaluation of the design principles shows the current design procedure to be deficient for the flow velocity and water depth targets. A channel design procedure based on a one-dimensional flow model may fail to properly represent the abiotic conditions favourable for the typical lowland stream organisms. We recommend to include two- or three-dimensional hydraulic modelling in the design procedure of lowland streams, which yields information required to evaluate the opportunities for habitat development. The design procedure may also involve prediction of the initial morphological development. Morphological models could provide a qualitative view on the initial morphological development of the channel bed and may be able to pin-point locations that are susceptible for channel incision or aggradation.

6. Conclusions

Three stream restoration projects have been evaluated focusing on morphological developments over a two-year period. During this period, longitudinal and lateral channel adjustments have been observed. Longitudinal channel bed adjustments were significant in each of the three streams, and were related to exogenous influences. Hydraulic structures (e.g. bridges and weirs), channel width variation and heterogeneity of the channel substrate caused channel bed incision and aggradation, and consequently, channel slope adjustments. Bank erosion was only observed in a limited number channel bends and was related to floodplain heterogeneity, which may be considered an exogenous influence. Other lateral channel adjustments were the result of autogenous morphological processes, including point bar formation due to secondary flow, resulting in asymmetrical cross-sectional profiles. In future stream restoration projects it may be worthwhile to anticipate the possible effects of exogenous influences, to prevent unwanted morphological developments.

The fine sediment characteristics (median grain size 125–250 μm) and relatively small flow depths cause the Shields stress to exceed the critical Shields stress more than 81% of the time. Despite this, no significant changes in sediment composition were observed, most likely associated with the uniformity of the prevailing sediment. At the habitat scale, changes occurred that may be related to the flow conditions, leading to the formation of a gravel bar and a silt bar. These observations are particularly relevant for the abiotic conditions determinative to stream ecology, showing that within 2-years' time natural processes cause an increase of the habitat heterogeneity in a reconstructed lowland stream.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.advwatres.2014.10.008. These data include Google maps of the most important areas described in this article.

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