

**RESEARCH ARTICLE**

Wood-induced backwater effects in lowland streams

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Abstract

Placement of wood in streams has become a common method to increase ecological value in river and stream restoration and is widely used in natural environments. Water managers, however, are often hesitant to introduce wood in channels that drain agricultural and urban areas because of backwater effect concerns. This study aims to better understand the dependence of wood-induced backwater effects on cross-sectional area reduction and on discharge variation. A newly developed, one-dimensional stationary model demonstrates how a reduction in water level over the wood patch significantly increases directly after wood insertion. The water level drop is found to increase with discharge, up to a maximum level. If the discharge increases beyond this maximum, the water level drop reduces to a value that may represent the situation without wood. This reduction predominately depends on the obstruction ratio, calculated as the area covered by wood in the channel cross section divided by the total cross-sectional area. The model was calibrated with data from a field study in four lowland streams in the Netherlands. The field study showed that morphologic adjustments in the stream and reorientation of the woody material reduced the water level reduction over the patches in time. The backwater effects can thus be reduced by optimizing the location where wood patches are placed and by manipulating the obstruction ratio. The model can function as a generic tool to achieve a stream design with wood that optimizes the hydrological and ecological potential of streams.

KEYWORDS

backwater effects, conceptual backwater effect model, stream hydraulics, woody debris in streams

1 | INTRODUCTION

In the last three decades, the attitude towards wood in streams and its effects has changed considerably. Throughout the 20th century, wood was systematically removed to increase flood conveyance as well as to improve navigability, to promote fish migration and to prevent erosion (Davidson & Eaton, 2013; Gippel, O'Neill, Finlayson, &

Schnatz, 1996; J. D. F. Shields & Smith, 1992; Young, 1991). In recent years, however, wood has been recognized as an integral part of the aquatic ecosystem and an important morphological trigger (Crook & Robertson, 1999; Gurnell et al., 2006; Kail, 2003; Piégay & Gurnell, 1997). Moreover, conserving wood in streams can even be economically beneficial (Lassette & Kondolf, 2012; J. D. F. Shields & Smith, 1992). In this light, EU water managers are encouraged to (re)

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introduce wood in streams following the Water Framework Directive (WFD), and US water managers are spending billions of US dollars on stream rehabilitation measures, many of which entail wood reintroduction (Bernhardt et al., 2005). Despite the current implementations, the flood conveyance effects of wood in streams are still poorly understood. Therefore, water resource managers are often hesitant to (re)introduce wood in streams, particularly in lowland areas and areas with significant economic value.

In recent years, numerous studies have investigated the hydraulic effects of wood in streams. These studies have mainly concentrated on the effects of flow deformation and friction (Daniels & Rhoads, 2004; Hygelund & Manga, 2003; Mutz, 2003; Nepf, 1999; Ruiz-Villanueva, Piégay, Gurnell, Marston, & Stoffel, 2016; Wohl, 2017) and on the development of wood jams (Abbe & Montgomery, 2003; Bocchiola, Rulli, & Rosso, 2008; Ruiz Villanueva, Bladé Castellet, Díez-Herrero, Bodoque, & Sánchez-Juny, 2014). Two studies have directly examined the water level increase of wood by setting up flume experiments based on a single cylindrical wood piece (Young, 1991) and multiple wood pieces with different sizes and characteristics (Gippel et al., 1996). Young (1991) found that the water level increase was logarithmically related to the reduction of cross-sectional area. Gippel et al. (1996) also saw a clear relation between water levels with obstruction area, but the relation was more irregular due to different wood sizes and characteristics. Although both studies showed an increase in water level, they found a minimal flood risk caused by wood in rivers.

Other studies on the hydraulic effects of wood used the measured water level increase to quantify the hydraulic roughness caused by wood (Davidson & Eaton, 2013; Manga & Kirchner, 2000; Manners, Doyle, & Small, 2007; Wilcox & Wohl, 2006). Wilcox and Wohl (2006) showed that the friction coefficient controlled by wood decreases with increasing discharges in the flume. They attribute the decrease in wood-induced friction with discharge to the decrease in turbulence during submergence of the wood patches. Thus, the friction coefficient in a stream with wood patches decreases when discharge and water levels increase, which was also discussed based on field studies (Dudley, Fischenich, & Abt, 1998; Manners et al., 2007; F. Shields Jr. & Alonso, 2012). These findings show that backwater effects are not only related to the reduction of cross-sectional area but also to friction and discharge. These relations are not extensively studied and were identified as a knowledge gap by Wohl (2017). Wohl (2017) argues that researchers are unable to quantitatively estimate the magnitude of flow resistance and obstruction associated with mobile or stable large wood at the segment scale, and that there is no widely applicable technique to quantify these effects. One of the reasons for this knowledge gap is that it is currently impossible to accurately measure the friction and cross-sectional area reduction of wood in the field (Manners et al., 2007). In short, it is poorly understood how wood patches with different obstruction ratios and hydraulic roughness respond to discharge variation.

The aim of this study is to better understand how the wood-induced backwater effect depends on wood obstruction area, enhanced hydraulic roughness and discharge. We propose a conceptual model that captures backwater development caused by wood

patches in terms of obstruction ratio and hydraulic roughness, which can serve as a widely applicable tool in water resource management. We analyzed the sensitivity of wood patch characteristics, such as wood height, width and friction and the wood patch shape and stream geometry. We validated our model with the data from four lowland streams with different wood patch and stream geometries. In the field analysis, we investigate the relation between water levels and discharge with and without wood patches, and the temporal variation of this relation. In addition, we calibrated the model using a field study investigation. We show that the water level increases with increasing discharge up to a maximum, after which the water level decreases with increasing discharge. The conceptual model is able to predict the discharge at which the water level changes from increasing to decreasing based on the wood and channel geometry. Hence, the model may help in the construction of wood patches such that target flood levels are achieved, and, in doing so, can serve to optimize the hydrological and ecological potential of streams and rivers.

2 | MODEL

A backwater effect model was used to understand interplay between cross-sectional reduction and enhanced friction. We studied the sensitivity of wood height, width and friction and different channel and wood geometries in relation to the reaction of water level to discharge. Wood in streams can be modelled using physics-based, empirical or conceptual models. Physics-based models attempt to incorporate all involved physical processes, aiming to resolve the detailed flow patterns (Baptist et al., 2007; Huthoff, Augustijn, & Hulscher, 2007; Marjoribanks, Hardy, Lane, & Parsons, 2017; Nepf & Vivoni, 2000; Verschoren et al., 2016). Therefore, these models require detailed input data for the wood elements, the stream geometry and the flow velocity, which are not always available at large spatial and temporal scales (Vargas-Luna, Crosato, & Uijttewaai, 2015). As opposed to physics-based models, empirical models require little input data but are often based on information from a limited number of sites (Green, 2005a, 2005b). Empirical models lack a physical basis and are site specific, consequently, limiting their generalizability. Here, we introduce a conceptual model with the intention to combine the best of both worlds, that is, to include the first-order physical processes while keeping the input data requirements minimal.

We consider one-dimensional, steady flow conditions where the wood patch is represented as an impermeable obstruction in the stream. Hence, the flow velocities inside the wood patch are many times smaller than they are in the area without wood (Bennett, Wu, Alonso, & Wang, 2008; Daniels & Rhoads, 2004; Nepf, 1999; Nepf & Vivoni, 2000). The wood patches become additionally less permeable over time because of clogging of small branches, vegetation and sediment. Manners et al. (2007) however showed that the assumption of impermeability can result in an overestimation of the drag force of 10 to 20%. The overestimation of water levels is much less, since the water level is roughly proportional to the square root of the drag force (e.g., Gippel et al., 1996; Wilcox & Wohl, 2006). The impermeability of

wood patches is thus a valid first-order assumption. In addition, Luhar, Rominger, and Nepf (2008) showed that at the channel reach scale, the flow resistance is predominantly affected by the blockage area by vegetation. These findings encourage the focus on the obstruction ratio and hydraulic resistance for reach scale studies. Regarding hydraulic resistance, we adopt the Manning's coefficient. We further

assume a gradual transition between water levels on both sides of the wood patch, such that gradually varied flow equations apply and the wood patch is not a control point in a hydraulic calculation. Since we are interested in the effects of wood patches that only partly blocking the stream width, we consider this assumption valid. It is important to consider the above-discussed assumptions when using the model.

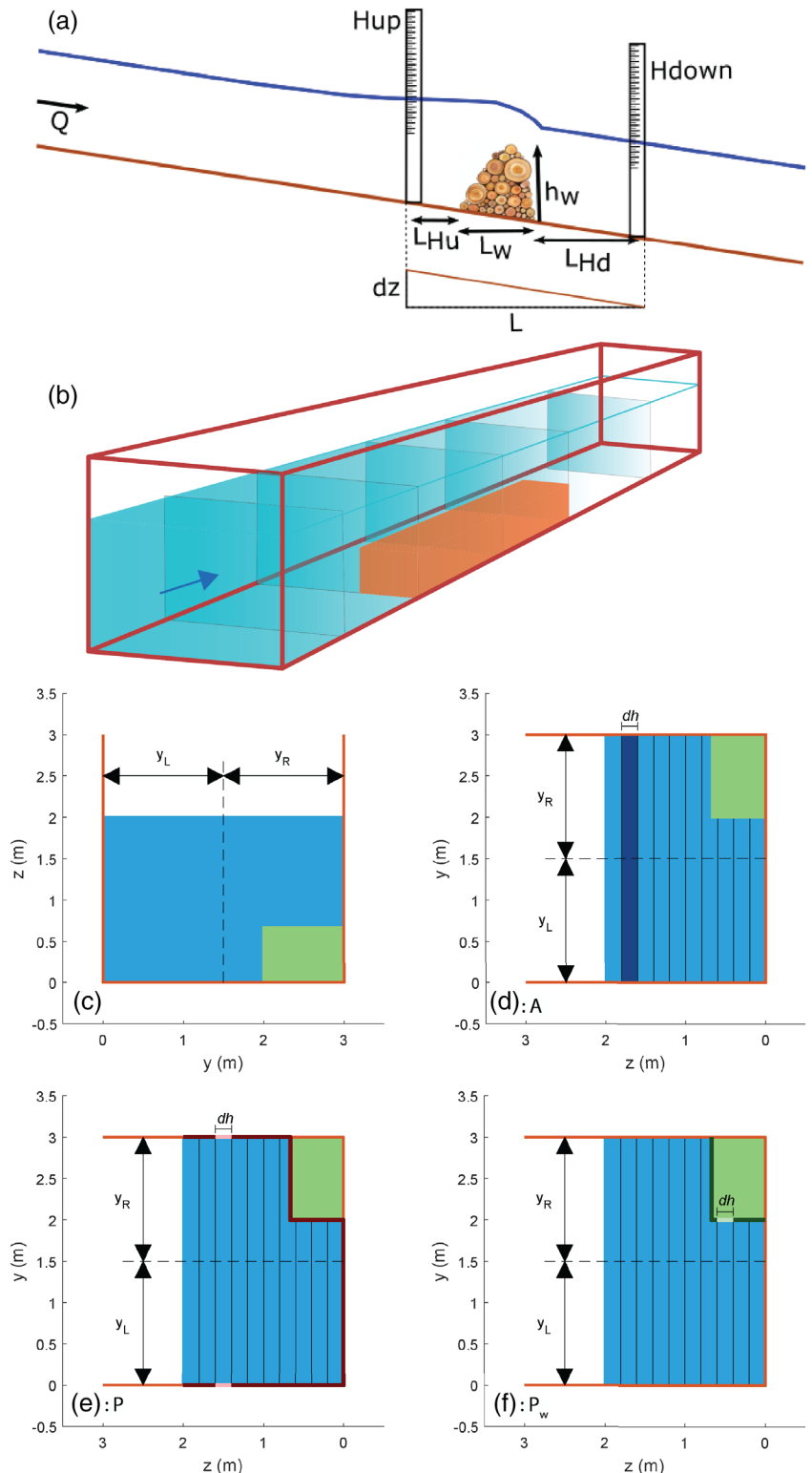


FIGURE 1 Illustration of the experimental set-up and of the backwater model. Panel a shows the experimental set-up with the water levels upstream (H_{up}) and downstream (H_{down}) of the wood patch. The model simplifies reality by constructing multiple cross sections in the longitudinal direction (panel b). These cross sections may contain wood. The origin of the cross section and y_L and y_R are illustrated in Panel c. The calculation of cross-sectional area and wetted perimeter are illustrated in Panel d and Panel e, respectively. The calculation of the wetted perimeter of the area covered by wood is shown in Panel f, in which w_L is 0 for all z -values and w_R is only 0 for z -values larger than 0.8 m

In terms of hydraulic theory, a wood patch in a lowland stream with a mild bed slope locally elevates the equilibrium depth. Along the length of the patch, the water surface is lower than the equilibrium depth, and the water surface profile is classified as “ M_2 ” (Figure 1a). Upstream of the patch, the depth is above the equilibrium depth, and an “ M_1 ” water surface profile is present. Downstream of the patch, the flow assumes equilibrium depth. The model assumes the cross-sectional geometry and hydraulic roughness to be uniform in the streamwise direction and only changes in cross-sectional area and friction at the location of a wood patch (Figure 1b). The channel and wood geometries are expressed in x (longitudinal), y (transverse) and z (vertical) coordinates. The origin corresponds to the deepest point of the cross section, at the left bank of the wood patch (Figure 1c). The $y_L(h)$ and $y_R(h)$ are the horizontal distances from the midpoint to the left and right banks at water level h , respectively (Figure 1c). The width, B (m), is obtained from:

$$B(h) = y_R(h) + y_L(h), \quad (1)$$

and the cross-sectional area, A (m), is obtained from (Figure 1d):

$$A(h) = \int_0^h B(z) dz. \quad (2)$$

The wetted perimeter, P (m), is calculated according to (Figure 1e):

$$P(h) = \int_0^h \left(\sqrt{1 + \left(\frac{dy_L}{dh}(z) \right)^2} + \sqrt{1 + \left(\frac{dy_R}{dh}(z) \right)^2} \right) dz, \quad (3)$$

and the hydraulic radius, R (m), according to:

$$R(h) = \frac{A(h)}{P(h)}. \quad (4)$$

Based on the geometry, the model determines whether the water level is in contact with wood on the right or left bank. Values of $w_L(z)$ and $w_R(z)$ are set to 1 when at elevation z , respectively, the left bank or the right bank is covered with wood (Figure 1f). Otherwise, these parameters are set to 0. The wetted perimeter of the area covered by wood, P_w (m), is obtained as:

$$P_w(h) = \int_0^h \left(w_L(z) \sqrt{1 + \left(\frac{dy_L}{dh}(z) \right)^2} + w_R(z) \sqrt{1 + \left(\frac{dy_R}{dh}(z) \right)^2} \right) dz, \quad (5)$$

which is used to establish the wood fraction as in:

$$f_{wood}(h) = \frac{P_w(h)}{P(h)}. \quad (6)$$

The wood fraction is used to calculate the effective Manning's coefficient, n_{eff} ($s/m^{1/3}$):

$$n_{eff}(h) = f_{wood}(h) n_{wood} + (1 - f_{wood}(h)) n_{stream}. \quad (7)$$

The average flow velocity over the cross section, u (m/s), is calculated with the specified total discharge, Q (m^3/s):

$$u(h) = \frac{Q}{A(h)}, \quad (8)$$

The Froude number, Fr (–), is calculated as:

$$Fr(h) = u(h) \sqrt{\frac{B(h)}{gA(h)}}, \quad (9)$$

and the friction slope, S_f (m/m), reads:

$$S_f(h) = \frac{(n_{eff}(h) Q)^2}{A(h)^2 R(h)^{4/3}}. \quad (10)$$

With the aid of the friction slope and the Froude number, the water slope (m/m) is determined as:

$$\frac{dh}{dx} = \frac{S_0 - S_f(h)}{1 - Fr^2(h)}, \quad (11)$$

where S_0 is the bed slope (m/m) and g is the gravitational acceleration (m/s^2). The downstream water level corresponds to equilibrium water depth, h_n :

$$h_n = S_0 - \frac{(n Q)^2}{A^2(h) R^{4/3}(h)}. \quad (12)$$

The elevation above equilibrium water depth corresponds to the wood-induced backwater effect.

3 | STUDY AREAS

In the field study, we investigated the water level response to discharge variation. Four field sites in the Netherlands were studied and referred to as Leerinkbeek, Tengelroysebeek, Tongelreep and Ramsbeek. These streams are located in the Rhine-Meuse delta, which is an alluvial basin composed of clayey and/or sandy soils. These areas were selected because they are located in agriculture and nature areas with few buildings in the neighbourhood. Floods in these areas will have limited impacts, while the natural processes and effects can be studied. To measure the backwater effects, the local water boards installed discharge measurement gauges and two level gauges upstream and downstream of the wood patches. The

gauges measured discharges and water levels hourly. In addition, the bed slope, geometry of the stream and length and height of the wood patches were measured.

The geometries of the streams are shown in Figure 2. The left side of the figure shows constructed cross-sectional areas from bathymetry measurements using rtk-gps with a total station before the wood was placed in the streams. The bed slope was calculated by the average bed slope established based on cross-sectional information from the Tungelroysebeek and Tongelreep. For the Leerinkbeek and Ramsbeek, the bed slope was approximated by the water level slope measured prior to wood placement under uniform flow conditions, because too few cross-sectional areas were available to reliably estimate the bed slope.

The left side of Figure 2 shows digital elevation maps (DEMs) based on a drone survey using stereo-photography. These DEMs were available for three of the four research sites. In case of the Tongelreep, it was prohibited to fly a drone because of the neighbouring airport. The composition of the wood patches was as follows.

- The wood patch in the Leerinkbeek was constructed at one side of the bank and consists of two or three tree trunks. The tree roots were about 0.75 m by 0.75 m with a trunk of 0.5 m. These trunks were piled up by large branches of 2 m in length and a diameter of 10 cm. The trunks and branches were anchored to the bed or banks to prevent movement.

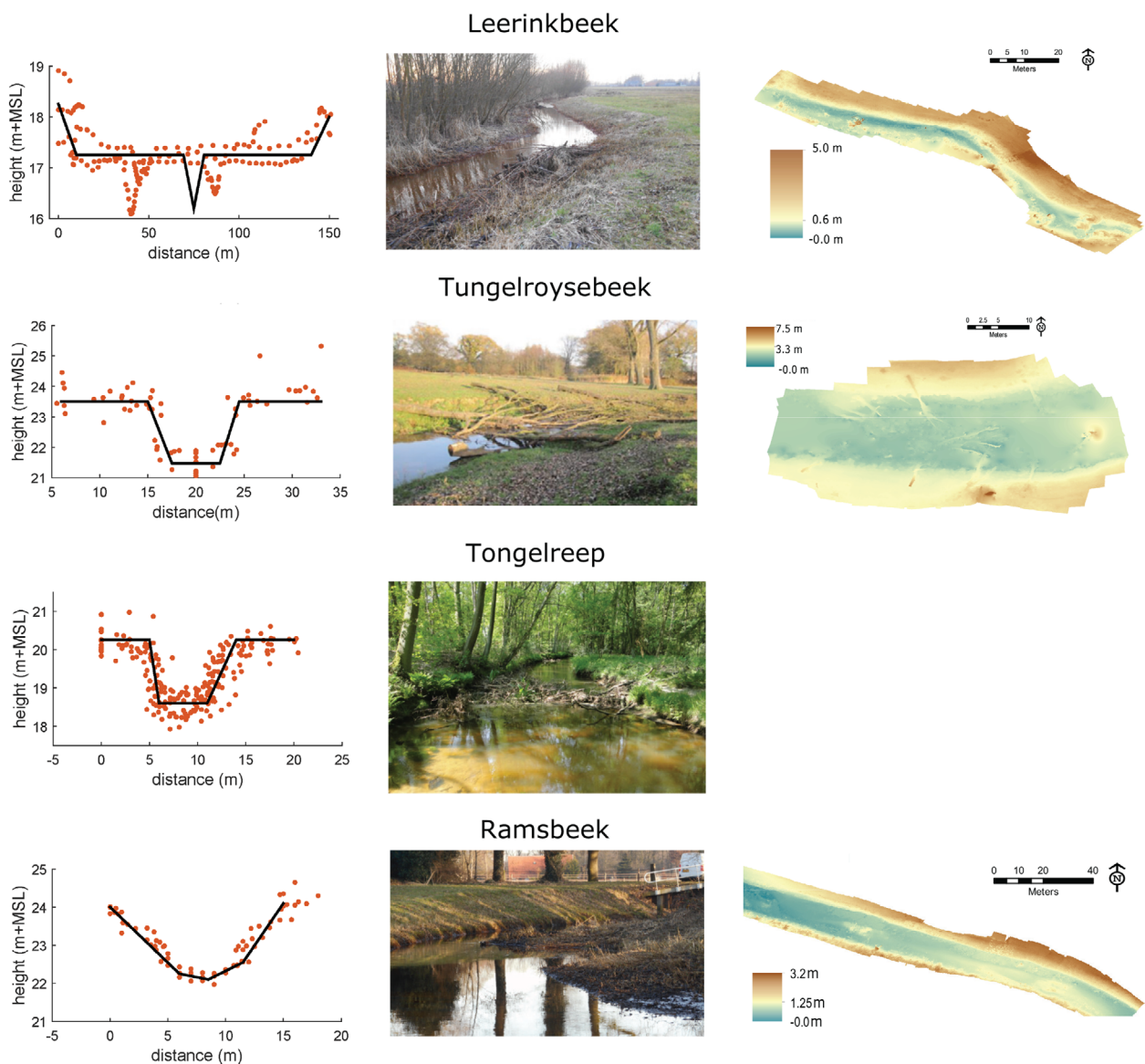


FIGURE 2 The bathymetry of the streams (right), the photos of the wood patches (middle) and the digital elevation of the studied streams (left). The orange dots are the measured cross sections in the reach of the wood patches before the placement of the wood patches. The black lines are cross sections used for the calibration

- The wood patch in the Tongelroysebeek was constructed following a protocol by Verdonschot and Besse-Lototskayay (2012). The protocol prescribes to place the branches of the tree from the channel bank into the stream, such that it covers more than 75% of the stream width. The trees were positioned such that the flow velocity was scattered across the stream width. It was advised to use a tree with a trunk diameter of more than 20 cm and with branches with a diameter of more than 5 cm. The trees were anchored in the bank to prevent movement.
- The wood patch in the Tongelreep was constructed with branches of 9 m length with a diameter of 10 cm including twigs. These branches covered 75% of the stream width and were anchored into the bed material.

TABLE 1 Overview of the average discharge, Q_a , average yearly discharge maximum, Q_{ay} , slope and length of the stream, and length, height and width of the wood patches of the four studied streams

Name	Q_a (m ³ /s)	Q_{ay} (m ³ /s)	S_0 (m/km)	S_0/L (km ⁻¹)	L (m)	L_w (m)	h_w (m)	B_w (m)	h_{bf} (m)
Leerinkbeek	0.50	4.2	0.57	0.11	208	110	0.5	2.22	1.20
Tongelroysebeek	0.83	5.0	0.34	0.37	1,289	242	1.72	6.27	2.02
Tongelreep	1.14	3.8	0.53	0.40	695	693	0.94	4.09	1.65
Ramsbeek	0.48	3.0	0.14	0.02	140	100	0.9	4.01	1.90

Note: The last column indicates the bankfull water level without wood in the studied streams.

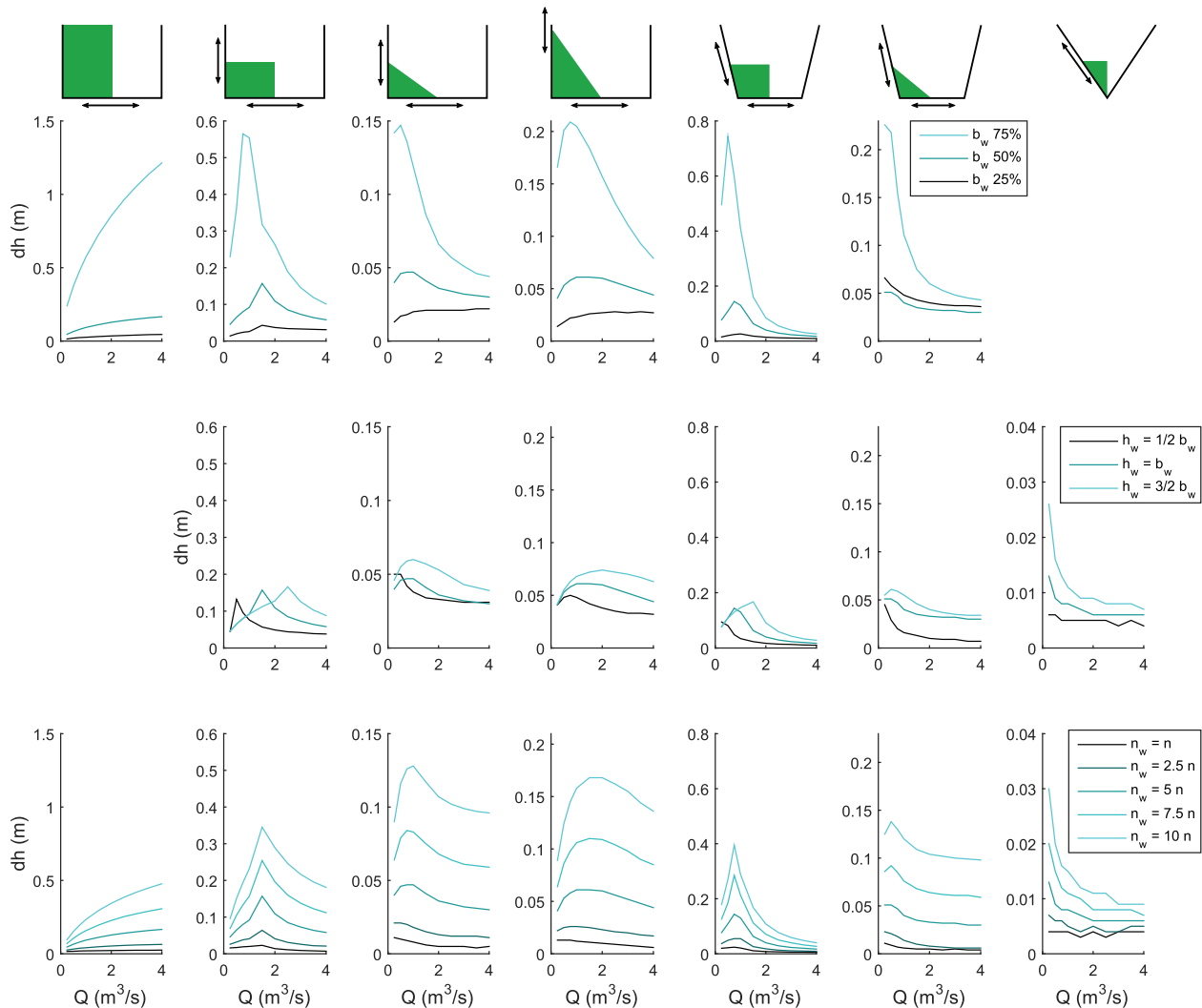


FIGURE 3 Model sensitivity to patch and channel characteristics. The obstruction width is changed in the first row, the obstruction height in the second row and the Manning's coefficient in the last row. The obstruction height in the first column is equal to the stream bank and therefore a panel in the second row is absent

- The wood patch in the Ramsbeek was constructed with branches of 2 m with a diameter of 3 cm intertwined and stacked on top of each other. The wood patch was fixed by anchoring the intertwined branches to the bed.

The anchoring of the patches prevents wood transport and, therefore, avoids wood jams. The permeability will not change with discharge because large wood pieces are not able to float. The smaller wood pieces, however, were collected from the wood patches shortly after insertion, resulting in more dense and less permeable patches (see photos in Figure 2). In reality, every wood pile is different. We have decided to simplify the wood configuration for calibration by using the average width and height of the wood patch constructed

from the drone survey. The studied wood patches had a length between 100 and 700 m in the various streams (Table 1). These patches consist of multiple wood piles of different lengths. The width and the height of the wood patches range from 2.22 to 6.27 m and 0.5 to 1.72 m, respectively.

4 | MODEL APPLICATION APPROACH

The model introduced in Section 2 was used to analyze the sensitivity of backwater effect to the channel geometry and details of the wood configuration and to calibrate the model with the field experiments. For the sensitivity analysis, we schematized the channel geometry as rectangular, triangular and v-shaped cross sections (Figure 3). Similarly, we schematized the wood obstruction area in the cross section as series of rectangles and triangles at one of the banks. The channel geometry was selected by a width of 3 m for the maximum water level, a n_{stream} of $0.04 \text{ s/m}^{1/3}$, a bed slope of 0.2×10^{-4} and a wood length of 16.5 m. The discharge varied between 0.25 and $4 \text{ m}^3/\text{s}$. The default setting of the wood patches was the wood width of 50% the stream width, the wood height equal to the wood width. The Manning's coefficient for the wood patch (n_{wood}) was five times the Manning's coefficient in the rest of the stream (n_{stream}). To consider

TABLE 2 Manning's coefficients of the uncovered and the wood-covered parts of the stream, derived from model calibration

Name	$n_{stream} (\text{sm}^{-1/3})$	$n_{wood} (\text{sm}^{-1/3})$
Leerinkbeek	0.025	0.1
Tungelroysebeek	0.03	0.045
Tongelreep	0.025	0.025
Ramsbeek	0.025	0.075

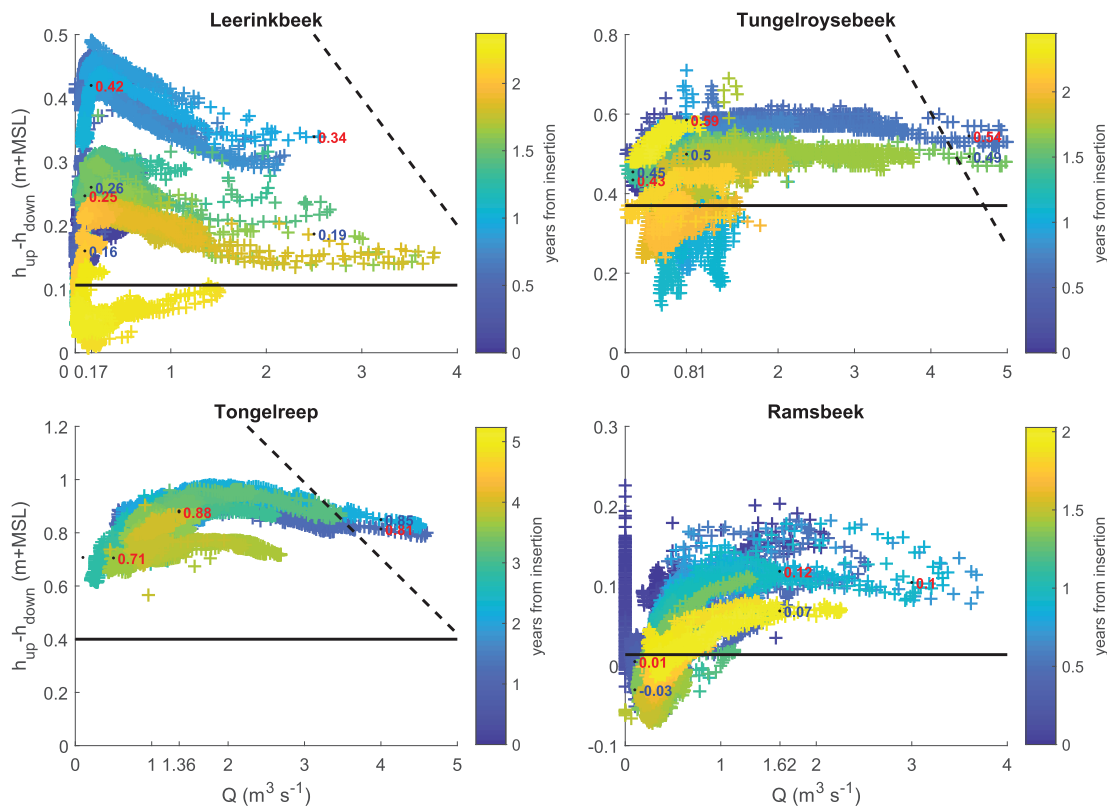


FIGURE 4 Dependence of the water level reduction over wood patches on flow conditions. The black solid line indicates the water level reduction before placement of the wood patches, and the plusses indicate the measurements after placement of the patches. The colour indicates the elapsed time after the placement of the wood. The red numbers show the average water level reduction at the smallest and highest discharge and at the maximum water level reduction in the first year after placement of the wood. The blue numbers show the average water level reductions for the years after the first year. The black dashed line indicates the bankfull situation. The right side of the dashed lines indicates local flooding

the sensitivity of these settings, we varied the wood width with 25, 50 and 75% of the stream width. The wood height was varied between 0.5 and 1.5 times the wood width. The n_{wood} was varied from equal to 2.5, 5, 7.5 and 10 times the n_{stream} .

To reproduce field measurements, we composed the n_{stream} based on discharge and water level measurements collected prior to insertion of wood (Table 2). The other stream characteristics were measured in the field (Table 1). The n_{wood} was then calibrated using measurements after insertion of the wood patches.

TABLE 3 Overview of the field observations in the first year; Q_{maxh} , the discharge with the maximum water level reduction (first column), the water level reduction increase from almost no discharge to the discharge with the maximum water level reduction (second column) and the water level reduction decrease from the discharge with the maximum water level reduction to the maximum measured discharge (third column)

Name	Q_{maxh} (m^3/s)	$\Delta h \uparrow$ (m)	$\Delta h \downarrow$ (m)
Leerinkbeek	0.17	0.17	0.08
Tungelroysebeek	0.8	0.16	0.05
Tongelreep	1.36	0.17	0.07
Ramsbeek	1.62	0.11	0.02

5 | RESULTS

Using the model described in Section 2, the effects of wood obstruction for a variety of cross-sectional configurations were studied. The effect of changing width, height and roughness of the wood patch in the rows and the effect of changing the obstruction area and the channel geometry for each of those configurations in separate columns are shown in Figure 3. The width of the wood patch has the strongest influence on the water level reduction over the wood patch in response to discharge increase, and this relation predominately affects the highest water level reduction. When the width of the wood area increases, the water level reduction increases more strongly with discharge. The height of the wood area does not influence the maximum water level reduction, but it does influence the discharge at which the water level reduction is at its maximum. As expected, a higher roughness coefficient results in an increase in the water level reduction.

The first four configurations in Figure 3 show rectangular cross-sectional geometries of the channel, with wood patch shapes of various types. For these cases, the sensitivity analysis shows that the obstruction area is a parameter that significantly influences the water level reduction. It increases with discharge when the top of the obstruction area corresponds to the bank height and reaches a local maximum when the obstruction area remains below the bank height

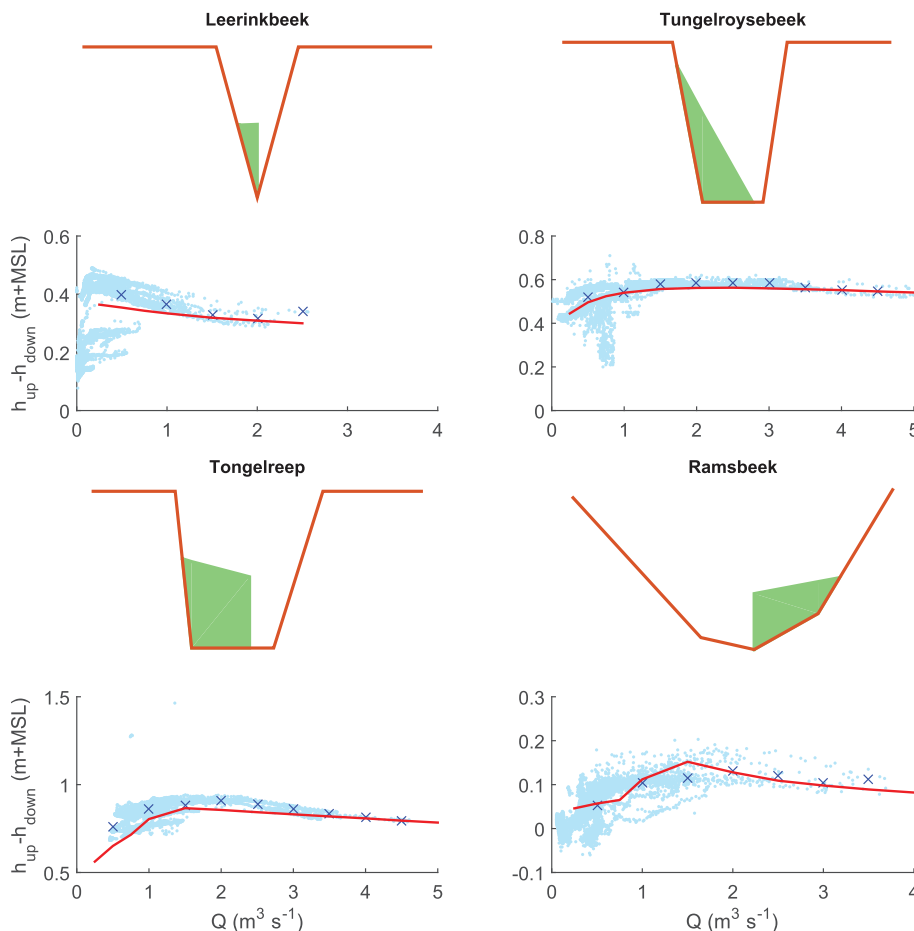


FIGURE 5 Calibration of the water level reduction over wood patches at the four experimental streams. The dots indicate the measurements after placement of the wood patches in the first year and the crosses are the average water level reduction in steps of $0.5 \text{ m}^3/\text{s}$ of discharge. The red line is the best fit through the crosses. The Manning's coefficient for the best fit is discussed in Table 3

FIGURE 6 Conceptual cross section illustrating the incremental increase of the wetted perimeter for a water level increase Δh . The wood patch is illustrated with the green colour. The blue colour indicates the wetted cross-section area increase, and the light red and green colours illustrate the wetted perimeter in contact with the channel bed or the wood patch, respectively

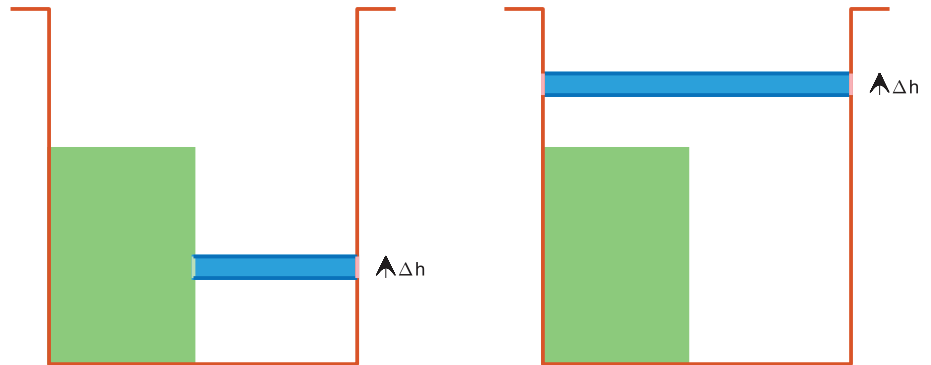


FIGURE 7 Morphological adaptations of a wood patch in three and half years at the Tungalroysebeek



(Figure 3). The strongest water level reduction was found for the rectangular obstruction area representing wood. A comparison between the fourth configuration with the second and third configurations shows that the shape of the wood area has a stronger effect than the obstruction area on the water level reduction.

The cross-sectional geometry of the channel was changed in the last three configurations in Figure 3. The fifth and sixth configurations show the same trapezoidal channel geometry, with the wood characteristics similar to those of the second and third configurations. The last configuration shows a v-shaped geometry with the wood on one side. The fifth and sixth configurations show the same backwater effect response as the second and fourth configurations, with the water levels reductions being about 33% higher, which is not surprising as the cross section is 17% smaller than the rectangular cross section. For the v-shaped configuration, a small discharge of $0.25 \text{ m}^3/\text{s}$ is enough to reach the top of the wood area. Beyond this discharge, the backwater effect decreases with increasing discharge.

The development of the water level difference over time is compared for each of the four experimental sites (Figure 4). The black line is the bed slope and the crosses are the measurements after placement of the wood patches. For all streams, the water level reduction over the wood patch increases with discharge, up to a maximum (Figure 4). When the discharge increases beyond this level, the water level reduction declined to values that eventually correspond to the situation without wood, as shown for the Leerinkbeek. The maximum water level reduction over the patches differs between the sites, and so does the rate of water level reduction for discharges beyond the

maximum (Table 3). Qualitatively, the initial water level increase and subsequent decrease were similar for the different streams, but the discharge at which the maximum water level reduction occurred ranges from 0.17 to $1.62 \text{ m}^3/\text{s}$.

The water level reduction decreased over time after placement of the wood patches (Figure 4). Figure 4 shows a reduction of the water level reduction within two to 5 years in the studied streams. The reduction of the maximum water level reduction was 0.17 m in the Leerinkbeek, 0.09 m for the Tungalroysebeek and 0.05 m for the Ramsbeek over 2 years (difference between the red and blue numbers in Figure 4). For the Tungalroysebeek, the water level reduction increased by 0.04 m after the first year (Figure 4). In the fifth year after wood insertion, the water level reduction decreased by 0.1 m .

The model was calibrated to simulate the four field experiments. Figure 5 shows the representation of cross sections and wood patch areas in the streams, as used in the calibration. In the same figure, the experimental data of the first year after the wood placement (blue dots) and the calibration results (red line) are shown. For the calibration, only the first year was used, as the water level reduction becomes smaller over time. Table 3 shows the calibrated Manning's n coefficients for the stream and wood. The calibration generally shows good agreement with the measurements. For the Tongelreep and Ramsbeek cases, the calibrations show more abrupt response changes than the measurements, especially for discharges from 0.5 to $1 \text{ m}^3/\text{s}$ and from 2 to $2.5 \text{ m}^3/\text{s}$ for the Tongelreep and for $1.5 \text{ m}^3/\text{s}$ in the Ramsbeek. These discrepancies were likely caused by the simplification of the wood patches and stream bed.

6 | DISCUSSION

Both the field experiments and the model study show that the water level reduction increases with increasing discharge until a maximum after which the water level reduction decreases with increasing discharge. This relationship is influenced by varying hydraulic roughness and flow area with increasing discharge. When the water level is below the wood height, a small water level increase will result in a higher effective roughness and in a small increase the cross-sectional area. When the water level is above the wood top, a similar water level increase will result in a lower effective hydraulic roughness, and in a larger cross-sectional area, increase than for water levels lower than the wood height (Figure 6). This implies that if the discharge causes the water levels to exceed the wood height, the water levels decrease with increasing discharge. This interaction was also described in the sensitivity analysis and by Wilcox and Wohl (2006). The friction slope is decreasing with discharge according to the Darcy-Weisbach formula, because the squared velocity term is increasing more rapidly than the linear depth term (Wilcox, Nelson, & Wohl, 2006). Furthermore, the reduction of water level increase as a response to discharge over time probably resulted from morphological adjustments of the stream bed and/or changes in wood configuration. From visual observations in the Tengelroysebeek thalweg (Figure 7), the wood was degraded especially at the average water level, which resulted in a reorientation of the wood at the bank and on the bed. Wood at the bank and bed resulted in a smaller conveyance area and additional obstructions at places where more shear was present.

In the field experiments, we showed that backwater effects are significant after placement of wood in streams and even result in flooding. Unlike Young (1991), we do not claim that wood in lowland rivers does not significantly affect flood levels. This study stresses that the exceedance of the flood levels are not only influenced by the width of the wood patch, but that the details of the wood obstruction area, channel geometry and amount of discharge all contribute. Just focussing on one element will not provide the necessary knowledge to make an informed decision on the placement of wood in streams. Although the conclusions are different from Young (1991), the field observations and insights from the simple model are in agreement with previous laboratory, field and physical model studies. The backwater effect increases logarithmically with wood width, similar to the findings of Young (1991) and Gippel et al. (1996). The backwater's dependence on wood height has previously been established by studies focussed on the hydraulics of step-pool rivers (Curran & Wohl, 2003; Thomas & Nisbet, 2012; Wilcox et al., 2006; Wilcox & Wohl, 2006). In addition, we also found a decrease of friction with increasing discharge based on the friction slope.

The model is made available as user-friendly html code along with this publication (doi.org/10.4121/uuid:55604c80-61d3-4c31-97e7-aa1d3e4c88af, Torfs & Geertsema, 2019) and can readily be used to investigate the effects of any other type of setting and wood configuration. The model allows to quantify the backwater effects for different channel and wood geometries and can be used to predict the effects in other rivers and natural conditions. The model is a

generic tool for scientists and practitioners who prepare the placement of wood in streams, to estimate the backwater effect that can be expected from alternative configurations. Wood has to be removed from streams only when it raises the water levels above the maximum allowable water levels. This management strategy can enhance the ecological and morphological effects of (lowland) streams. Similarly, the model can be employed to estimate the peak backwater level as a result of wood jams or beaver dams, provided that the basic model input is available.

7 | CONCLUSIONS

Based on model simulations and field evidence, this study explains how wood-induced backwater effects are governed by discharge, wood patch characteristics and channel geometry. Wood in streams gradually increases the water level towards a wood patch, where the water level reduces to resume equilibrium depth downstream of the patch. This water level reduction increases with increasing discharge, up to a maximum after which the water level reduction decreases with discharge. The characteristics of this relationship depend on wood configuration and on channel geometry. The wood orientation and channel geometry may change over time, exerting an impact on the backwater response to discharge change. Significant morphological adjustments and wood degradation were observed within two to 5 years after wood placement.

A conceptual model is proposed to simulate the wood-induced backwater effect variation. Using the model, a sensitivity study of wood characteristics showed that the width of the wood is responsible for the peak in the backwater elevation, and the height of the wood configuration controls the discharge at which the highest backwater effect was observed. We conclude that the obstruction area and hydraulic roughness variation exert a similar influence on the backwater effect in streams. The model introduced herein can be employed by scientists and practitioners to allow for controlled insertion of wood in streams, without jeopardizing flood protection.

DATA AVAILABILITY STATEMENT

The presented model is available using doi.org/10.4121/uuid:55604c80-61d3-4c31-97e7-aa1d3e4c88af. The data can be requested from the following organizations:

- Leerinkbeek and Ramsbeek discharges, water levels, bathymetries and measurements setup are measured by Rijn en IJssel waterboard and are available from the contact person Gerry Roelofs and/or Ellen Bollen.
- Tengelroysebeek discharges, water levels, bathymetries and measurements setup are measured by Limburg waterboard and are available from the contact person Erik Raaijmakers.
- Tongelreep discharges, water levels, bathymetries, measurements setup and photo are measured by Dommel waterboard and are available from the contact person Mark Scheepens and/or Michelle Berg.

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