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Hydrological effect of vegetation against rainfall-induced landslides

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Abstract

The hydrological effect of vegetation on rainfall-induced landslides has rarely been quantified and its integration into slope stability analysis methods remains a challenge. Our goal was to establish a reproducible, novel framework to evaluate the hydrological effect of vegetation on shallow landslides. This was achieved by accomplishing three objectives: (i) quantification in situ of the hydrological mechanisms by which woody vegetation (i.e. Salix sp.) might impact slope stability under wetting and drying conditions; (ii) to propose a new approach to predict plant-derived matric suctions under drying conditions; and (iii) to evaluate the suitability of the unified effective stress principle and framework (UES) to quantify the hydrological effect of vegetation against landslides. The results revealed that plant water uptake was the main hydrological mechanism contributing to slope stability, as the vegetated slope was, on average, 12.84% drier and had matric suctions three times higher than the fallow slope. The plant-related mechanisms under wetting conditions had a minimal effect on slope stability. The plant aerial parts intercepted up to 26.73% of the rainfall and concentrated a further 10.78% of it around the stem. Our approach successfully predicted the plant-derived matric suctions and UES proved to be adequate for evaluating the hydrological effect of vegetation on landslides. Although the UES framework presented here sets the basis for effectively evaluating the hydrological effect of vegetation on slope stability, it requires knowledge of the specific hydro-mechanical properties of plant-soil composites and this in itself needs further investigation.

Keywords: hydrological, vegetation, willow, matric suction, landslide, slope stability
1. Introduction

Rainfall-induced landslides are global phenomena that result in loss of human life and damage to property every year (Sidle and Bogaard, 2016). They are normally triggered by a decrease in the soil shear strength after heavy rainfall events on sloped terrain (Lu and Godt, 2013). As a consequence of the predicted intensification of the hydrological cycle due to climate change (Roderick et al., 2014), the likelihood of rainfall-induced landslides is expected to increase, making the implementation of mitigation and remediation measures a priority.

Vegetation has been proven to be an effective landslide mitigation measure, as it enhances the soil shear strength via a series of mechanical and hydrological effects (Norris et al., 2008). While the mechanical effect of vegetation on slope stabilisation has been extensively studied (Wu et al. 1979; Mickovski et al., 2009; Bordoni et al., 2016), the plant hydrological effect, although acknowledged (Simon and Collison, 2002), has rarely been quantified and reported in the scientific literature (Stokes et al., 2014). Information on how vegetation performs hydrologically could significantly contribute to the effective and sustainable selection of plant species (Duan et al., 2016; McVicar et al., 2010) to reduce the likelihood of slope instability and the risks associated with it (Lu and Godt, 2013; Fell et al., 2005).

The hydrological effect of vegetation results from the interaction of different mechanisms occurring at the soil-plant-atmosphere continuum (Rodriguez-Iturbe and Porporato, 2004). These could be broadly divided into wetting and drying. During a rainfall event (wetting), vegetation may regulate the amount of water reaching the soil. The aerial parts (e.g. tree canopy) can intercept part of the precipitation (Llorens
and Domingo, 2007) creating an “umbrella effect” that could attenuate the amount of rainfall available to infiltrate into the soil. However, part of the rainwater will reach the soil by flowing along the stem (i.e. stemflow; Levia and Germer, 2015). Stemflow could have negative consequences upon slope stability as the water funnels around the tree base and enters the soil as a jet through the root channels (i.e. bypass flow; e.g. Liang et al., 2011). Bypass flow may induce changes in the soil stress-state (Lu and Godt, 2013) or facilitate the formation of perched water tables at depth (e.g. Simon and Collison, 2002).

The drying mechanisms are those that tend to reduce the degree of saturation of the soil after a rainfall event. Vegetation may support the drainage of water from the root zone by loosening the soil and opening preferential flow channels via the root system (Liang et al., 2011). However, the most acknowledged drying mechanism is the plant water uptake (e.g. Laio, 2006), which involves the withdrawal of water from the soil to satisfy plant physiological needs and transpiration into the atmosphere (i.e. evapotranspiration; e.g. Rodriguez-Iturbe and Porporato, 2004). Plant transpiration is a markedly seasonal process in temperate climates (e.g. Wever et al., 2002) and the shading effect produced by the vegetation cover can further reduce direct soil evaporation (e.g. Raz-Yaseef et al., 2010). Nonetheless, plant transpiration is meant to generate a water flow exiting the soil (Laio, 2006). This would reduce the degree of soil saturation as well as the pore-water pressures (i.e. increasing the matric suction), potentially increasing the soil shear strength (Vanapalli et al., 1996; Gonzalez-Ollauri and Mickovski, 2017). To date, models predicting the effect of plant transpiration on the soil stress-state are severely lacking (e.g. Scanlan, 2009).

The mechanisms by which vegetation may contribute hydrologically to slope stability have been investigated before (for review see Stokes et al., 2014). A
recognised challenge, however, is their integration into slope stability analysis methods. The *unified effective stress principle* (UES; Lu and Likos, 2004) and framework (Lu and Griffiths, 2006; Lu and Godt, 2008; Lu et al., 2010), known in soil mechanics, permits the assessment of the state of stress in steep soil-mantled hillslopes under a range of water flow conditions - i.e. infiltration (wetting) or evaporation (drying). Considering these, the UES quantifies the resulting soil matric suction (Lu and Griffiths, 2006) and the associated suction stress (Lu et al., 2010); defined as the mechanical equivalent of the soil inter-particle stress. The suction stress has a negative value and affects positively (i.e. increases) the soil strength as its value becomes more negative (Lu and Godt, 2013). The intimate relationship of the suction stress to the matric suction (Lu and Likos, 2004, 2006) makes the former an ideal proxy to quantify plant-derived hydrological effects on slope stability (Gonzalez-Ollauri and Mickovski, 2017). Vegetation affects the water flow conditions through the different mechanisms discussed above (i.e. rainfall interception, stemflow, water uptake) and, hence, the soil matric suction. However, this effect has not been tested before on soils under woody vegetation using field-derived information and the UES. The UES was conceived for soil only, while the plant roots form a composite material with the soil (Thorne, 1990). This material is likely to behave hydro-mechanically differently from a fallow soil (Gonzalez-Ollauri and Mickovski, 2017) because the root systems will alter, among others, the pore size and distribution (Scanlan, 2009), the water retention dynamics (Carminati et al., 2010; Scholl et al., 2014) and the permeability of the soil (Vergani and Graf, 2015).

The aim of this study was to establish a reproducible novel framework for the evaluation of the hydrological effect of vegetation against rainfall-induced landslides. To achieve this, the following three objectives were set:
(i) To quantify *in situ* the hydrological mechanisms by which woody vegetation (i.e. *Salix* sp.) may impact the stability of a small-scale, landslide-prone, temperate humid hillslope under wetting and drying conditions.

(ii) To propose a new simplified approach to predict the plant-derived matric suction under drying conditions.

(iii) To evaluate the suitability of the unified effective stress principle and framework for quantification of the hydrological effect of vegetation against rainfall-induced landslides.

2. Study site and plant individuals

The study site is located adjacent to Catterline Bay, Aberdeenshire, UK (WGS84 Long: -2.21 Lat: 56.90; Fig. 1a), within the temperate humid climate zone (Cgc: subpolar oceanic climate; Köppen, 1884). The mean annual temperature at the site is 8.9°C and the mean annual rainfall is 565.13 mm (2011-2014; Gonzalez-Ollauri and Mickovski, 2016). The precipitation at the site is characterised by frequent, low-intensity rainfall events (Gonzalez-Ollauri and Mickovski, 2016). Well-drained (saturated hydraulic conductivity (*K*): 5.82x10^{-5} m s^{-1}), shallow (ca. 600 mm), sloped (25-50°), and landslide-prone silty sands (sand: 79.82%; silt: 5.85%; clay: 3.08%) overlie conglomerate rock. The topsoil at the site (0-400 mm below ground level, b.g.l.) has a mean dry bulk density of 0.86 g cm^{-3}, a drained apparent cohesion of 33.4 kPa, a mean angle of internal friction of 22° and a mean organic matter content of 5.57%.

Two adjacent 10 m x 20 m hillslope transects with similar slope gradient (mean slope gradient: 25.6°; Figs. 1b, c) were available for studying the hydrological
effect of woody vegetation against rainfall-induced landslides. These comprised (i) a stable, willow-vegetated transect with a dense mixture of two different species of 10-year-old willow (i.e. *Salix viminalis* L. and *Salix caprea* L.) and (ii) a poorly or non-vegetated (fallow) transect that failed during the last reported instability event in the winter of 2013. Five willow individuals (two *Salix caprea* and three *Salix viminalis*) representative of the tree stand present in our study site (Fig.1) were selected for study from the willow-vegetated transect (Table 1).

Table 1. Tree metrics for the different willow individuals selected for study. *H*: tree height; *DBH*: diameter at breast height; *Ac*: canopy-crown area; *LAI*: leaf area index; *Ma*: mean aboveground biomass estimated from allometric equations for *S. viminalis* (Nordh and Verwijst, 2004) and *S. caprea* (Muukkonen and Makipää, 2006) using *H* and *DBH* as inputs. ‘*Individuals on which rainfall interception was studied.’

<table>
<thead>
<tr>
<th>Species</th>
<th>Individual</th>
<th><em>H</em> (m)</th>
<th><em>DBH</em> (m)</th>
<th><em>Ac</em> (m²)</th>
<th><em>LAI</em></th>
<th><em>Ma</em> (g m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>S. viminalis</em></td>
<td>SV I</td>
<td>2.84</td>
<td>0.44</td>
<td>6.54</td>
<td>3.26</td>
<td>354.68</td>
</tr>
<tr>
<td><em>S. viminalis</em></td>
<td>SV II*</td>
<td>3.65</td>
<td>0.39</td>
<td>4.24</td>
<td>2.67</td>
<td>-</td>
</tr>
<tr>
<td><em>S. viminalis</em></td>
<td>SV III</td>
<td>13.04</td>
<td>0.37</td>
<td>13.14</td>
<td>1.56</td>
<td>-</td>
</tr>
<tr>
<td><em>S. caprea</em></td>
<td>SC I</td>
<td>4.93</td>
<td>0.20</td>
<td>13.05</td>
<td>3.63</td>
<td>2373.18</td>
</tr>
<tr>
<td><em>S. caprea</em></td>
<td>SC II</td>
<td>4.52</td>
<td>0.11</td>
<td>8.77</td>
<td>4.46</td>
<td>-</td>
</tr>
</tbody>
</table>

3. Methods

3.1. Quantification of the hydrological mechanisms of willow affecting slope stability under wetting and drying conditions

3.1.1. Wetting conditions

Stemflow volume was measured for the five selected willow individuals (Table 1) during the growing (July – October, 2014) and dormant seasons (November 2014 –
February 2015), respectively. For this, PVC stemflow gutters (Fig. 2a) were installed
at breast height, spiralling around each tree stem and discharging into 25 L plastic
containers. The stemflow volume (m$^3$) was scaled with the canopy-crown area ($Ac$;
$m^2$; Table 1) and regressed against the gross rainfall ($P_g$; Deguchi et al., 2006) in the
statistical software R v.3.2.1 (R Core Team, 2015). The magnitude of gross rainfall
($P_g$) was averaged from the volumes collected in 5 exposed rain gauges distributed
randomly over the study site and consisting of 75 mm diameter plastic funnels
attached to 2000 ml PVC bottles (Fig. 2a).

The rainfall interception could only be quantified on three individuals (i.e. two
$S. viminalis$ and one $S. caprea$; Table 1) with clearly delineated canopies separated
from the entwined canopies in the stand. The interception was quantified during the
growing (July – October, 2014) and dormant season (November 2014 – February
2015), respectively, by collecting the rainfall passing through the canopy (i.e.
throughfall; Fig. 2a) into three different rain gauges placed below the canopy and at
different distances from the stem for each studied individual (Table 1). The average of
the water volumes collected by the undercanopy rain gauges was compared against
the volume of gross rainfall ($P_g$). Linear regression models were fitted between the
registered throughfall and gross rainfall volumes in R v.3.2.1 (i.e. revised Gash
model; van Dijk and Bruijnzeel, 2001; Deguchi et al., 2006). The canopy storage
capacity was appraised from the fitted regression lines (Leyton et al., 1967). The
rainfall interception loss was estimated to be the difference between the gross rainfall and throughfall.

3.1.2. Drying conditions

The plant water uptake from the soil was quantified as soil matric suction \( u_a - u_w \); kPa; \( u_a \): pore-air pressure; \( u_w \): pore-water pressure; Fig. 2b; e.g. Persson, 1995) and soil volumetric moisture content \( \theta_v \) differences between the vegetated and the fallow slope transect. Daily measurements of \( u_a - u_w \) and \( \theta_v \) were taken with a field tensiometer (Irrometer®; Fig. 2b) and a moisture profile probe (Delta-T®), respectively, during the period of maximum atmospheric water demand (7th July- 18th August, 2014). \( u_a - u_w \) and \( \theta_v \) measurements were collected from within the soil-root zone (0 - 400 mm b.g.l.; Tardio et al., 2016) at four different slope points (i.e. LT: lower toe; UT: upper toe; LC: lower crest; UC: upper crest), spaced every 2 m over each slope transect (Fig. 1b). The matric suction readings were collected at a single soil depth (350 mm b.g.l.) at the four slope points, while the moisture readings were collected at 300 and 400 mm b.g.l. at the four slope points.

3.2. Prediction of plant-derived matric suction under drying conditions

3.2.1. Approach

To predict the plant-derived \( u_a - u_w \) under drying conditions (Eq.1; Table 2), we modified an existing closed-form equation designed to predict \( u_a - u_w \) under variable steady-state water flow situations (i.e. negative sign flow: infiltration; positive sign flow: evaporation) in isotropic soil materials (Eq. 2; Table 2; Lu and Griffiths, 2006; for numerical derivation see Lu and Godt, 2013). Eq.2 (Table 2) is derived from the integration of Darcy’s law over time and space using the soil water characteristic.
curve (SWCC) and the hydraulic conductivity function (HCF). We modified the original equation by: (a) replacing $K_s$ by the unsaturated hydraulic conductivity ($K(\theta)$; Eq.6; Table 2), or HCF, because the soil will de-saturate as it drains or dries and because the plant water uptake will be negligible in waterlogged soils (Rodriguez-Iturbe and Porporato, 2004); and (b) introducing the canopy-crown area ($A_c$; m$^2$; Table 1) as a scaling parameter, because the entire plant crown may contribute to soil suction through plant water uptake if a top-down uptake approach is adopted (Shukla, 2014). Eq.1 (Table 2) assumes steady plant transpiration rates within the whole root zone (i.e. 0-400 m b.g.l).

3.2.2. Parameterisation

To implement Eq.1 (Table 2), knowledge of the potential daily plant transpiration rate ($E_{tp}$; m d$^{-1}$ m$^{-2}$; Eq.3; Table 2) and the soil hydro-mechanical parameters ($\alpha$: inverse of air-entry pressure, kPa$^{-1}$; $n$: pore-size distribution parameter, unitless) is needed.

To estimate $E_{tp}$ (Eq.3; Table 2), the potential daily evapotranspiration rate ($E_u$; m d$^{-1}$ m$^{-2}$) was calculated using the Priestly and Taylor (1972) method. For this, we employed meteorological records (i.e. daily air temperature, atmospheric pressure, and sunshine duration) retrieved from an in situ weather station (voor de Porte, 2011). The input variables to estimate $E_u$ (i.e. daily solar radiation, psychrometric constant, and slope of the saturated vapor pressure at mean air temperature) were calculated as specified in Allen et al. (1998). The extension suggested by Savabi and Williams (1995) was adopted to account for different vegetation covers in terms of the leaf area index ($LAI$; Eq.4; Table 2) and to obtain $E_{tp}$ from $E_u$ (Eq.3; Table 2).
### Table 2. List of equations used in this study.

<table>
<thead>
<tr>
<th>Definition</th>
<th>Equation</th>
<th>N°</th>
<th>Parameters</th>
<th>Units</th>
<th>Equation source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetated soil matric suction under drying conditions</td>
<td>$u_a - u_w = Ac[-1\alpha \ln \left( 1 + \frac{E_{ip}}{K(\theta t)} \right) e^{-\gamma wax} - \frac{E_{ip}}{K(\theta t)}}$</td>
<td>Eq.1</td>
<td>$u_a, u_w$: matric suction; $A$: canopy-crown area; $\alpha$: inverse air-entry pressure</td>
<td>kPa</td>
<td>This study</td>
</tr>
<tr>
<td>Soil matric suction</td>
<td>$u_a - u_w = -\frac{1}{\alpha} \ln \left( 1 + \frac{q}{K_s} \right) e^{-\gamma wax} - \frac{q}{K_s}$</td>
<td>Eq.2</td>
<td>$\alpha$: saturated hydraulic conductivity; $q$: water flow (infiltration: negative sign; evapotranspiration: positive sign)</td>
<td>m s$^{-1}$</td>
<td>Lu and Griffiths (2006)</td>
</tr>
<tr>
<td>Plant transpiration</td>
<td>$E_{ip} = \left( 1 - \frac{E_{wp}}{E_s} \right) E_s$</td>
<td>Eq.3</td>
<td>$E_{ip}$: potential direct soil evaporation rate; $E_{wp}$: potential evapotranspiration rate</td>
<td>m s$^{-1}$</td>
<td>Savabi and Williams (1995)</td>
</tr>
<tr>
<td>Direct water evaporation</td>
<td>$E_{wp} = E_{uw} e^{-0.4LAi}$</td>
<td>Eq.4</td>
<td>$LAi$: leaf area index; Ununitless</td>
<td></td>
<td>Savabi and Williams (1995)</td>
</tr>
<tr>
<td>Soil water characteristic curve$^c$</td>
<td>$\theta_i = \theta r + (\theta s - \theta r)(\frac{1}{1 + (\alpha(\theta s - \theta w))^n})^{n-1}$</td>
<td>Eq.5</td>
<td>$\theta_i$: residual soil volumetric moisture content; $\theta r$: saturated soil volumetric moisture content</td>
<td>/1</td>
<td>Van Genuchten (1980)</td>
</tr>
<tr>
<td>Hydraulic conductivity function</td>
<td>$K(\theta t) = K_s(\theta s)^n$</td>
<td>Eq.6</td>
<td>$n$: pore size distribution parameter</td>
<td>Ununitless</td>
<td></td>
</tr>
<tr>
<td>Suction stress function</td>
<td>$\sigma^z = -\frac{u_w - u_a}{1 + \alpha(\theta s - \theta w)^n}^{n-1}$</td>
<td>Eq.7</td>
<td>$\sigma^z$: suction stress</td>
<td>kPa</td>
<td>Lu et al. (2010)</td>
</tr>
<tr>
<td>Soil shear strength (unified effective stress principle)</td>
<td>$\tau = c' + (\sigma - u_a - \sigma^z)\tan \phi$</td>
<td>Eq.8</td>
<td>$\tau$: soil shear strength; $c'$: soil effective cohesion; $\sigma$: normal stress; $u_a$: pore-air pressure</td>
<td>kPa</td>
<td>Lu and Likos (2004)</td>
</tr>
<tr>
<td>Factor of Safety</td>
<td>$FoS = \frac{c' + (\sigma(z) - \sigma^z(z))\tan \phi}{\sigma(z)\sin \phi \cos \beta}$</td>
<td>Eq.9</td>
<td>$\beta$: slope gradient or angle; Degrees</td>
<td>/1</td>
<td>Lu and Godt (2008)</td>
</tr>
<tr>
<td>Normal stress</td>
<td>$\sigma(z) = (\gamma s(Hwt - z) + Wv)\cos^2 \beta$</td>
<td>Eq.10</td>
<td>$\gamma s$: soil moist unit weight; $Hwt$: water table (lower soil boundary) height</td>
<td>kPa m$^{-1}$</td>
<td>This study</td>
</tr>
<tr>
<td>Bypass flow rate</td>
<td>$q_{by} = AcSt / t_r$</td>
<td>Eq.11</td>
<td>$q_{by}$: bypass flow rate; $Ac$: stemflow volume per unit area of tree-crown</td>
<td>m s$^{-1}$</td>
<td>This study</td>
</tr>
<tr>
<td>Evaporative soil depth</td>
<td>$d_s = 0.09 - 0.0077Cl + 0.000006Sa^2$</td>
<td>Eq.12</td>
<td>$d_s$: maximum evaporative soil depth; $Cl$: percentage of clay in soil; Sa: percentage of sand in soil</td>
<td>m</td>
<td>Savabi and Williams (1995)</td>
</tr>
</tbody>
</table>
The soil hydro-mechanical parameters ($\alpha$ and $n$) under vegetated and fallow soil conditions, respectively, were retrieved by fitting the soil water characteristic curve (SWCC; Eq.5; Table 2; van Genuchten, 1980) for the drying path (Lu and Likos, 2004) in R v.3.2.1. To fit the SWCC, we examined the relationship between the coupled measurements of matric suction ($u_a-u_w$; kPa) and soil volumetric moisture content ($\theta_v$; %) collected in situ over time (see 3.1.2) (e.g. Lu and Godt, 2013). Then, Eq.5 (Table 2) was fitted iteratively to the observed data points by assigning values to $\alpha$ and $n$ in Eq.5 until the maximum goodness of fit ($R^2$) was achieved. Once the soil hydro-mechanical parameters were estimated, HCF (Eq.6; Table 2; Brooks and Corey, 1964) could be implemented in Eq.1 (Table 2) before proceeding with the plant-derived $u_a$-$u_w$ predictions.

The predictions of $u_a$-$u_w$ under vegetated soil were carried out using Eq.1 (Table 2) for the same days on which in situ $u_a$-$u_w$ records were taken at the four different slope positions (see 3.1.2). For the $u_a$-$u_w$ predictions, the soil moisture was assumed to be constant and at field capacity (i.e. $\theta_v=0.23$), while the soil depth ($z$) was fixed at 350 mm b.g.l. The mean $Ac$ among the assessed willow individuals (Table 1) was employed for the lower toe (LT), upper toe (UT) and lower crest (LC) positions. For the upper crest (UC), the canopy area of the individual adjacent to the tensiometer was used (i.e. $Ac = 3.74$ m$^2$).

3.3. Evaluation of willow hydrological effect on slope stability using the unified effective stress principle

3.3.1. Approach
We employed an existing conceptual model to evaluate the hydrological effect of willow on slope stability (Gonzalez-Ollauri and Mickovski, 2014; Fig. 3). This model considers the hydrological mechanisms quantified at the soil-plant-atmosphere interface (i.e. rainfall interception, stemflow, and plant water uptake; see 3.1) as driving functions that induce changes on the system state variables - the soil matric suction (Eq. 1 and Eq. 2; Table 2) and degree of saturation (intrinsically related to SWCC; Eq.5; Table 2). On the basis of the soil hydro-mechanical parameters (i.e. $\alpha$ and $n$; see 3.2.2), the model defines the stress-state in the soil and, ultimately, the slope stability (Figs. 3 and 4). The stress-state in the soil is depicted by the suction stress ( $\sigma_s$; Eq.7; Table 2; Lu et al., 2010) featured in Coulomb’s law (e.g. Head and Epps, 2011) for the estimation of the soil shear resistance ( $\tau$; Eq.8; Table 2) under variable soil saturation conditions (i.e. unified effective stress principle; UES; Lu and Likos, 2004). The slope stability was evaluated with the infinite slope limit equilibrium method (LEM; e.g. Craig, 2004). This estimates a factor of safety (i.e. $\text{FoS} = \text{resisting forces}/\text{driving forces}$; Eq.9; Table 2; Lu and Godt, 2008) and includes the UES within the resisting forces (Eq.8; Table 2). The driving forces are depicted by the normal stress ( $\sigma(z)$; Eq. 10; Table 2), which includes the vegetation surcharge ($W_v$; Table 2), and the slope gradient ( $\beta$). Herein, $W_v$ was derived from the vegetation aboveground biomass ($Ma$; Table 1).

3.3.2 Approach testing: case scenarios and further assumptions
We tested the approach described in 3.3.1 (Fig. 3) using four discrete meteorological events (i.e. two events under wetting and drying conditions, respectively) for vegetated and fallow soil covers, and under limit equilibrium conditions (aimed at stressing the hydrological effect of vegetation under critical slope stability conditions; Lu and Godt, 2013). In all of the scenarios, the slope inclination ($\beta$) was taken as 45°, the angle of internal friction as 22°, and the soil at saturation ($c=0$ kPa), mimicking the onset of a rainfall-induced landslide.

a) Wetting conditions

Two rainfall episodes of different intensity were considered: (S1) the maximum rainfall event registered during the monitoring period - i.e. 15.6 mm of cumulative rainfall during 10 h; and (S2) the maximum recorded precipitation event at the study site which, presumably, triggered multiple shallow landslide events - i.e. 42.2 mm of cumulative rainfall during 10 h.

The throughfall and stemflow derived from each rainfall event were evaluated under growing and dormant states, using the regression models obtained for each mechanism and season (see 3.1.1). Both mechanisms were treated differently in terms of the infiltration process they triggered (Fig. 4). Throughfall water was assumed to infiltrate the soil as a piston flow once ponding formed on the ground surface (i.e. Green & Ampt model; Mein and Larson, 1973; see Gonzalez-Ollauri and Mickovski, 2014). The piston flow was assumed to saturate the soil (i.e. $u_a-u_w = 0$ kPa) as the wetting front travelled down the soil profile (Neitsch et al., 2011). The same infiltration process was considered for the fallow soil (Fig. 4). The stemflow water, however, was assumed to bypass the soil-root zone (Liang et al. 2011) as a jet flow without considering the soil anisotropy produced by the root system. Thus, stemflow
water would result in a water flow that infiltrates the root zone at a steady rate \( q_{by} \), Eq.11; Table 2), and produces changes in the soil stress-state as indicated in Fig.4.

Eq.11 (Table 2) assumed that the entire tree-crown contributed to the stemflow. The formation of perched water tables in depth was neglected, and hydrostatic conditions (i.e. \( q=0 \) m s\(^{-1}\)) were assumed to be below the wetting front.

b) Drying conditions

Two different evapotranspiration events were considered. These corresponded to the days of maximum and minimum atmospheric demand registered during the monitoring period (i.e. July, 7\(^{th}\) – August, 18\(^{th}\), 2014). The soil moisture content was assumed to be constant throughout the soil profile and at field capacity (i.e. \( \theta_v=0.23 \)).

For the vegetated soil, the soil stress-state was evaluated using Eq.1 (Table 2; Fig. 4) assuming that the whole root system (0-400 mm b.g.l) contributed to \( E_{tp} \) (i.e. steady plant transpiration rate). Hydrostatic conditions were considered to be below the root zone (i.e. \( E_{tp}=0 \) m s\(^{-1}\)).

For fallow soil, the soil stress-state was evaluated using Eq.1 (Table 2; Fig. 4), with \( A_c \) equal to 1 m\(^2\), and the potential soil evaporation \( (E_{sp}; \text{Eq.4}; \text{Table 2}) \) was considered to be the driving function. The evaporative soil depth \( (d_e) \) was estimated to be a function of the soil particle size distribution (Eq.12; Table 2; Savabi and Williams, 1995). Hydrostatic conditions were assumed to be below \( d_e \).

3.4. Statistical analysis
The statistical differences between the fitted regression models for the throughfall and stemflow were examined by estimating the t-statistic at the 95% and 99% confidence levels (Paternoster, 1998).

The statistical differences between the vegetated and fallow transects, and among the slope transect positions (i.e. LT, UT, LC, UC), in terms of $u_o-u_w$ and $\theta_i$ were evaluated with Kruskal-Wallis ($\chi^2$) tests at the 95% and 99% confidence levels on the basis of the degrees of freedom (df) and after pertinent statistical distribution testing. When statistically significant differences were found, the differences within the groups were assessed with Wilcoxon tests (W). The $\theta_i$ differences between the two evaluated soil depths (i.e. 300 and 400 mm b.g.l) were assessed in the same manner. The slope stability (FoS) differences between the considered treatments (i.e. vegetated vs. fallow and wetting vs. drying) were evaluated using Kruskal-Wallis and Wilcoxon tests.

The statistical differences between the observations and predictions (i.e. goodness of fit) for the plant-derived soil matric suction under drying conditions were analysed with F-tests (i.e. variance test). Additionally, ARIMA (autoregressive integrated moving average) models were fitted to each time series (i.e. observed and predicted) after carrying out autocorrelation tests (Cowpertwait and Metcalfe, 2009). The models were then compared on the basis of AIC (Akaike information criterion).

4. Results

4.1. Quantification of the hydrological mechanisms of willow affecting slope stability under wetting and drying conditions

4.1.1. Wetting conditions
The throughfall and stemflow (Table 3 and Fig. 5) showed a linear correlation with the gross rainfall \( (P_g) \) in all cases. *S. viminalis* showed a positive rainfall interception capacity for the growing (S1: 26.73%; S2: 22.03%) and dormant (S1: 8.91%; S2: 2.25%) seasons under both rainfall scenarios (Table 3). *S. caprea*, however, only presented a positive rainfall interception capacity for the dormant season under both rainfall scenarios (S1: 16.73%; S2: 16.27%; Table 3). The overall canopy storage capacity was 0.72 and 0.41 for *S. viminalis* and *S. caprea*, respectively.

There were no statistical differences in throughfall between the two willow species for the global fitted models (i.e. using all monitoring points; \( t=0.84, \text{df}=48, p>0.05 \)). However, significant differences between the growing and dormant seasons in terms of throughfall were observed for *S. caprea* \( (t=2.61, \text{df}=3, p<0.05) \).

The water volume concentrated around the stem was higher for *S. caprea*, reaching volumes beyond 45 L (10.78% of rainfall) under the heavy rainfall scenario (S2) for both seasons (Table 3). The stemflow showed significant differences between the two willow species for the fitted global regressions \( (t=2.95, \text{df}=48, p<0.01) \). Seasonal differences were also observed for the two willow species (*S. viminalis*: \( t=6.86, \text{df}=6, p<0.01; \) *S. caprea*: \( t=2.07, \text{df}=11, p<0.05 \)). The bypass flow rates derived from the stemflow under the two considered rainfall scenarios (S1 and S2) are shown in Table 3.
Table 3. Throughfall (Th) and stemflow (St) linear relationships with gross rainfall (P_g), and predicted outcomes for rainfall interception (i_x), stemflow volume (St_x) and bypass flow rate (q_by-x) under the two rainfall scenarios considered - i.e. S1: 15.6 mm during 10 h ; S2: 42.2 mm during 10 h. R^2: regression lines goodness of fit. Global fit: linear regression fitted with every monitoring data.

<table>
<thead>
<tr>
<th>Species</th>
<th>Individual</th>
<th>Season</th>
<th>Throughfall</th>
<th>R^2</th>
<th>i_x1 (mm)</th>
<th>i_x2 (mm)</th>
<th>Stemflow</th>
<th>R^2</th>
<th>St_x1 (L)</th>
<th>St_x2 (L)</th>
<th>q_by-x S1 (m s^-1)</th>
<th>q_by-x S2 (m s^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. viminalis</td>
<td>SV I</td>
<td>Th=1.42P_g+9.09</td>
<td>0.89</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Th=0.01P_g+0.03</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. viminalis</td>
<td>SV II</td>
<td>Th=0.61P_g+1.21</td>
<td>0.93</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.06P_g+0.10</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. viminalis</td>
<td>SV III</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.05P_g+0.12</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. viminalis</td>
<td>Growing</td>
<td>Th=0.81P_g+1.21</td>
<td>0.68</td>
<td>4.17</td>
<td>8.81</td>
<td>0.66</td>
<td>5.10</td>
<td>14.82</td>
<td>-1.23e-07</td>
<td>-3.79e-07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. viminalis</td>
<td>Dormant</td>
<td>Th=1.02P_g+1.7</td>
<td>0.60</td>
<td>1.39</td>
<td>0.90</td>
<td>0.97</td>
<td>2.10</td>
<td>5.02</td>
<td>-5.08e-08</td>
<td>-1.27e-07</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. viminalis</td>
<td>Combined</td>
<td>Th=1.02P_g+5.14</td>
<td>0.74</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.03P_g+0.23</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. caprea</td>
<td>SC I</td>
<td>Th=0.91P_g+4.86</td>
<td>0.82</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.05P_g+0.13</td>
<td>0.67</td>
<td></td>
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</tr>
<tr>
<td>S. caprea</td>
<td>SC II</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.06P_g+0.04</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. caprea</td>
<td>Growing</td>
<td>Th=1.50P_g+6.77</td>
<td>0.83</td>
<td>-1.03</td>
<td>-13.23</td>
<td>0.58</td>
<td>8.25</td>
<td>45.50</td>
<td>-7.77e-07</td>
<td>-3.37e-06</td>
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<td></td>
</tr>
<tr>
<td>S. caprea</td>
<td>Dormant</td>
<td>Th=0.84P_g+0.11</td>
<td>0.86</td>
<td>2.61</td>
<td>6.51</td>
<td>0.48</td>
<td>12.37</td>
<td>49.64</td>
<td>-4.66e-07</td>
<td>-1.38e-06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S. caprea</td>
<td>Global</td>
<td>Th=0.91P_g+4.86</td>
<td>0.82</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>St=0.05P_g+0.10</td>
<td>0.61</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
4.1.2. Drying conditions

When compared with the fallow slope transect, the vegetated transect showed significantly lower ($\chi^2=53.94$, df=1, p<0.01) soil moisture and ($\theta_v$, Fig. 6a-d) and significantly higher matric suction ($u_a-u_w$, Fig. 7a-d) ($\chi^2=52.07$, df=1, p<0.01). The soil moisture increased significantly with soil depth ($W=6027$, p<0.01; Fig. 6a-d), and was, on average, 12.84% higher in the fallow transect when compared with the vegetated one. The fallow transect showed significant differences in terms of $\theta_v$ between the slope positions ($\chi^2=28.35$, df=3, p<0.01) with the UC shown to be the driest (Fig. 1b; $W=1284$, p<0.01) position on the slope. The vegetated transect did not show significant differences in soil moisture between the slope positions ($\chi^2=5.78$, df=3, p=0.12).

In the willow-vegetated transect, where the suction was kept above 10 kPa over the monitoring period at all slope positions (Fig. 1b), $u_a-u_w$ (Fig. 7a-d) reached peaks of ca. 60 kPa. In the fallow transect, $u_a-u_w$ was well below 20 kPa for most of the monitoring time and at all 4 slope positions, where saturation levels of suction (i.e. 0 kPa) were reached during the monitoring period (Fig. 7a-d). For both treatments, $u_a-u_w$ showed significant differences between slope positions (Willow: $\chi^2=27.89$, df=3, p<0.01; Fallow: $\chi^2=15.04$, df=3, p<0.01). UC (Fig. 1b) showed the lowest suction levels in the vegetated transect ($W=342$, p<0.01).
4.2. Prediction of plant-derived matric suction under drying conditions

4.2.1. Approach parameters

The parameter values using Eq.1 (Table 2) and predicting plant-induced $u_a-u_w$ under drying conditions are shown in Table 4. A statistically significant relationship between $u_a-u_w$ and $\theta_v$ (i.e. SWCC; Table 4; Fig. 8a) was found at all slope positions for the fallow transect after fitting Eq.5 (Table 2) using the monitoring data (Figs. 6 and 7). Only the SWCC fitted for LC (Fig. 1b) differed from the curves fitted for the other three slope positions (Fig. 8a). A statistically significant relationship between $u_a-u_w$ and $\theta_v$ was not encountered for the vegetated slope transect (Fig. 8b). Consequently, the hydro-mechanical parameters for the willow-vegetated soil could not be obtained. The mean $\alpha$ (Table 2) from the LT, UT, and UC slope positions (Table 4) was used in Eq.1 (Table 2). To evaluate the soil stress-state (Eq. 7; Table 2) under vegetation cover and drying conditions, the value of $n$ (Table 2) was assigned arbitrarily (Table 4) in agreement with published values for vegetated soil (Carminati et al., 2010).

4.2.2. Matric suction predictions

The plant-derived soil matric suctions under drying conditions were successfully predicted using Eq. 1 (Fig. 7). No statistical differences were detected between the observations and model predictions except for the LC position (Table 4).
Table 4. Parameters value used in the implementation of Eqs. 1 and 7 (Table 1) for predicting plant-derived matric suctions, and the subsequent suction stress, under the scenarios of maximum (Max) and minimum (Min) atmospheric demand. Bottom part: goodness of fit (i.e. F-statistic and AIC) between predicted plant-derived matric suction time series and monitored field values. Slope positions: LT: lower toe; UT: Upper toe; LC: lower crest; UC: upper crest.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Fallow soil</th>
<th>Vegetated soil</th>
<th>Salix viminalis</th>
<th>Salix caprea</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_u$</td>
<td>Potential daily evapotranspiration rate; m d^{-1} m^{-2}</td>
<td>-</td>
<td>-</td>
<td>6.28e-08</td>
<td>1.96e-08</td>
</tr>
<tr>
<td>$E_p$</td>
<td>Potential daily plant transpiration rate; m d^{-1} m^{-2}</td>
<td>-</td>
<td>-</td>
<td>3.97e-08</td>
<td>1.23e-08</td>
</tr>
<tr>
<td>$E_r$</td>
<td>Potential daily soil evaporation rate; m d^{-1} m^{-2}</td>
<td>1.42e-11</td>
<td>4.42e-12</td>
<td>1.83e-11</td>
<td>5.71e-12</td>
</tr>
<tr>
<td>$d_s$</td>
<td>Evaporative soil depth; m</td>
<td>0.13</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K(\theta)$</td>
<td>Unsaturated hydraulic conductivity; m s^{-1}</td>
<td>2.31e-08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Inverse air-entry pressure; kPa^{-1}</td>
<td>0.06</td>
<td>0.05</td>
<td>0.2</td>
<td>0.06</td>
</tr>
<tr>
<td>$n$</td>
<td>Pore-size distribution parameter; unitless</td>
<td>6.00</td>
<td>5.00</td>
<td>2.23</td>
<td>5.00</td>
</tr>
<tr>
<td>$R^2$</td>
<td>Coefficient of determination for SWCC</td>
<td>0.90</td>
<td>0.74</td>
<td>0.70</td>
<td>0.73</td>
</tr>
<tr>
<td>F-statistic (df=15)</td>
<td>Variance test statistic from $u_o-u_w$ model validation</td>
<td>0.91</td>
<td>2.62</td>
<td>4.58</td>
<td>0.92</td>
</tr>
<tr>
<td>p-value</td>
<td>Significance level from variance test</td>
<td>0.86</td>
<td>0.07</td>
<td>&lt; 0.01</td>
<td>0.87</td>
</tr>
<tr>
<td>AIC</td>
<td>Akaike information criterion from ARIMA</td>
<td>115.18</td>
<td>132.21</td>
<td>141.07</td>
<td>90.56</td>
</tr>
</tbody>
</table>

All of the studied time series were stationary on the basis of the autocorrelation tests. The ARIMA models fitted for the LT and UC positions presented higher goodness of fit (Table 4) than ??????.

4.3. Evaluation of willow hydrological effect on slope stability using the unified effective stress principle

The suction stress profiles (Figs. 9a-d) predicted with Eq.7 (Table 2) presented consistent differences between wetting (Figs. 9a-c) and drying (Fig. 9d) conditions as well as between fallow and vegetated soil. These differences were mainly attributed to the differences in the hydro-mechanical parameters between the fallow and willow-vegetated soil (Table 4) and the infiltration process under consideration (Fig. 4). While the infiltration as a piston flow tended to dramatically reduce the suction stress (Figs. 9a-c), the stemflow-derived bypass infiltration did not significantly change the soil stress-state conditions with respect to hydrostatic state (shown in Fig. 9d as grey dashed line).

The FoS profiles (Figs. 9e-f) predicted with Eq.9 (Table 2) showed agreement with the suction stress profiles (Figs. 9a-d). Drastic reductions in suction stress resulted in instability zones (i.e. FoS < 1) in the FoS profiles (Figs. 9e-f). The increase
in suction stress under drying conditions (Fig. 9d) appeared to shift the FoS profiles towards values denoting stability (i.e. FoS > 1; Figs. 9e-f) when compared with the wetting conditions. As a result of this, the FoS distribution showed significant differences between the wetting and drying conditions ($\chi^2=82.18$, df=1, p<0.01), as well as between the fallow and vegetated soil ($\chi^2=11.75$, df=1, p<0.01). FoS differences between the willow species were not detected under wetting or drying conditions. However, the FoS derived from the throughfall effect (Fig. 9e) showed significant differences under the heavy rain scenario (S2; $\chi^2=7.49$, df=1, p<0.01). Under drying conditions, significant differences were observed between the maximum and minimum $E_{tp}$ scenarios ($\chi^2=19.13$, df=1, p<0.01).

Values of FoS below unity were predicted for soil depths of 400 mm b.g.l and deeper (Figs. 9e-f). This outcome was due to the assumptions of soil strength (i.e. $c=0$ kPa) and a very steep slope (i.e. $\beta=45^\circ$) which highlighted the hydrological effect of Salix sp. under critical stability conditions. Under this setting (unrealistic for our study site with mean soil cohesion of 33 kPa and mean slope gradient of 25°), the stress generated by the weight of the soil column counteracted the shear resistance provided by the angle of internal friction. The latter was not high enough to provide stable slope conditions in the absence of cohesion (Lu and Godt, 2013), leading to the occurrence of failure zones in the FoS profiles (Figs. 9e-f).

5. Discussion

5.1. Quantification of the hydrological mechanisms of willow affecting slope stability under wetting and drying conditions

5.1.1. Wetting conditions:
The rainfall interception (i.e. gross rainfall minus throughfall) by *Salix viminalis* (Fig. 5a; Table 3) noticeably affected the amount of rain that eventually reached and entered the ground. This effect was observed to be seasonal (Table 3; Fig. 5a) due to foliage cover (Deguchi et al., 2006). However, under the heavy rainfall scenario (i.e., S2; see 3.3.1), the interception capacity decreased (Table 3) as a result of the canopy saturation (van Dijk and Bruijnzeel, 2001). This suggests that under heavy precipitation events, such as the ones normally triggering landslides (Sidle and Bogaard, 2016), most of the rain will reach the ground. However, rainfall interception can still be useful in regulating the water mass balance in the soil (Llorens and Domingo, 2007), preventing the soil from reaching saturation moisture levels during prolonged periods of gentle rain (i.e. typical meteorological conditions at our study site) and, potentially improving the slope stability conditions (Lu and Godt, 2013).

The throughfall regression model for *Salix caprea* predicted more throughfall than the gross rainfall for the growing season (Table 3). This may result from dripfall (Zimmermann and Zimmermann, 2014) – the rainwater that accumulates on leaves and falls to the ground once the canopy has become saturated (van Dijk and Bruijnzeel, 2001) – which would have been significant due to the fact that the observed canopy storage capacity for *S. caprea* was rather low (see 4.1.1; Deguchi et al., 2006). Dripfall patterns are likely to be random, as the architecture of tree canopies is highly heterogeneous (e.g. Bohrer et al., 2009). As a result, a given interception rain gauge may collect larger water volumes than originally expected. This anomaly could be corrected by changing the setup approach to monitor a larger canopy area (Zimmermann and Zimmermann, 2014). In our case, however, a broader canopy area could not be taken for study due to the site operational difficulties (i.e. steep and densely vegetated slope prone to instability) and the entwined canopies in
the stand. Nonetheless, the method outlined here for evaluating throughfall for slopes under dense vegetated zones was shown to be feasible. Future studies should focus on addressing the indicated shortcomings to obtain reliable rainfall interception models in these environmental contexts.

The stemflow results (Figs. 5c-d; Table 3) indicated that the concentration of water around the stem can be substantial (Liang et al., 2011; Levia and Germer, 2015). Stemflow differences observed between the studied species suggest that the canopy morphology (e.g. branch architecture, tree-crown spread) may also govern this mechanism (Yuan et al., 2016). Stemflow water could be funnelled around the tree base and enter the soil as a bypass flow (Liang et al., 2011) with potential effects on the soil stress-state (Lu and Godt, 2013). Thus, careful consideration of plant aerial traits may help to highlight the intra-species differences in terms of stemflow (Levia and Germer, 2015). In any case, the method presented here was shown to be viable for quantifying the volumes of water concentrated around the stems of woody vegetation growing on slopes. Our study has also shown that the stemflow process deserves more attention in order to better understand the water cycle dynamics on vegetated slopes (Levia and Germer, 2015).

5.1.2. Drying conditions

The plant-water uptake, assessed through the measurement of $\theta$, (Fig. 6a-d) and $u_a-u_w$ differences between vegetated and fallow soil over time (Fig. 7a-d), was evident in all cases (Persson, 1995; Ng et al., 2013). This stresses the positive hydrological effect of vegetation in terms of the soil water balance regulation in a slope stability context (Stokes et al., 2008). The vegetation showed a pronounced effect upon the increase of $u_a-u_w$ (Fig. 7a-d) and on the desaturation or drainage (i.e.
\( \theta_v \) increased with soil depth; Fig. 6a-d) of the soil profile, suggesting that vegetation increases slope stability (Wilkinson et al., 2002). This effect appeared to be stronger at the lower toe of the slope (Fig. 7a) which may have been due to a denser vegetation cover at the slope toe in the willow-vegetated transect. The denser vegetation cover may have been favoured by a more gentle slope gradient at the landslide deposition zone (i.e. slope toe), where soil nutrients tend to accumulate (Walker et al., 2009; Gonzalez-Ollauri and Mickovski, In Press). A denser plant cover could have led to a higher plant-water demand (Jia et al., 2017) which, in turn, helped to maintain higher suction (Fig. 7a) and lower moisture levels (Fig. 6a) in the soil.

There appeared to be an effect of climate on the soil moisture dynamics (e.g. Zhang et al., 2016) in our observations as both \( u_a-u_w \) and \( \theta_v \) were affected by changes in precipitation patterns (Figs. 6 and 7) – soil input water from rainfall led to marked decreases in \( u_a-u_w \) and increases in \( \theta_v \) as rain infiltrated into the soil profile. However, this observation could not be fully quantified because of the relatively short monitoring period, which we acknowledge to be a limitation of our study. A temporal expansion of the study would help the evaluation the hydrological effect of vegetation under different seasonal conditions (e.g. winter, when atmospheric demand of water is low in temperate climates), and derivation of a clearer numerical relationship between rainfall, \( u_a-u_w \), and \( \theta_v \).

5.2. Prediction of plant-derived matric suction under drying conditions

The plant-derived matric suction predictions (Fig. 7a-d) using Eq. 1 (Table 2) matched well the monitoring (Fig. 7a-d) and fell within the range observed in situ. The predictive capacity of our approach could be enhanced in the future by revising some of the assumptions made to reduce the computational effort. For example, we
considered a constant $K(\theta)$ (i.e. the one corresponding to the water content at field capacity; Table 4) instead of allowing it to vary with the soil moisture overtime. Additionally, the same $Ac$ (Table 1) was considered for three of the four monitored slope positions. Finally, $E_{wp}$ (Table 4) estimations can vary from approach to approach (Li et al., 2016) and the required inputs are subject to many inaccuracies depending upon the meteorological station from where they had been retrieved. The $E_{wp}$ estimation was particularly sensitive to sunlight duration, which, at our site with mainly overcast days, tended to be negligible and led to low estimation of $E_{wp}$. All of these, together with the soil moisture buffering behaviour induced by plant roots (i.e. upon drying the root system tends to hold more water, while upon wetting it tends to remain drier than the surrounding bulk soil; Carminati et al., 2010), could explain the time lags between predictions and observations (Fig. 7a-c).

The original equation (Eq.2; Lu and Griffiths, 2006) predicted invariant (ca. 2.5 kPa) $u_a-u_w$ time series that were well below the in situ observations (Fig. 7a-d) because it did not incorporate the effects of vegetation. The unsuccessful determination of the hydro-mechanical parameters ($\alpha$ and $n$) for vegetated soil (Fig. 8b; Table 4) suggests that the relationship between plant, soil and water is more complex than the one between soil and water alone. This supports the idea of plant-soil composite materials (Thorne, 1990) behaving hydro-mechanically differently from soil alone (Scanlan, 2009; Gonzalez-Ollauri and Mickovski, 2017). The determination of $\alpha$ and $n$ could potentially have been obscured by either microscopic or macroscopic issues. On the one hand, the release of root mucilage could have altered the relationship between water content and matric potential in the root zone (Read and Gregory, 1997; Read et al., 2003). On the other, plant effects on the soil structural properties (e.g. Bronick and Lal, 2005; Scholl et al., 2014) may have
modified the hydrological behaviour of the soil (Liang et al., 2011). Further investigation should be carried out to confirm our observations and develop new, robust models that are able to predict $u_r-u_w$, as well as SWCC, under the effect of vegetation, instead of assigning new and different hydro-mechanical parameters to vegetated soils alone (Scanlan, 2009; Carminati et al., 2010; Leung et al., 2015). Moreover, an extension of the monitoring period, as indicated before, and inclusion of different plant species, would potentially clarify the feasibility of the suggested approach. Nonetheless, we believe that our model opens up an exciting possibility for the assessment of the plant-derived hydrological effect in a slope stability context, given the high relevance of $u_r-u_w$ to the soil stress-state (Vanapalli et al., 1996; Lu and Likos, 2004; Gonzalez-Ollauri and Mickovski, 2017).

5.3. Evaluation of willow hydrological effect on slope stability using the unified effective stress principle

Overall, the unified effective stress principle (UES) was shown to be adequate for capturing the hydrological effect of vegetation on slope stability (Fig. 9). Our results support the hypothesis that plant-water uptake is the main hydrological mechanism by which vegetation can improve slope stability (Figs. 9d and e; Stokes et al., 2014). Under drying conditions, the soil strength (i.e. $\sigma^s$; Fig. 9d) improved substantially with respect to the wetting (Figs. 9a-c) and hydrostatic (dashed dark grey line in Fig. 9d) conditions. However, this effect is expected to be markedly seasonal in temperate climates where the atmospheric water demand is expected to be negligible in winter (Wever et al., 2002). The differences between the two willow species upon drying (Figs. 9d and e) reflect the assumption made with regard to the effect of canopy features (i.e. $A_c$ and $LAI$; Table 1; Eqs. 1, 3 and 4; Table 2) on the soil
stress-state and slope stability. A wider canopy with broader leaves (i.e. higher LAI; Table 1) led to higher transpiration rates (Table 4; Allen et al., 1998), which increased the soil strength (Fig. 9d) and slope stability (Fig. 9e). Our results (Fig. 9d) reflect the differences in water flow rates upon drying (i.e. plant transpiration vs. soil evaporation; Table 4) as well as the hydro-mechanical differences between plant-soil composites and soil materials (Table 4). If alternative, and lower n values were not given to vegetated soil (Table 4), the hydrological effect of willow on the soil stress-state would have been negative in respect of the fallow soil upon drying (Fig. 9d) which would have been contradictory to the field observations (e.g. Simon and Collison, 2002). Thus, the hydro-mechanical change provoked by the presence of vegetation in the soil is expected to have considerable hydrological implications for slope stability (e.g. Gonzalez-Ollauri and Mickovski, 2017). The quantification of these emergent plant-soil composite properties is still a major knowledge gap that needs further investigation (e.g. Scanlan, 2009; Carminati et al., 2010).

Under wetting conditions (Figs. 9a-c), vegetation effect on slope stability was minimal (Fig. 9e-f). This outcome stresses the mechanical role of vegetation (i.e. soil-root reinforcement; Stokes et al., 2008; Gonzalez-Ollauri and Mickovski, 2016) under critical hydrological conditions of slope stability. The FoS profiles (Fig. 9e) would not have presented failure zones (i.e. FoS < 1) under wetting conditions if the apparent root cohesion had been included in the analysis (Wu et al., 1979; Mickovski et al., 2009; Gonzalez-Ollauri and Mickovski, 2014). Yet, the effect of plant aerial features on the belowground hydrological dynamics became evident with the implementation of UES. The investigation of shortcomings discussed for Salix caprea in Section 5.1 led to the prediction of a negative hydrological effect on the soil-stress state (Figs. 9a-b) with respect to the fallow soil (Fig. 9c). However, Salix viminalis
showed a positive ability to intercept rainfall (Table 3; Fig. 5a). This resulted in a shallower wetting front (Figs. 9a and b) with respect to the fallow soil (Fig. 9c). The latter was particularly noticeable during the growing season and under the heavy rainfall scenario (Fig. 9b). As a result, the location of the potential slope failure plane was shown to be shallower under S. viminalis with respect to the fallow soil (Figs. 9e-f). This effect, albeit small, could make a difference in terms of slope stability and in terms of the soil volume wasted during landslide episodes (Gonzalez-Ollauri and Mickovski, 2016).

The bypass flow (Table 2) triggered by stemflow (Table 3; Figs. 5c-d; Liang et al., 2011) did not produce soil stress-state changes (Fig. 9a-b) with respect to the hydrostatic conditions (Fig. 9d). As a result, the stemflow had a negligible effect on slope stability (Fig. 9e). Nonetheless, we stress, once again, that stemflow deserves further attention (Levia and Germer, 2015) in studies focusing on slope stability with the use of vegetation. Such studies should focus on the plant traits favouring the formation of stemflow (Yuan et al., 2016) and on the clarification of the features of the infiltration process triggered by stemflow (Liang et al., 2011).

6. Conclusions

This study provides a novel and reproducible framework that sets the basis for effective evaluation of the hydrological effect of vegetation on slope stability and to shed more light on the hydrological mechanisms involved. In light of our observations and findings, it can be concluded that:
• When compared to fallow soil, willow had a noticeable hydrological effect on the soil. This was seen in differences in the recorded time series for $u_a-u_w$ and $\theta_v$, revealing the potential soil desaturation effect of vegetation and its subsequent positive effect on slope stability.

• Willow throughfall and stemflow mechanisms were observed and they followed a linear relationship with the gross rainfall that changed seasonally. However, they were highly influenced by canopy heterogeneity and their effect on slope stability was minimal.

• Plant-derived matric suction under drying conditions was successfully predicted with the proposed approach within the onsite observed $u_a-u_w$ range. This novel approach for assessment of the hydrological effect of vegetation on slope stability can be improved and further validated with longer time series and different plant species.

• The unified effective stress principle and framework (UES) was shown to be adequate for evaluating the hydrological effect of vegetation on slope stability. This approach, however, requires knowledge of the soil hydro-mechanical properties, which showed differences between plant-soil composite and fallow soil materials that need further investigation.

In this paper, we have pointed out the aspects that deserve further consideration upon using UES for the evaluation of the hydrological effect of vegetation on rainfall-induced landslides. We encourage testing the framework presented herein under different environmental settings (i.e. climate, vegetation, soil hysteretical conditions, seasons, etc.).
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FIGURE 1

Catterline Bay

North Sea

Shallow landslides

willow-vegetated transect

fallow transect

Scotland
FIGURE 2

a) throughfall

Water containers
Stemflow gutter
stemflow
Rain gauge

b) ETP
Field tensiometer
Matric suction
Plant-water uptake

wetting
drying
FIGURE 5

(a) INTERCEPTION S. viminalis

(b) INTERCEPTION S. caprea

(c) STEMFLOW S. viminalis

(d) STEMFLOW S. caprea

Throughfall (mm) vs. Gross rainfall (mm) for different seasons and growth phases.
FIGURE 6

Moisture lower toe
(a)

Moisture upper toe
(b)

Moisture lower crest
(c)

Moisture upper crest
(d)

Rainfall (mm d⁻¹)

Moisture (%)
FIGURE 7

Matric suction lower toe (a)
Matric suction upper toe (b)
Matric suction lower crest (c)
Matric suction upper crest (d)

Legend:
- Red: Fallow
- Green: Willows
- Blue: Precipitation
- Dashed: Model 1
- Dash-dotted: Model 2

Day
Rainfall (mm day^{-1})
Rainfall (mm day^{-1})
Matric suction (kPa)
Matric suction (kPa)
Matric suction (kPa)
Matric suction (kPa)

Jul 07 Jul 21 Aug 04 Aug 18
Jul 07 Jul 21 Aug 04 Aug 18
Jul 07 Jul 21 Aug 04 Aug 18
Jul 07 Jul 21 Aug 04 Aug 18
FIGURE 8

(a) SWCC fallow

(b) SWCC vegetated

Matric suction (kPa)

Moisture (%)