Modeling Ground Water Recharge Under Vetiver Hedgerows

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Abstract:

While vetiver hedgerows have demonstrated a marked capacity for recharge of ground water, the explanation is not satisfactory. Current viewpoint is that the shoot part of the vetiver hedgerow slows down the surface flow, filters out the sediments, and diverts the flow sideways. These effects may explain part of the increased water recharge. A complete explanation of the recharge has to consider and model the subsurface architecture of vetiver, its deep dense vertical root system.

In the vadose zone, hydraulic conductivity is highly dependent on the water content which in turn is dependent on the source of water like rainfall. The conventional matrix flow model, based on capillarity, is unable to explain fast recharge of ground water. Preferential flow based on films of water on macro-pores (Nimmo, J.R., 2010, Theory for Source-Responsive and Free-Surface Film Modeling of Unsaturated Flow: Vadose Zone Journal, v. 9, no. 2, p. 295-306) has been put forth to explain the fast recharge. The film model states that substantial water input at the surface, like rainfall or irrigation, moves down at a rapid and constant speed as films on the vertical surfaces of macro pores. At a particular three dimensional parcel of soil, the area available for film flow, the Facial Area Density, is the vertical surface of all macro-pores in the parcel.

While vetiver roots may age and disintegrate to form vertical macro-pores, it is the surface of the roots themselves that provides a high Facial Area Density for regions under a vetiver hedgerow. The Facial Area Density can be related to the Root Length Density. For vetiver this surface is vertical and long. Hence the phenomenal capacity of vetiver hedgerows to increase ground water recharge can be attributed to the high vertical surface area provided by the vetiver roots for film flow. The shoot parts of the plant, start the film flow from the surface water and the myriad long vertical roots of vetiver, connected to the shoot, seamlessly transfer the water as surface film at a fast rate to the deeper regions. The film flow over the vetiver roots will be modeled qualitatively and computationally. We give a satisfactory model for the most important characteristic of vetiver- its phenomenal ability for ground water recharge.

Keywords: Ground water recharge, preferential flow, film flow on root, Facial Area Density

1 INTRODUCTION

Vetiver hedgerows have demonstrated a remarkable capacity to increase infiltration and recharge ground water. The effectiveness of vetiver for increasing ground water and soil moisture is quantified by Deesaeng et al. 2006. However, the study does not go into the mechanisms of this quantitative improvement. Current viewpoint is that the shoot part of the vetiver hedgerow slows down the surface flow, filters out the sediments, and diverts the flow sideways. These effects may explain part of the increased water recharge. A complete explanation of the recharge has to consider and model the subsurface architecture of vetiver, its deep dense vertical root system. Smeal and Truong 2006, had started an ambitious program in this direction.

Several studies (Metcalfe et al. 2003, Hussein et al. 2007) have focused on the backwater properties. But we have not come across any analysis that combines the effects of the vetiver hedgerow, the backwater, the vetiver root zone and the infiltration. Without such an analysis, it is difficult to quantify the effectiveness of vetiver to increase ground water recharge.

In this study we have modelled the vetiver hedgerow, the backwater, the preferential flow as film on the roots and diffusion in the soil mathematically. Parameters of the component models have been taken from reported studies as far as possible. The interplay and interaction between these components have been captured by a computational model. The computational model gives results that agree reasonably well with experimental data on backwater dynamics and ground water recharge.

The main finding of our study is that the preferential flow as laminar film on the dense vertical roots of vetiver is the most important contribution of vetiver for ground water recharge, directly through increased fast infiltration and indirectly through absorbing the backwater when the rain has stopped.

2 MATERIALS AND METHODS

2.1 MATERIALS

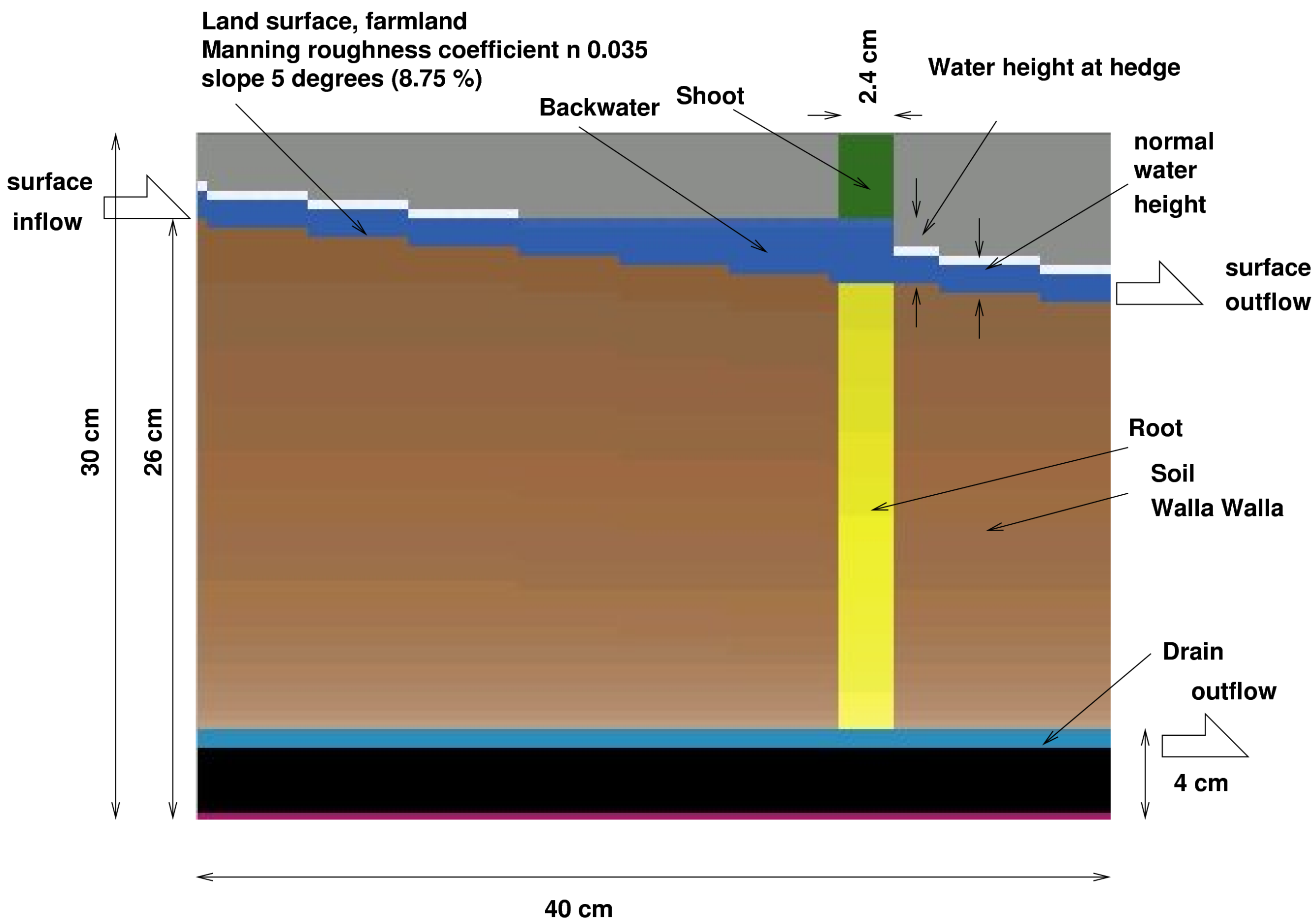
Soil (Silt loam Walla Walla) parameters. *(Head units cm of water)*			
Parameter description	value	units	source
Saturated moisture content θ_s	0.39		Rossi, Nimmo 1994
Residual moisture content θ_r	0.07		Rossi, Nimmo 1994
θ_r Used in simulation	0.04		
Owen dry suction Ψ_d	1.0×10^{7}	cm	Rossi, Nimmo 1994
Ψ_i fitted for 3-Parameter Sum model	104.6	cm	Table 2 („)
Ψ_o fitted for 3-Parameter Sum model	35.6	cm	Table 2 („)
λ fitted for 3-Parameter Sum model	0.61		Table 2 („)
α computed for 3-Parameter Sum model	0.04		
c computed for 3-Parameter Sum model	2.8005×10^{-3}		
K_s Saturated hydraulic conductivity	345.6	$mm\,d^{-1}$	Chen, Payne 2001

Vetiver Hedge, Shoot and Root parameters			
Parameter description	value	units	source
Vetiver hill (clump) diameter	12	cm	Inthapan, Boonchee 2000
No of tillers per hill	10 - 35	cm	„
Hill height	89 - 106	cm	„
Spacing of hills in a row	10 ~ 20	cm	„
Spacing between rows	30	cm	„

Root Length density (RLD)	<1	cm^{-2}	Tscherning et al. 1995
Root Length density L_v for grasses	2×10^5	m^{-2}	Gregory 2006
L_v Used in simulation	6×10^5	m^{-2}	
Average root radius R	330	μm	Hengchaovanich, D, 2003
Film thickness h_c	100	μm	
Average velocity across the film $V_{c\,avg}$	1.5×10^{-4}	$m s^{-1}$	
Vetiver shoots N_{vs}	0-100	m^{-1}	
Vetiver shoot radius r_v	1.2	mm	
Hedge width w_h	2.4	cm	

Simulation (NetLogo) Parameters		
Parameter description	value	units
No of patches in x direction	100	
No of patches in y direction	75	
Patch (square) dimension Δz	0.4	cm
Tick time Δt	4	s

Simulated Field



Soil Conductivity and Diffusivity from simulation model

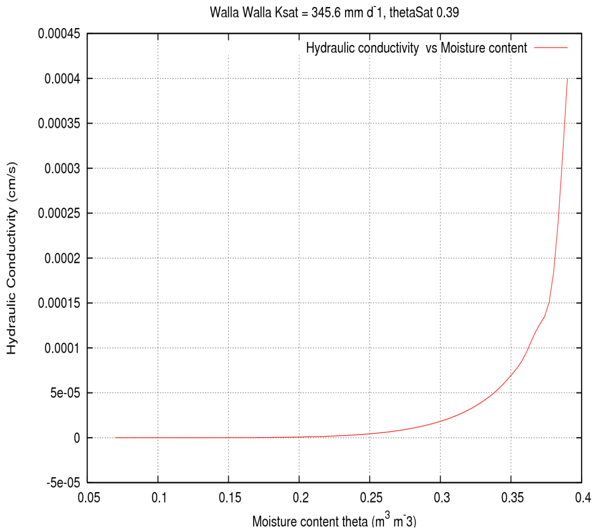


Fig. 2: From simulation model based on Chen and Payne 2001

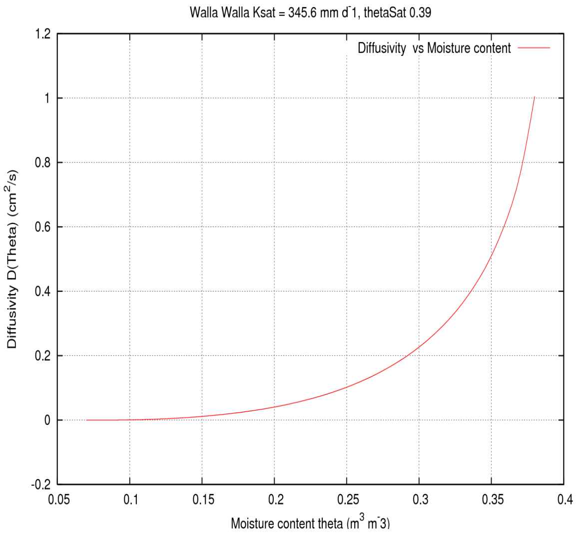


Fig. 3: From simulation model based on Rossi and Nimmo 1994

2.2 METHODS

2.2.1 Steady Flow

The flows can be studied by a two dimensional model. The flows are generally (Nimmo 2005) transient but then the analysis and theory become complicated. Steady flow simplifies the issues and provides valuable insights into the surface, diffuse and preferential flow. For steady flow, the source and sinks of the flow have to be carefully specified. For surface flow, it is assumed that a hinterland with area that can be varied provides the inflow from rain that falls on the hinterland. The sink for infiltrated water is provided by a horizontal drain 4 cm from the bottom (fig. 1). The steady flow state is obtained after an initial period when the moisture stores and fluxes are built up. Once the fluxes and contents have stabilized, the variables are measured to understand and characterize the model.

2.2.2 Surface Flow

Hydraulic Radius reduction by vetiver hedgerow

The Manning equation for open channel gravity flow (Engineering Toolbox 2011) is used to model the surface flow. The Manning formula (Veissman et. Al 2003, Engineering Toolbox 2011) states:

$$v = \frac{k}{n} R_h^{2/3} . S^{1/2} \qquad R_h = \frac{A}{P} \qquad R_h \cong h_m \text{ for wide channels}$$

where:

v cross-sectional average velocity (m/s) $\quad$ P wetted perimeter (m).

k	conversion constant equal to 1.0	A	cross sectional area of flow (m^2)
n	Manning roughness coefficient ($s/m^{1/3}$)	R_h	hydraulic radius (m)
S	slope of the surface (m/m)	h_m	Height of water (m)

The Manning equation has been used by (Metcalfe et al 2003) to study the hydraulic characteristics of vetiver hedgerows in deep flows. Deep flows can occur on channel banks. Vetiver hedgerows planted across fields for soil and moisture conservation encounter sheet flow (Veissman et al. 2003) most often and not deep flows. Dalton et al 1996, attribute the effect of the vetiver hedgerow into Manning roughness coefficient n and fit an empirical equation to the experimental data. In this work, the vetiver hedgerow is modeled within the Manning formula into the hydraulic radius R_h instead of the roughness coefficient n . The hydraulic radius is a characterization of an open channel flow as if it was a circular pipe with a known actual radius. The physical meaning is that stationary surfaces cannot have water velocities on them to be other than zero. Viscosity then limits the velocity water can have as its distance from the surface increases. In our model, each vetiver tiller shoot offers two contact lines of zero velocity to the shallow flow. In addition, the width of the shoot reduces the area available to the flow but also reduces the contact length along the bottom of the channel.

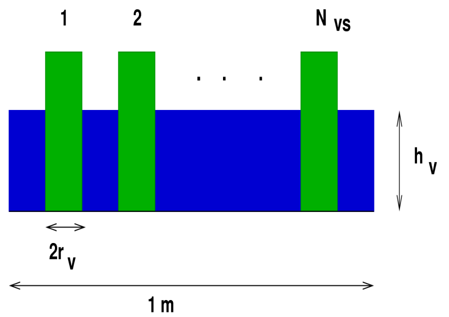


Fig. 4: Vetiver hedgerow in shallow flow

For vetiver hedgerow (shown in Fig. 4)

$$R_{hv} = \frac{h_v(1-2N_{vs}r_v)}{1+2N_{vs}(h_v-r_v)} \tag{1}$$

$$R_{hv} \cong \frac{1-2N_{vs}r_v}{2N_{vs}}$$

(when $h_v \gg r_v$, $2N_{vs}h_v \gg 1$)

R_{hv}	Hydraulic radius for vetiver hedgerow [m]	r_v	radius of vetiver shoot [m]
h_v	Height h of water along vetiver shoot [m]	A	$h_v(1-2N_{vs}r_v)$
N_{vs}	Number of vetiver shoots per m [m^{-1}]	P	$1+2N_{vs}(h_v-r_v)$

For wide open channels with no vetiver, the hydraulic radius R_{hv} reduces to h_v as is seen by setting N_{vs} to 0. Interestingly, R_{hv} is independent of h_v in the approximation. The input flow q ($m^3 s^{-1}$) is known and equated to Av . The height of water for wide channels can be easily computed. For the vetiver hedgerow, the height h_v can be computed using a numerical method.

The vetiver shoot takes away some contact length from the bottom invariably and provides two vertical contact lines. The wetted perimeter will increase unless the flow is so low that the height is less than the radius of the shoot. Unless the radius is zero, the cross sectional area for flow will decrease with vetiver. So it is to be expected that the hydraulic radius will decrease with a vetiver hedgerow across the flow path. Consequently the average velocity would decrease and hence the height of water level at the hedgerow will increase.

Backwaters

If the water level at the vetiver hedge is increased, the level behind it should also increase. The model illustrated in (Dalton et al 1996, Fig 5) shows a hydraulic jump between two hedgerows. They also indicate that the height difference before and after the hedgerow can be modeled as a submerged orifice. While the submerged orifice can account for the increased height behind it, the velocity through the orifice has to be greater than the normal velocity to maintain the flow rate.

Consider a micro dam wall in the path of the steady flow. At distances far behind the dam wall or after the wall, the water height would be given by the Manning equation with normal R_h . Immediately behind the dam, we can assume a triangular (in the two dimensional picture) volume of dead water with a flat horizontal surface line extending from the top of the dam wall to the sloped surface. As a first approximation, the water flow can be assumed to be flat with the same height over this dead water.

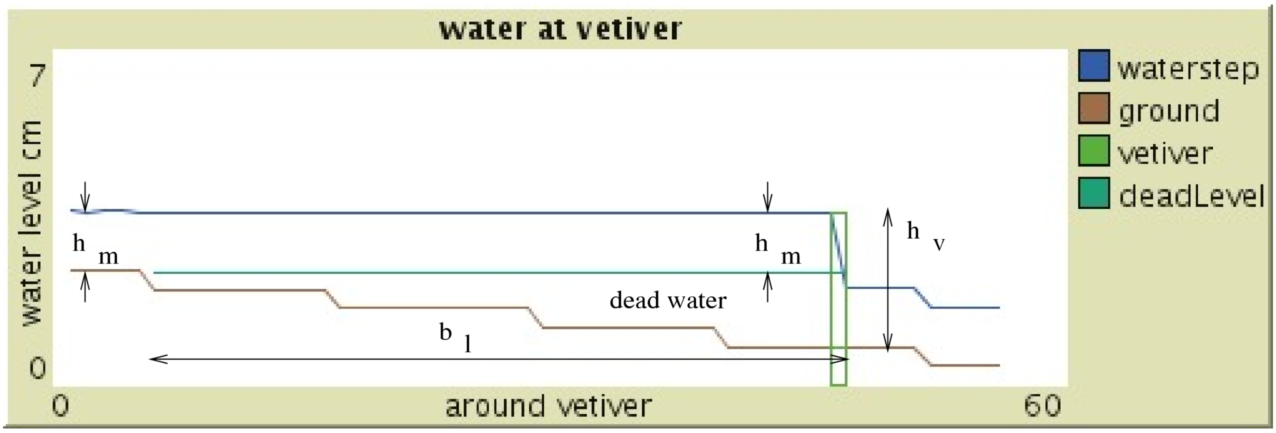


Fig. 5: Backwater formation behind a vetiver hedgerow

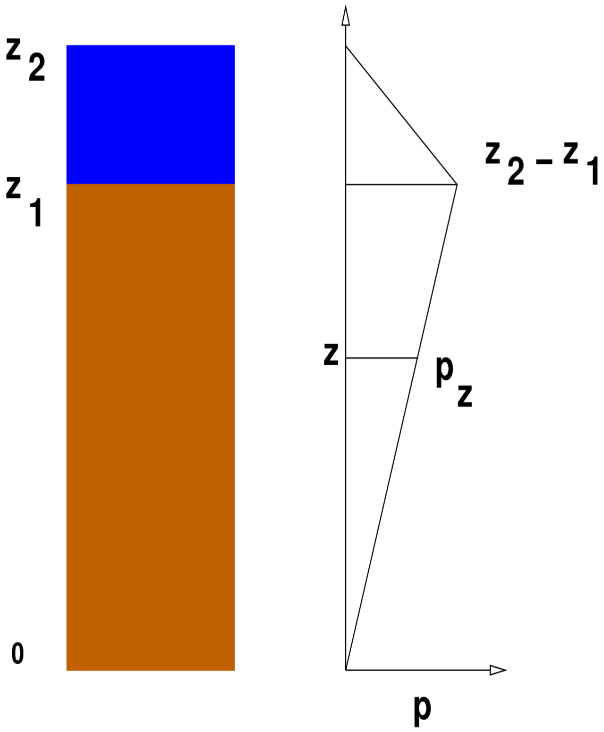
In our model for the vetiver hedgerow (shown in Fig. 4) h_v is the increased height at the vetiver hedge and h_m the heights far behind the hedge. The height of the dead water is then $h_v - h_m$. The backwater length is then given by

$$b_l = (h_v - h_m) / S \qquad (2)$$

The model can also be viewed as if the actual height of water increases from h_m at the start of the backwater to h_v at the vetiver hedge. The other model, where the flow is at height of h_m everywhere over a triangle of immobile backwater is better suited for a dam wall obstruction.

2.2.3 Diffusive Flow

In the vadose zone, hydraulic conductivity is highly dependent on the water content which in turn is dependent on the source of water like rainfall. The conventional matrix flow model, based on capillarity, can model the flow in regions other than that below the vetiver hedgerow. The vetiver hedgerow may increase the water content both on the surface and under the hedgerow, but the water content and fluxes at other regions are governed by the matrix diffusion equations.



$$\phi = p_z + z + \psi$$

$$p_z = (z_2 - z_1) z / z_1 \qquad D_\theta = K_\theta \frac{d\psi}{d\theta}$$

$$q_D = -K_\theta \frac{d\phi}{dz} =$$

$$-K_\theta \left[\frac{z_2 - z_1}{z_1} + 1 + \frac{d\psi}{dz} \right] = -K_\theta \frac{z_2}{z_1} - D_\theta \frac{d\theta}{dz}$$

Fig. 6: Vertical diffusion. Pressure from water over soil.

In head units

p_z	pressure from surface water at z	m	z	potential due to gravity at z	m
ψ	matric potential	m	ϕ	total potential	m
q_D	diffuse flow flux density	m/s	θ	volumetric moisture content	m^3/m^3
K_θ	Hydraulic conductivity	m/s	D_θ	Hydraulic diffusivity	m^2/s
z_2	Water surface level	m	z_1	Land surface level	m

How to attain steady diffuse flow

First we rewrite the diffuse flow flux density with q_D and the z axis downwards. A term for the rate of change of moisture in the volume element is added too.

$$q_D = K_\theta \frac{z_2}{z_1} - D_\theta \frac{d\theta}{dz} \quad + \Delta v \frac{d\theta}{dt}$$

$$q_{i,n,t+\Delta t} = q_{o,n-1,t}$$

$$q_{i,n,t+\Delta t} = K_{\theta,n,t} \frac{z_2}{z_1} \quad - D_{\theta,n,t} \frac{\theta_{n+1,t} - \theta_{n,t+\Delta t}}{\Delta z} \quad + \Delta z \frac{\theta_{n,t+\Delta t} - \theta_{n,t}}{\Delta t} \qquad (3)$$

$q_{i,n,t}$ input at element n time t m/s . $q_{o,n,t}$ output at element n time t m/s .

At time $t + \Delta t$, all parameters (θ, q_i, q_o) at time t are known at all elements. Then q_i at each element at the new instant is set from the q_o of the element atop it at the previous instant. Then, using equation 3, $\theta_{n,t+\Delta t}$ can be computed. Once θ is known K_θ is calculated using the Method 2 of Chen and Payne 2001. D_θ is calculated employing equations from Rossi and Nimmo 1994. Finally, q_o of the element can be computed.

2.2.4 Preferential flow

The vadose zone below the vetiver hedgerow, cannot be adequately modeled as a matrix for diffusive flow. The porosity of this region will decrease as the roots fill up the space and according to the diffusive matrix model, the diffusion can only decrease. Even if we say that vetiver roots will lead to anisotropic hydraulic conductivities with vertical conductivity larger than horizontal conductivity, the vertical conductivity would still be less than the one without the roots.

(Deesaeng et al 2006 Table 1, maize) show that vetiver hedgerows reduce the runoff from 12.9% to 5.7% and correspondingly increase the water recharge from 30.8 % to 37 %. Since the groundwater increase matches the reduction in runoff and runoff is a fast process, a comparable fast process is needed to explain the ground water recharge.

Preferential flow based on films of water on macro-pores (Nimmo, J.R., 2010) has been put forth to explain fast subsurface flow processes. The film model states that substantial water input at the surface, like rainfall or irrigation, moves down at a rapid and constant speed as films on continuous vertical surfaces. This model could explain many observations on fast recharge of ground water by heavy rains that could not be accounted for by matrix diffusive flow.

The vertical surfaces are the flat surfaces of parallel plane fractures, inner surfaces of macropores made by earthworm holes or decayed roots, and outer surface of roots. The laminar film flow theory (Nimmo, J.R., 2010) for flat surfaces is first presented.

The velocity at the outer surface of the film and the film thickness, using momentum balance are related by:

$$V_{f\,max}=\frac{1}{2}\frac{g}{\nu}h_f^2 \qquad V_{f\,avg}=\frac{2}{3}V_{f\,max} \tag{4}$$

The source responsive flux density q_{fs} and water content θ_{fs} are related to the Facial Area density M , velocity and thickness.

$$q_{fs} = M V_{f\,avg} h_f = \frac{1}{3}\frac{g}{\nu}h_f^3 M \qquad \theta_{fs}=M h_f$$

Experimentally it is observed (Nimmo, J R, 2010) that both the maximum velocity and the maximum thickness vary within a small range. The empirically determined nominal maximum transport speed for continuous supply conditions (Nimmo, J R, 2010) is $1.5\times10^{-4} m s^{-1}$ and so the average maximum velocity for flat films is $1.0\times10^{-4} m s^{-1}$. From equation (4), the maximum thickness is calculated as $5.53\,\mu m$. Assuming that all laminar film flows on flat surfaces have these velocities and thickness uniformly, the maximum flux can be written. The maximum preferential flux modulated with an active area fraction gives the actual flux density.

$$q_{fs\,max}=M V_u h_{fu} \qquad q_{fs}=f\, M V_u h_{fu}$$

where:

g	acceleration due to gravity $9.81\, m s^{-2}$	ν	kinematic viscosity (water) $1.0\times10^{-6} m^2 s^{-1}$
$V_{f\,max}$	Maximum velocity (at surface) $m s^{-1}$	h_f	thickness of the film m
$V_{f\,avg}$	Average velocity over the film $m s^{-1}$	M	Facial area density (FAD) $(m^2)/(m^3)$

q_{fs}	Flat film flux density $m^3 s^{-1}/m^2$		θ_{fs}	Flat film moisture $(m^3)/(m^3)$	
V_u	Average uniform velocity $1.0\times10^{-4} m s^{-1}$		$V_u h_u$	property of earth and water $5.531\times10^{-10} m^2 s^{-1}$	
h_{fu}	uniform film thickness 5.531 μm		f	active area fraction	
$M h_{fu}$	Cross sectional area density of laminar films on flat vertical surface $m^{-1} m$		h_{fu}	Cross sectional area density per unit FAD for flat surface m	

It is useful to identify $M h_{fu}$ [$m^{-1} m$] as the cross sectional area density of the films on flat surfaces.

Surface Film Flow on root

The velocity and thickness of laminar film over a vertical cylinder are given in (Bird et al 2002, Ruyer-Quil et al 2008) as

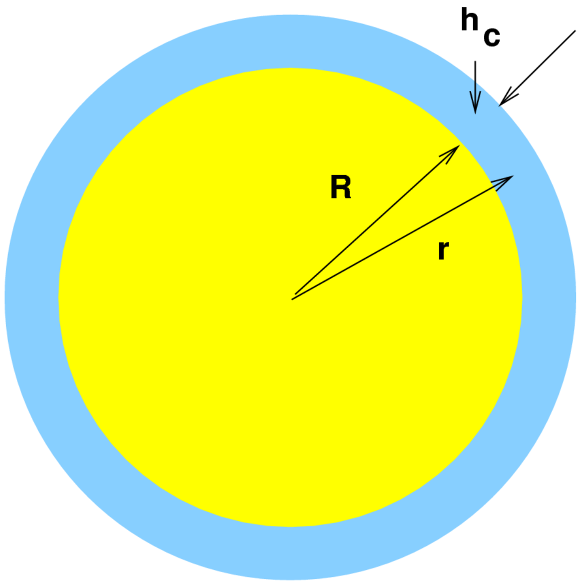


Fig. 7: Thin film on a root

$$v_{cr}=\frac{g}{\nu}\left[\frac{1}{2}(R+h_c)^2\ln\frac{r}{R}-\frac{1}{4}(r^2-R^2)\right]$$

$$v_{c\,max}=\frac{g}{\nu}\left[\frac{1}{2}(R+h_c)^2\ln\frac{R+h_c}{R}-\frac{1}{4}(2Rh_c+h_c^2)\right] \quad (5)$$

When the film is thin ($h\ll R$), (Bird et al 2002) have given it as an exercise to prove that:

$$v_{c\,avg}=\frac{2}{3}v_{c\,max} \quad (6)$$

where (see Fig: 7)

R	Radius of root m	h_c	Radial thickness of film m
r	point within film ($R<r<R+h_c$) m	v_{cr}	Downward velocity at r m/s
$v_{c\,max}$	The maximum velocity at $R+h_c$	$v_{c\,avg}$	Average velocity across the film

Root Length Density

The Root Length density in a volume is the total length of roots in the volume divided by the volume. With anisotropic root systems, like that of vetiver, it is feasible to treat it as a vector. Then the Root Length Density in the vertical direction is the same as the number of roots per unit area in the horizontal plane.

$$L_{vz}=N_{vr} \qquad q_{cs} = \pi((R+h_c)^2-R^2)N_{vr}v_{c\,avg} \quad (6b)$$

where:

L_{vz}	Vertical Root length density m^{-2}		N_{vr}	Number of roots per sq m m^{-2}
q_{cs}	preferential flux density on roots $m\,s^{-1}$			

Facial Area Density

The Facial Area Density is the total vertical area available for film flow divided by the volume in which it is calculated. It is same as the total contact length over a unit area. Vetiver sports vertical roots with very little spread (Lavania 2003) and so the normal RLD can be taken as the vertical root length density.

$$M = 2\pi R N_{vr} = 2\pi R L_{vz} \quad (7)$$

Simplified Film flow over roots

With the maximum average film velocity taken as $1.0\times10^{-4} m\,s^{-1}$, and vetiver root radius R taken as $0.33\,mm$ equation (5) can be numerically solved to get h_c as 5.516 μm. From this q_{cs} is computed (6b) as 59.8 $mm\,d^{-1}$ with N_{vr} = 60×10^4 m^{-2} and $v_{c\,avg}$ 1.0×10^{-4} $m\,s^{-1}$. This is much lower than the K_s for Walla Walla (345 $mm\,d^{-1}$). So we have assumed h_c to be 100 μm and $v_{c\,avg}$ to be 1.5×10^{-4} $m\,s^{-1}$. This film thickness matches the maximum reported in Nimmo 2010. The maximum and not average velocity is taken as the film achieves the maximum velocity in 5 μm and is expected to remain at that value for the rest 95 μm. With these assumptions q_{cs} gets respectable at 1857 $mm\,d^{-1}$ (5 times K_s for Walla Walla).

2.2.5 Fate of Backwater

The backwater length is calculated following the model that there is a triangular volume of dead water behind the hedgerow over which the water flows with the normal Manning velocity and height. It is difficult to quantify the effect of the backwater. We calculate how much time it will take for the rain input to fill the backwater and for the backed water to infiltrate into the ground through diffusive and preferential flows.

$$Q_b = Q_d + Q_s \qquad t_{bf} = Q_b / q_r$$

The t_{bi} is calculated by assuming a partition between the column over the vetiver hedgerow and the remaining triangular backwater. The flux density in the column is the sum of the diffusive and preferential mechanisms. In the triangular volume, diffusion alone is active. In time t_{bi} the column will infiltrate more than the water in its partition. The deficit is equated to the water remaining in the triangular partition after the same time. This leads to a quadratic equation in t_{bi} :

$$\frac{(H_d - q_d t_{bi})^2}{2S} = ((q_s + q_d) t_{bi} - H_s) w_h \;;\quad H_s = h_v - h_m \;;\quad H_d = H_s - w_h S \qquad (8)$$

Q_b	Water in backwater cm^2	Q_d	Part of Q_b that diffuses in cm^2
Q_s	Part of Q_b preferentially in cm^2	q_d	Diffusive flux density $cm\,s^{-1}$
H_s	Backwater height cm	H_d	Height of water in triangular area. cm
q_s	Preferential flow flux density $cm\,s^{-1}$	b_l	Backwater length cm
w_h	Width of hedgerow cm	t_{bi}	Time to fully infiltrate Q_b s

q_r	Surface inflow (rain)	$cm^2 s^{-1}$	t_{bf}	Time for inflow to fill Q_b	s

2.2.6 Agent Based Simulation

Agent Based modelling and simulation has found favour with hydrologists (Cook et al. 2008, Sapkota, P, 2010) as the simulation can bring out emergent, unexpected or hard to imagine, or mathematically intractable behaviour from simple mathematical models of the components. Netlogo (Wilensky 1999) is a preferred ABM tool for wide range of domains including biology, physics, sociology and economics. In this study, we have used the patches as finite elements representing a soil or surface volume. The other active element, the turtle, is used to model, water for example, that moves from patch to patch (Sapkota, P, 2010). However, we feel that the quantity of water that moves is not a constant and it is easier to manage the simulation with these variable quantities being passed from patch to neighbour patch. Thus we used a Finite element method with NetLogo.

3 RESULTS

The water balance mandates that the rain would be expended as infiltration into the ground, surface runoff and increase in storage on the surface. We ignore evapotranspiration, unlike Deesaeng et al, 2006, as its effect is seen only in the long term. A vetiver hedgerow affects the water balance in several ways. Firstly it will reduce the surface runoff velocity at the hedge, create a heightened backwater behind the hedge. The increased height contributes to higher infiltration. According to our model, the vetiver hedgerow increases infiltration through preferential flow as surface film on the roots.

The quantities that can be varied are N_{vs} the vetiver shoot density, L_v or N_{vr} the vetiver root length density, the rain by varying the hinterland and the rain fall density, and the slope of the surface S. The quantities to be monitored are infiltration both by diffusion and preferential flow. The diffuse and preferential flow flux densities are important quantities for the effectiveness of vetiver hedgerows. The backwater formed due to water level difference at a vetiver hedgerow is also to be characterized and interpreted. The surface runoff is not found to be a useful measure as it is invariably close to the surface runin. Alternately, the surface runin could be reduced so much that there is no runoff at all.

The gist of our findings is that the preferential flow flux density is about 5 times that of the diffuse flow flux density.

3.1 Surface flow

Height difference at hedgerow

Fig. 8 shows how the vetiver hedgerow increases the water height. Interestingly, the water level at the hedge is linear to the flow whereas the level far behind is not. It is seen that h_v and $h_m^{5/3}$ are linear to the flow rate q at high rates. Fig. 9 shows how the backwater length and volume vary.

We compare (table 1) the experimental data from Hussein et al. 2007 with interpolated data from simulation. While the water levels and backwater lengths are comparable, the inflows differ by an order of magnitude. Hussein et al. manage the same level at the hedgerow from a lower level far behind. This probably means that their vetiver hedgerow ($0.3 \times 0.3\, m^2$; 4300 stems m^{-2} ; stem radius 4.5 mm) is more dense than ours.

Backwater

In this model, unlike (Dalton et al 1996, Fig 5), there is no hydraulic jump behind a vetiver hedgerow. The picture as seen in Fig. 1 shows a flat surface behind a hedgerow very similar to (Hussein et al 2007 Fig 2). The length of the backwater and the volume impounded in the conceptual dead water zone are plotted in fig. 9. It is seen that the volume of water impounded behind the vetiver increases as q^2 at high flow regimes.

Source	Water height at		Backwater	Inflow
	hedgerow h_v cm	far behind h_m cm	length cm	$m^2 s^{-1}$
Hussein et al 2007	2.7	0.8	50	0.001
Reduced hydraulic radius model. Simulated.	2.45	1.22	49	0.025
	3.13	1.45	62.6	0.033
Interpolated	2.7	1.31	54	0.028

Table 1: Comparison of experimental data with simulated data for backwater height and length. Vetiver density 80 for simulated model

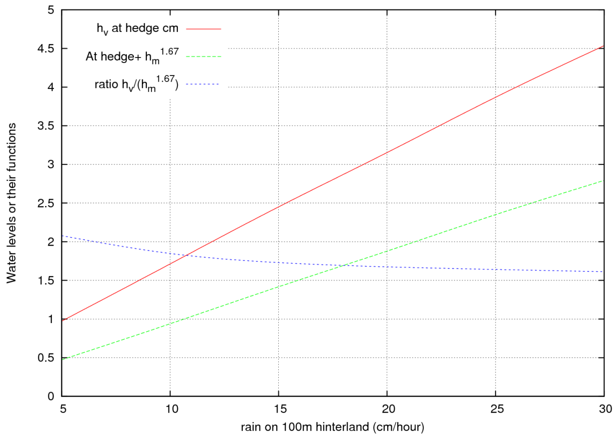


Fig. 8: Slope 5%; N_{vs} 80 m^{-1} ; L_v 60e04 m^{-2} simulation duration 10 mins; hinterland 100 m; rain varies

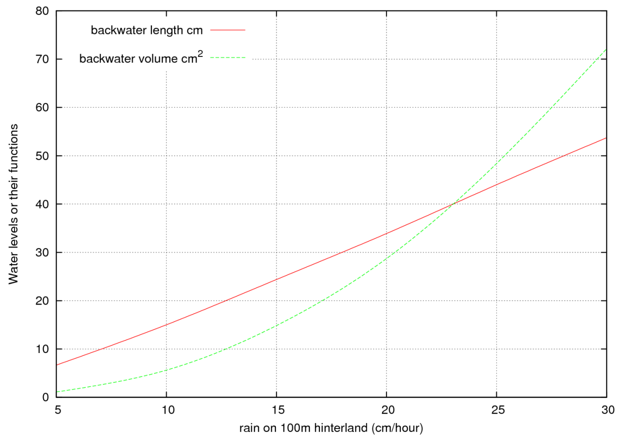


Fig. 9: Slope 5%; N_{vs} 80 m^{-1} L_v 60e04 m^{-2} ; simulation duration 10 mins; hinterland 100 m; rain varies.

3.2 Diffusive and Film Flow

Figs (10, 11) show the total water that diffused over the surface of the model and over the vetiver patch as preferential flow. The diffused volume in 10 minutes varies little around 10 cm^2 however the rain or the hedgerow denseness varies. The diffused volume increases from 9.98 cm^2 for rain at 5 cm/hour to 11.25 cm^2 for rain at 30 cm/hour (12% increase). The preferential flow volume is at 3.12 cm^2 with RLD at 60×10^4 m^{-2} . As expected of a source responsive flow, it does not vary with the rain in this range. The area available for diffusion is 40 cm whereas preferential flow manages only 2.4 cm. Thus the diffusive flux density q_d is $0.469 \times 10^{-3} cm\, s^{-1}$ and preferential flux density q_s is 2.16×10^{-3} . It is seen that the *preferential flux density is 4.6 times that of the diffusive flux density*. That is why the quantity diffused over a wide area of 40 cms is comparable to the quantity that infiltrated through a mere 2.4 cm wide vetiver patch. In fig. 12 The preferential flow flux density increases linearly with root length density. The proportional increase in hedgerow denseness, leads to increase in height of surface water and a corresponding slight increase in diffusive flux density.

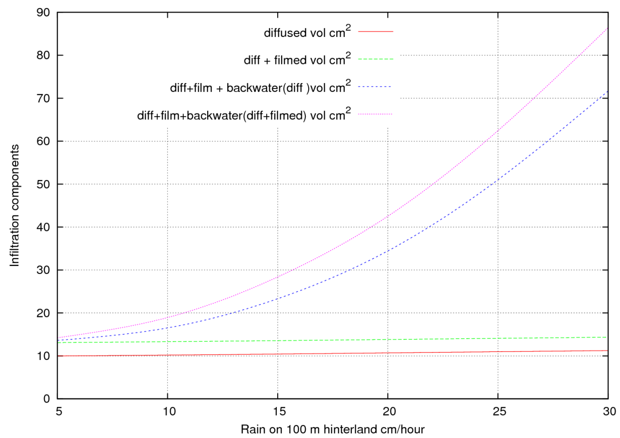


Fig 10: Slope 5%; N_{vs} *80* m^{-1} *;* L_v *60e04* m^{-2} *; simulation duration 10 mins; hinterland 100 m; rain varies*

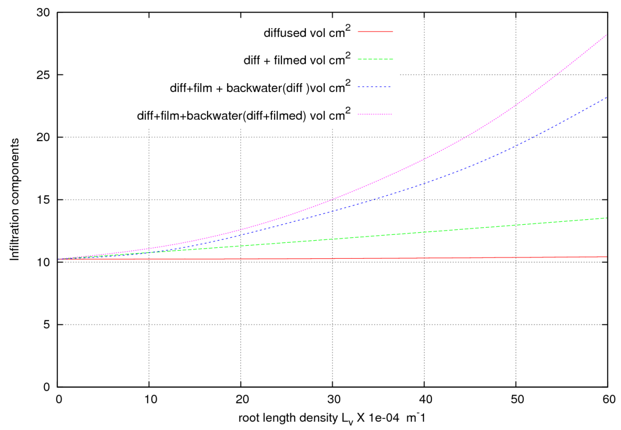


Fig. 11: Slope 5%; N_{vs} *(vetiver per m) and* L_v *(Root Length Density) vary; simulation duration 10 mins; hinterland 100 m; rain 15 cm/hour*

Hedge effects on subsurface flow

The diffusive flow increases slightly with the rain flow rate q_r , as the h_v and backwater push up the surface level. Lower the drain or the water table, less is the increase in diffusion due to surface water height. Even with the drain at absurdly shallow position, the effect of the surface water height is below 12%. The preferential flow is unaffected by the potential effects and is completely source dependent. Thus the increase in the water level at the hedgerow increases the diffusion slightly and the preferential flow not at all. What about the water impounded in the backwater? The backwater formed behind the hedgerow could be a source when the rain stops. The volume of backwater and the time to infiltrate it are shown in fig. 13. For rainfall at 30 cm/hour over 100 m hinterland, a backwater of length 54 cms and volume 72 cm^2 is formed. It takes 48 mins (t_{bi}) to empty this backwater. Diffusion takes 57.3 cm^2 and preferential flow takes the rest 14.7 cm^2 . The rain inflow takes hardly any time to fill (t_{bf}) the backwater. The backwater of volume 72 cm^2 is filled in 0.86 seconds.

Overall contribution of vetiver to ground water recharge

Assuming that the rain stops for the time to empty the backwater, fig. 11 shows what difference vetiver hedgerow and its root system make to ground water recharge at rain intensity of 15 cm/hour. Even without any vetiver, the diffusion through the soil conveys 10.23 c m^2 . With vetiver of root length density 60×10^4 m^{-2} and hedgerow denseness 80 m^{-1} , the diffusion increases to 10.43 cm^2 because of the surface level increase due to hedgerow. The preferential flow by the roots now conveys additional 3.12 cm^2 . From the backwater of 14.71 cm^2 , 9.68 cm^2 are conveyed by diffusion and 5.03 cm^2 by root film flow if there was no rain for 16.6 mins. Fig. 10 conveys the contribution of a vetiver hedgerow as the input rain varies.

4 DISCUSSION

Hedge and sedimentation

The model with reduced Manning hydraulic radius and backwater length computed by assuming a flat surface back to the normal flow surface behind can be used for the engineering design of hedges for erosion control on flood plains (Dalton et al 1996). In experiments reported by (Hussein et al 2007, Fig 2), the initial water level behind the vetiver hedgerow is horizontal behind the vetiver hedgerow till it meets the slopped water level behind. Over a time, sediments raise the ground surface, especially at the start of the backwater where momentum changes of the water aid the deposit of sediments. But the experiments concur with our model where the water surface behind the vetiver hedgerow is flat as the first approximation.

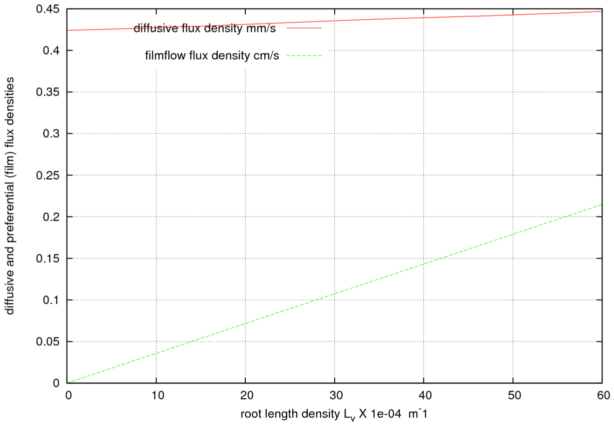


Fig. 12: Slope 5% Rain 15 cm/hour over 100 m hinterland. Root Length Density L_v *varies*

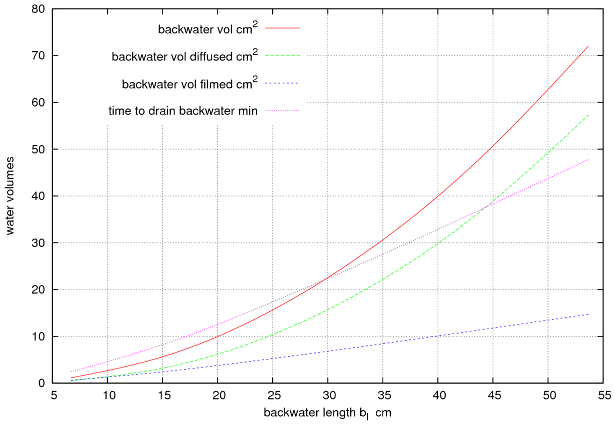


Fig. 13: Slope 5% vary rain over 100 m hinterland; rain duration 10 mins; hedgerow denseness 80 m^{-1} L_v *60e04* m^{-2}

Undrained film flow on roots

The drain below our model allows us to film flow the water without any backlash. Normally the film flow would quickly fill the root column with water. Unless it is removed from the root column, further film flow from the surface is stopped. Fortunately, the side walls on the two sides of the root column provide area for horizontal diffusion. In our model, we have not introduced horizontal diffusion. For vertical flows, we have seen that the preferential flow flux density q_s is around 5 times that of the vertical diffusive flux density q_d or a vetiver patch of X cms width will infiltrate as much water as can be diffused by soil surface of 5X cm. Similarly we expect that a vertical surface of 5-10 X cms can diffuse out as much water as can be filmed in by the patch of width X.

Film flow on roots

Sway of the vetiver shoots in wind or water can vary the gap between the shoot and the soil. This can be equated with a peristaltic pump action of the soil sleeve surrounding the shoot stem.

Role of Surface Tension in film flow

The film flow equations, we used, do not consider surface tension. Even though (Ruyer-Quil et al 2008) involve surface tension in the analysis, the equation (Ruyer-Quil et al 2008, eq. 4.2) from the first-order model does not require surface tension. It is also useful to wonder why the laminar film maximum velocity and thickness vary within a small range. We conjecture that it has something to do with surface tension. Consider the film on the outer surface of a root. The surface tension will try to squeeze the outer perimeter and thin the film. Intermittent feed from top, coupled with gravity, could lead to a peristaltic pump action on the film. When the film thickness is reduced by surface tension, the velocity at the perimeter reduces, less water flows down and so the momentum balance equations will work toward increasing the thickness. For laminar flow on the inner surface of a macro-pore, the surface tension would tend to increase the film thickness, leading to increased velocity, increased downflow and consequent thinning of the film. Thus the experimentally observed maximum film velocity and film thickness may be a consequence of the fine balance between surface tension, gravity and viscosity. (Nimmo, J R, 2010) fix the maximum film velocity from observed data and then derive the film thickness. Our model suggests that it is the other way. The film thickness is the result of the interplay between the various forces and the velocity is the resultant of the thickness. As velocity is easier to measure than film thickness, it can come first. It is not really important whether the chicken comes first or the egg as long as you can have the egg for the breakfast!

5 CONCLUSIONS

Preferential flow as laminar film on the surface of roots of vetiver can account for the capacity of vetiver hedgerows to increase ground water recharge. The backwater formed by the dense hedgerow allows diffusion and preferential flow to continue to recharge even after the rain has stopped. It is better that the backwater is emptied fast. Otherwise, further rain will disappear as runoff. It is the preferential flow that reduces the time to empty the backwater.

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Brief introduction to the author K Vinod Kumar

He is an Electrical Engineer working as software specialist at the Centre for Development of Advanced Computing, Mumbai, India. Dissatisfied with the current models on the phenomenal capacity of vetiver to recharge ground water, he seeks to explain it through film flow on the numerous, long, vertical roots of vetiver. His dream is to catalyse transgenic research for transfer of genes responsible for the root system traits and submergence tolerance of vetiver to rice.