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College on Soil Physics: Soil Physical Properties and Processes under Climate Change

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The Combined Effect of Wind and Rain on the Interrill Erosion Processes

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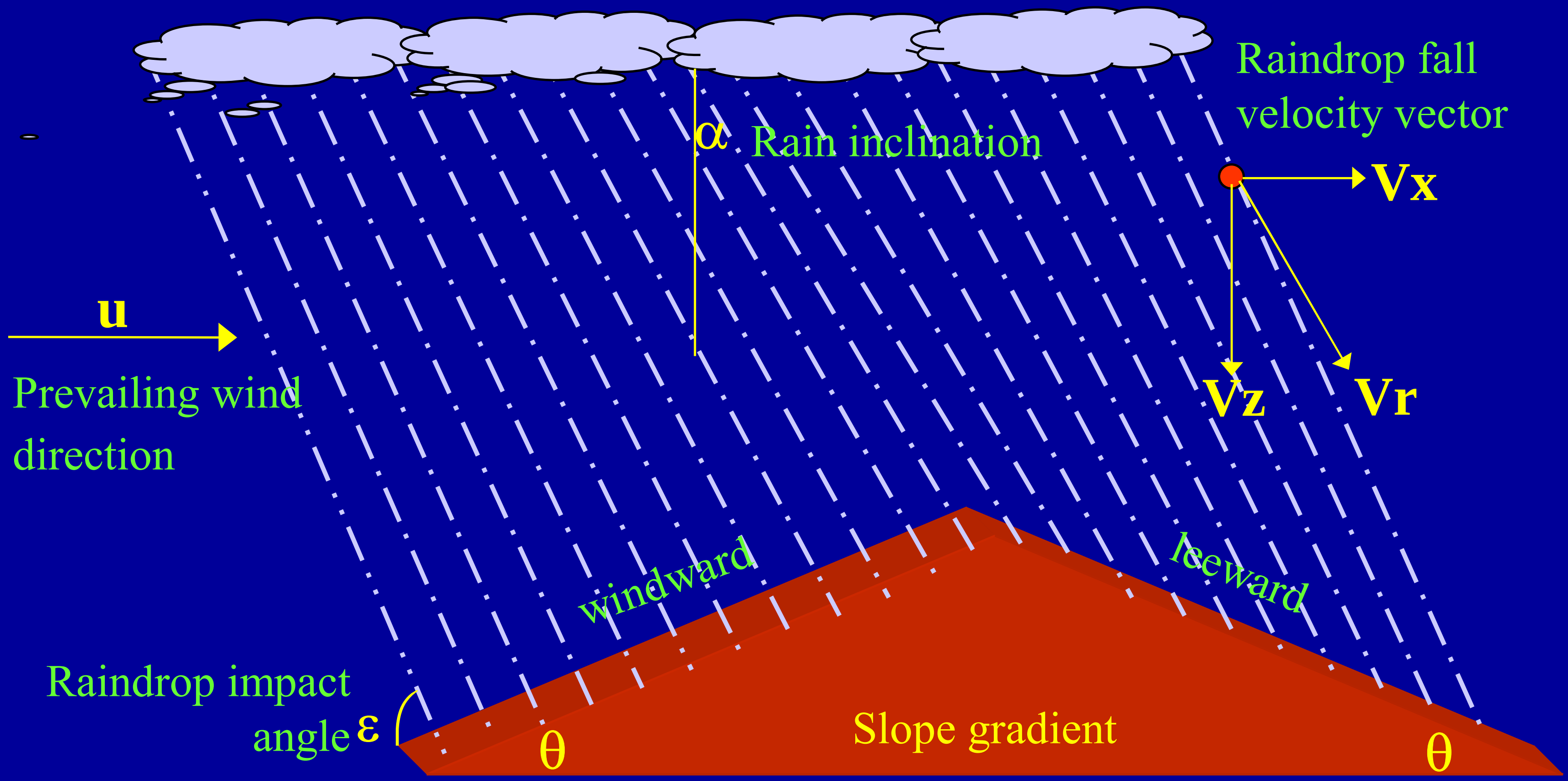
Coverage

- Description of wind-driven rain
- The effect of wind on raindrop impact and rainsplash detachment
  - Raindrop size distribution
  - Raindrop impact frequency
  - Raindrop impact angle
  - Raindrop impact velocity
  - Wind-driven rainsplash detachment
- Sediment transport from interrill areas under wind-driven rain
  - Wind-driven rainsplash transport
  - Sediment transport by raindrop-impacted shallow flow

Schematic presentation of wind-driven rain with an angle from vertical and incident on sloping surface



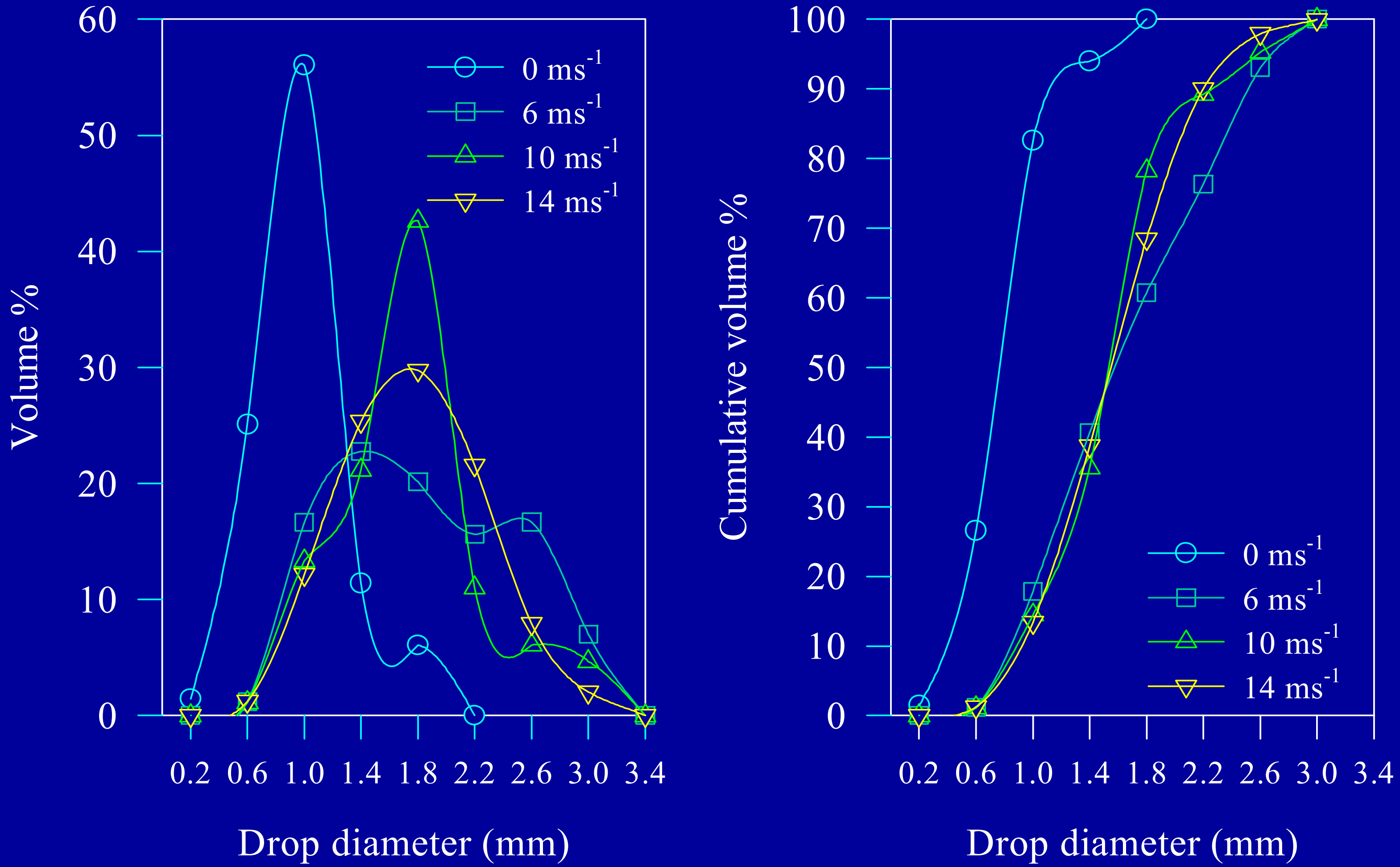
Wind-driven rain is described as raindrops falling through a wind field and moving at an oblique direction to the vertical under the effects of both gravitational and drag forces

Raindrop Size Distribution

- Knowledge of raindrop distribution in natural rain is required since the physical characteristics of impacting raindrops have an effect on the soil detachment process
- The size distribution can considerably vary with wind
  - For example
    - Collisions between small drops occur more frequently as a result of their greater number per unit volume in air leading to an increase in mean drop size
    - For large drops, however, this doesn't occur as large drops are less stable, and wind causes some of them to break up into smaller drops

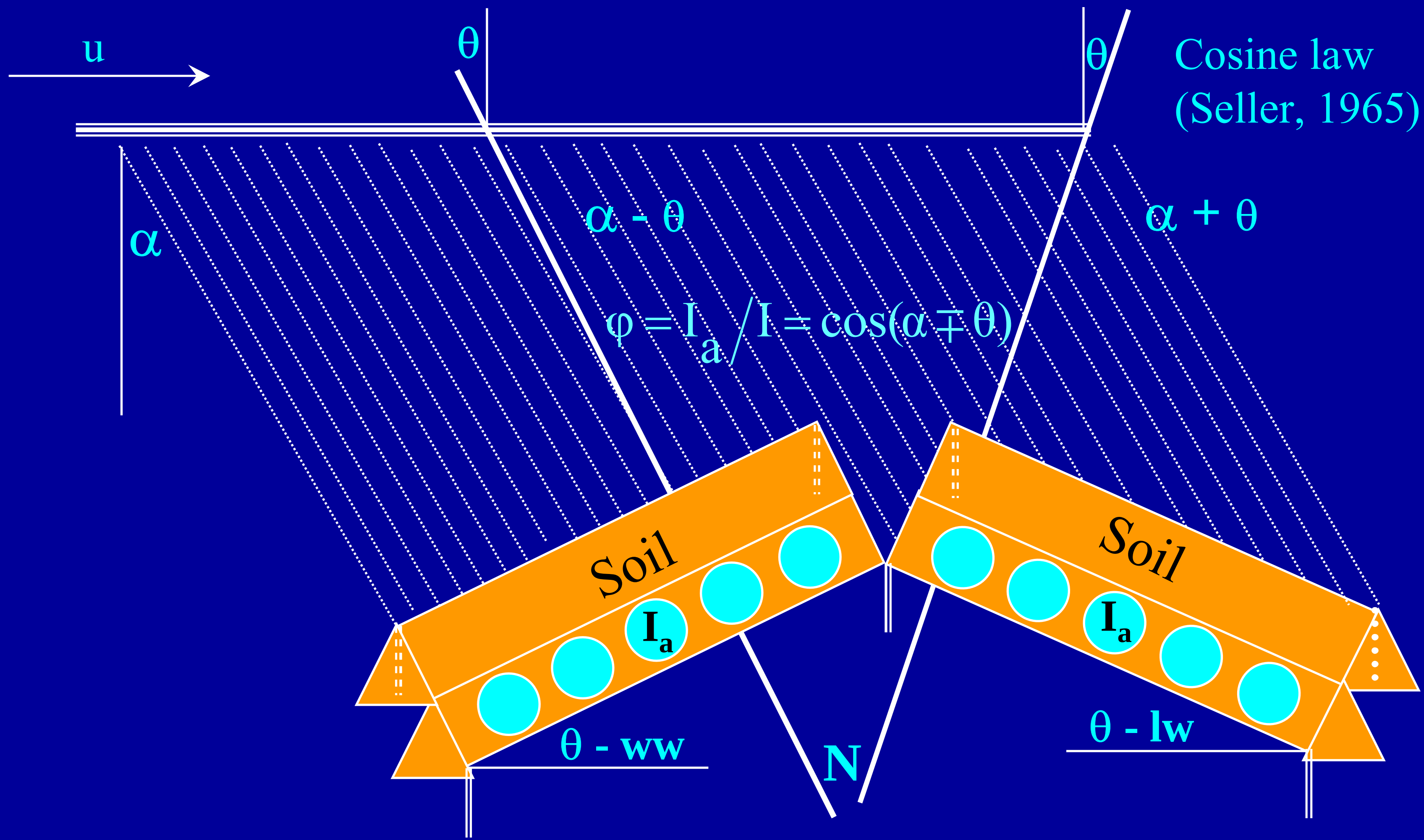
Raindrop Size Distribution

Drop size distributions and cumulative frequency of drop sizes for windless and the rains driven by 6, 10, 14 m s^{-1} (Erpul, Gabriels, Jansens, 1998)



The effect of wind on raindrop size distribution is a potentially important effect that needs to be considered when estimating the rainfall erosivity

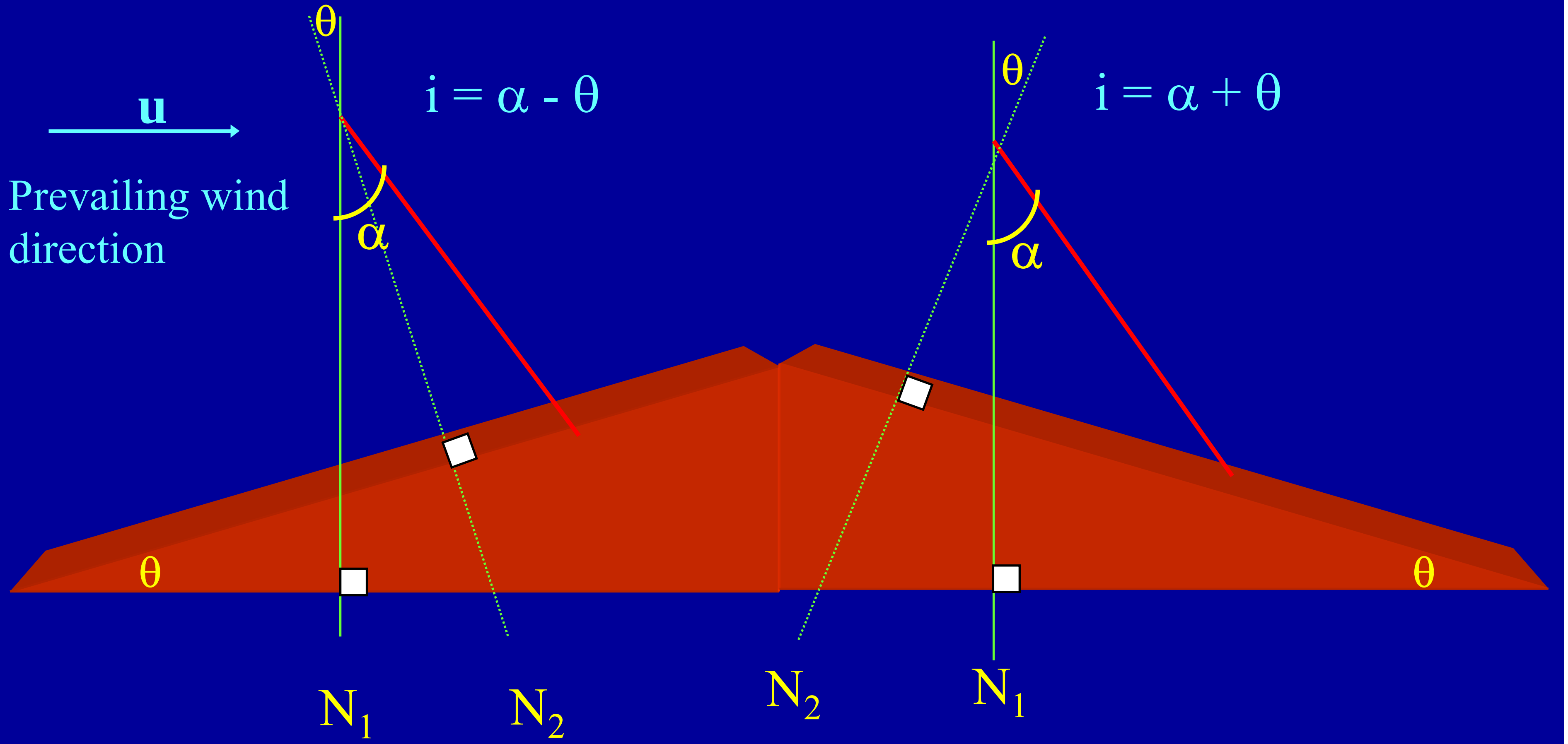
The angle of rain incidence measured from the normal to the plane of incidence determines the raindrop impact frequency



Cosine law (Seller, 1965)

– I_a: actual intensity intercepted by a sloping surface
– I: the maximum intensity in respect to a plane normal to the storm vector
– φ: the impact efficiency

Raindrop Impact Frequency



windward slopes

$$I_a = I \cos(\alpha - \theta) = I\,[\cos\alpha \cos\theta + \sin\alpha \sin\theta]$$

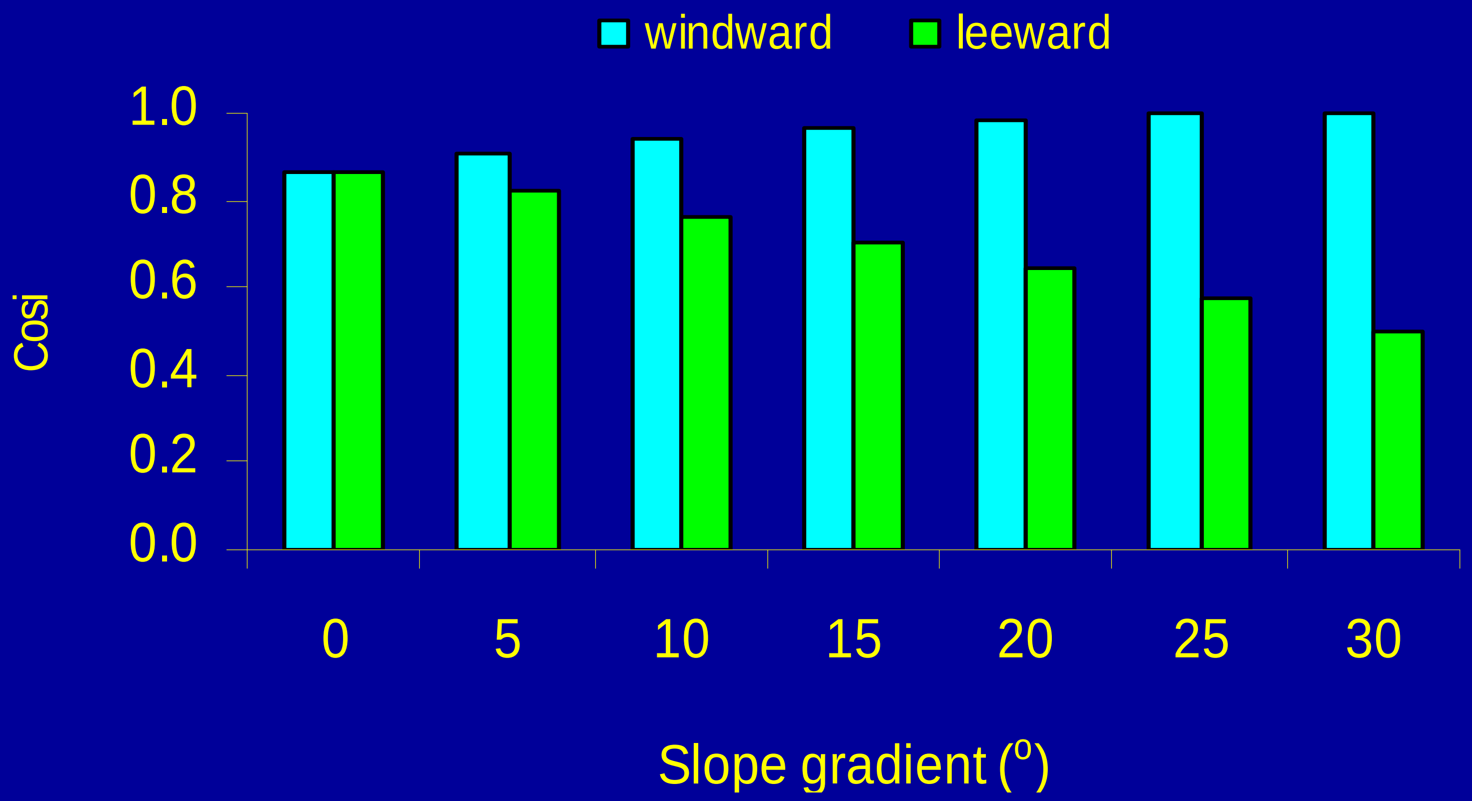
leeward slopes

$$I_a = I \cos(\alpha + \theta) = I\,[\cos\alpha \cos\theta - \sin\alpha \sin\theta]$$

Calculated cos(i) values for varying rain inclination and slope gradient [$I_a \propto \cos(i)$]

Rain inclination (°)	Slope gradient (°)						
	0	5	10	15	20	25	30
	windward						
0	1.00	1.00	0.98	0.97	0.94	0.91	0.87
10	0.98	1.00	1.00	1.00	0.98	0.97	0.94
20	0.94	0.97	0.98	1.00	1.00	1.00	0.98
30	**0.87**	**0.91**	**0.94**	**0.97**	**0.98**	**1.00**	**1.00**
40	0.77	0.82	0.87	0.91	0.94	0.97	0.98
50	0.64	0.71	0.77	0.82	0.87	0.91	0.94
60	0.50	0.57	0.64	0.71	0.77	0.82	0.87
	leeward						
0	1.00	1.00	0.98	0.97	0.94	0.91	0.87
10	0.98	0.97	0.94	0.91	0.87	0.82	0.77
20	0.94	0.91	0.87	0.82	0.77	0.71	0.64
30	**0.87**	**0.82**	**0.77**	**0.71**	**0.64**	**0.57**	**0.50**
40	0.77	0.71	0.64	0.57	0.50	0.42	0.34
50	0.64	0.57	0.50	0.42	0.34	0.26	0.17
60	0.50	0.42	0.34	0.26	0.17	0.09	0.00

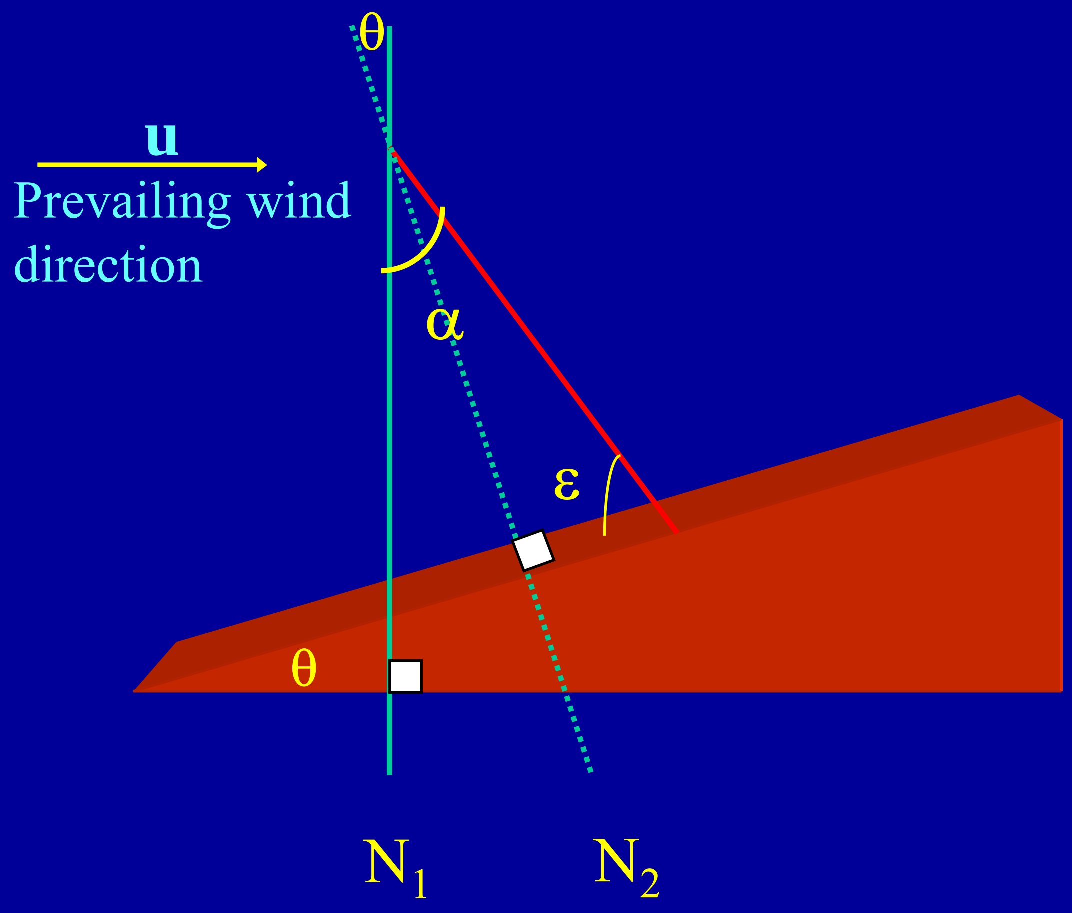
Difference in angle of rain incidence for 30^o rain inclination between windward and leeward slopes



$$\varphi = I_a / I = \cos(\alpha \mp \theta)$$

Plus and minus signs in the equation indicates the raindrop impact deficit with the same values of the raindrop inclination and slope gradient

Wind-driven raindrops strike the soil surface with an angle deviated from the vertical because of their horizontal velocities. In a two dimentional model, raindrop impact angle is a complementary angle of the angle of rainfall incidence



α: rain inclination

θ: slope gradient

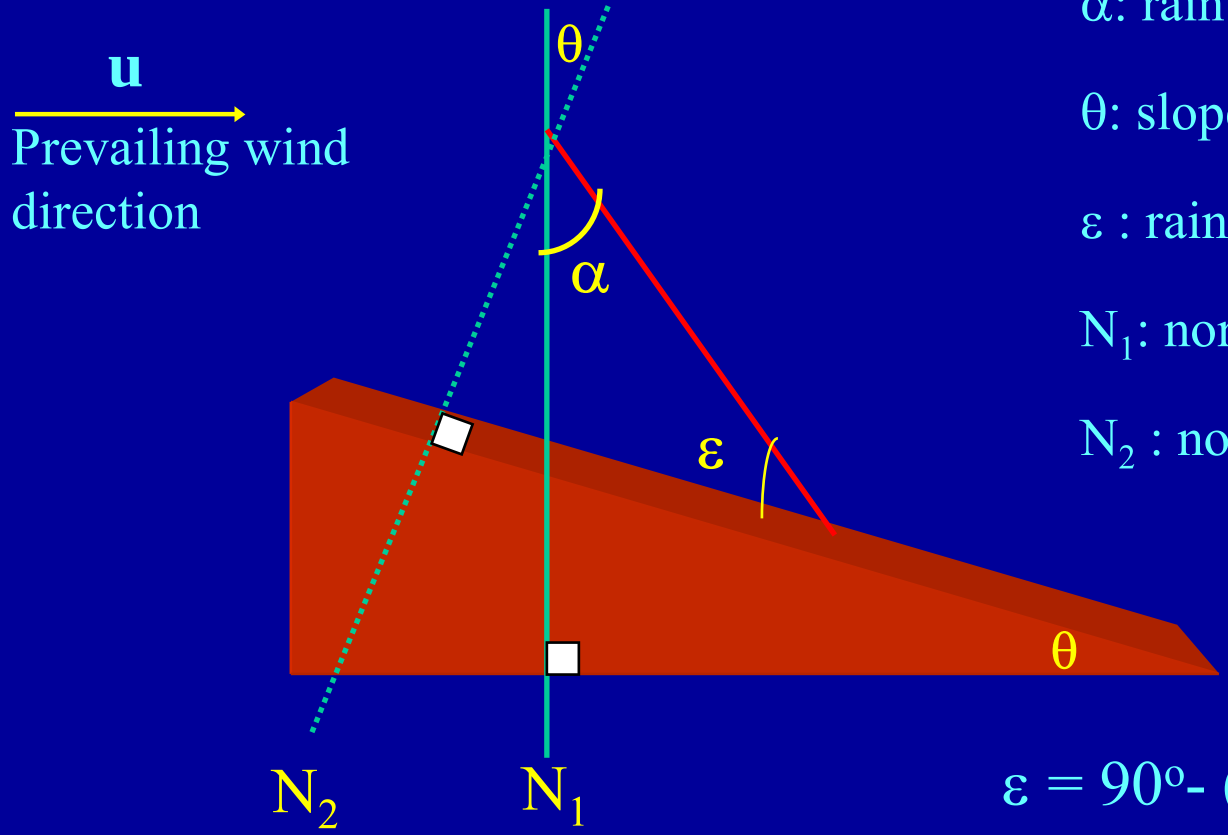
ε : raindrop impact angle

N_1: normal to horizontal plane

N_2 : normal to sloping surface

$$\varepsilon = 90^{o} - (\alpha - \theta) = 90^{o} - \alpha + \theta$$

Raindrop impact angle as a function of the rain inclination, slope gradient and aspect (leeward)



α: rain inclination

θ: slope gradient

ε : raindrop impact angle

N_1: normal to horizontal plane

N_2 : normal to sloping surface

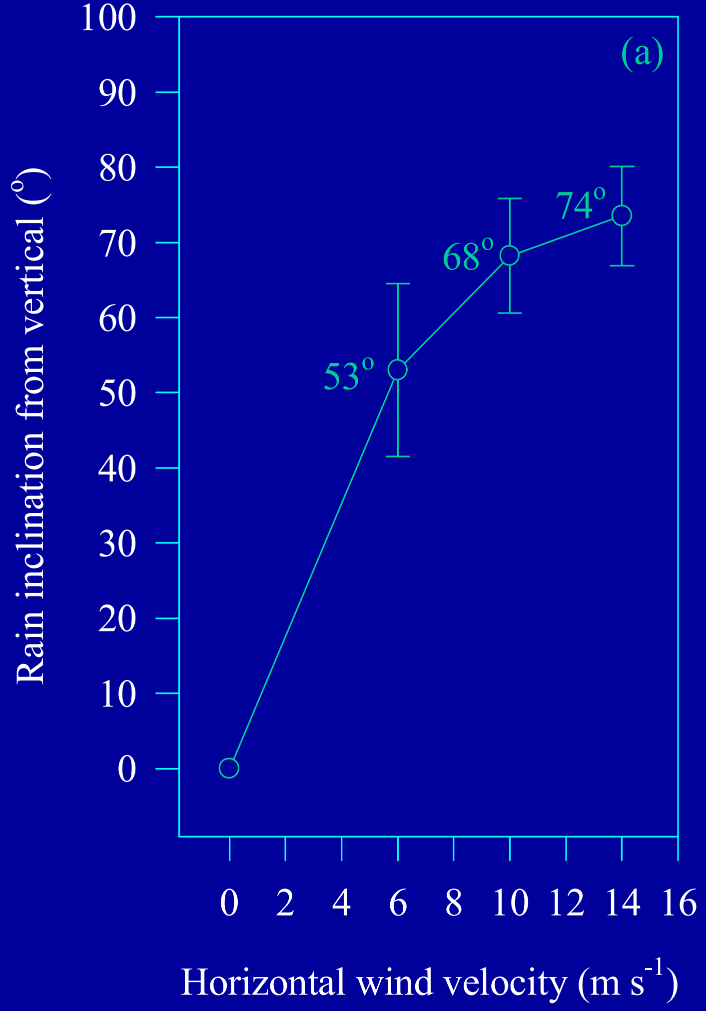
$$\varepsilon = 90^o - (\alpha + \theta) = 90^o - \alpha - \theta$$

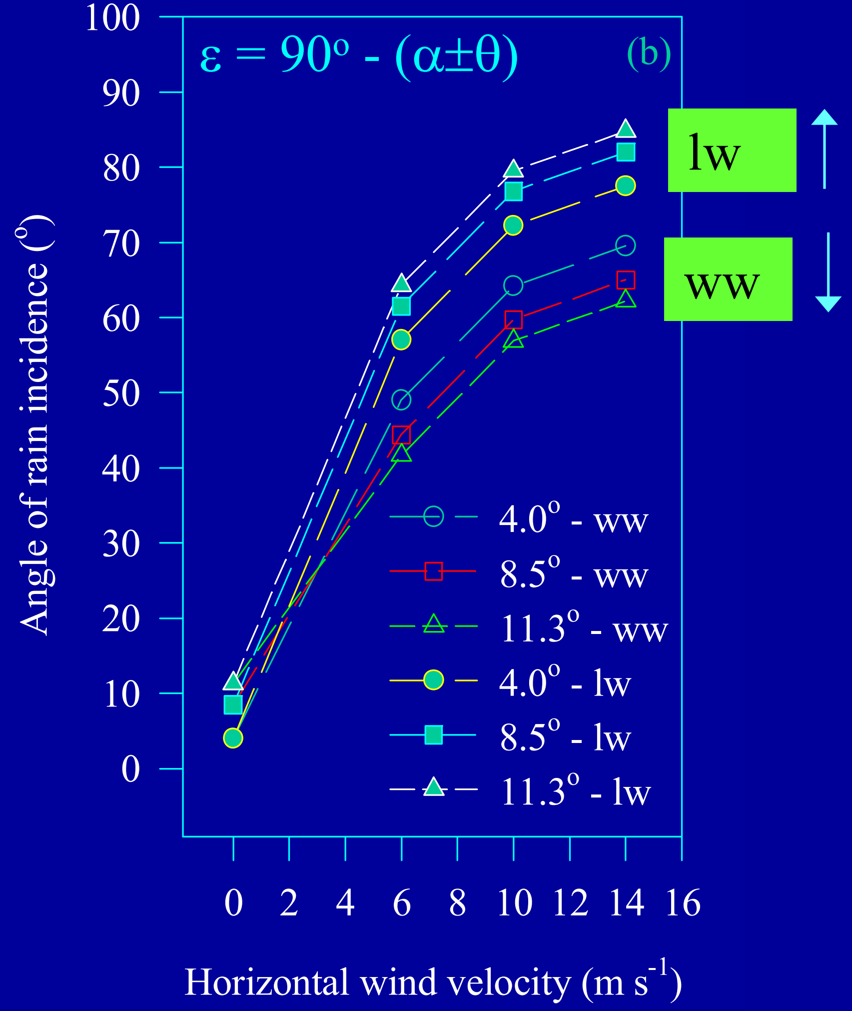
Raindrop Impact Angle

Mean rain inclination (a) and the mean angle of rain incidence between wind vector and plane of the surface (b) as a function of horizontal wind velocity

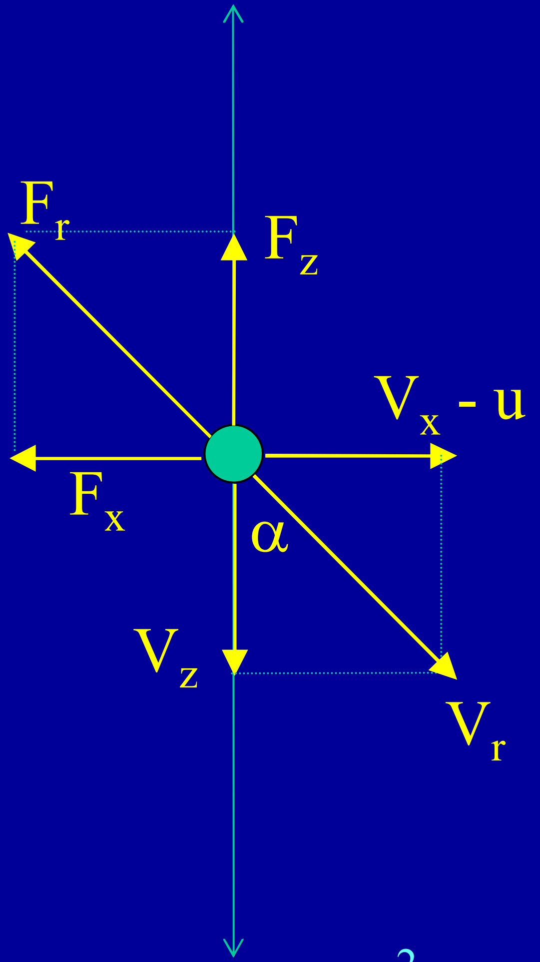
$$\alpha = \tan^{-1}\left[\frac{\cos\theta_1 - \left(I_{\theta_1}/I_{\theta_2}\right)\cos\theta_2}{\left(I_{\theta_1}/I_{\theta_2}\right)\sin\theta_2 - \sin\theta_1}\right]$$

$$\alpha = \tan^{-1}\left[\frac{\cos\theta_1 - \left(I_{\theta_1}/I_{\theta_2}\right)\cos\theta_2}{\sin\theta_1 - \left(I_{\theta_1}/I_{\theta_2}\right)\sin\theta_2}\right]$$





Free body diagram of a raindrop falling through a wind profile (Pedersen and Hasholt, 1995)



$$m\frac{\partial^2 z}{\partial t^2} = mg - \rho_a g \forall - \frac{1}{2} C_d \rho_a \left(\frac{\partial z}{\partial t}\right)^2 A$$

$$m\frac{\partial^2 x}{\partial t^2} = -\frac{1}{2} C_d \rho_a \left(\frac{\partial x}{\partial t}\right)^2 A$$

$$\sum F_z = m\left(\frac{d^2 z}{dt^2}\right) = 0$$

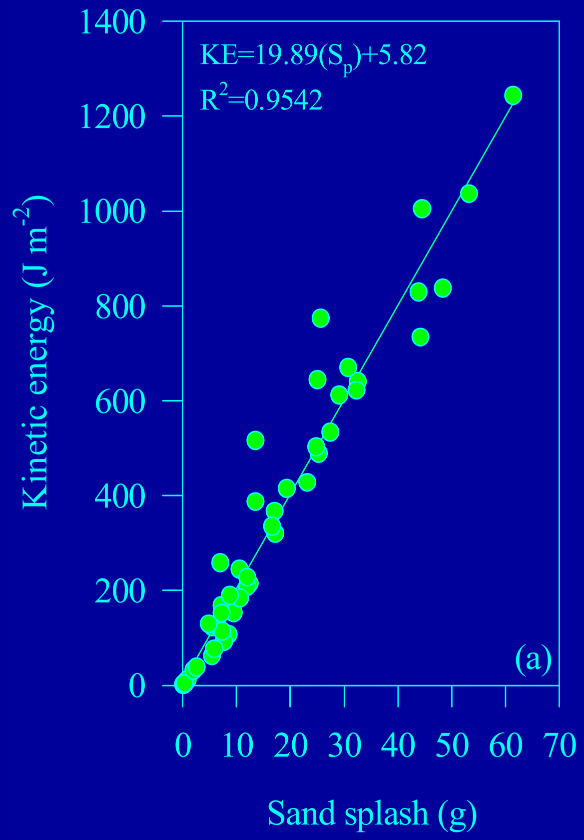
$$\sum F_x = m\left(\frac{d^2 x}{dt^2}\right) = f(u)$$

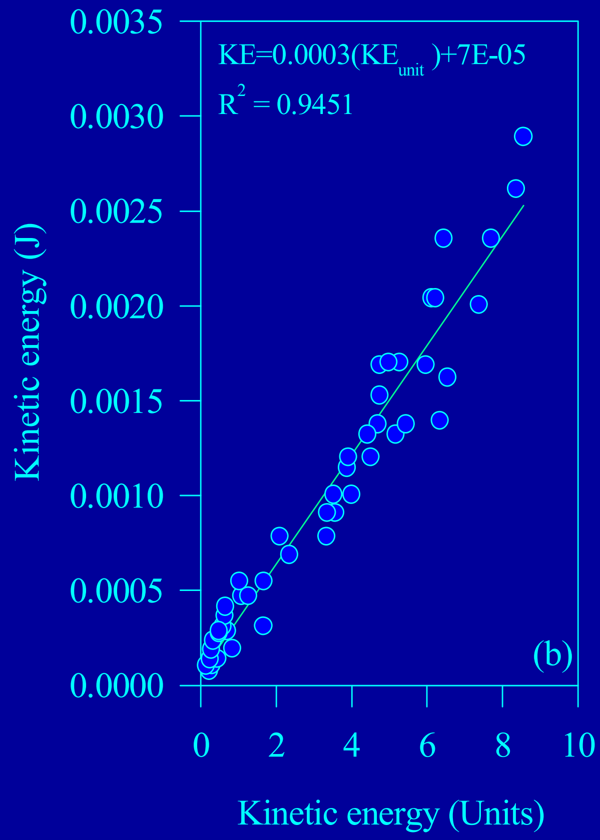
$$V_r^2 = V_z^2 + V_x^2 \qquad V_z = \partial z / \partial t \qquad V_x = \partial x / \partial t$$

Raindrop Impact Velocity

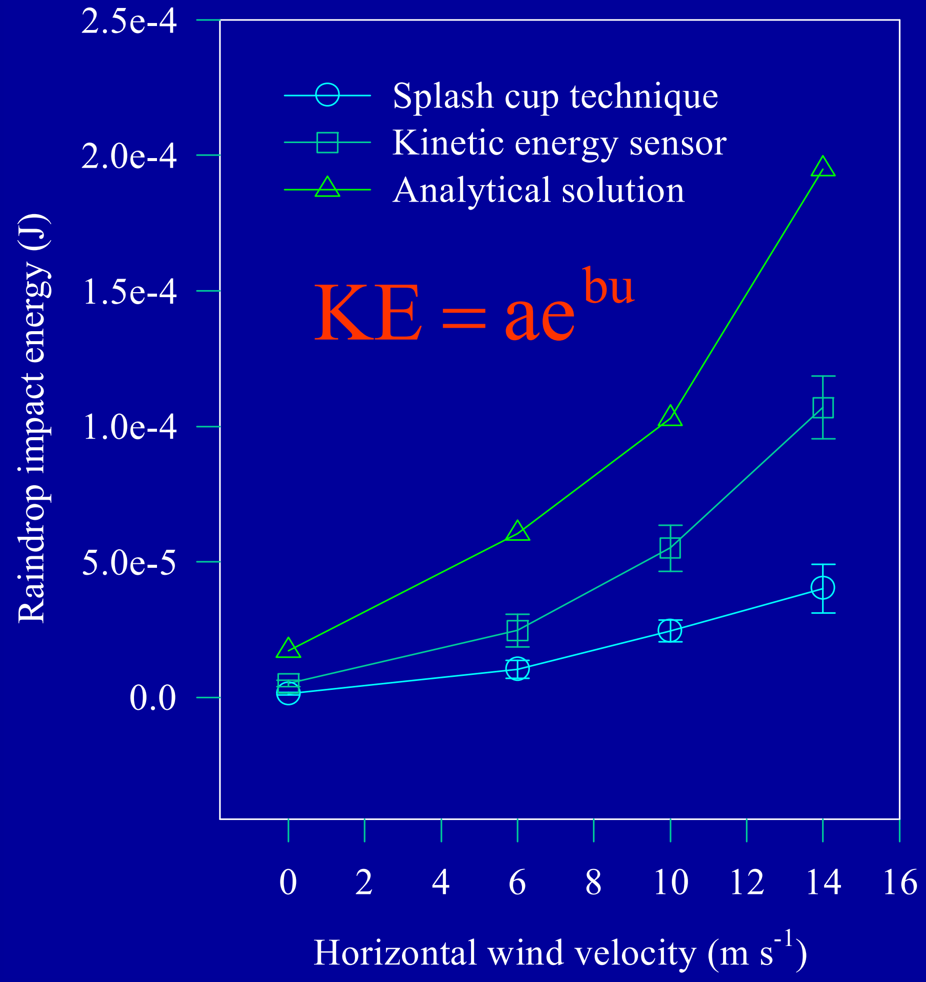
1. Splash cup technique

2. Kinetic energy sensor





Kinetic energy of simulated rainfall as a function of the horizontal wind velocity evaluated by the splash cup technique, kinetic energy sensor and analytical solution



$$KE = 2E - 05e^{0.1712u}$$

$R^2 = 0.99$

$$KE = 6E - 06e^{0.2184u}$$

$R^2 = 0.99$

$$KE = 2E - 06e^{0.2473u}$$

$R^2 = 0.96$

Main differences between windless and wind-driven rains

Rain	Windless	Wind-driven	
Slope aspect	makes no difference	windward	leeward
Raindrop impact frequency	$I = f(\theta)$ and max if $\theta = 0$	$I = f(\alpha,\theta)$ and max if $\theta = \alpha$	$I = f(\alpha,\theta)$ and 0 if $\theta + \alpha = 90^o$
Raindrop impact angle	$\varepsilon = f(\theta)$ and max if $\theta = 0$	$\varepsilon = f(\alpha,\theta)$ and max if $\theta = \alpha$	$\varepsilon = f(\alpha,\theta)$ and 0 if $\theta + \alpha = 90^o$
Raindrop impact energy	$E = f(I)$	$E = f(I,u)$	$E = f(I,u)$

- An erosivity index
  - describes the relationship between E and u
  - introduces the angle of rain incidence
    - to deal with variability in
      - the raindrop impact frequency
      - impact angles

- In most erosion models, interrill delivery rate is assumed to be a function of the raindrop impact parameter
  - $D = f(\Theta)$
  - D is the rainsplash detachment rate
  - Θ is the rainfall impact parameter
    - Evaluated by
      - The rain intensity
      - Fluxes of rain energy and momentum
      - Total rain pressure

Wind-Driven Rainsplash Detachment

$$M_r = \Xi_a (mV_r) \quad (\mathrm{N\ m^{-2}})$$

$$\Xi_a = I_a / \forall \quad (\#\ \mathrm{m^{-2} s^{-1}})$$

$$E_r = \Xi_a (0.5 m V_r^2) \quad (\mathrm{W\ m^{-2}})$$

$$M_{rn} = M_r \varphi \quad (\mathrm{N\ m^{-2}})$$

$$E_{rn} = E_r \varphi^2 \quad (\mathrm{W\ m^{-2}})$$

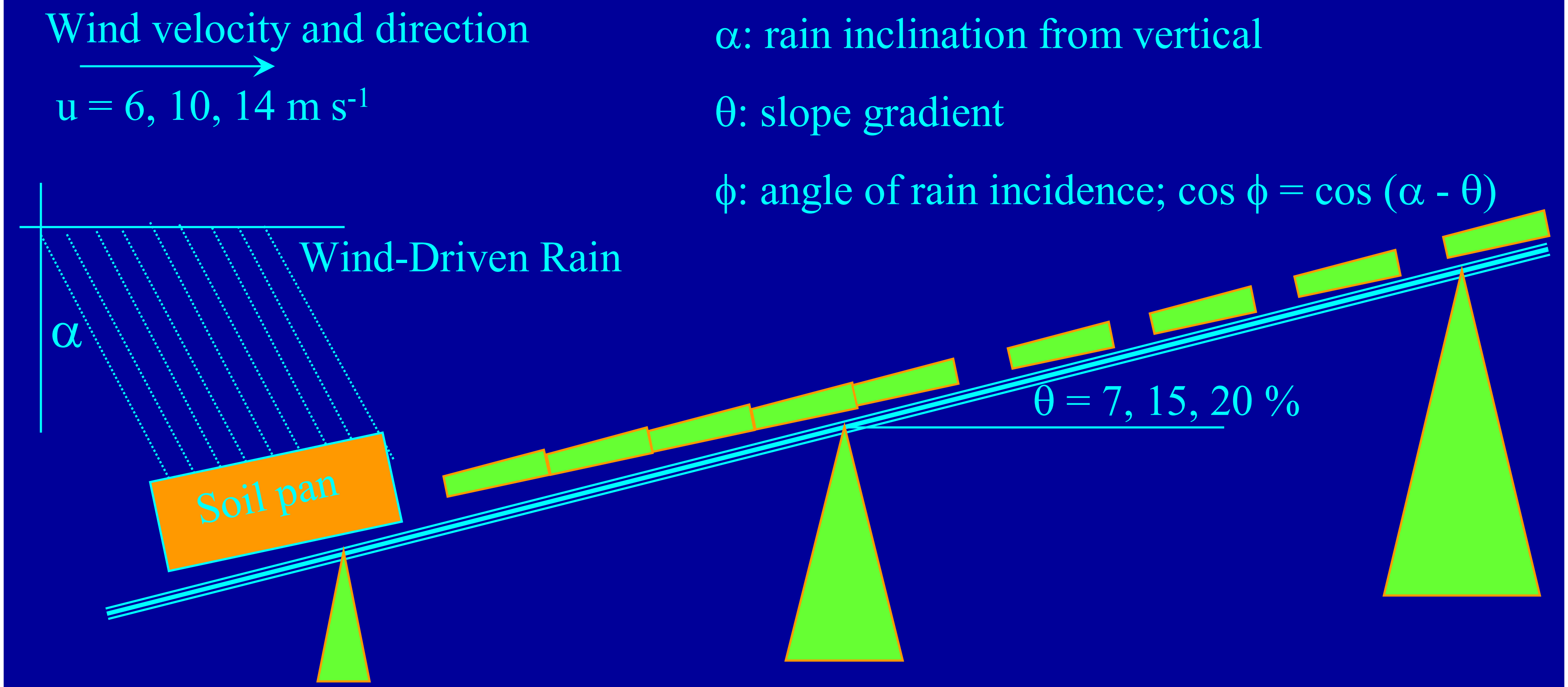
$$\varphi = \cos(\alpha \mp \theta)$$

$$\Gamma = \Xi_a (\rho_w V_r^2) \varphi^2 \quad (\mathrm{MPa})$$

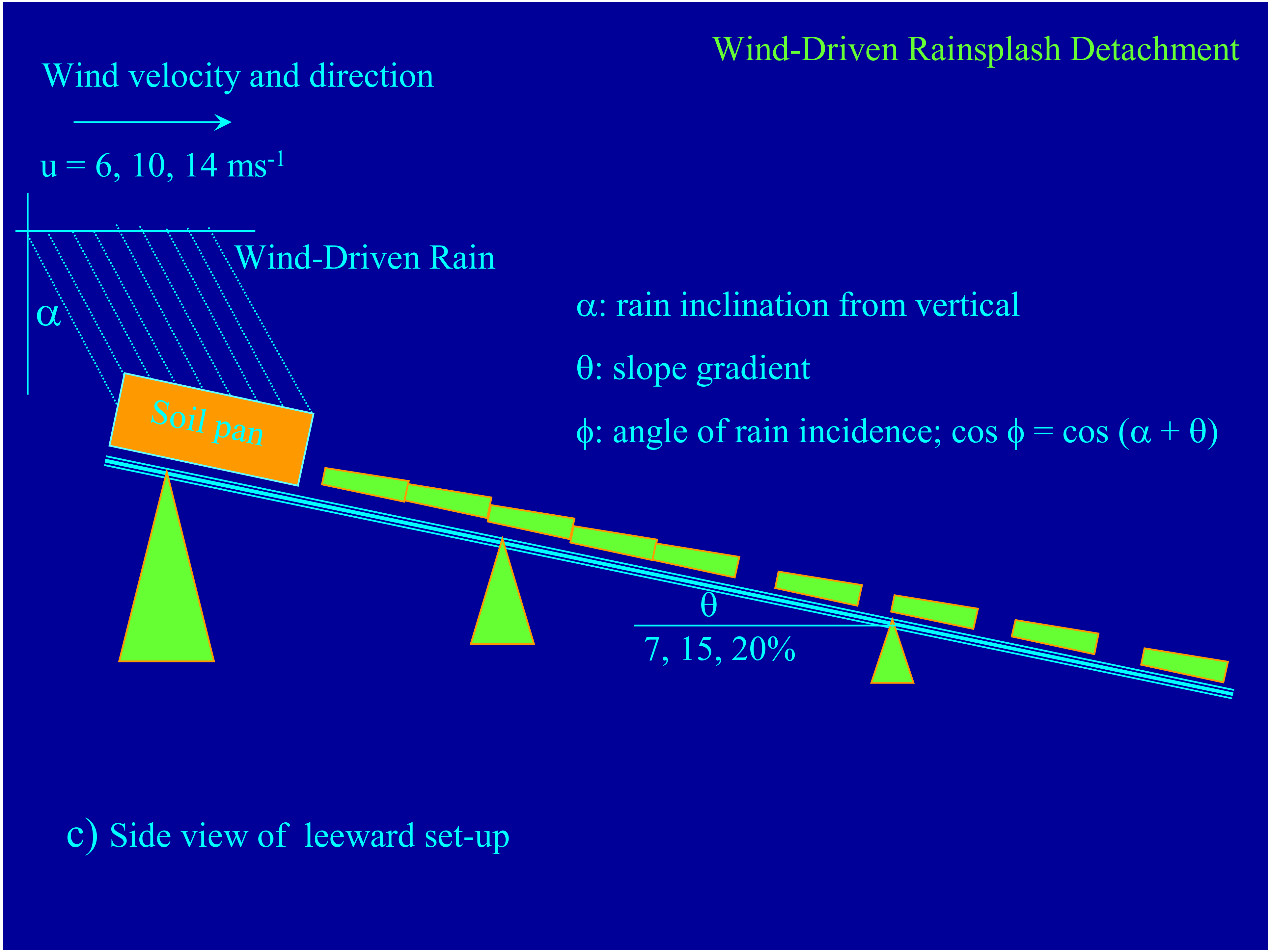
Wind-Driven Rainsplash Detachment

a) Top view

Wind-Driven Rainsplash Detachment

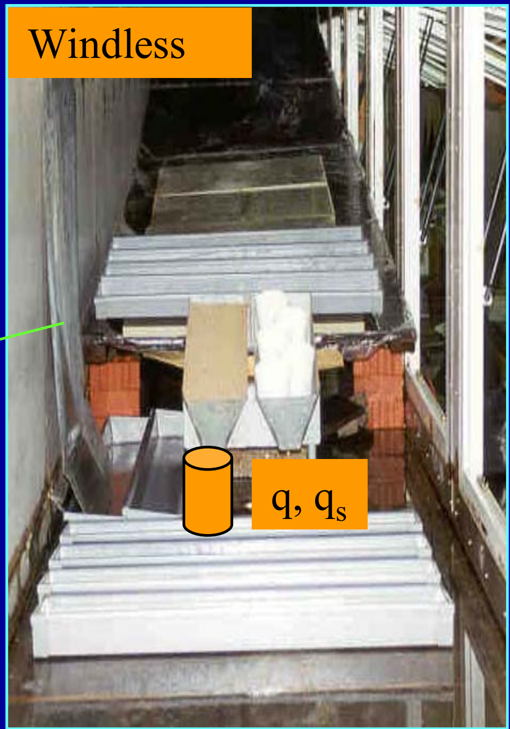


b) Side view of windward set-up


Wind-Driven Rainsplash Detachment
Wind velocity and direction
u = 6, 10, 14 ms-1
Wind-Driven Rain
α
α: rain inclination from vertical
θ: slope gradient
ϕ: angle of rain incidence; cos ϕ = cos (α + θ)
Soil pan
θ
7, 15, 20%
c) Side view of leeward set-up

Wind-Driven Rainsplash Detachment

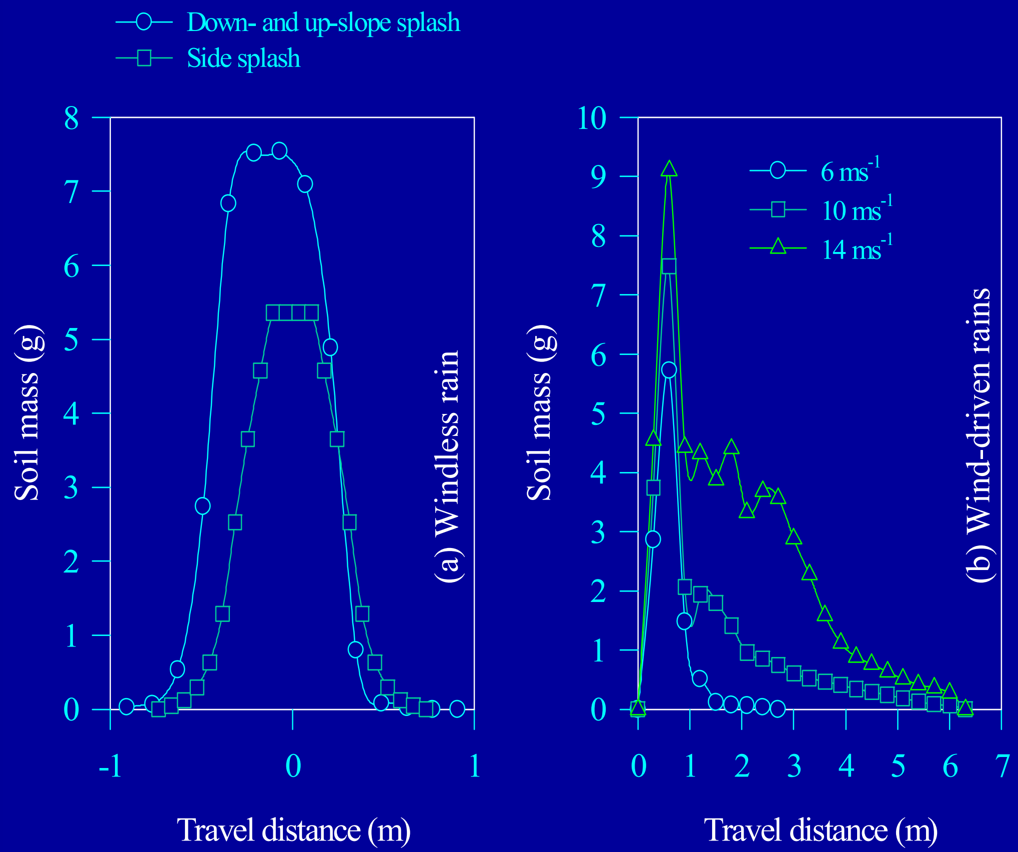
Experimental set-up with the soil pan and sediment traps arranged on the slopes of windward and leeward (7, 15, 20 %) in the wind tunnel



3 × 4 × 3 × 2 × 3 = 216 rainfall simulations (45 min)

soil × wind velocity × slope gradient × slope aspect × replicate

Mass distribution curves used for calculating the wind-driven rainsplash detachment



$$Q_s = \sum_{i=1}^{n} m_i x_i$$

Van Heerden, 1967

$$D = \frac{1}{At_a} \int \left(\frac{m_i}{x_i} \right) dx$$

D: rainsplash detachment rate ($g\ m^{-2}\ s^{-1}$)

A: the surface area of soil pan (m^2)

m_i: the mass of a particle, which is splashed over a distance x_i measured along the x-axis (g)

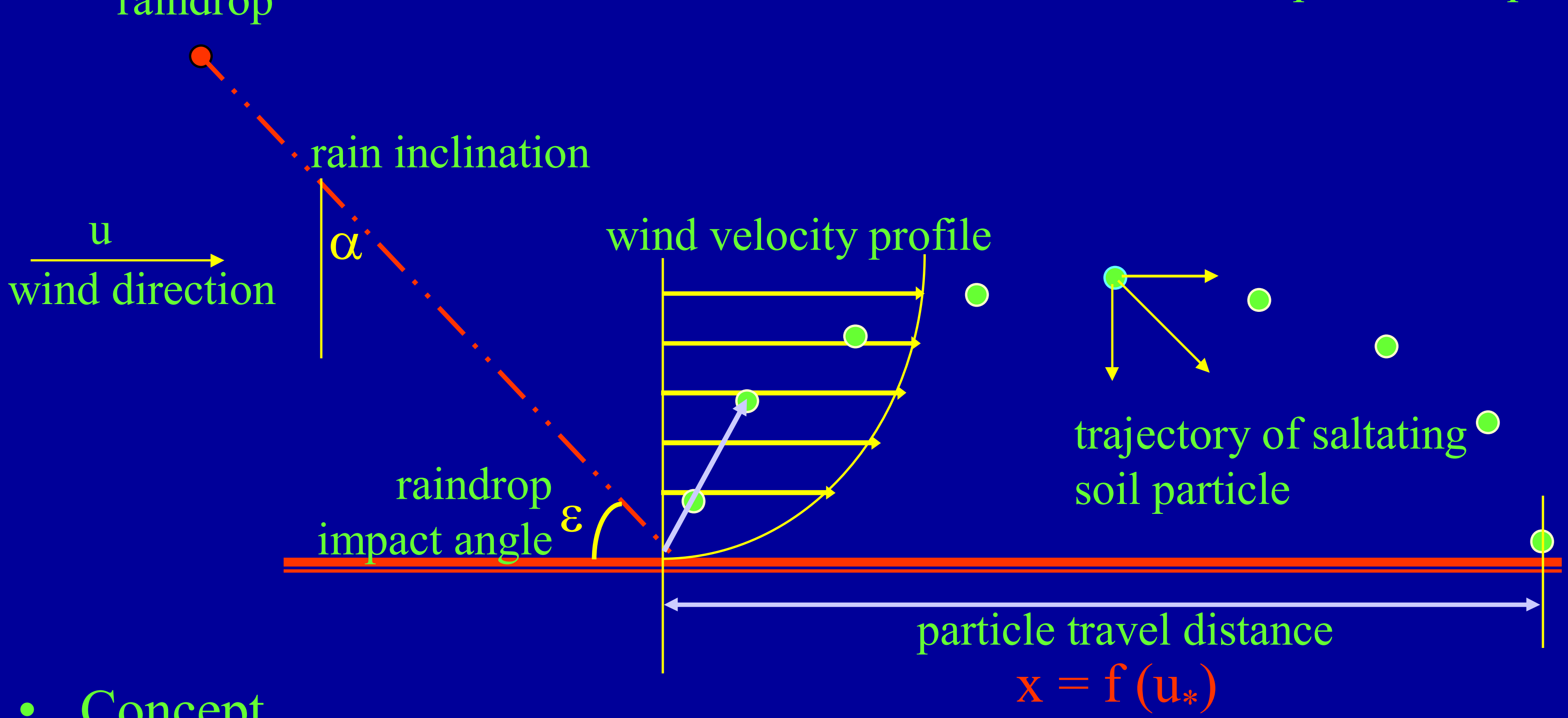
t_a: time during which rainsplash process occurred before runoff starts (s)

Pearson correlation coefficients between the rainsplash detachment rate and the rainfall impact parameters

Soil	Rainfall Parameter (Θ)					
	I_a	E_r	M_r	E_{rn}	M_{rn}	Γ
Nukerke	0.73	0.02	0.29	0.87	0.84	0.92
Kemmel1	0.76	-0.14	0.20	0.83	0.82	0.95
Kemmel2	0.77	-0.17	0.17	0.83	0.82	0.97
All data	0.75	-0.10	0.21	0.84	0.82	0.94

- The results showed that
  - Soil detachment under wind-driven rain differed from those under windless rain
  - The most widely used parameters, fluxes of energy and momentum, to predict the soil loss in windless rains were found to be insensitive to the spatial variability in the detachment rates in the wind-driven rains
  - The introduction of the angle of rain incidence to the raindrop impact parameters significantly improved their ability to account for the variations in the detachment rates

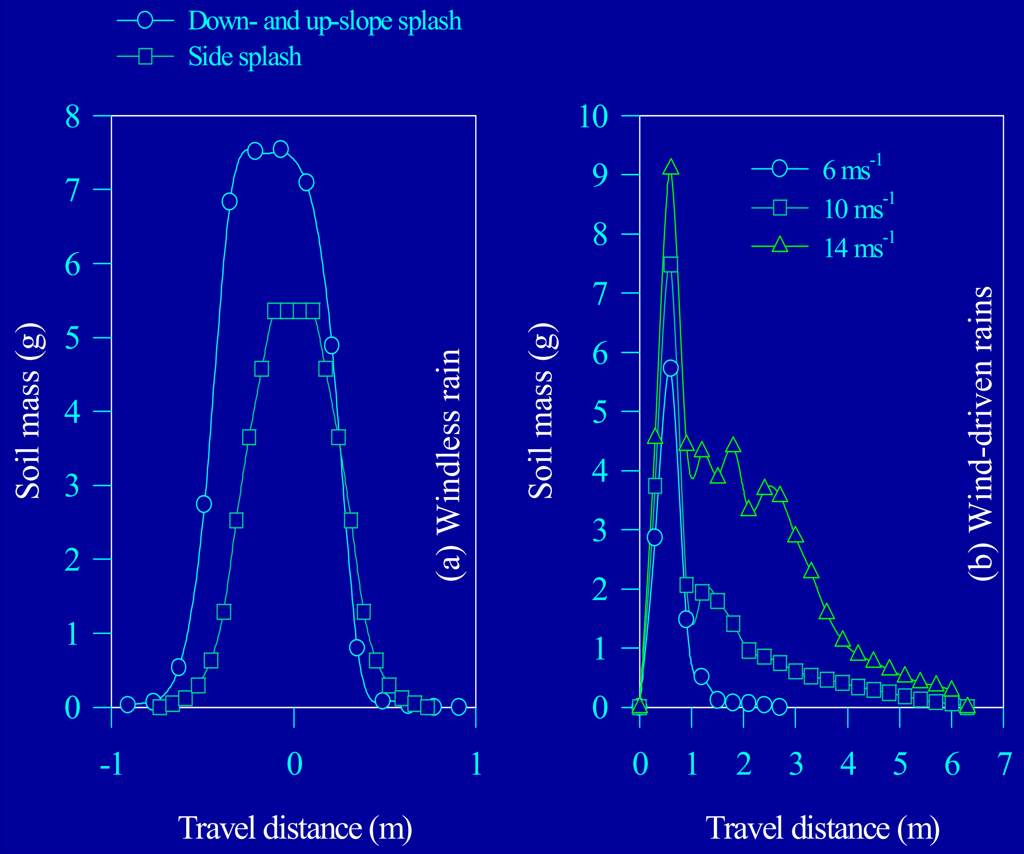
Wind-Driven Rainsplash Transport



- Concept
  - the rate at which soil particles are supplied into the air is function of the raindrop impact (Θ), subsequently, wind velocity gradient (u_*) will determine the travel distance.
    - the raindrop impact induces the process that wind would otherwise be incapable of transporting

$$Q_s = f(\Theta, u_*)$$

Mass distribution curves used for calculating the wind-driven rainsplash transport rates and mean rainsplash distance



$$Q_s = \frac{1}{A_T t_a} \int m_i \, dx$$

Center of gravity

$$\sum_{i=1}^{n} \left(x_i - \bar{X} \right) m_i = 0$$

$\bar{X}$: Mean rainsplash distance (m)

Q_s: rainsplash transport rate (g m^{-1} s^{-1})

A_T: surface area of the collecting traps (1.20m × 0.14m = 0.168m^2)

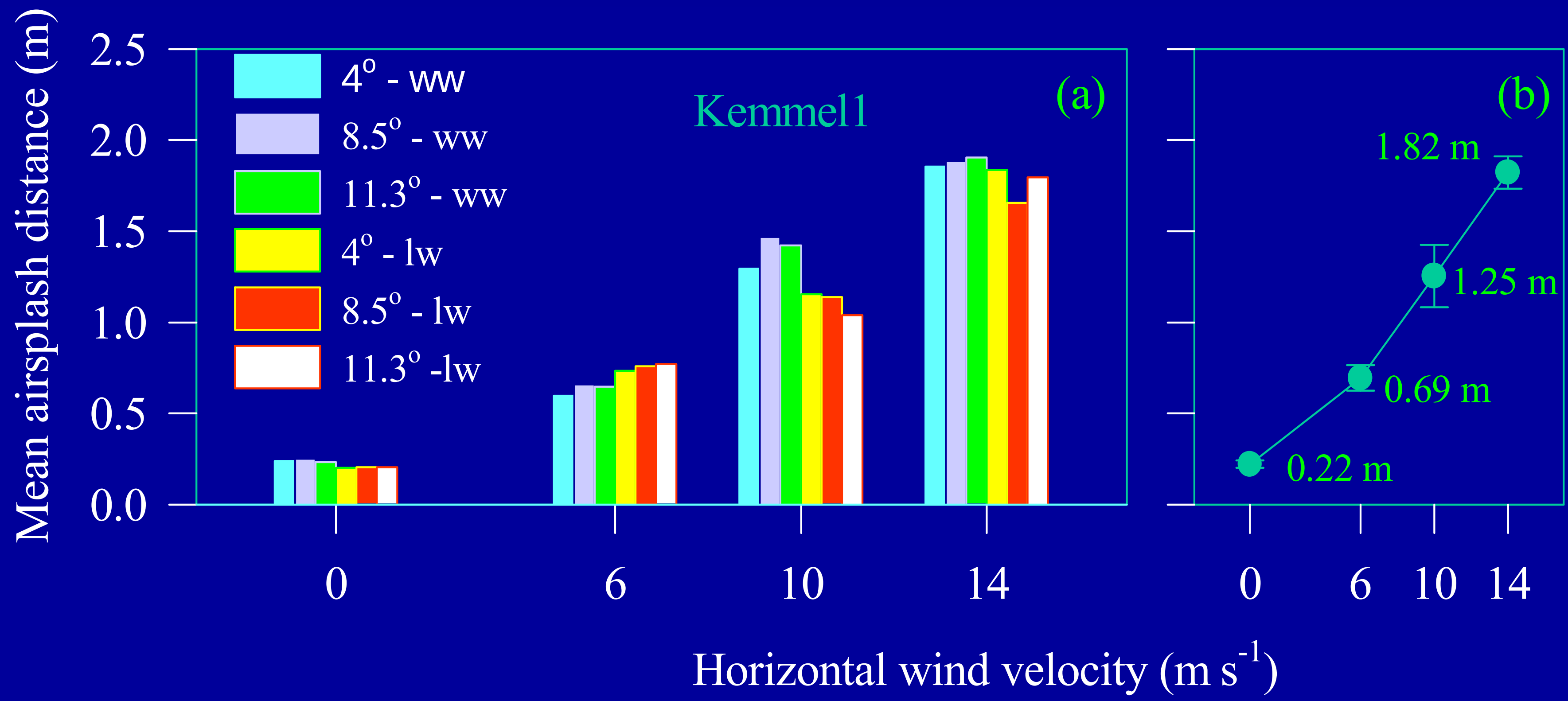
t_a: time during which rainsplash process occurred before runoff starts (s)

Statistical analyses for rainsplash transport rate as function of rainfall parameter and wind shear velocity

Soil	$Q_s=K_1E_{rn}^{a1}u_*^{b1}$			
	K_1	a_1	b_1	R^2
Nukerke	1.99×10^{-3}	0.79	2.00	0.96
Kemmel1	2.41×10^{-3}	0.86	2.32	0.95
Kemmel2	1.66×10^{-3}	0.79	1.95	0.94
Soil	$Q_s=K_1M_{rn}^{a1}u_*^{b1}$			
	K_1	a_1	b_1	R^2
Nukerke	8.97×10^{-3}	1.21	2.17	0.96
Kemmel1	12.59×10^{-3}	1.34	2.51	0.94
Kemmel2	8.07×10^{-3}	1.25	2.12	0.95
Soil	$Q_s=K_1\Gamma^{a1}u_*^{b1}$			
	K_1	a_1	b_1	R^2
Nukerke	4.65×10^{-5}	0.78	1.83	0.96
Kemmel1	3.68×10^{-5}	0.86	2.13	0.96
Kemmel2	3.73×10^{-5}	0.78	1.78	0.94

*K_1, a_1 and b_1 were significant at the level of P = 0.01%

Variation in mean rainsplash distance influenced by horizontal wind velocity, slope gradient and slope aspect (a), and as a function of horizontal wind velocity regardless of slope gradient and aspect (b)

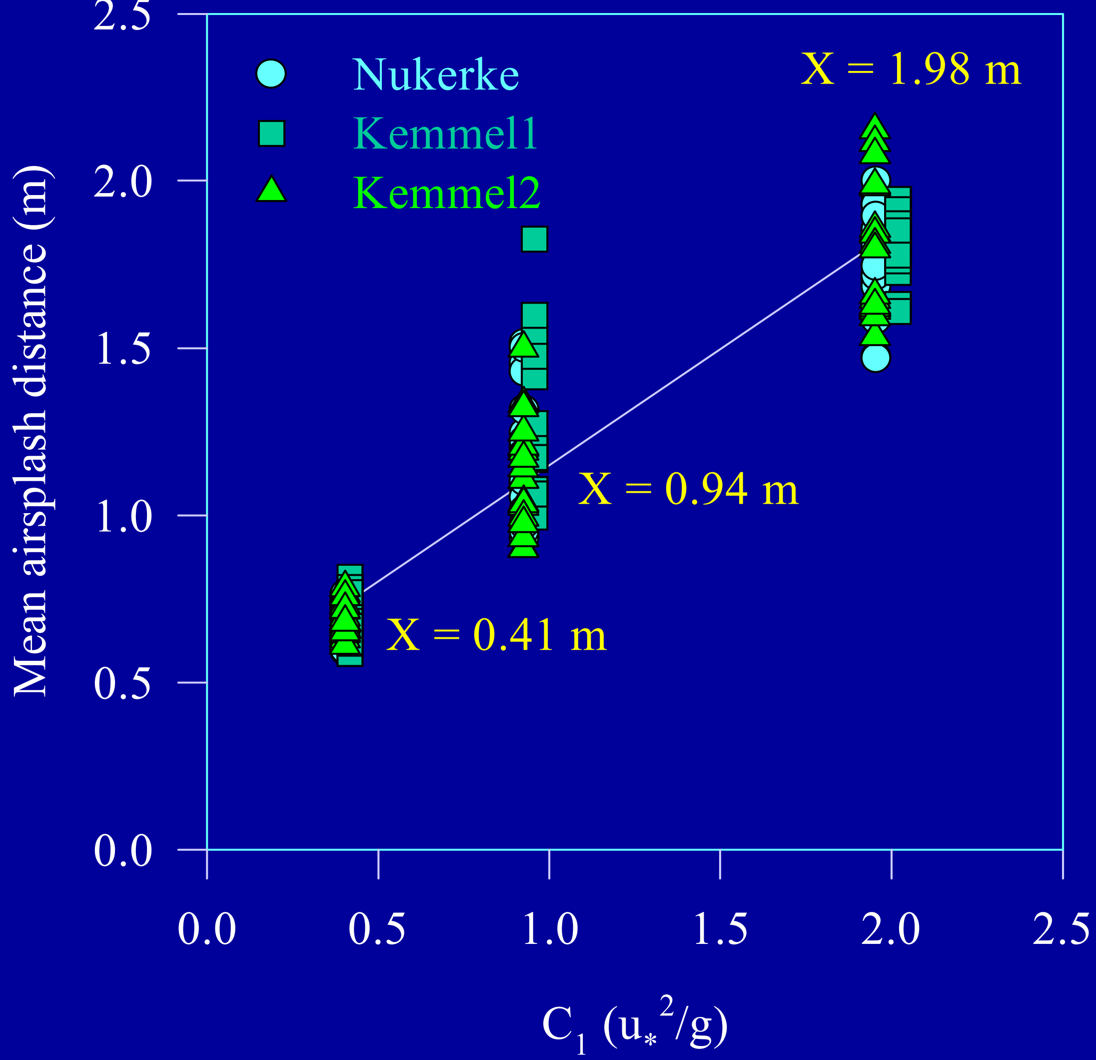


- Momentum loss per unit time per unit length of travel per unit lateral dimension (Bagnold, 1941; Greeley and Iversen, 1985)
  - (u_*^2/g) (m)
  - assumed vertical lift-off speed of a sand particle

$$\bar{X} = C_1\left(\frac{u_*^2}{g}\right)$$ (Owen, 1980) $C_1 = 10.3$

Soil	Parameter C_1	95% Confidence Interval Lower	95% Confidence Interval Upper	R^2
Nukerke	32.3	30.4	34.3	0.95
Kemmel1	33.4	31.3	35.5	0.95
Kemmel2	32.3	30.4	34.1	0.96
All data	32.7	31.6	33.8	0.95

Prediction of mean wind-driven rainsplash distance



$$\bar{X} = 32.7\left(\frac{u_*^2}{g}\right)$$

(Erpul, Norton, Gabriels, 2002)

- Basic processes
  - detachment by raindrop impact
  - transport by shallow overland flow

$$q_s = f(\Theta, \Lambda)$$

q_s: sediment transport rate by rain-impacted shallow flow (g m^{-1} s^{-1})

Λ: flow parameter

Flow parameter (Λ)

The product of unit discharge and slope in the form of $q^{b2}S_o^{c2}$
Boundary shear stress, τ_o (N m^{-2})
Stream power, Ω (kg s^{-3})
Flow momentum flux, φ_q (N m^{-2})

$$\tau_o = \gamma y S_o \quad (\mathrm{N\ m^{-2}})$$

$$\gamma = \rho_w g$$

$$\Omega = \gamma q S_o \quad (\mathrm{kg\ s^{-3}})$$

$$\varphi_q = \frac{\rho_w}{\Delta x} q u_f \quad (\mathrm{N\ m^{-2}})$$

γ: Specific weight of water ($\mathrm{N\ m^{-3}}$)

y: Flow depth (m)

u_f: Flow velocity ($\mathrm{m\ s^{-1}}$)

Δx: Slope length (m)

- Kinematic wave approximation
  - $S_o = S_f$
- Continuity equation
  - $q = u_f y$

$$S_f = \left(\frac{f}{8}\right)\left(\frac{u_f^2}{gy}\right)$$

f: The Darcy-Weisbach friction coefficient (Shen and Li, 1973; Julien and Simons, 1985; Gilley et al., 1985; Katz et al., 1995)

Laminar flows with raindrop impact

$$f = f_r + f_o$$

$$f_o = \frac{24}{R_e}$$ (Chow, 1959)

$$f_r = \frac{bI_a^c}{R_e}$$ (Shen and Li, 1973)

$$f = \left(\frac{24 + bI_a^c}{R_e}\right)$$ (b = 7.21; c = 0.41)

($R_e = q / \nu$)

$$y = \left[\left(\frac{24 + bI_a^c}{8gS_o}\right)\nu q\right]^{1/3}$$

f_r: friction coefficient due to raindrop impact

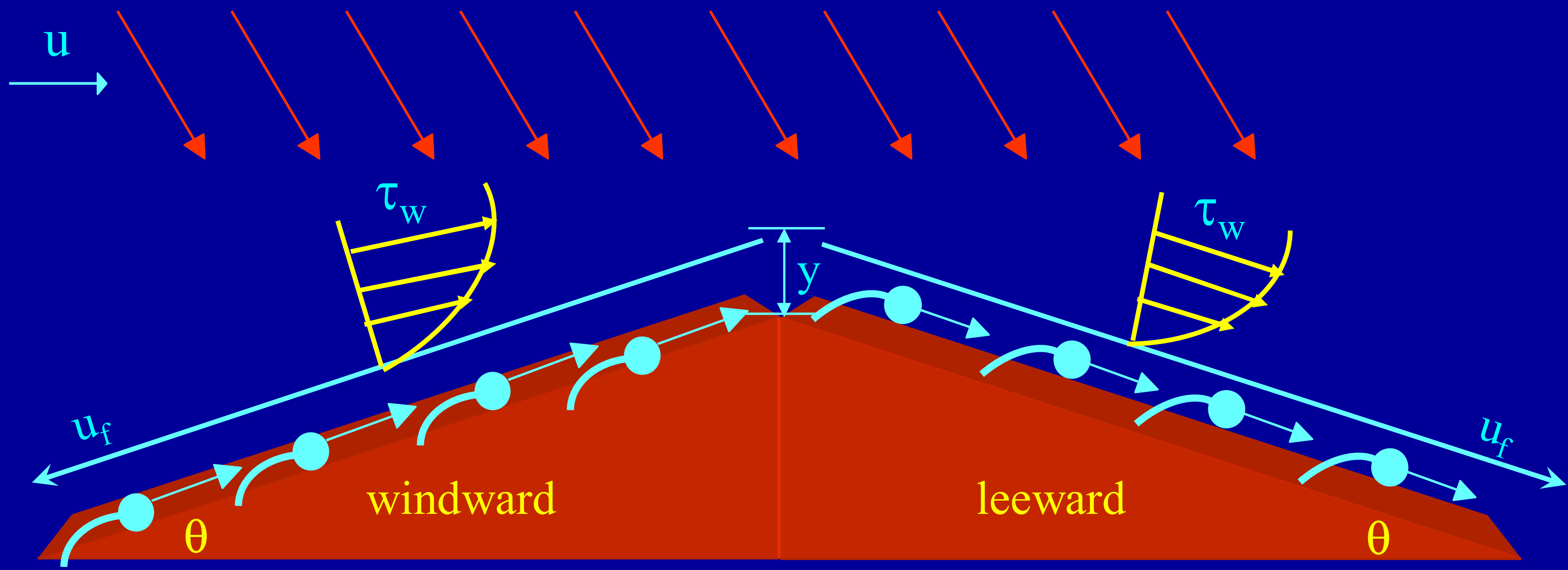
f_o: friction coefficient for laminar flow over smooth surfaces

ν: kinematic viscosity of water ($m^2\ s^{-1}$)

Pearson correlation coefficients between the sediment transport rate and the selected rainfall and flow parameters

	Rainfall (Θ) and flow (Λ) parameters						
	I_a	E_{rn}	M_{rn}	Γ	qS_o	τ_o	φ_q
Windward	0.45	0.55	0.54	-0.03	0.88	0.81	0.82
Leeward	0.87	0.92	0.92	0.91	0.91	0.83	0.93

Within flow rainsplash trajectories and the horizontal momentum of impacting raindrops with respect to shallow flow direction

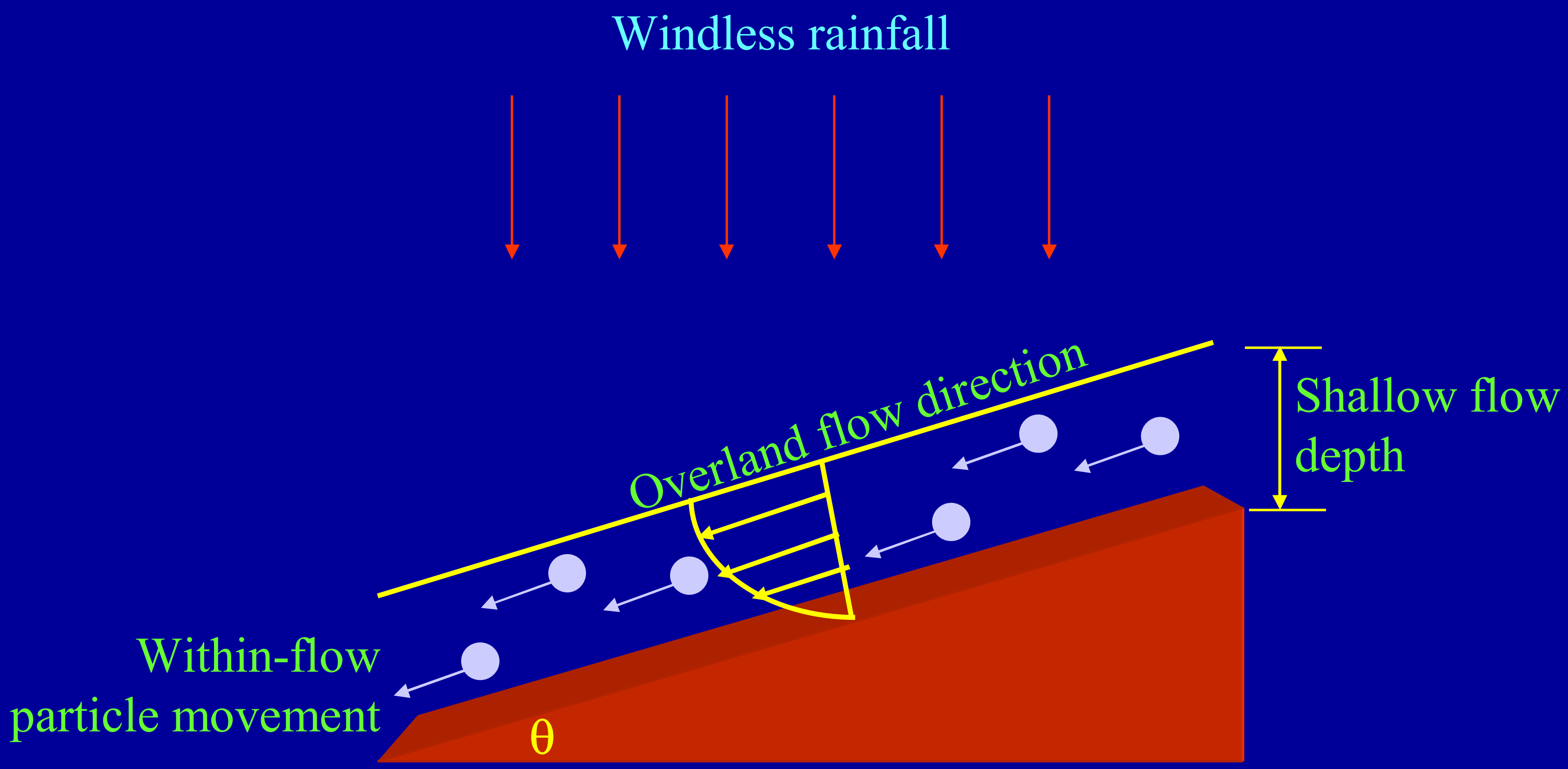


$$\Phi = 0.2\left(\frac{d}{y}\right)^{1.83} \qquad \left(\frac{d}{y}\right) < 1$$

(Wang and Wenzel, 1970; Gilley et al., 1985)

- $(D_{50} / y) > 1$
  - windward
    - 2.71 - 6.37
  - leeward
    - 2.45 - 11.86
- The Darcy-Weisbach friction coefficient (f)
  - k_o, k_r

Sediment Transport by Raindrop-Impacted Shallow Flow



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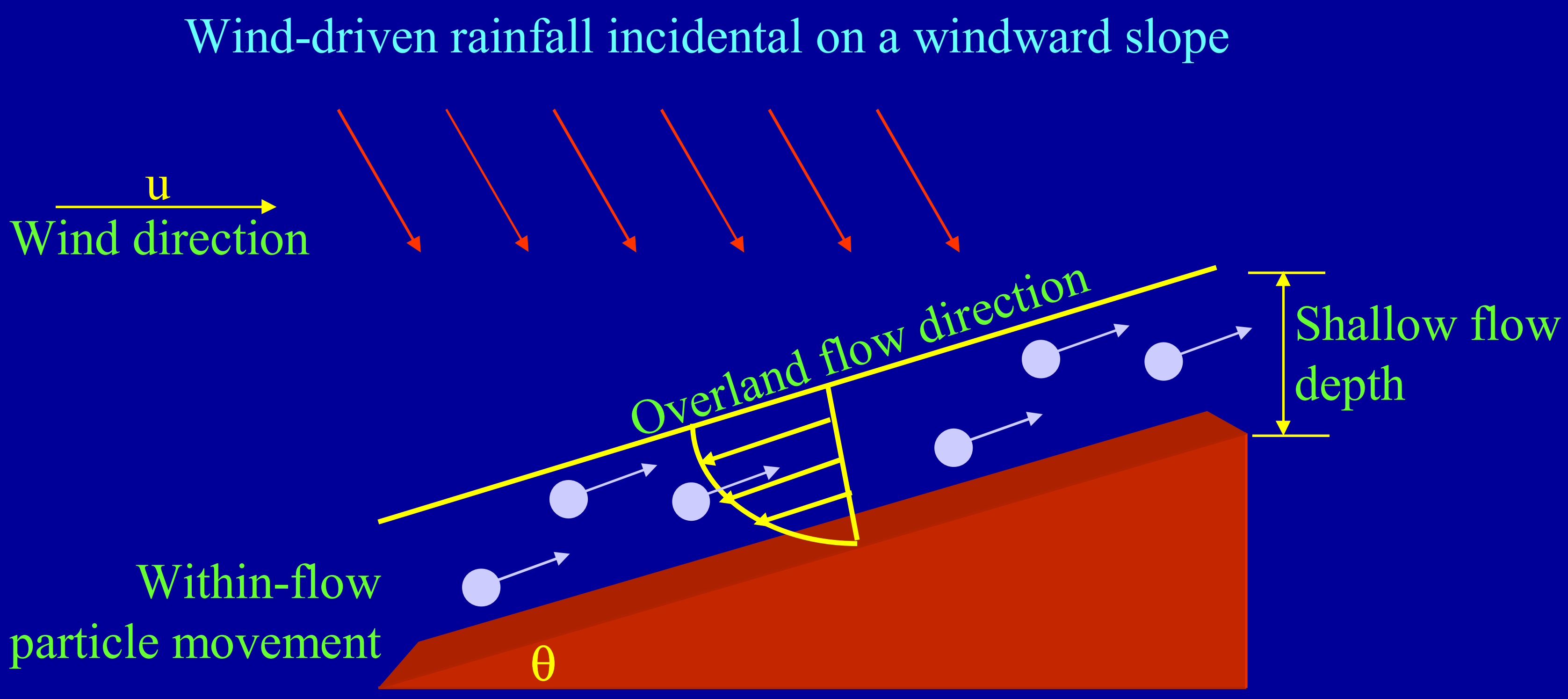
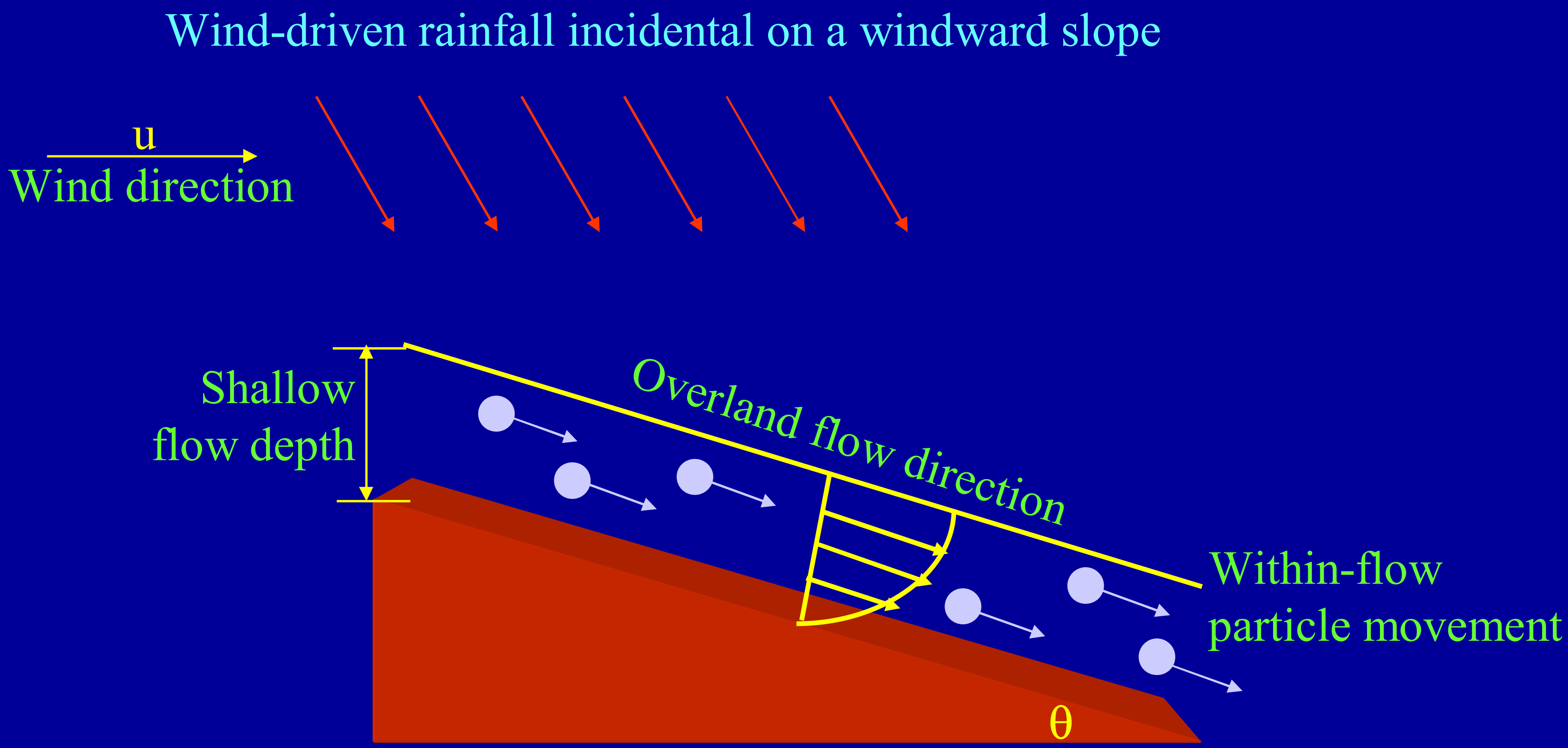


Sediment Transport by Raindrop-Impacted Shallow Flow



- Poor prediction
  - flow depth, y
    - raindrop impact pressure, Γ
    - boundary shear stress, τ_o
  - flow velocity, u_f
    - flow momentum flux, φ_q
- more reliable parameters
  - fluxes of momentum and energy, M_{rn} and E_{rn}, respectively.
  - unit discharge and slope
    - $q^{b2} S_o^{c2}$
    - Ω

Statistical analyses for the relationship between the sediment transport rate and the selected rainfall and flow parameters

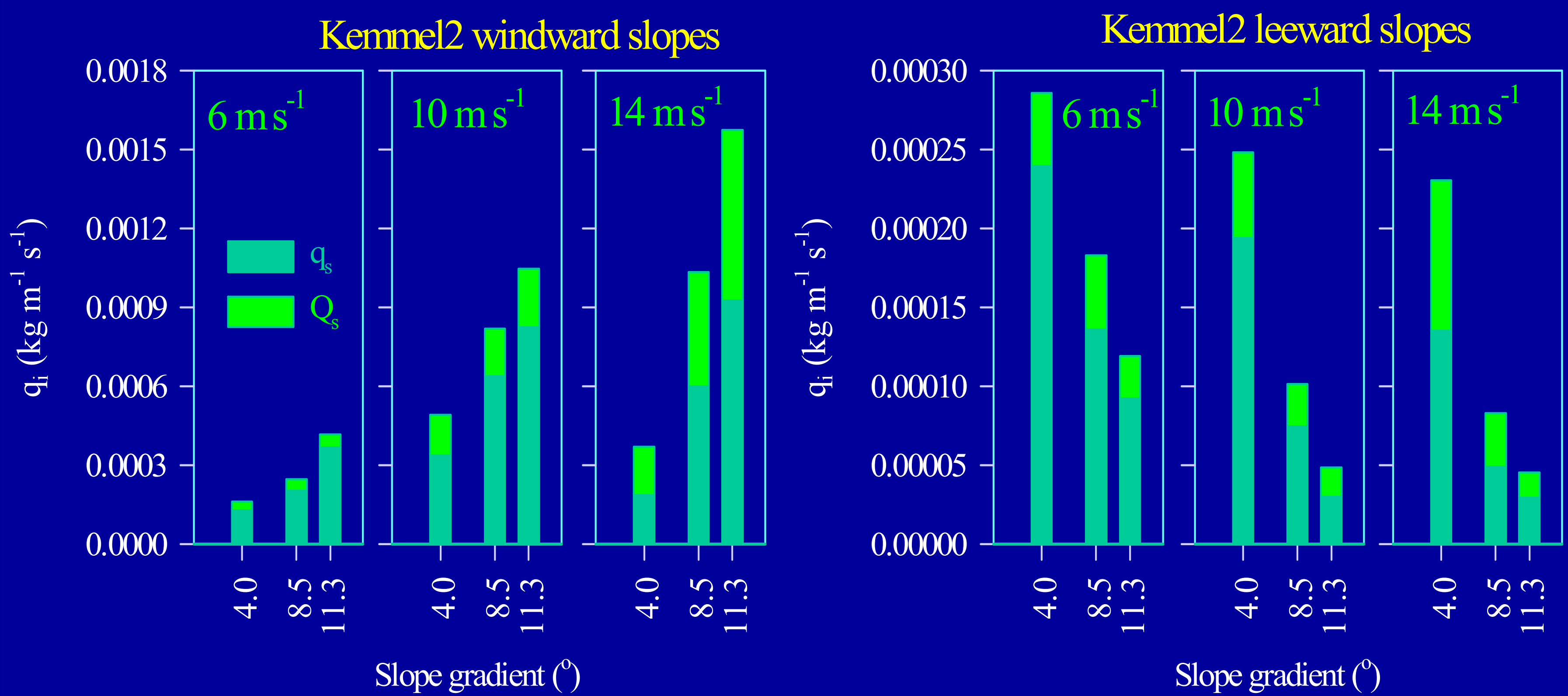
Models	K_2	a_2	b_2	c_2	R^2
	Nukerke				
$K_2E_{rn}^{a2} q^{b2} S_o^{c2}$	0.225*	0.45	0.34	0.65	0.91
$K_2E_{rn}^{a2} \Omega^{b2}$	0.012	0.34	0.56		0.90
$K_2M_{rn}^{a2} q^{b2} S_o^{c2}$	0.338*	0.71	0.31	0.65	0.90
$K_2M_{rn}^{a2} \Omega^{b2}$	0.020	0.50	0.56		0.89
	Kemmel1				
$K_2E_{rn}^{a2} q^{b2} S_o^{c2}$	12.231*	0.51	0.67	0.73	0.94
$K_2E_{rn}^{a2} \Omega^{b2}$	0.028	0.48	0.72		0.94
$K_2M_{rn}^{a2} q^{b2} S_o^{c2}$	116.862	0.63	0.82	0.72	0.94
$K_2M_{rn}^{a2} \Omega^{b2}$	0.064	0.71	0.74		0.94
	Kemmel2				
$K_2E_{rn}^{a2} q^{b2} S_o^{c2}$	0.185*	0.55	0.39	0.31	0.91
$K_2E_{rn}^{a2} \Omega^{b2}$	4.78×10^{-3}	0.59	0.33		0.91
$K_2M_{rn}^{a2} q^{b2} S_o^{c2}$	0.338*	0.85	0.36	0.30	0.90
$K_2M_{rn}^{a2} \Omega^{b2}$	0.118	0.90	0.31		0.90

* insignificant at the P = 5% level of significance

- Two distinct mechanisms
  - raindrop-induced and wind-driven sediment transport
    - Q_s
  - rain-impacted shallow flow sediment transport
    - q_s
- Total sediment transport
  - $q_i = Q_s + q_s$

Interrill Sediment Transport under Wind-Driven Rain

Total sediment transport rated based on airsplash and rain-impacted shallow overland flow sediment transport from interrill areas for Kemmel2 loam



$R = Q_s / q_i$

3% : 0 ms^{-1}

15% : 6 ms^{-1}

24% : 10 ms^{-1}

38% : 14 ms^{-1}

- Input of wind-driven raindrop impact, characterized by the combination of velocity, frequency and angle, on the soil surface highly varies with wind velocity and direction
- Raindrop-induced and wind-driven soil particle transport is a significant process under wind-driven rain
- Wind affects thin flow hydraulics
  - reverse/advance
    - the horizontal momentum of impacting raindrops
    - within-flow particle trajectories