The Abdus Salam International Centre for Theoretical Physics

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College on Soil Physics - 30th Anniversary (1983-2013)

25 February - 1 March, 2013

Wind-driven Rain
Erosion Processes

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The Abdus Salam
International Centre for Theoretical Physics

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Wind-driven Rain Erosion Processes

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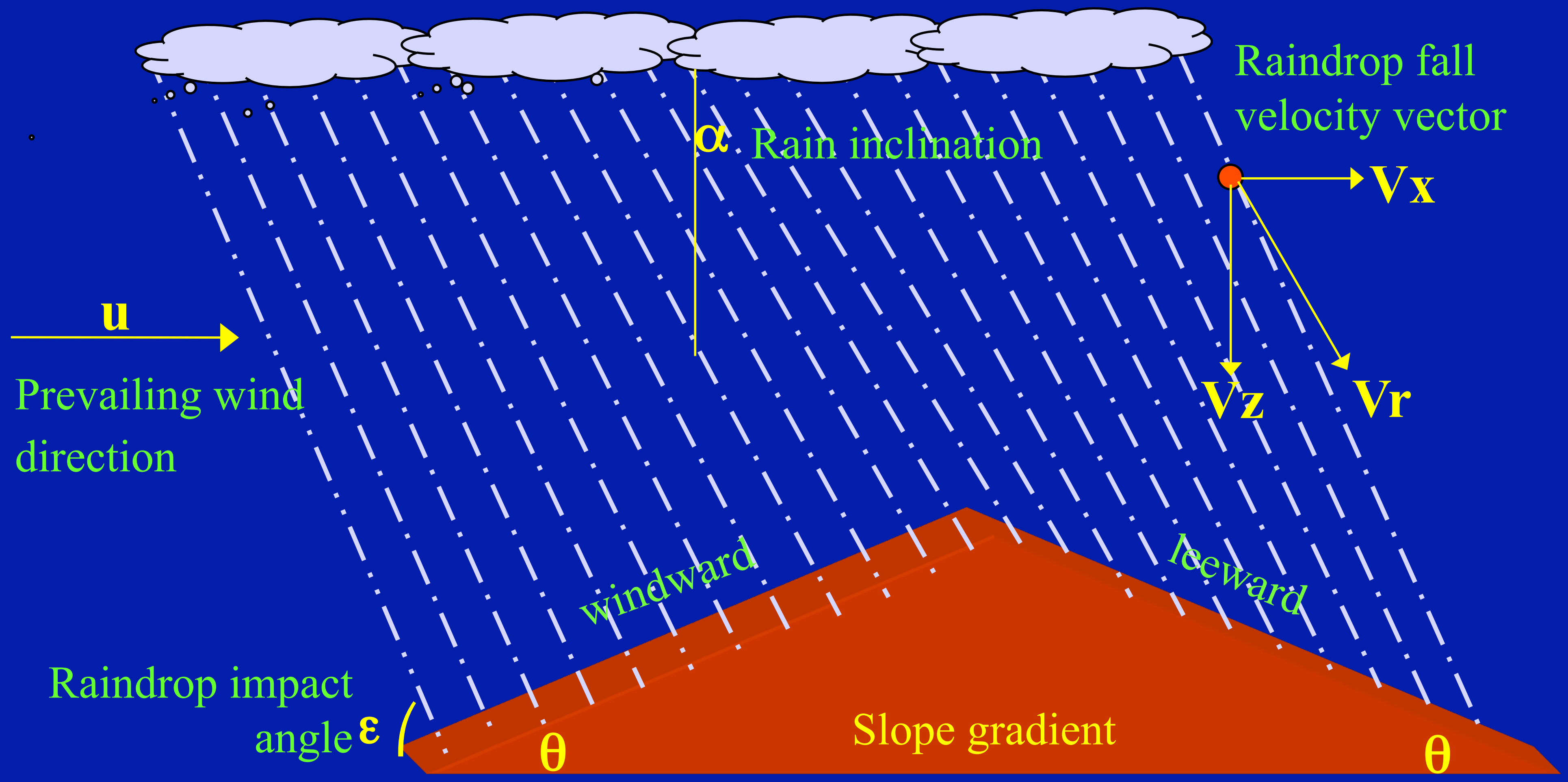
What is "inclined rainfall" (wind-driven rain [WDR])?

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.

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



Why WDR erosion studies?

- More event-based
  - WDR events
  - Rain & Wind coincide?

- More physically-based (vs. lumped models)
  - model physical parameters that change when wind is in play

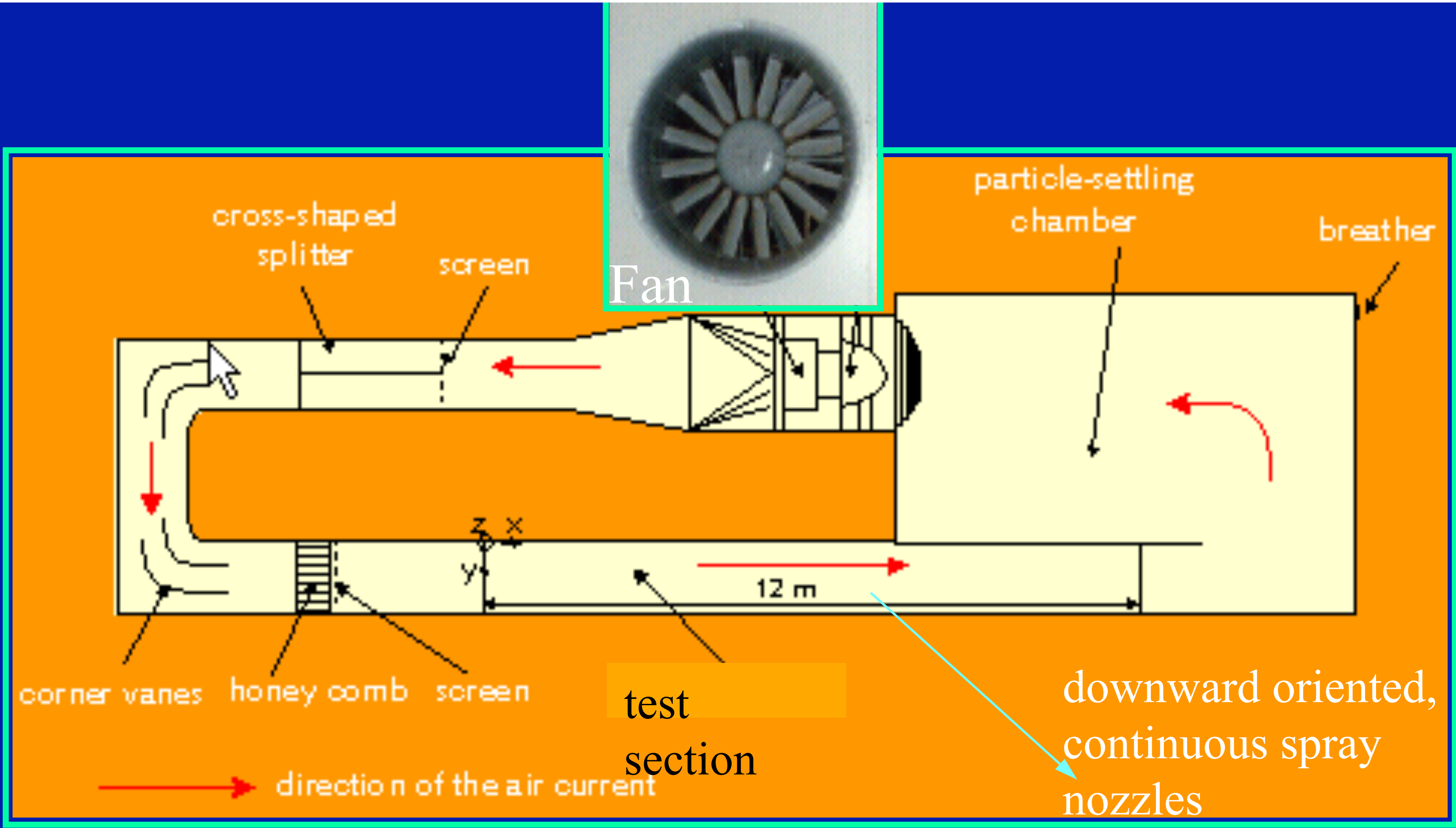
Why WDR erosion studies?

- More process-based
  - physical sub-processes of water erosion change when wind is in play
    - Detachment processes
    - Transport processes

Where are the controlled studies of WDR conducted?

A System of Dual Fluids

The research facility for simulating wind and rain simultaneously (a combination of a wind tunnel with a rainfall simulator) over a long test area, constructed at the International Centre for Eremology, Ghent University, Belgium offers ample opportunities for research on erosion processes.


Fan
cross-shaped splitter
screen
particle-settling chamber
breather
corner vanes
honey comb
screen
test section
12 m
z
x
y
direction of the air current
downward oriented, continuous spray nozzles


Test section

The I.C.E. Wind Tunnel for Wind and Water Interaction Research

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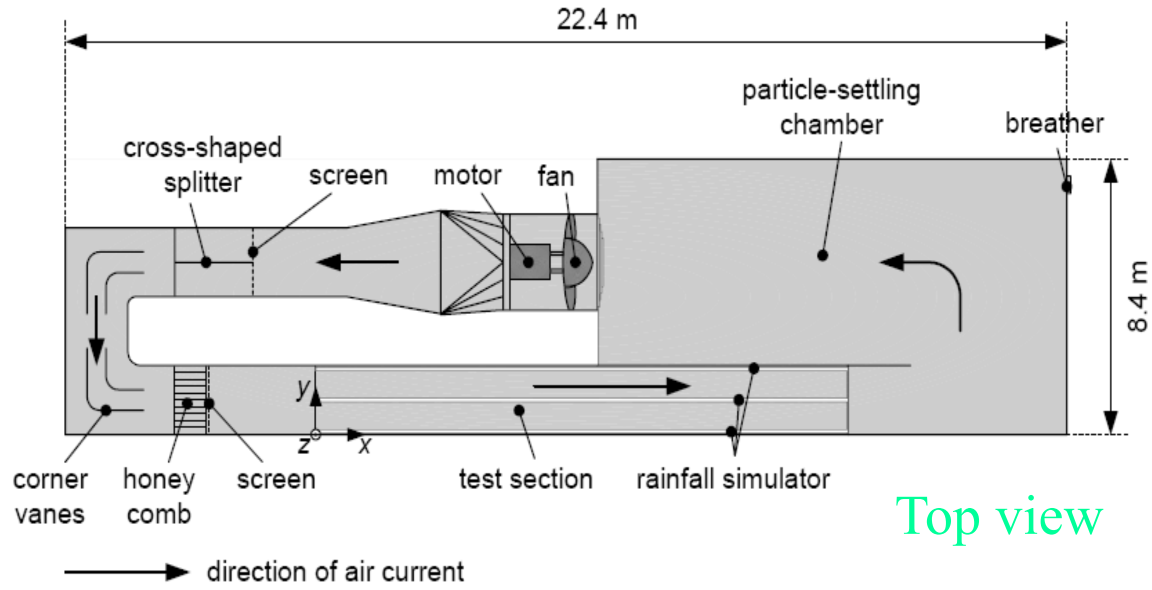
Department of Soil Science, Faculty of Agriculture, Ankara University, Diskapi, Ankara 06110, Turkey; Email: erpul@agri.ankara.edu.tr



Top view

Wind tunnel rainfall facility of ICE

Air Flow Dynamics

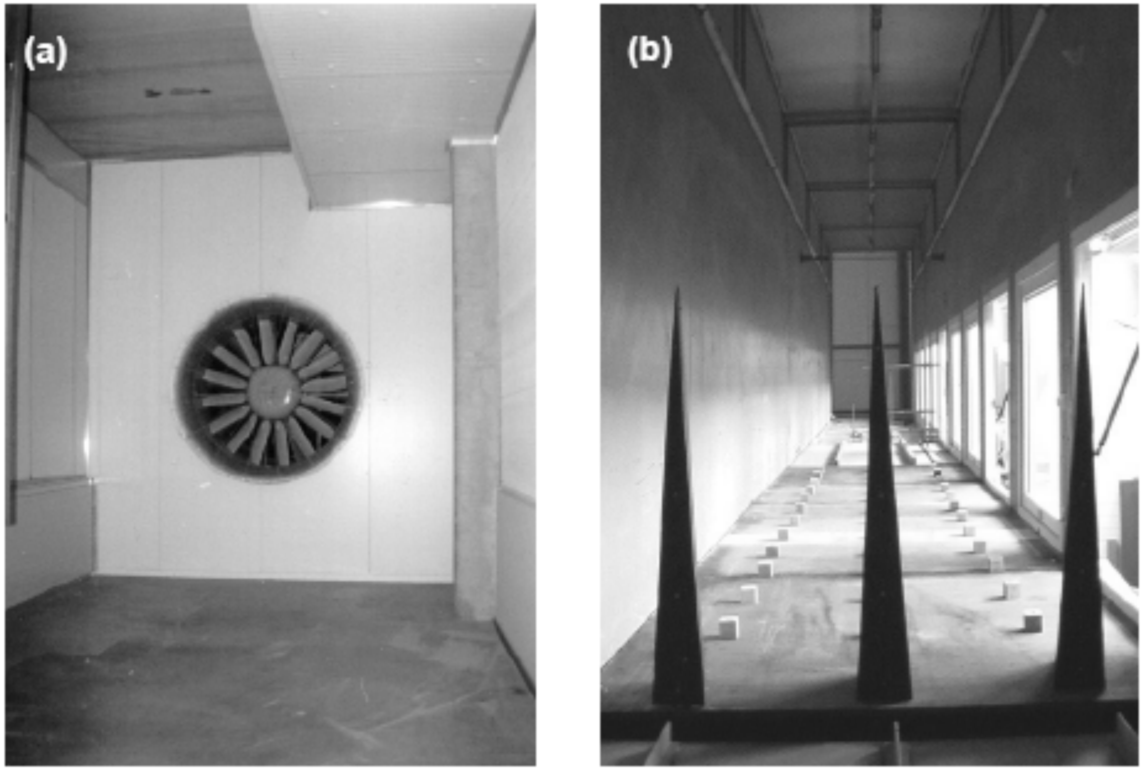


Figure 2. a) The axial fan with 16 adjustable blades and b) cross-sectional view of the test section with an array of spires and roughness elements.

Vertical wind-velocity profiles and boundary layer thickness

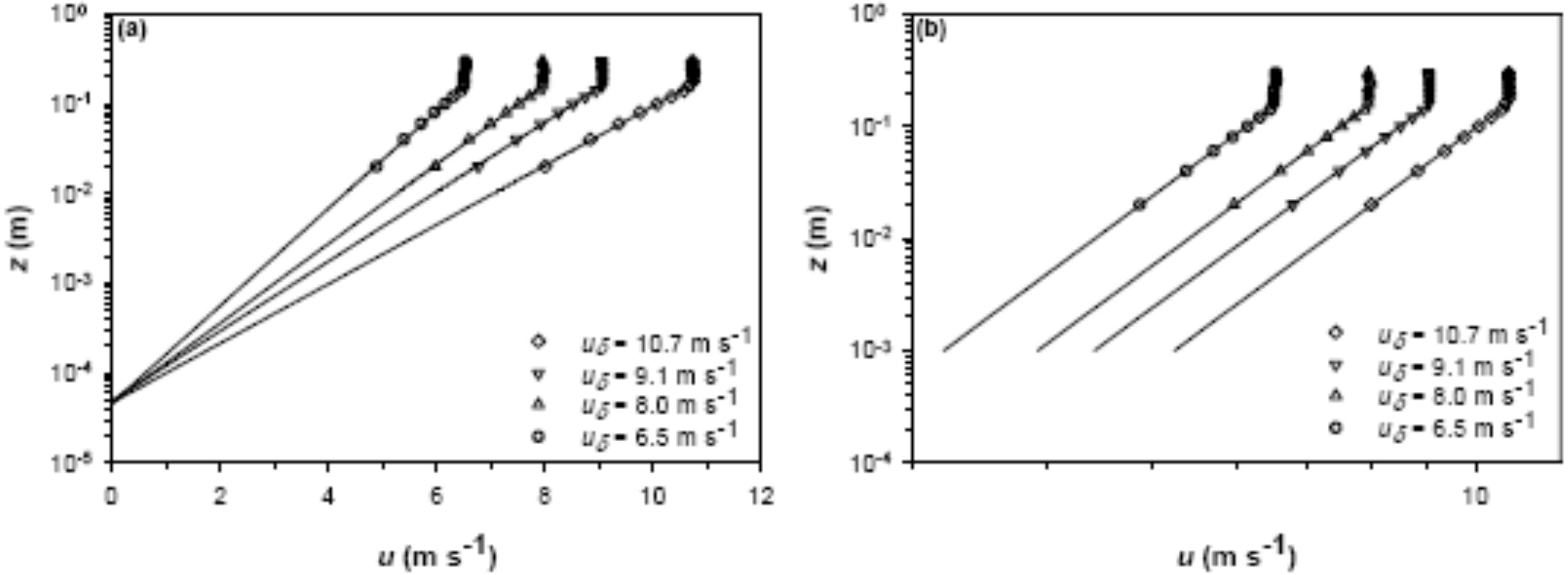


Figure 6. Vertical wind-velocity profiles measured at x = 6.0 m and y = 0.6 m at different free-stream wind velocities u_δ: wind velocity u as a function of height z. The logarithmic law (Eq. (3)) (a) and the power law (Eq. (4)) (b) were fitted to the within-boundary-layer data by linear regression. Note that (a) is on semi-log scale, whereas (b) is on log-log scale. Spires and roughness elements were absent.

$$u = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$$

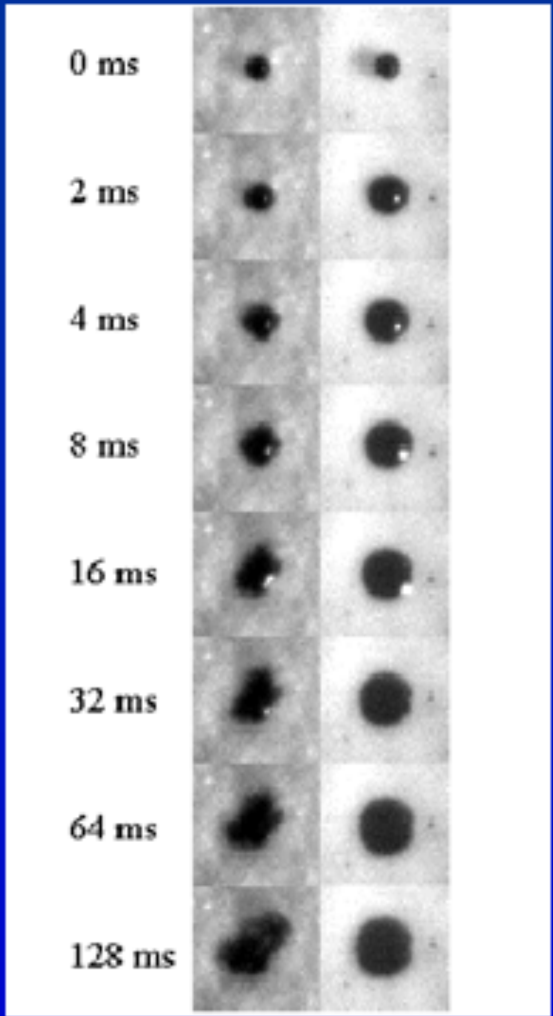
Prandtl-von Kármán law (Prandtl, 1932)

WDR Characteristics

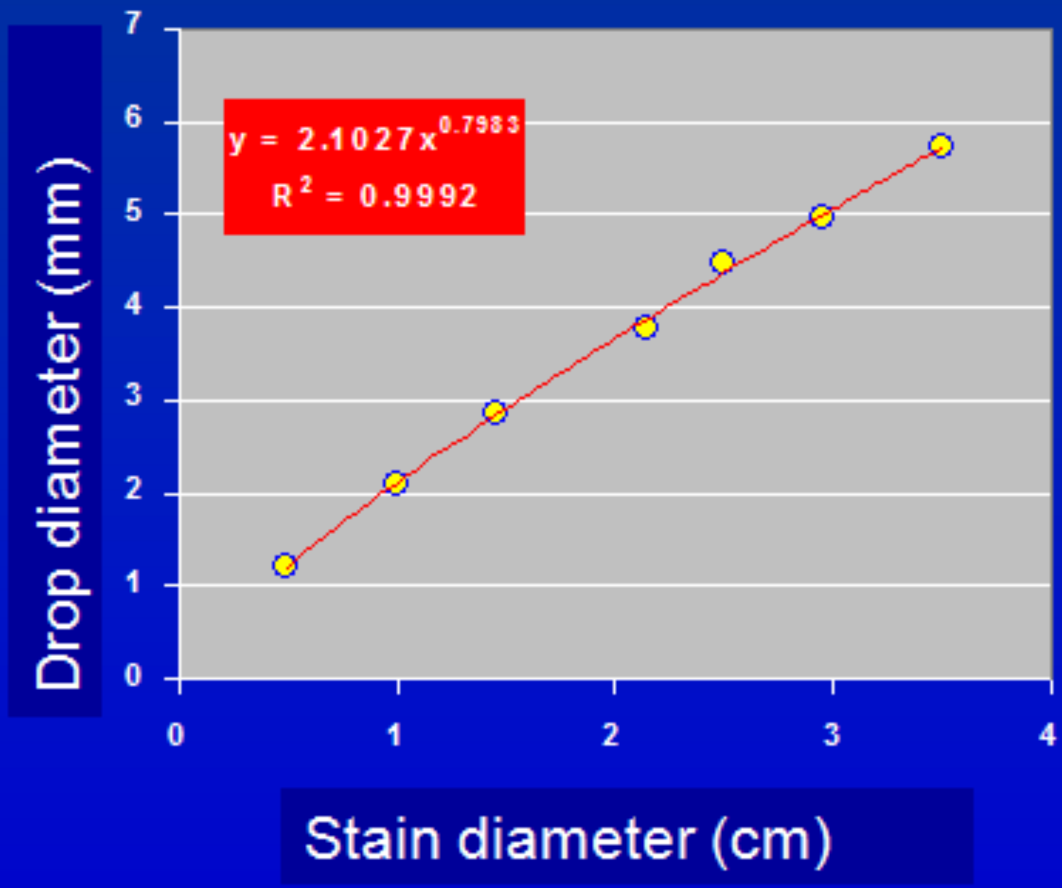
- Size distribution
- Inclination
- Impact velocity (energy)
- Impact frequency (intensity)

Raindrop size distribution

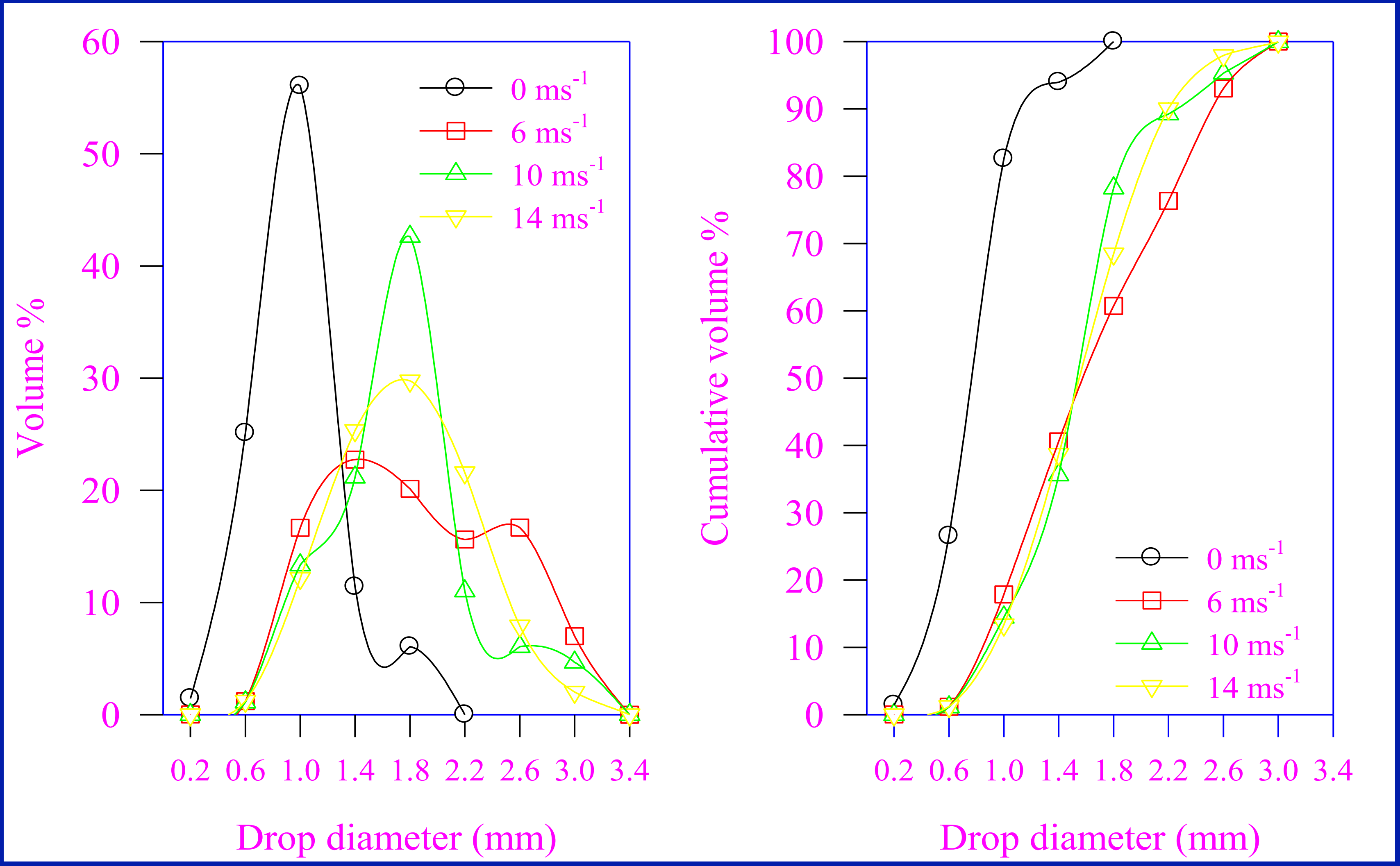
Stain method



Calibration curve



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

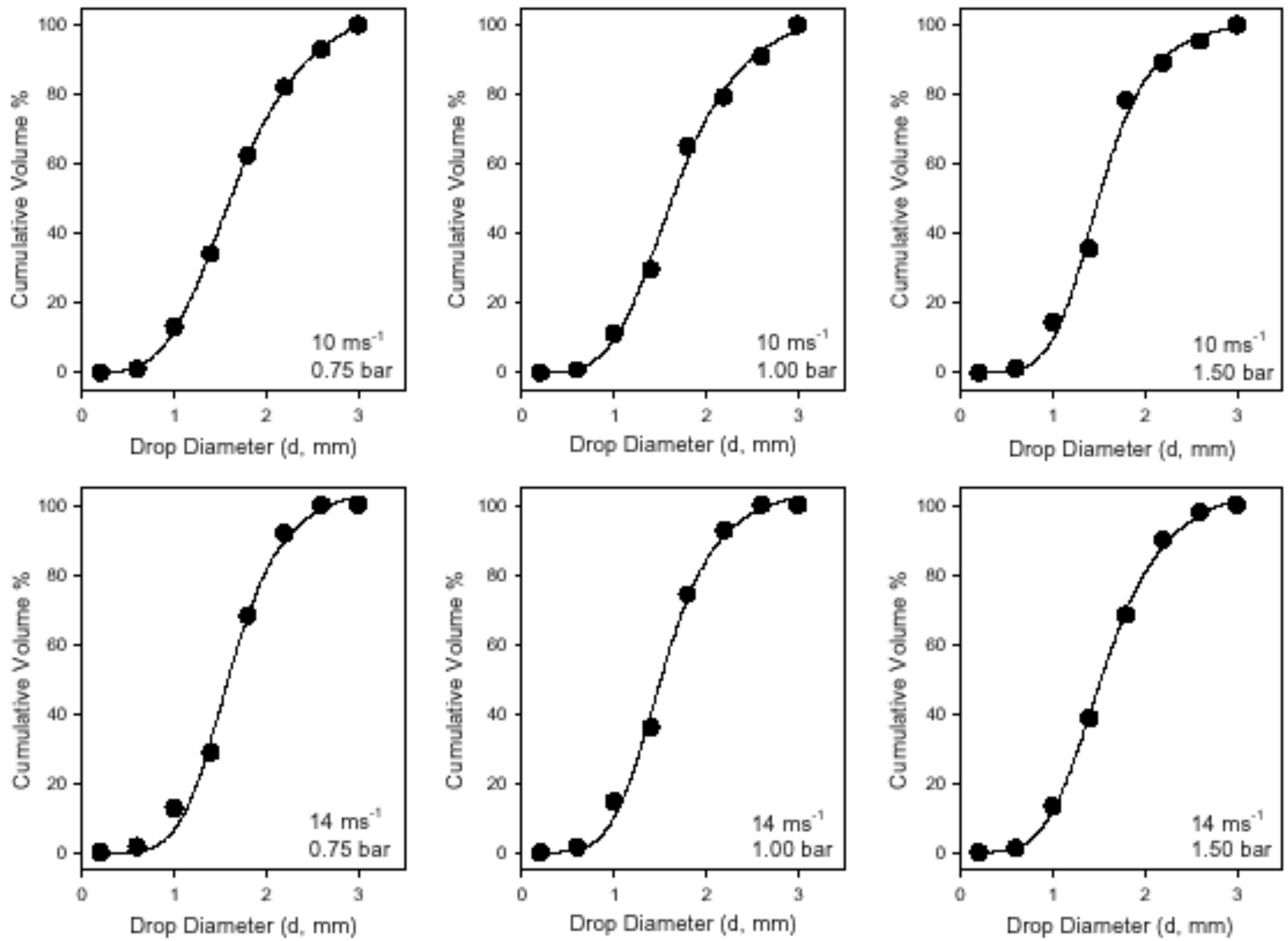


Fig. 17. Cumulative volume percentage of drop sizes for windless rains and the rains driven by 6, 10, and 14 m s^{-1} wind velocities at 75, 100, and 150 kPa operating pressures.

Lojistic growth model to assess the drop size distributions

$$F(d) = \frac{100}{1 + \exp\left[-\beta d - \gamma\right]}$$

$$d_{25} = -\left(\frac{\ln(3) + \gamma}{\beta}\right) \qquad d_{50} = -\left(\frac{\gamma}{\beta}\right) \qquad d_{75} = -\left(\frac{\ln\left(\frac{1}{3}\right) + \gamma}{\beta}\right)$$

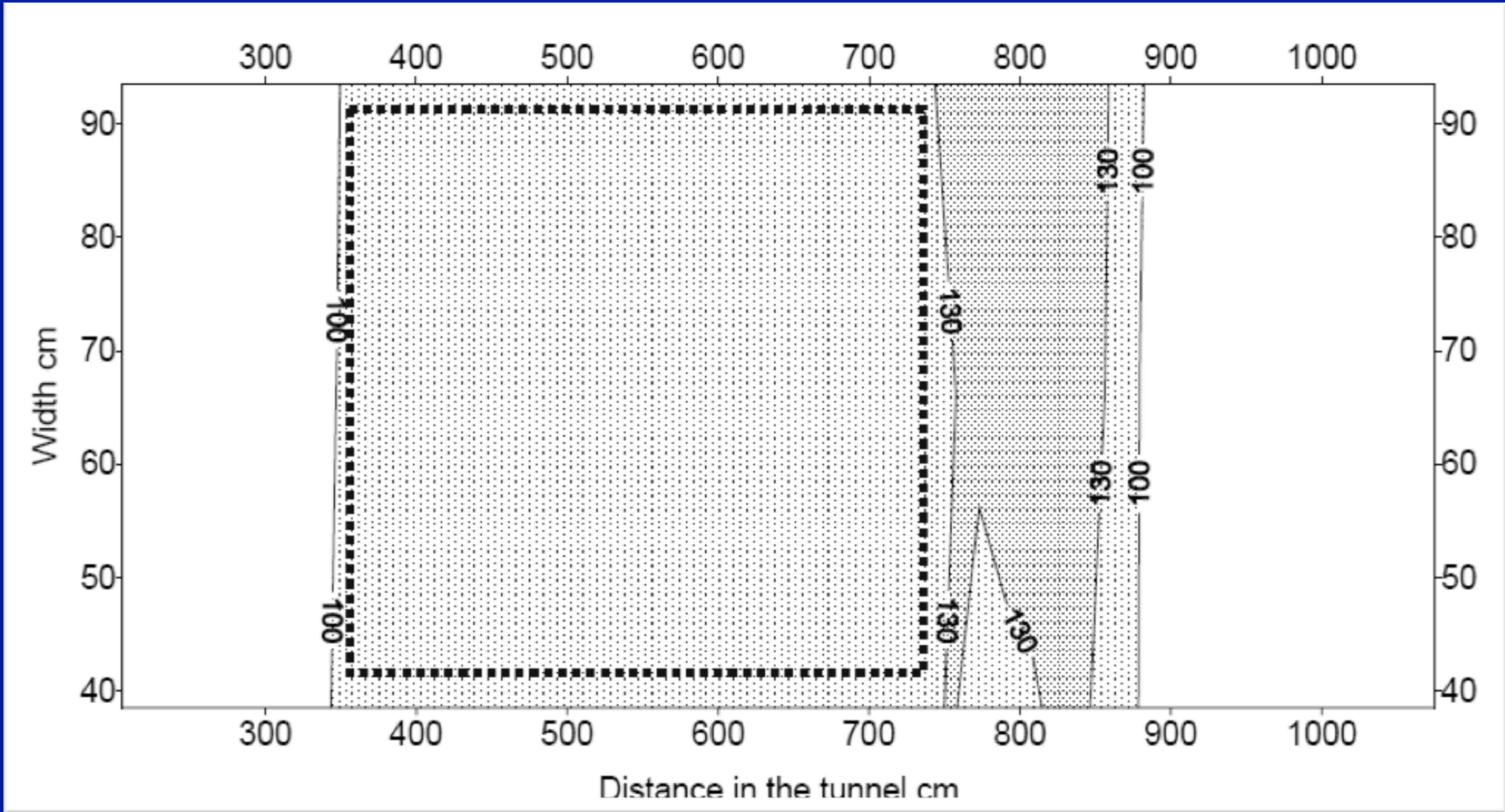
$$\Psi = \left[\left(d_{75} - d_{25}\right)/d_{50}\right]$$

$$\Phi = \left(d_{75}/d_{25}\right)$$

Ψ: sorting coefficient

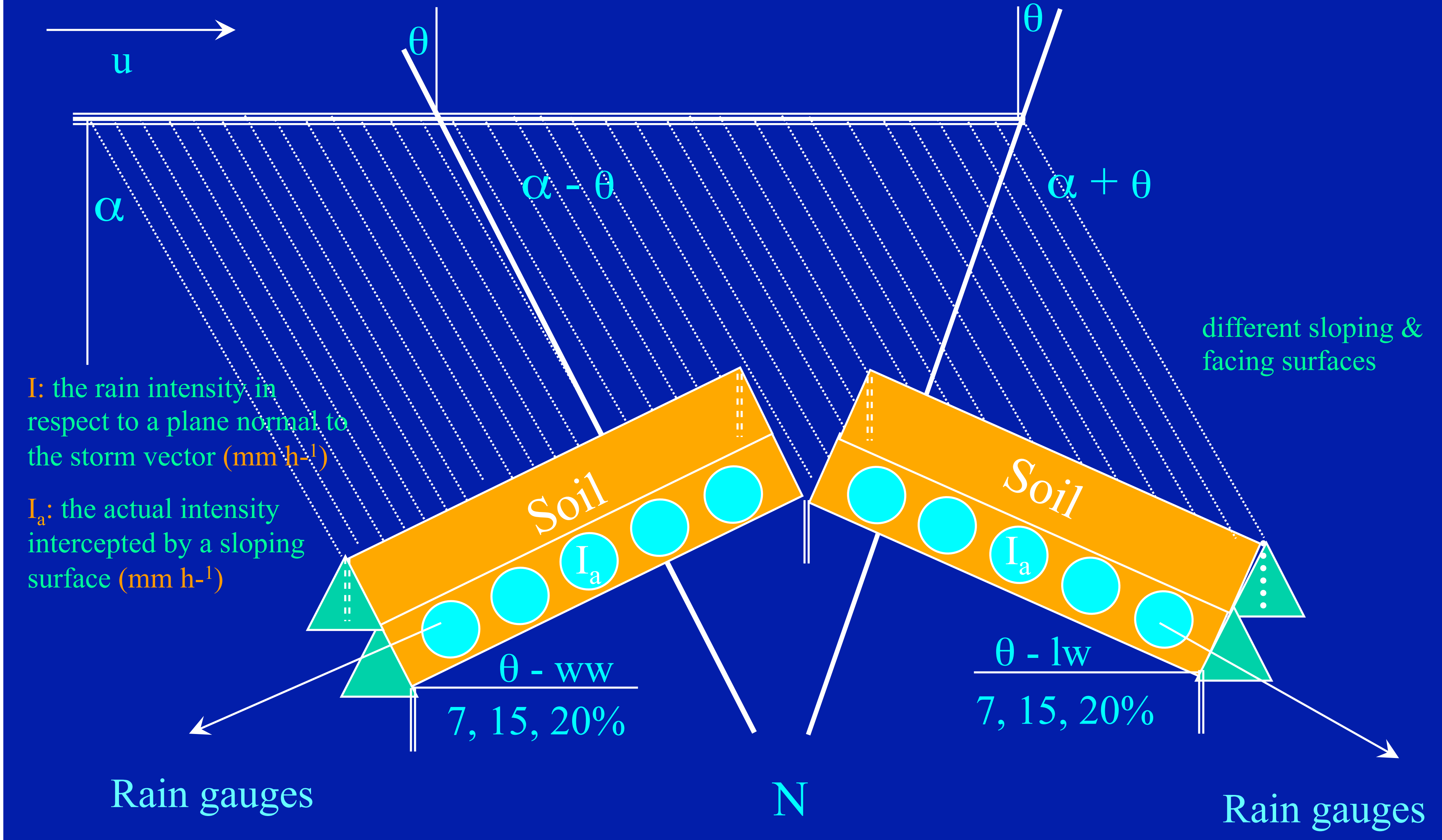
Φ: spreading coefficient

Raindrop impact frequency



The iso-intensity lines to locate the working area (rectangle), which was the basis for the calculations of Cv and the determination of the drop size distribution in the wind tunnel

Rain inclination



$$\cos(\alpha \mp \theta) = \cos\alpha\cos\theta \pm \sin\alpha\sin\theta\cos(z_\alpha \mp z_\theta)$$

$$\phi = \frac{I_a}{I} = \frac{\Xi_a}{\Xi} = \cos(\alpha \mp \theta)$$

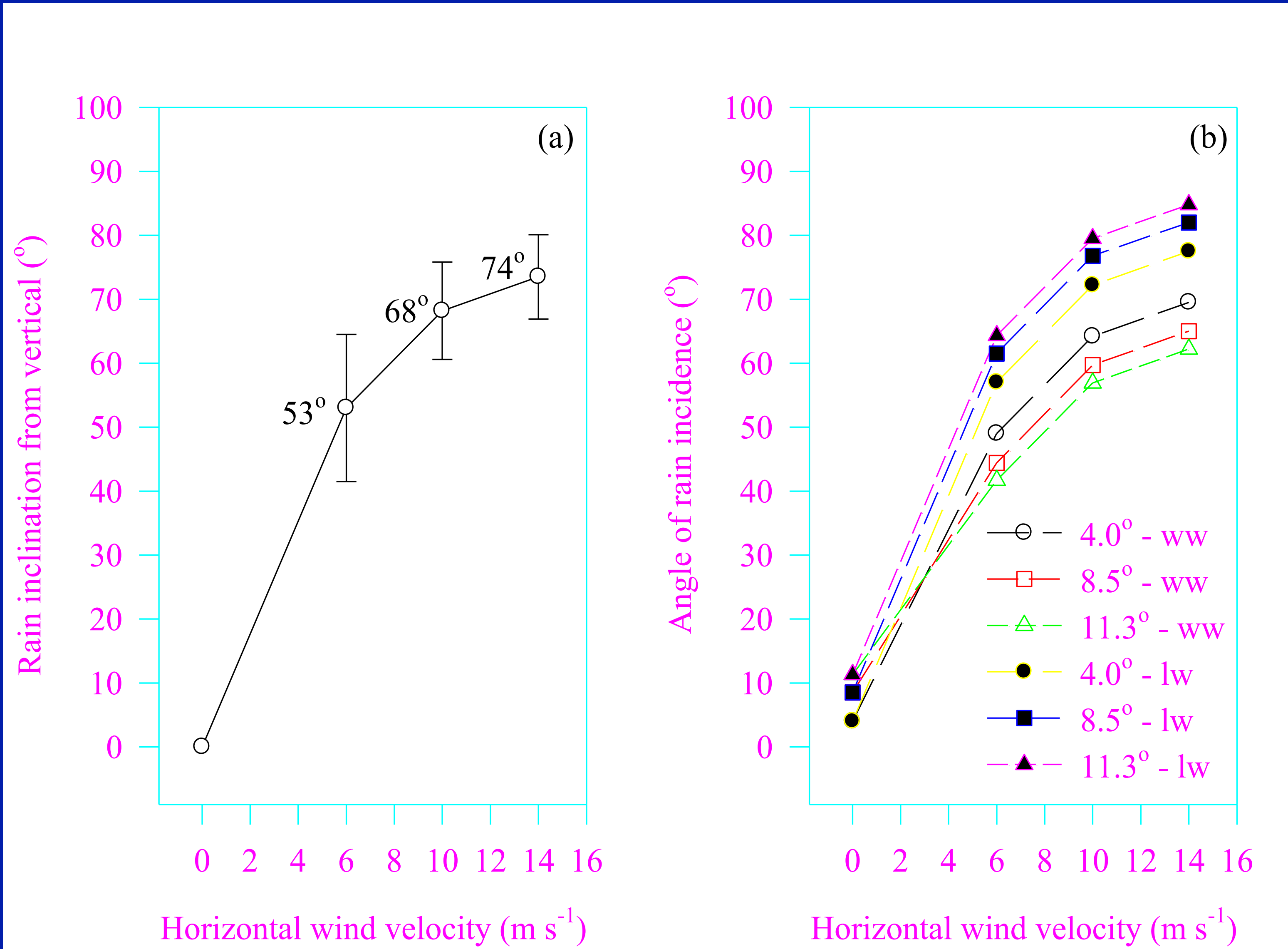
$$I = \frac{I_{ww1}}{\cos(\alpha - \theta_1)} = \frac{I_{ww2}}{\cos(\alpha - \theta_2)} = \frac{I_{ww3}}{\cos(\alpha - \theta_3)}$$

$$I = \frac{I_{lw1}}{\cos(\alpha + \theta_1)} = \frac{I_{lw2}}{\cos(\alpha + \theta_2)} = \frac{I_{lw3}}{\cos(\alpha + \theta_3)}$$

$$\alpha = \tan^{-1}\left[\frac{\cos\theta_1 - (I_{ww1}/I_{ww2})\cos\theta_2}{(I_{ww1}/I_{ww2})\sin\theta_2 - \sin\theta_1}\right] = \tan^{-1}\left[\frac{\cos\theta_1 - (I_{ww1}/I_{ww2})\cos\theta_3}{(I_{ww1}/I_{ww3})\sin\theta_3 - \sin\theta_1}\right]$$
$$= \tan^{-1}\left[\frac{\cos\theta_2 - (I_{ww2}/I_{ww3})\cos\theta_3}{(I_{ww2}/I_{ww3})\sin\theta_3 - \sin\theta_2}\right]$$

$$\alpha = \tan^{-1}\left[\frac{\cos\theta_1 - (I_{lw1}/I_{lw2})\cos\theta_2}{\sin\theta_1 - (I_{lw1}/I_{lw2})\sin\theta_2}\right] = \tan^{-1}\left[\frac{\cos\theta_1 - (I_{lw1}/I_{lw3})\cos\theta_3}{\sin\theta_1 - (I_{lw1}/I_{lw3})\sin\theta_3}\right]$$
$$= \tan^{-1}\left[\frac{\cos\theta_2 - (I_{lw2}/I_{lw3})\cos\theta_3}{\sin\theta_2 - (I_{lw2}/I_{lw3})\sin\theta_3}\right]$$

Rain inclination & ARI

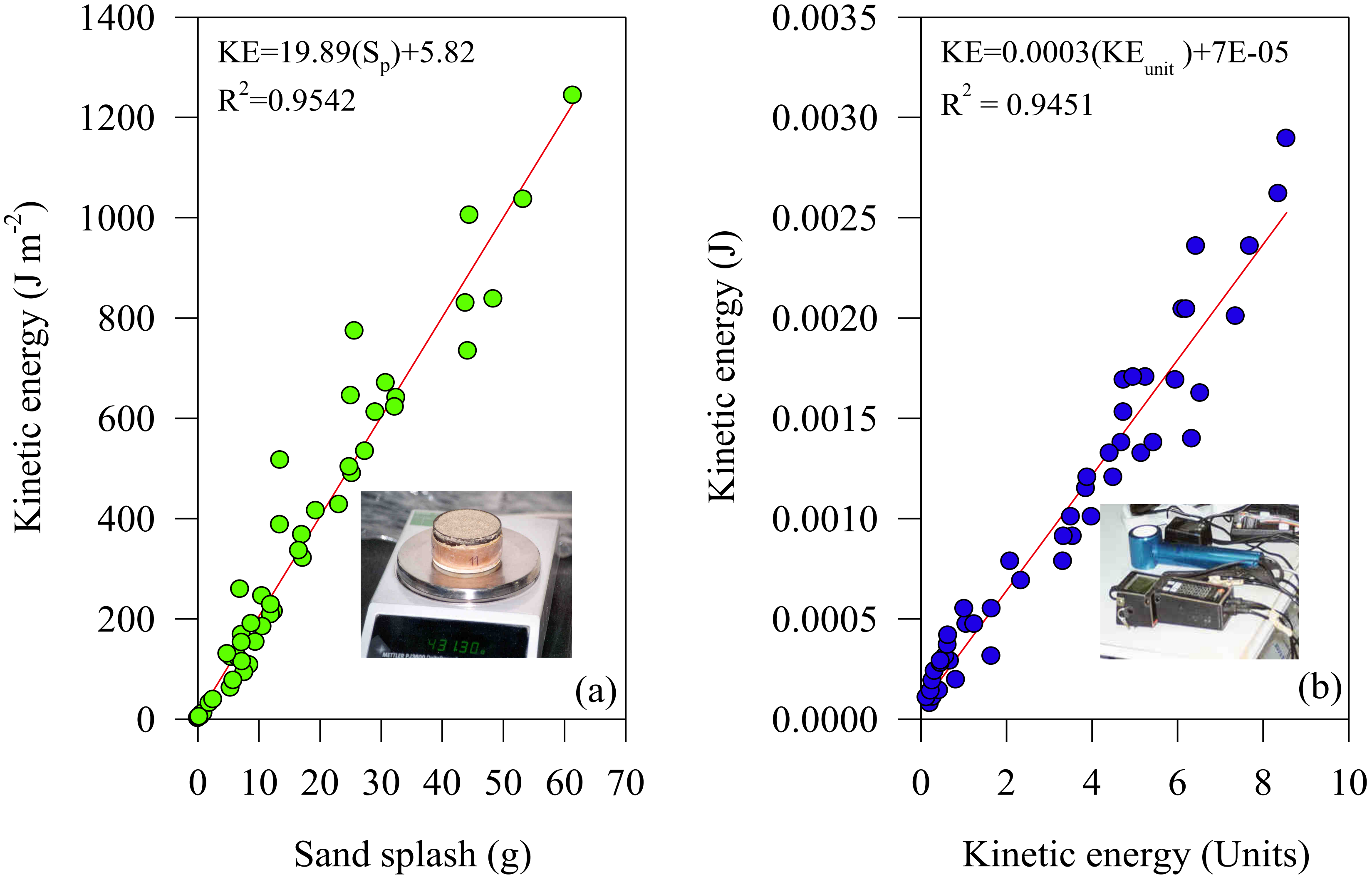


- Impact velocity (energy)
  - Splash cup technique
  - Kinetic energy sensor
  - Analytical calculation

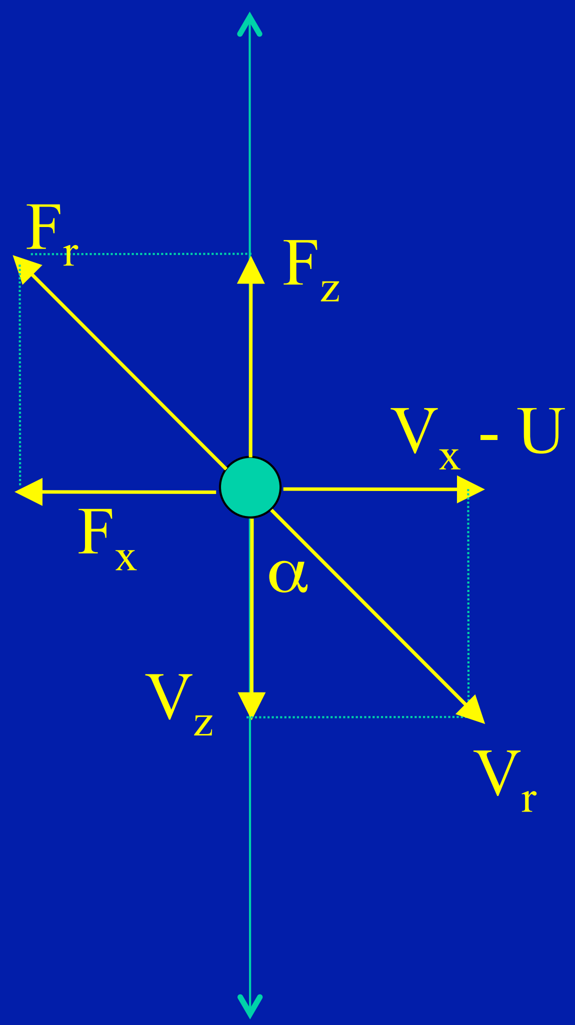
Splash cup technique

Sensit

Raindrop impact energy



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



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

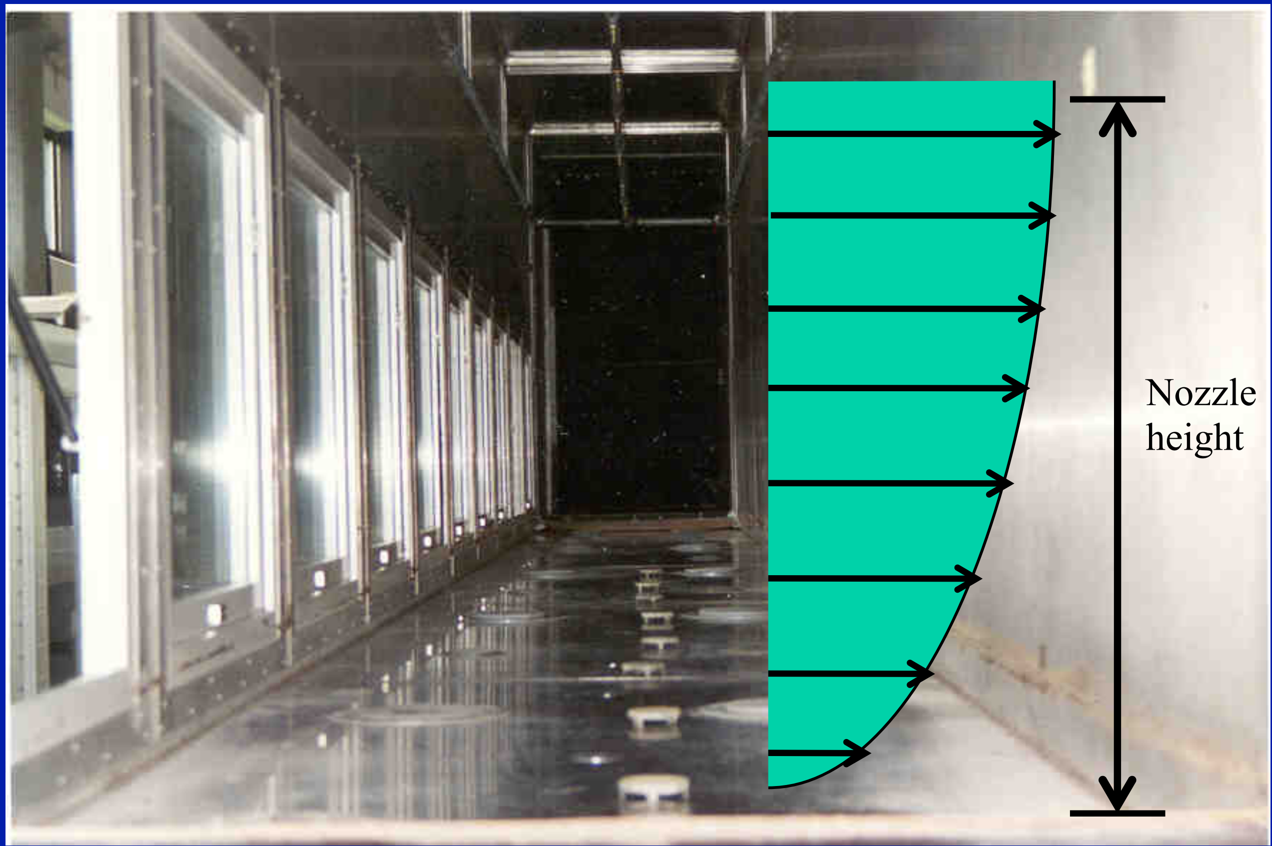
$$m\frac{\partial^2 x}{\partial t^2} = -\frac{1}{2} C_d \rho_a \left(\frac{\partial x}{\partial t}\right)^2 A$$

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

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

$$\frac{\left(\partial x/\partial t\right)}{\partial z} = \frac{3C_D \rho_a}{4D\rho_w}\left(\left(\partial x/\partial t\right) - U\right)$$

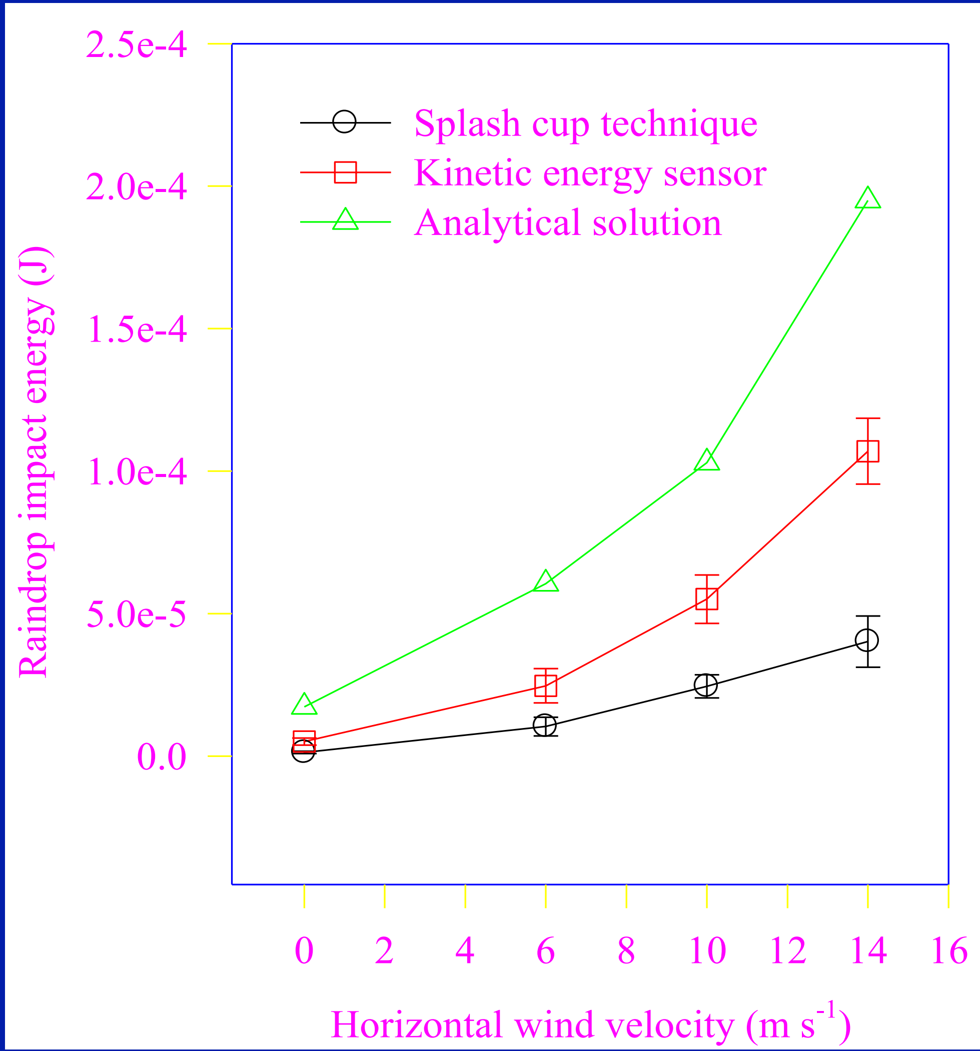
A very small value of relative velocity in the horizontal direction, $[(\partial x \ \partial t) - u] = 0.0001$, was used in order to initiate the downward integration.



$$u = \frac{u_*}{\kappa} \ln \frac{z}{z_0}$$

$$\frac{(\partial x/\partial t)}{\partial z} = \frac{3 C_D \rho_a}{4 D \rho_w} \left((\partial x/\partial t) - u \right)$$

Raindrop impact energy



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

$R^2 = 0.99$

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

$R^2 = 0.99$

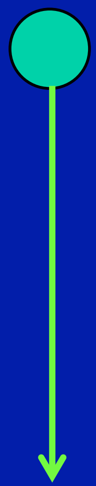
$$KE = 2E-06e^{0.2473u}$$

$R^2 = 0.96$

Where to start up with?

The main assumptions of Wind-Free Rains (WFR) (Water Erosion) & Rain-Free Wind (RFW) (Wind Erosion) used in current methodologies should be re-visited & questioned.

WFR-Assumption: vertical fall of raindrops under the gravitational and drag forces with no wind shear forces

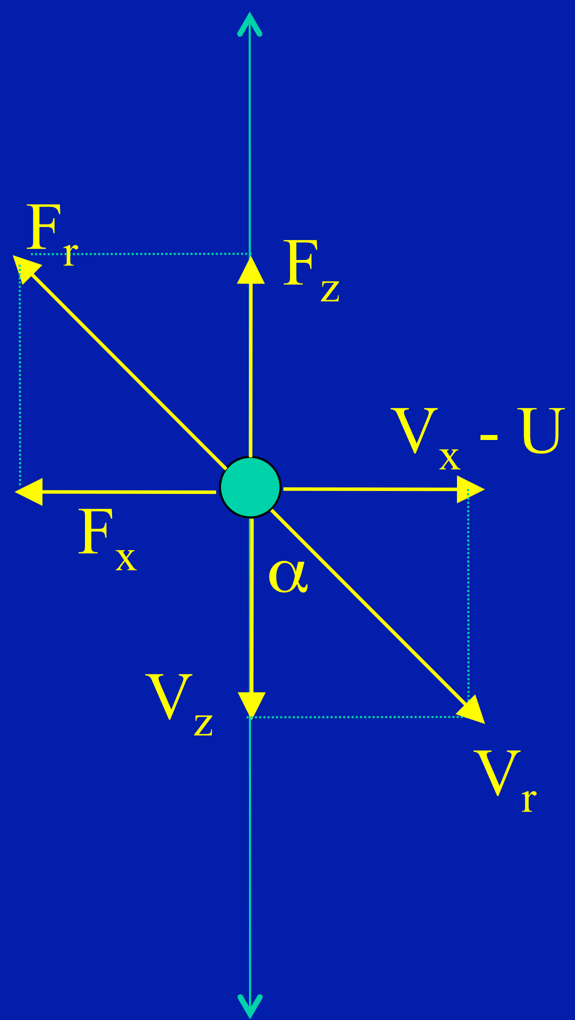


$$m\frac{\partial^2 z}{\partial t^2} = mg - \rho_a g \forall - \frac{1}{2} C_d \rho_a \left(\frac{\partial z}{\partial t}\right)^2 A$$

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

$$\left(\frac{\partial z}{\partial t}\right)^2 = \left[\frac{4}{3}\frac{gd}{C_D}\left(\frac{\rho_w}{\rho_a} - 1\right)\right]$$

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



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

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

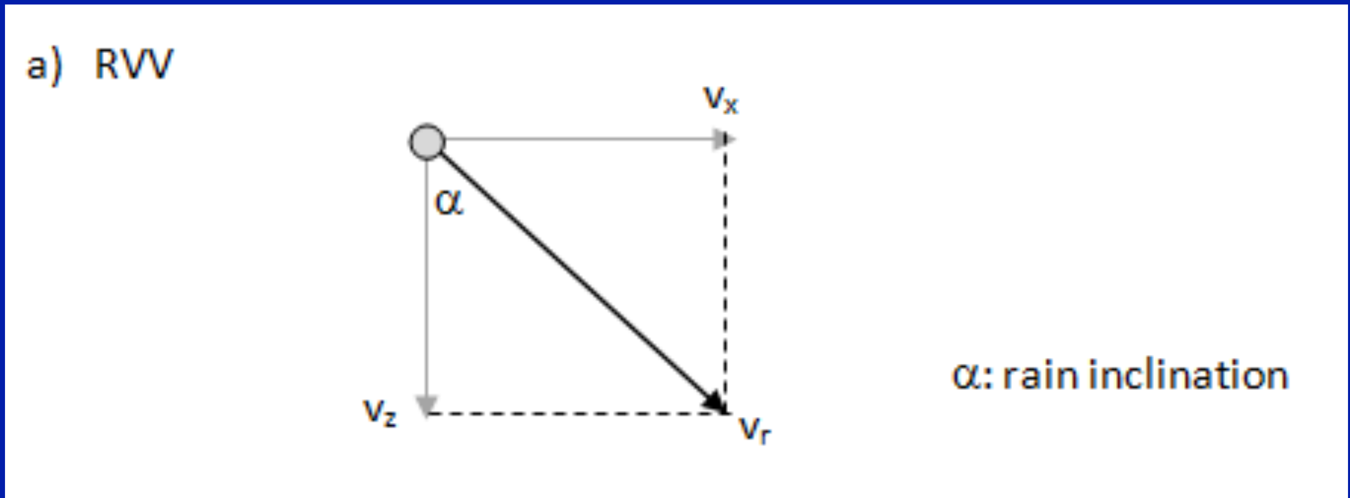
$$\sum F_z = m\left(\frac{d^2 z}{dt^2}\right) = 0$$

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

$$\frac{\left(\partial x/\partial t\right)}{\partial z} = \frac{3 C_D \rho_a}{4 D \rho_w}\left(\left(\partial x/\partial t\right) - U\right)$$

Raindrop impact velocity status of WDR changes before they hit the surface with wind shear forces.

Rainfall Velocity Vector (RVV): A vector field with no plane of incidence



$$\tan\alpha = \frac{\left(\left(\partial x / \partial t\right) - U\right)}{\left(\partial z / \partial t\right)}$$

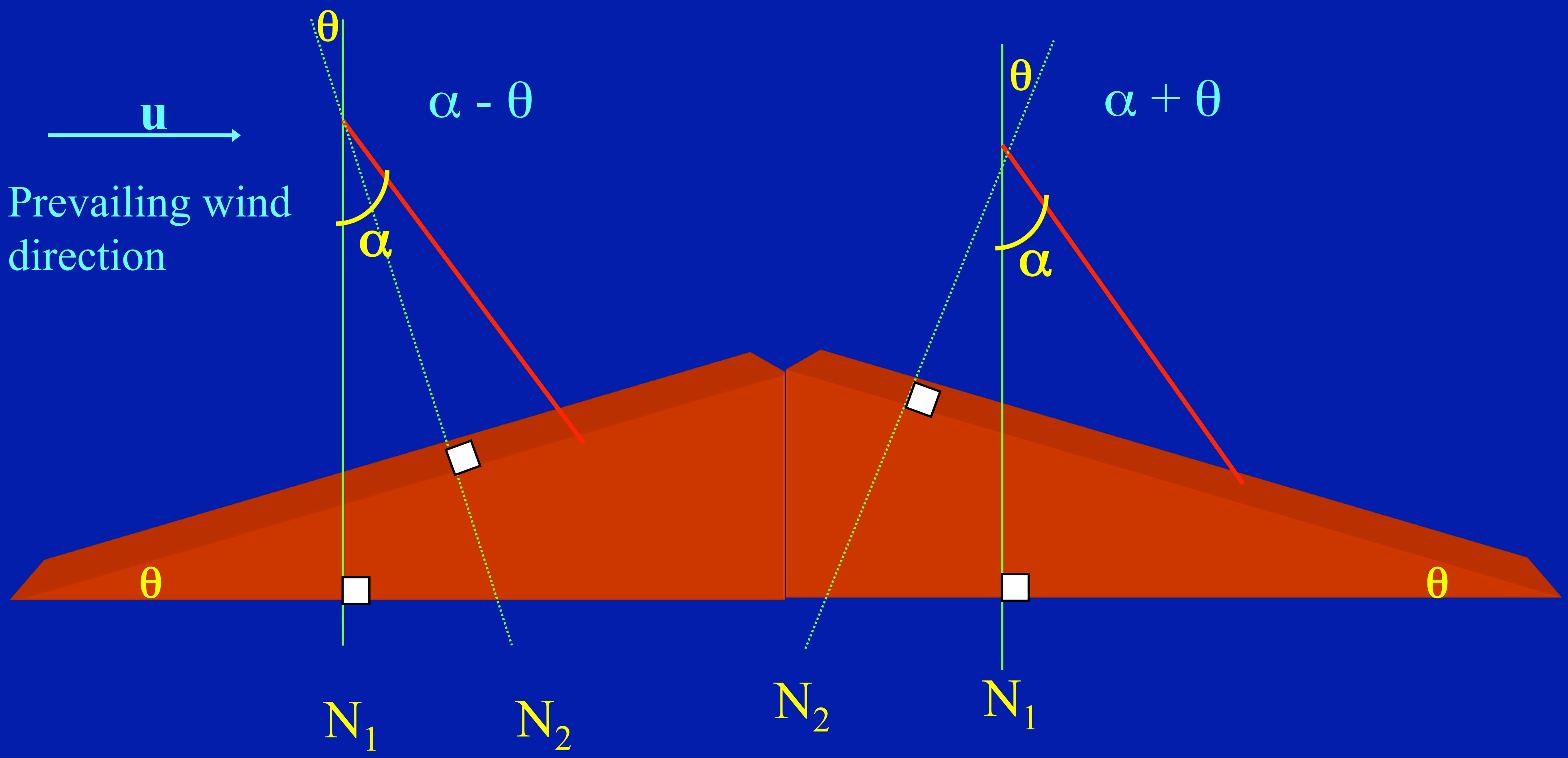
What happens at impact-soil interface?

A vector field changes not only with rain inclination but also with slope aspect and slope degree of the plane

Rainfall Impact Velocity Vector (RIVV):

A vector field together with plane of incidence

The angle of rain incidence (ARI) is measured from the normal to the plane of incidence (WDR)



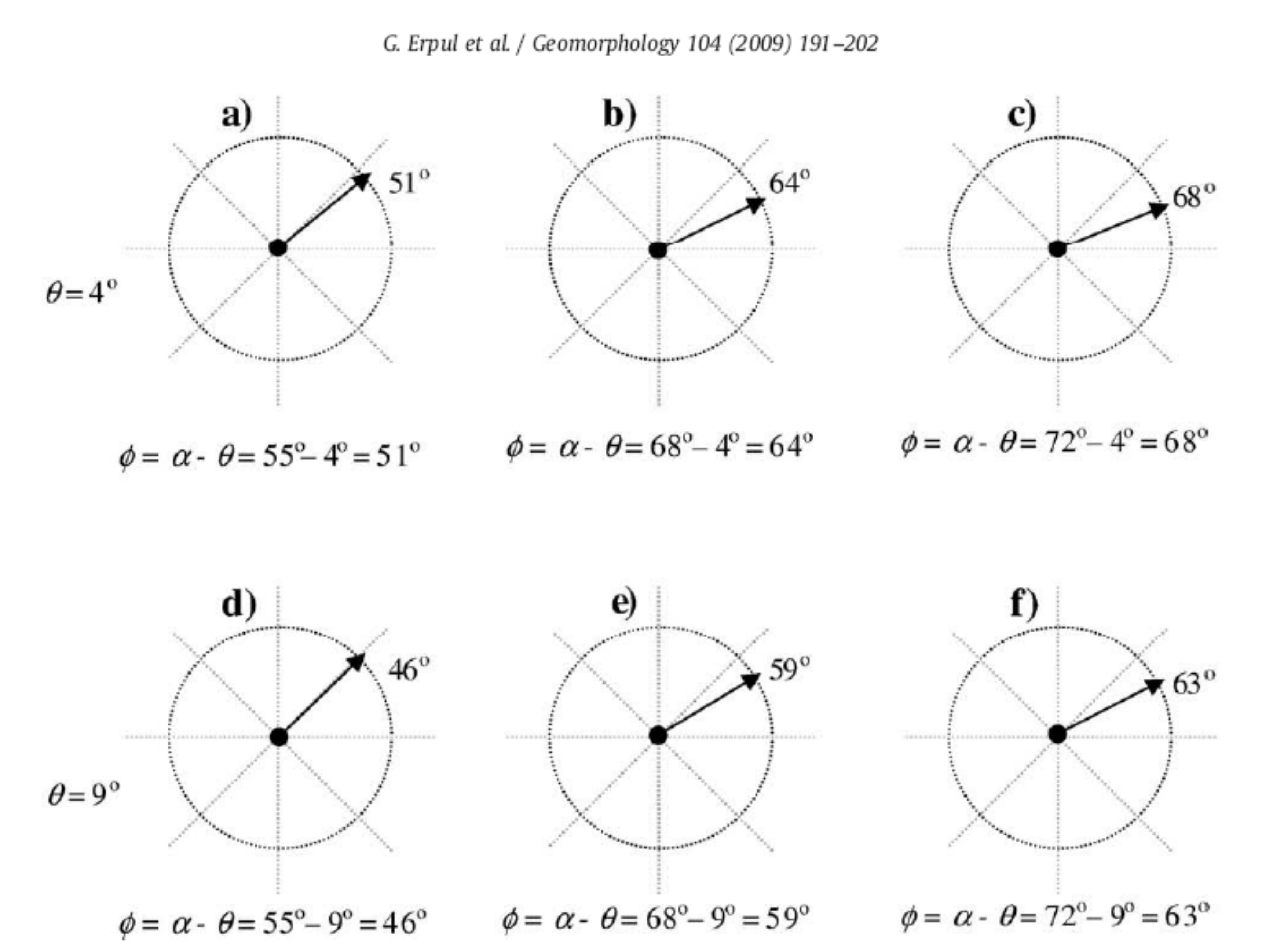


Fig. 5. The angle of rains incident on the sand test surface placed at windward slopes

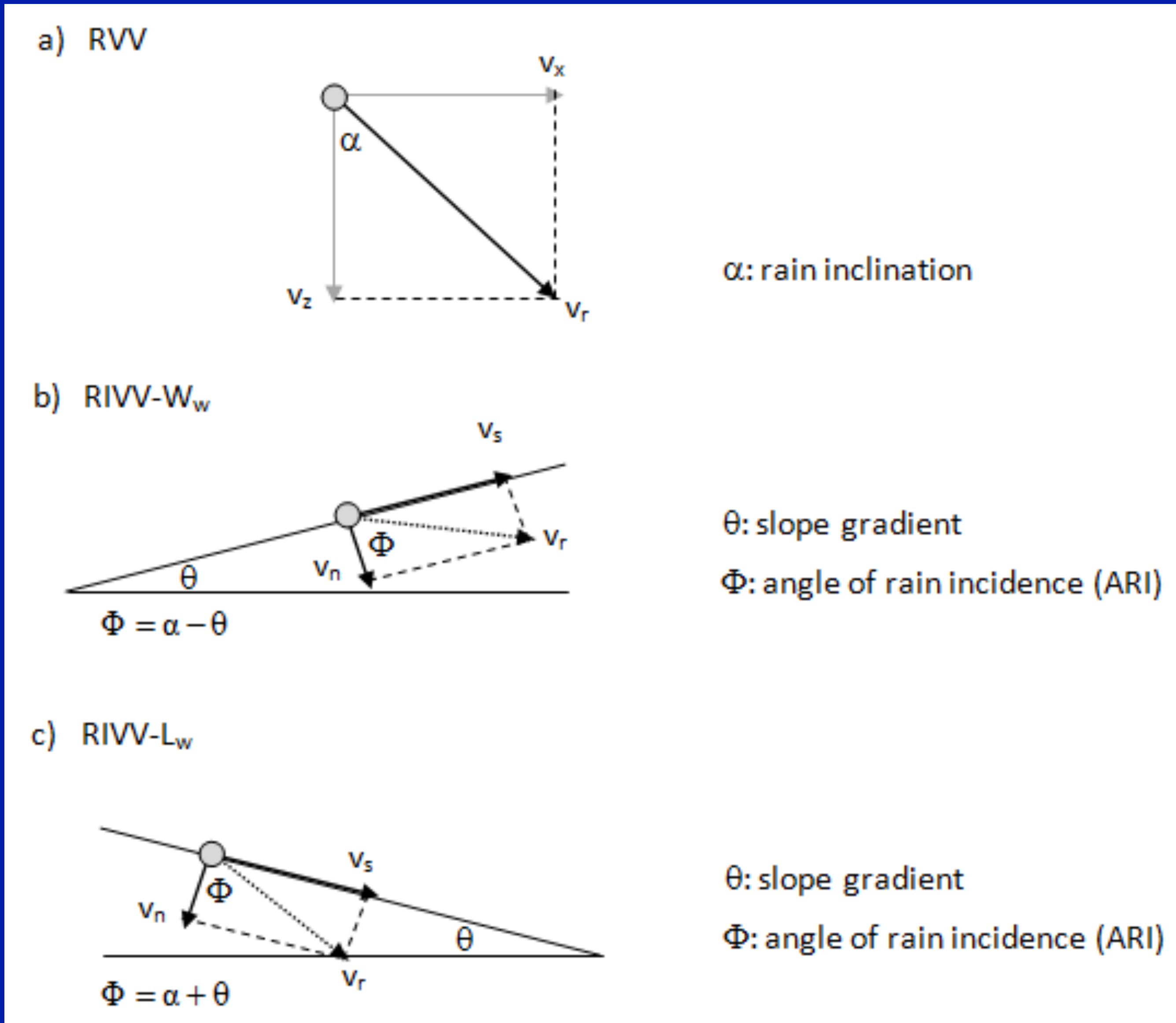
Partition of the resultant impact velocity of the wind-driven raindrop

The cosine law of spherical trigonometry (Sellers, 1965; Sharon, 1980)

$$\cos(\alpha \mp \theta) = \cos\alpha\cos\theta \pm \sin\alpha\sin\theta\cos(z_\alpha \mp z_\theta)$$

z_α and z_θ: azimuth from which rain is falling and azimuth towards which the plane of surface is inclined, respectively.

Partition of the resultant impact velocity using Angle of Rain Incidence (ARI)



$$v_r^{\ 2} = v_n^{\ 2} + v_s^{\ 2}$$

$$v_s = v_r \sin\Phi$$

$$v_n = v_r \cos\Phi$$

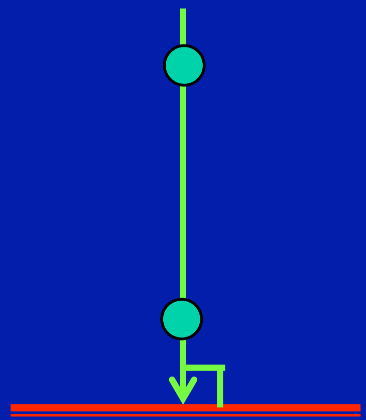
The effect of ARI on the raindrop impact energy status of WDR doubles up

$$v = f(\Phi)$$

$$E = f(v^2)$$

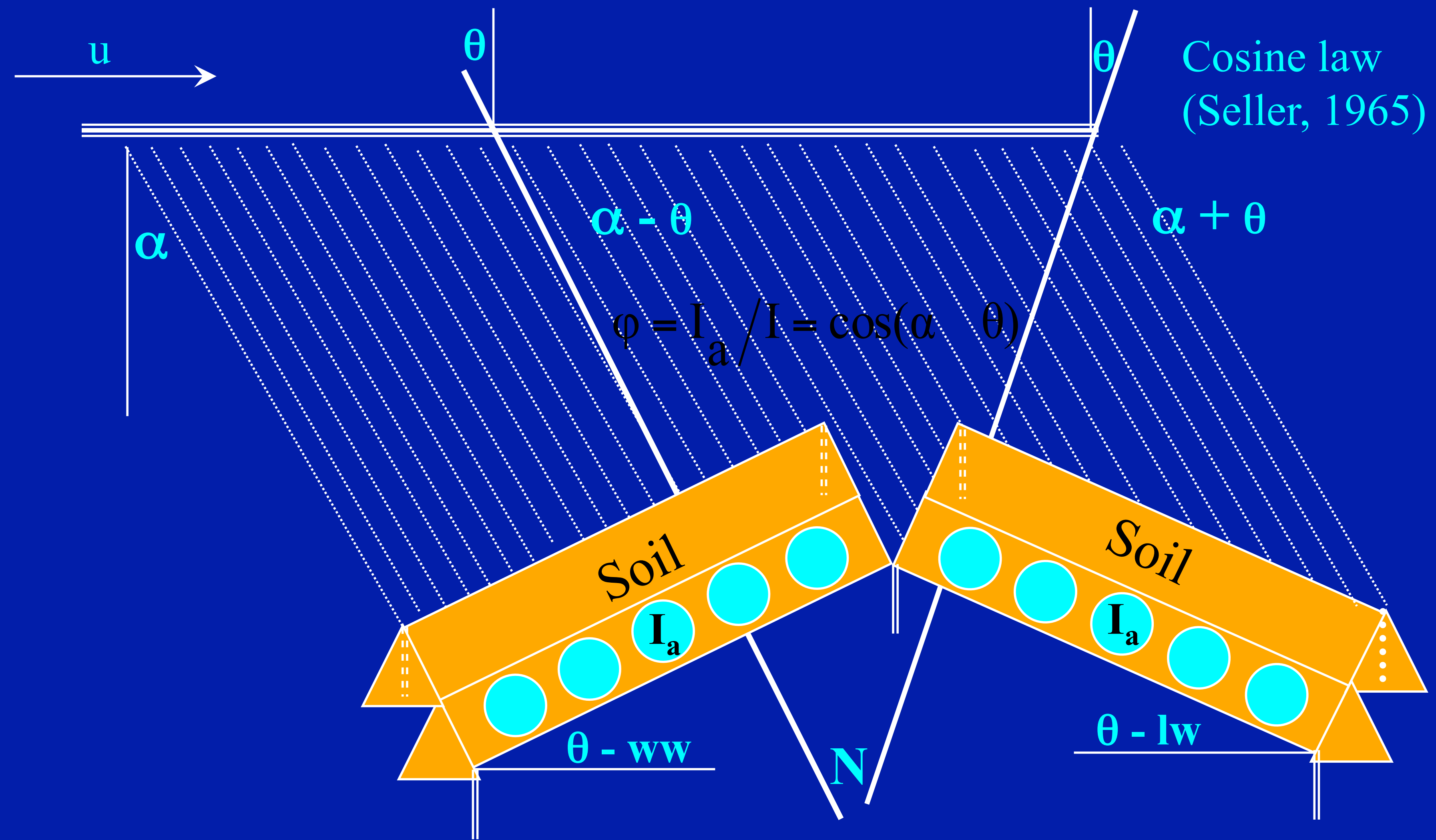
$$E = f(\Phi^2)$$

WFR-Assumption : maximum interception of vertically hitting raindrops by soil surface



- Max. rain intensity
- Max. raindrop impact frequency

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



- 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

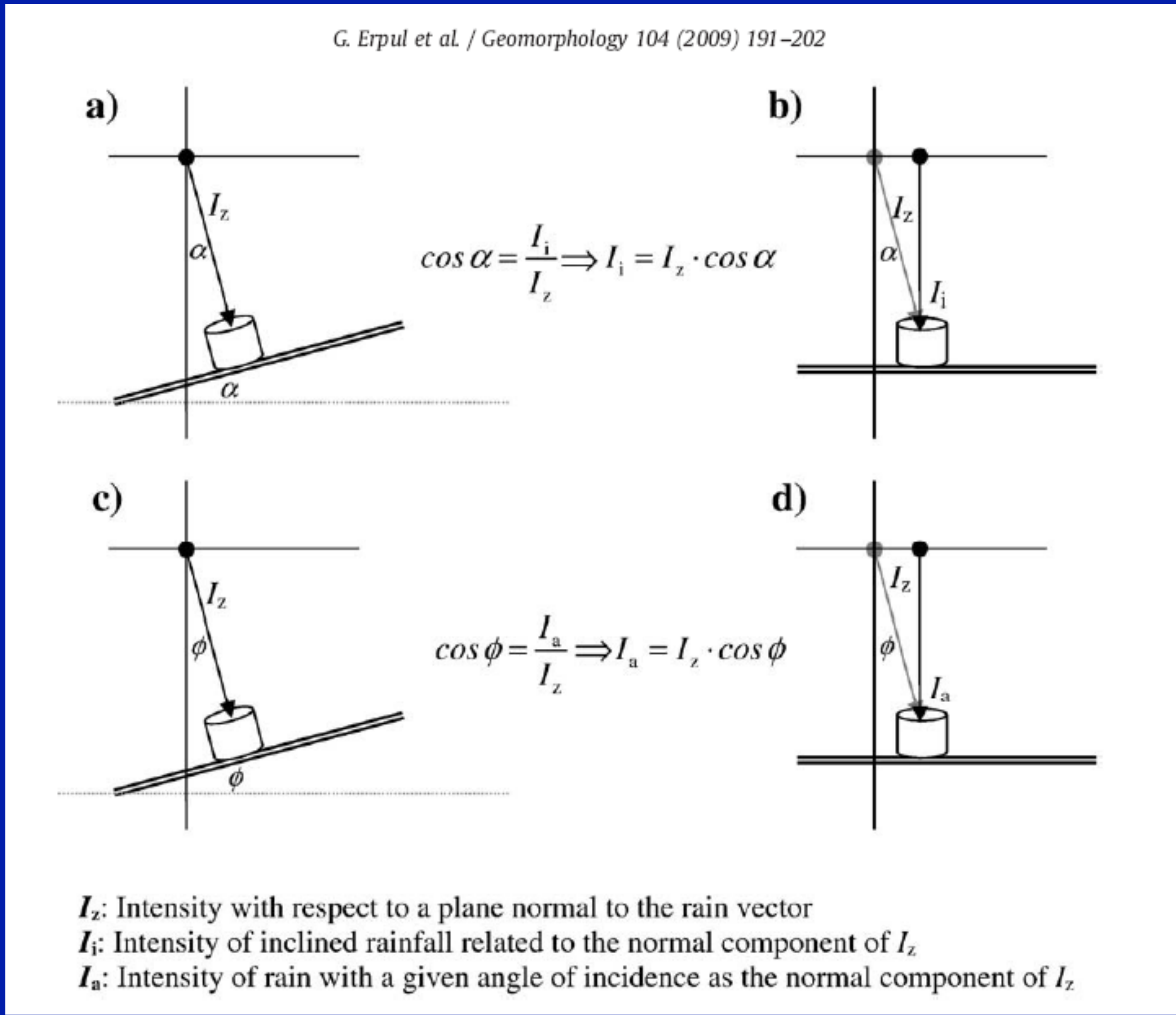


Fig. 3. Inclined rain intensity measurements (I_i) on the horizontal plane (a, b) (Erpul, 1996) and the calculation of the actual rain intensity (I_a) from Ii values under a given angle of incidence (c, d).

The effect of ARI on the energy flux status of WDR triples up

$$I = f(\Phi)$$

$$E = f(\Phi^2)$$

$$E \times I = f(\Phi^3)$$

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	$E = f(I)$	$E = f(I,u)$	$E = f(I,u)$

→ WEPP, RUSLE

- at parameter level
  - A vector field is very significant for WDR studies
    - Wind-driven raindrop velocity
    - Wind-driven raindrop energy
    - Wind-driven rain intensity (amount, frequency)
    - Wind-driven rain energy flux (energy multiplied by frequency)

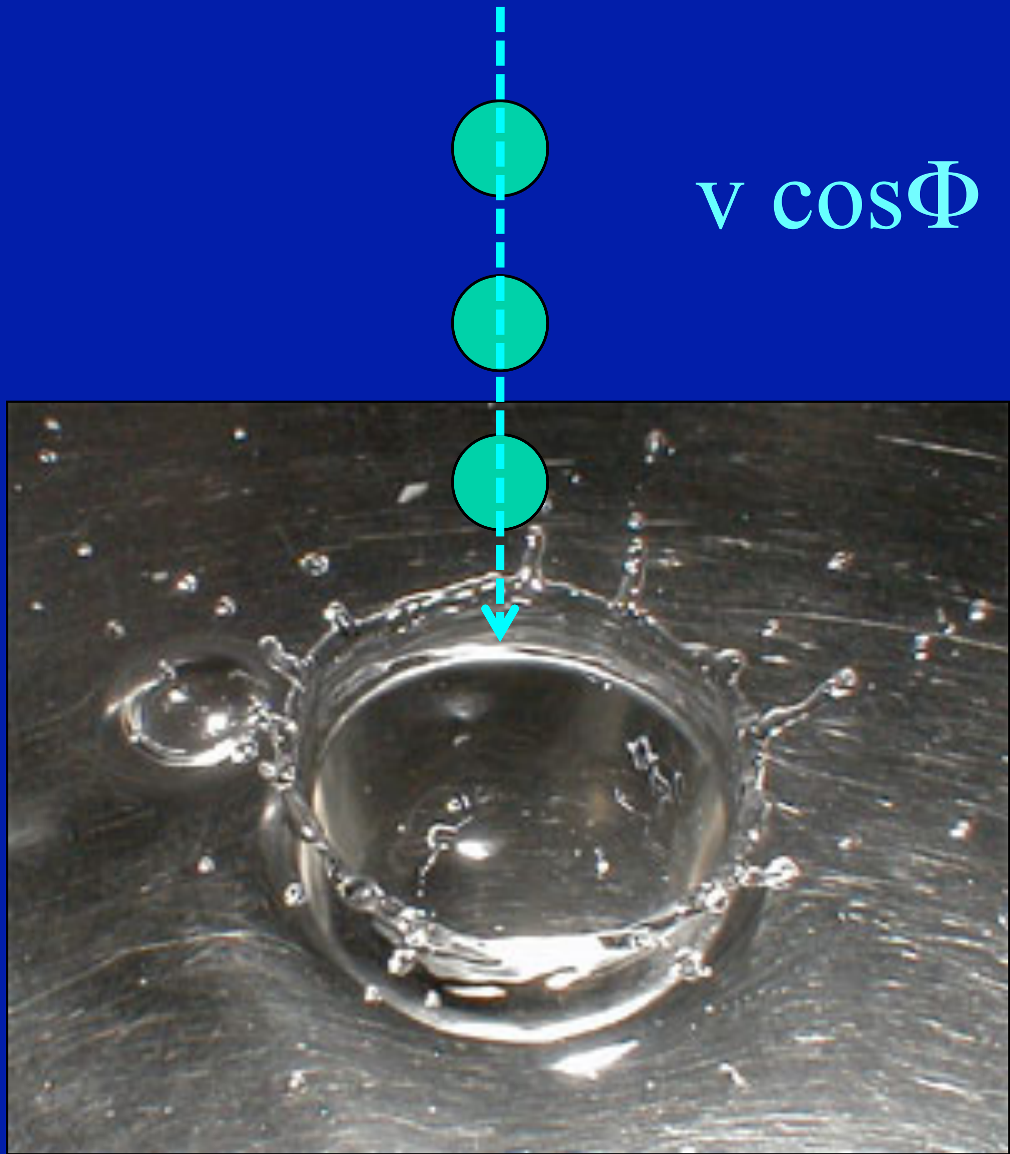
What about WDR erosion processes?

WFR-Assumption: Rainsplash Detachment

Compensatory Lateral Jet Development

No impact pressure acts on a soil surface by a raindrop with a velocity *v* regardless of its magnitude that is parallel to the surface, and the soil surface experiences a maximum impact pressure when raindrops fall perpendicular to the soil surface (Ellison, 1947). In general, if a raindrop falls at an ARI, only the component of velocity $v \cos\Phi$ (ms^{-1}) normal to the soil surface gives rise to an impact pressure (Heymann, 1967; Springer, 1976).

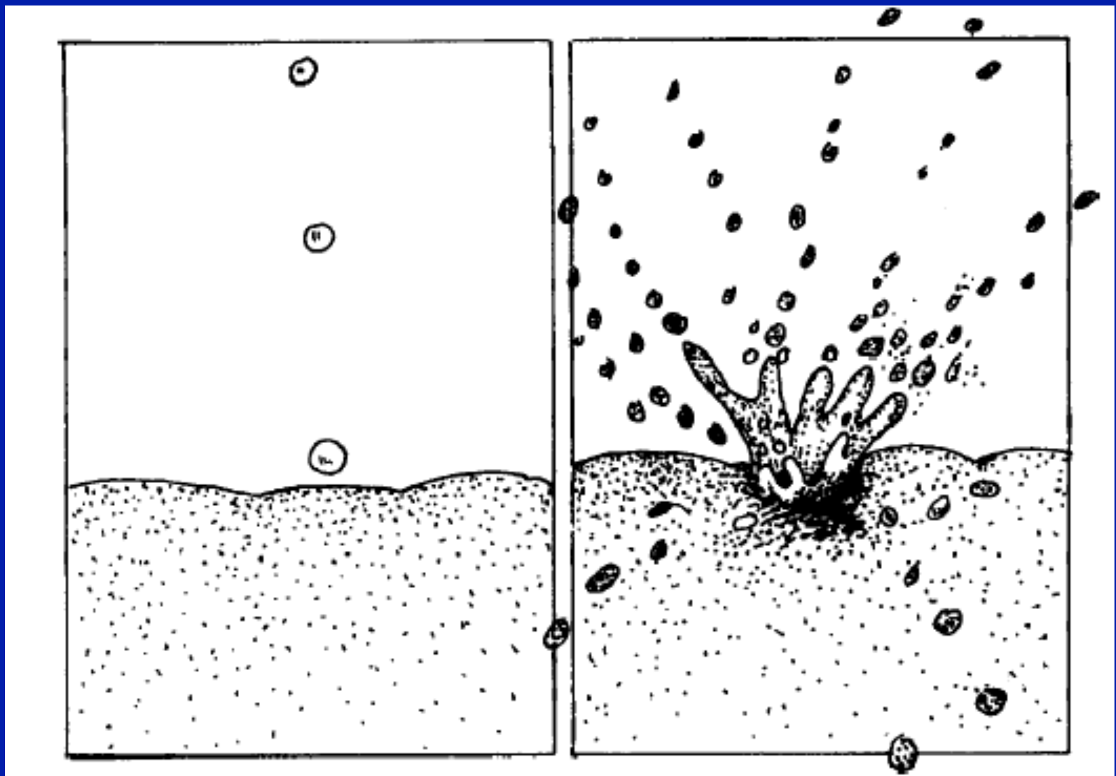
WFR-Assumption: the compressive pressure build-up at the raindrop–soil interface

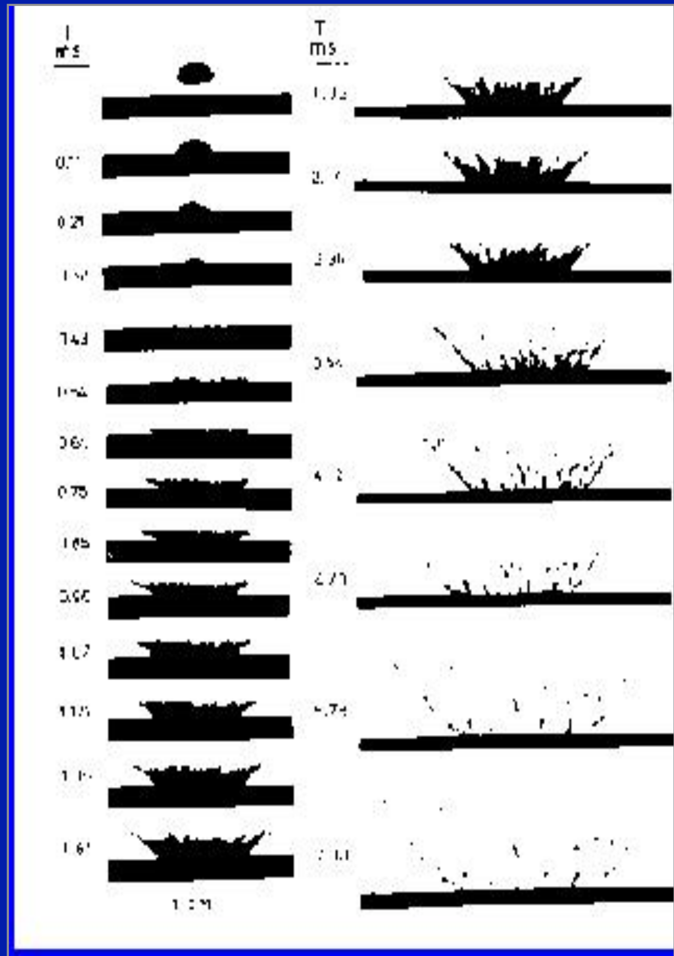


$v \cos\Phi$ (ms^{-1})

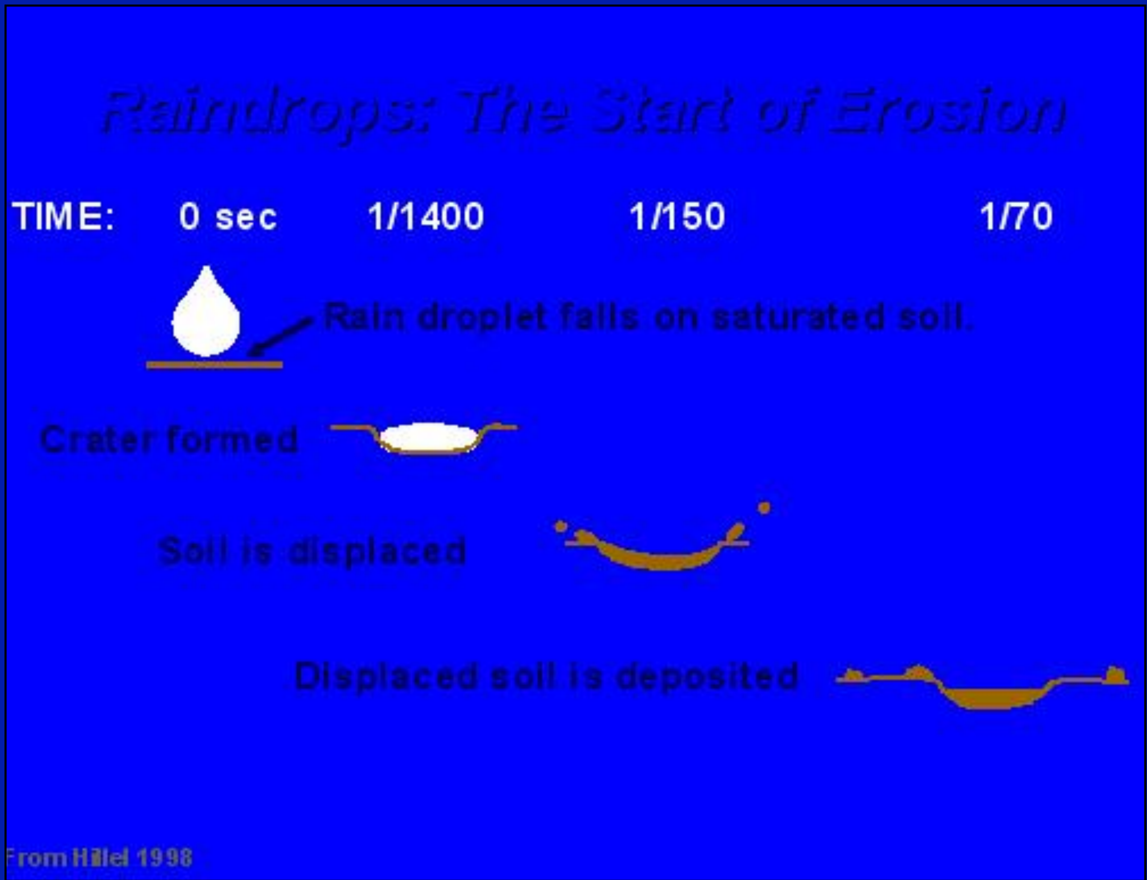
WFR-Assumption: Rainsplash detachment

The compensatory lateral jet development by the compressive pressure build-up at the raindrop–soil interface.



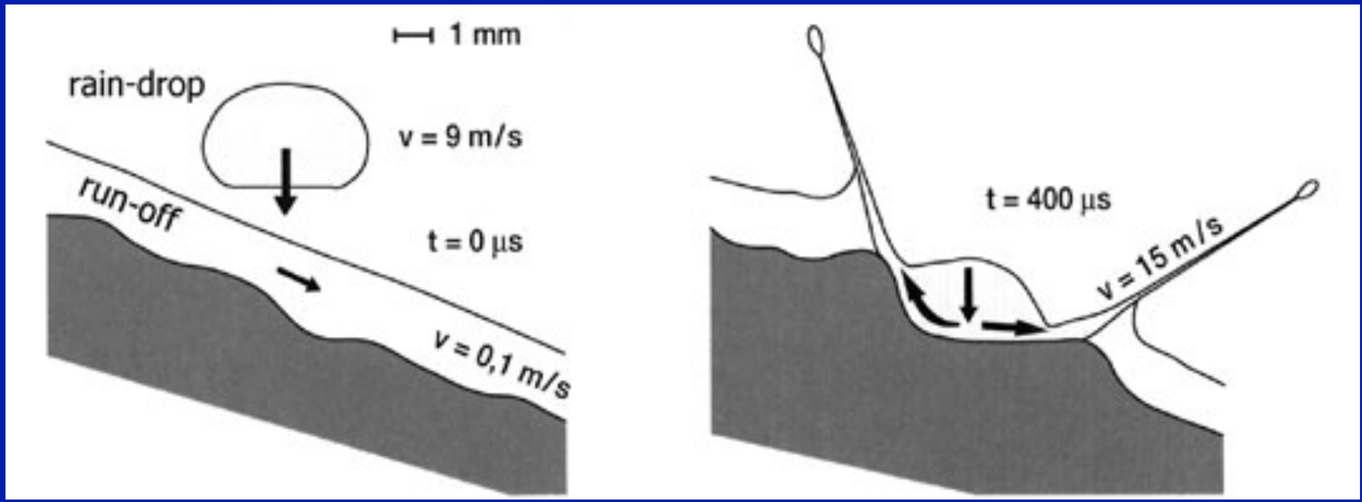


Huang et al. (1982) showed that the magnitude of the lateral shear stress of a vertically impacting raindrop was straightforwardly correlated to that of the compressive stress, and later, Al-Durrah and Bradford (1982) described the fact how compressive stress was transformed to or compensated by lateral shear stress from the radial splashes.



Huang et al. (1983) explained the lateral jet development depending on the compressive stress and elasticity or rigidity of rain-impacted surface.

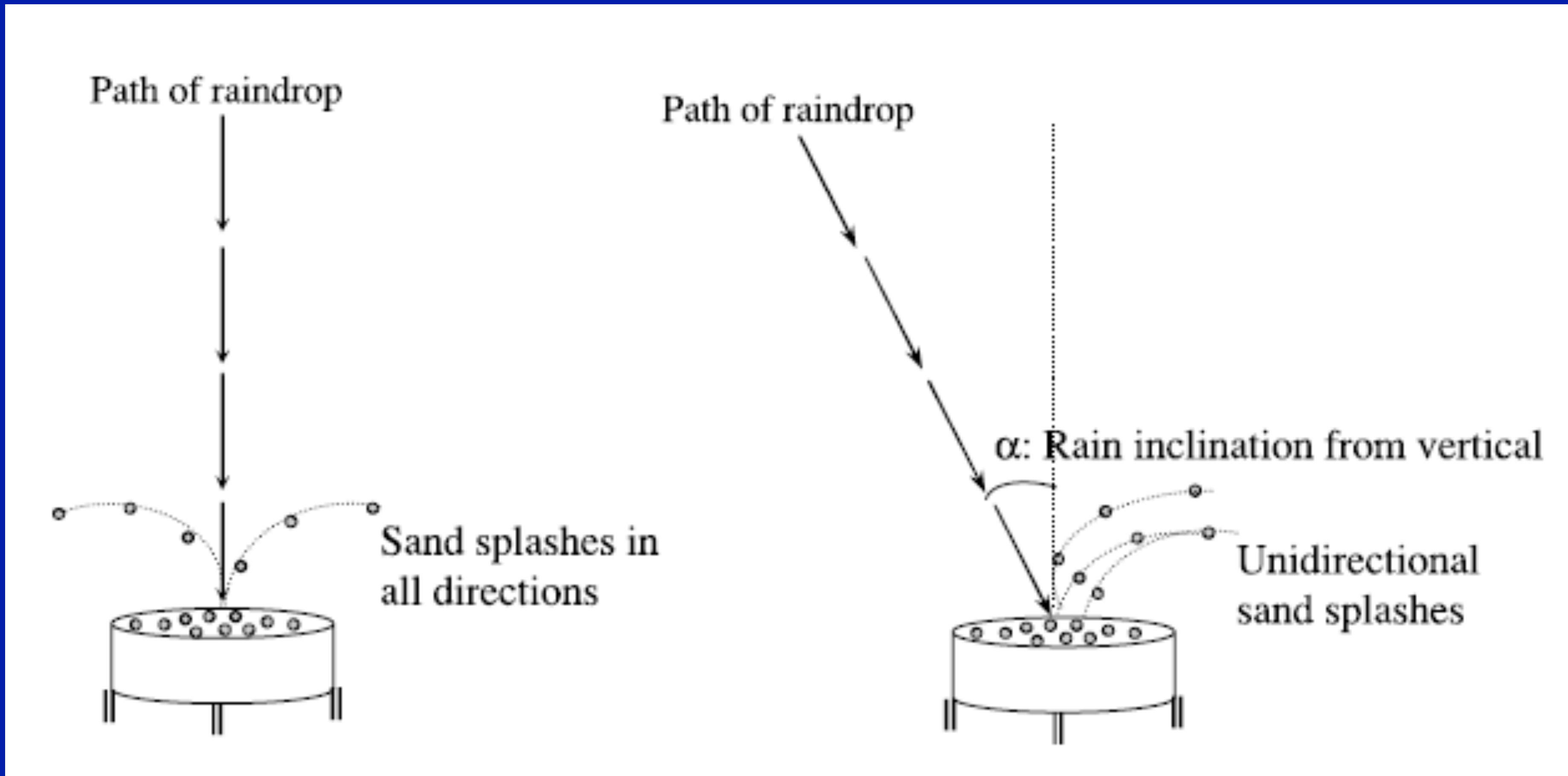
However, Cruse et al. (2000) reported that the relative importance of compressive and shear forces in soil detachment was vague.



Implicit WFR-Assumption (Summary)

The lateral jets (shear forces) are only produced by the perpendicular hit of a raindrop and the magnitude of these shear forces depends mainly on the condition of soil surface (sand, clay etc.) Obviously, no lateral jets during hit process.

What changes occur in the rainsplash detachment when there are induced lateral jets by the horizontal wind velocity?



Is it same as it is under WFR?

- Conclusion
  - Lateral jets are not a function of compressional forces but wind shear forces under WDR.
  - Rainsplash detachment is function of not only compressional forces but also shear forces induced by wind under WDR.

WFR-Assumption: Rainsplash Transport

Momentum-Transfer Approach

Downslope Asymmetry in Momentum Transfer

As slope gradient increases, more rainsplash particles move downslope and move farther downslope than upslope (gravitational forces) (Savat and Poesen, 1981; Poesen and Savat, 1981; Moeyersons, 1983; Poesen, 1985; Riezebos and Epema, 1985; Wright, 1986, 1987), and recently, Furbish et al., 2007).

WFR-Assumption: Rainsplash Transport

A Transport-Limited Process

The greatest radial distance that a sand grain moved was around 20 cm or less. Because of this, rainsplash transport is generally described as a transport-limited process, particularly when it functions on large areas (Kinnell, 1999, 2005).

Implicit WFR-Assumption (Modeling)

The contribution of rainsplash transport is very small when compared to overland flow transport. Because of this, rainsplash transport has been most widely neglected in recent erosion models (Kinnell, 1991), and therefore, there is a general tendency that the soil detached by rainsplash will be subsequently transported by overland flow (Hairsine and Rose, 1991; Parsons et al., 1994; Sharma et al., 1995).

Implicit WFR-Assumption (Summary)

Rainsplash transport occurs under the effect of gravitational forces (slope degree),
Only downslope particle transport occurs,
which is negligible in erosion modeling.

RFW (Rain Free Wind) Assumption
Saltation

The initial vertical velocity of particle lift-off is to be of the order of wind shear velocity (u_*, ms^{-1}), and the force of transporting particles is expressed with u_* (Bagnold (1941).

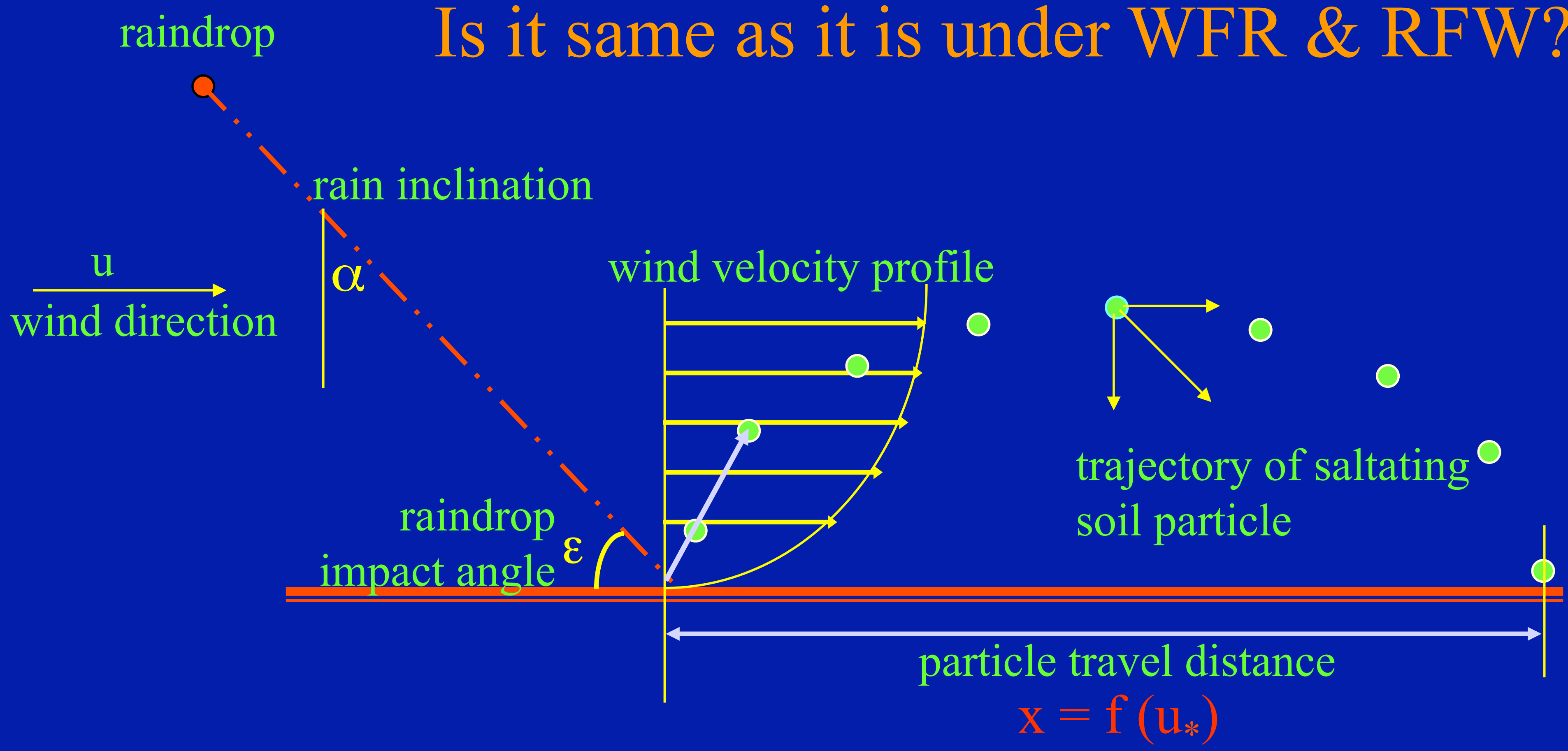
$$\tau_w = \rho_a u_*^2$$

τ_w: wind shear stress ($N\ m^{-2}$)
ρ_a: air density ($kg\ m^{-3}$) ($1.2\ kg\ m^{-3}$)

What changes occur in the rainsplash transport under WDR when compared to those under both WFR & RFW?

Splash – Saltation Transport (Raindrop-Detachment & Wind-Driven Transport)

Is it same as it is under WFR & RFW?



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

The rainsplash transport under WDR when compared to that under RFW?

The initial vertical velocity of particle lift-off is function of raindrop shear velocity (v_s, ms^{-1}) other than wind shear velocity (u_*, ms^{-1}).

$$\tau_d = \rho_d V_s^2$$

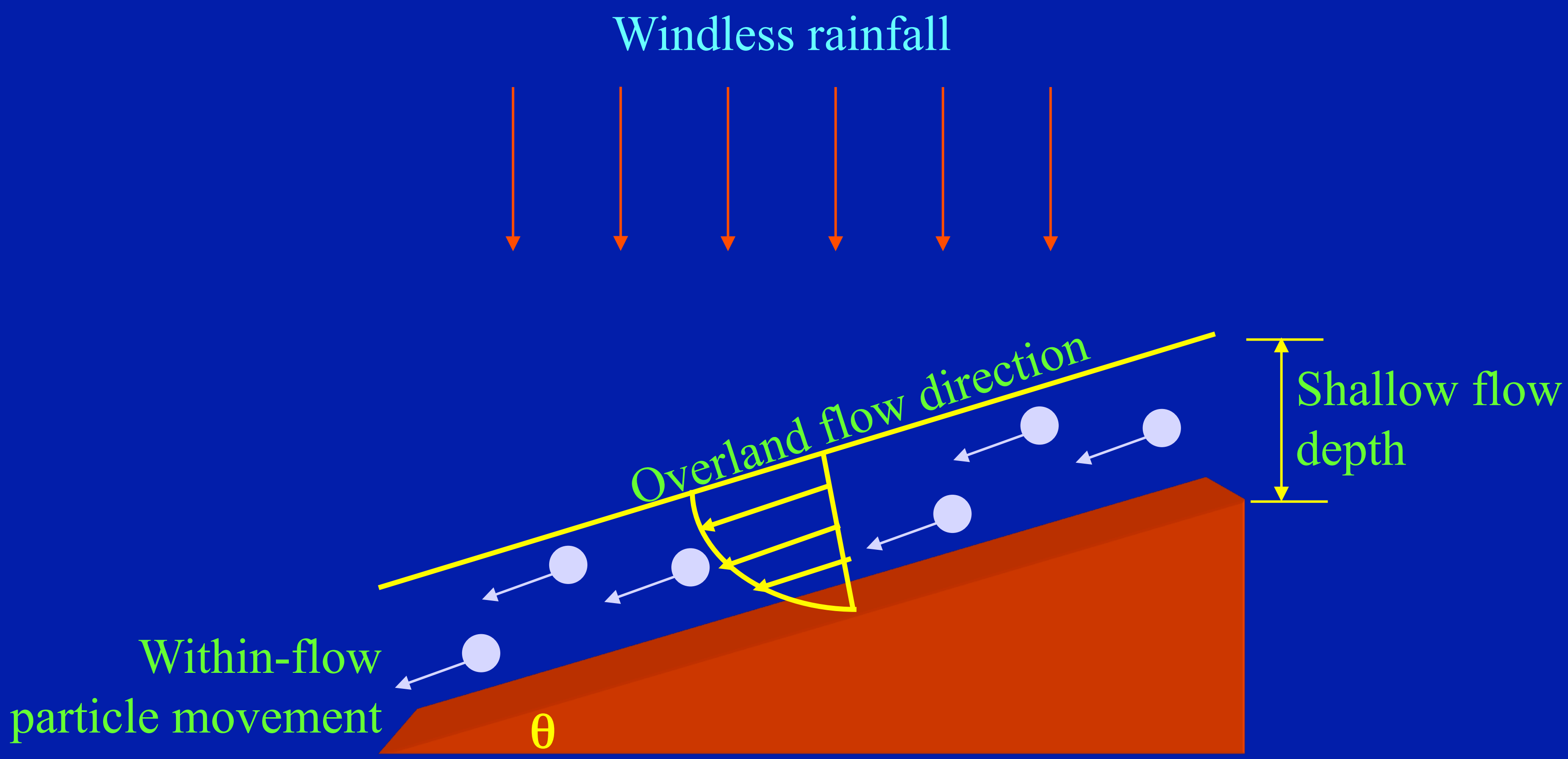
τ_d: wind-driven raindrop shear stress ($N\ m^{-2}$)
ρ_d: raindrop density ($kg\ m^{-3}$) ($997\ kg\ m^{-3}$)

- Conclusion
  - Rainsplash transport occurs under the effect of wind shear forces instead of gravitational forces (slope degree),
  - The twin effect of wind: one is on the detachment by changing the raindrop impact parameter, and the other is on transport by carrying the detached and lifted soil particles.
  - Not only downslope particle transport but also upslope particle transport occurs depending upon the prevailing wind direction.

WFR-Approach: Sediment Transport by Raindrop Impacted Shallow Flow

The interrill delivery mechanics includes an integrated action of raindrop detachment and raindrop impacted flow transport (Flanagan and Nearing, 1995; Kinnell, 2005).

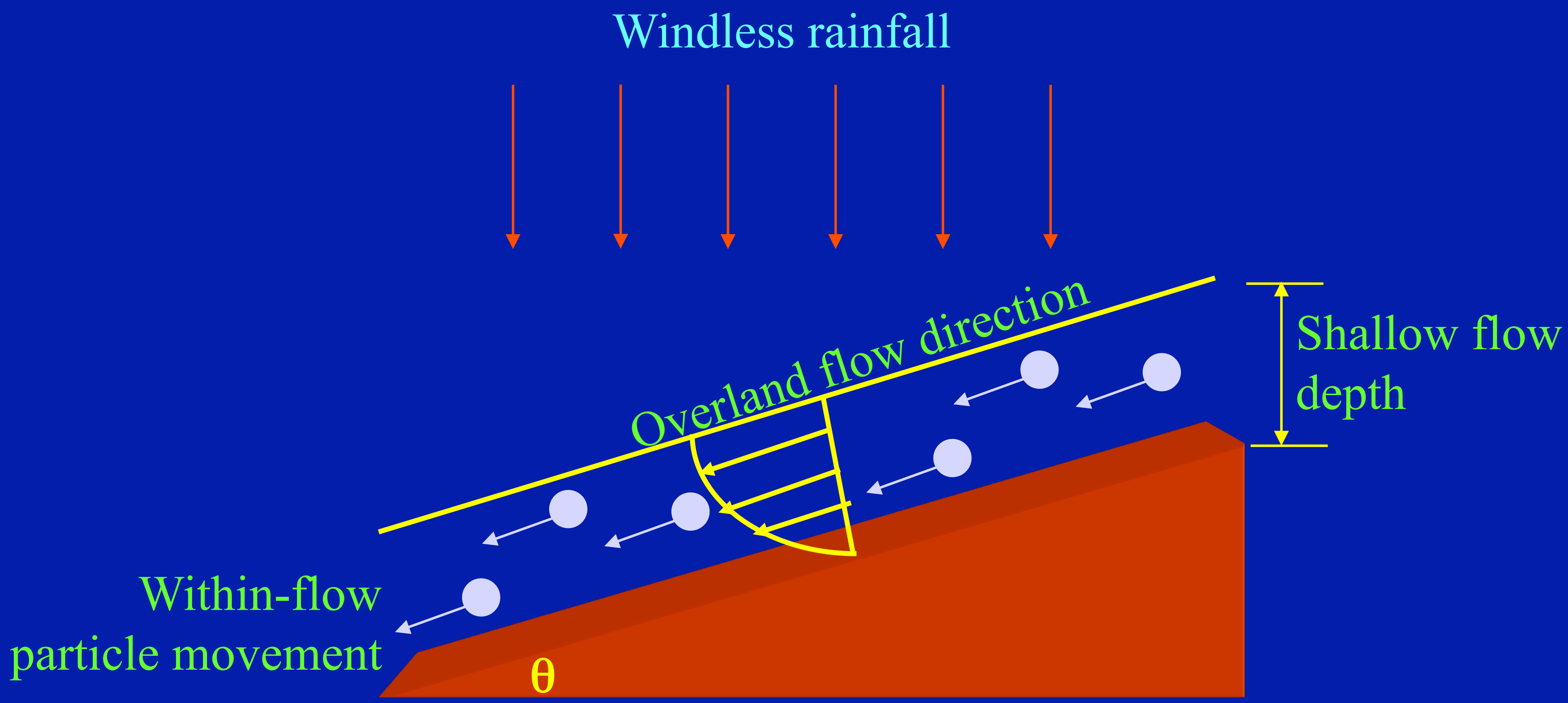
Sediment Transport by Raindrop Impacted Shallow Flow under WFR



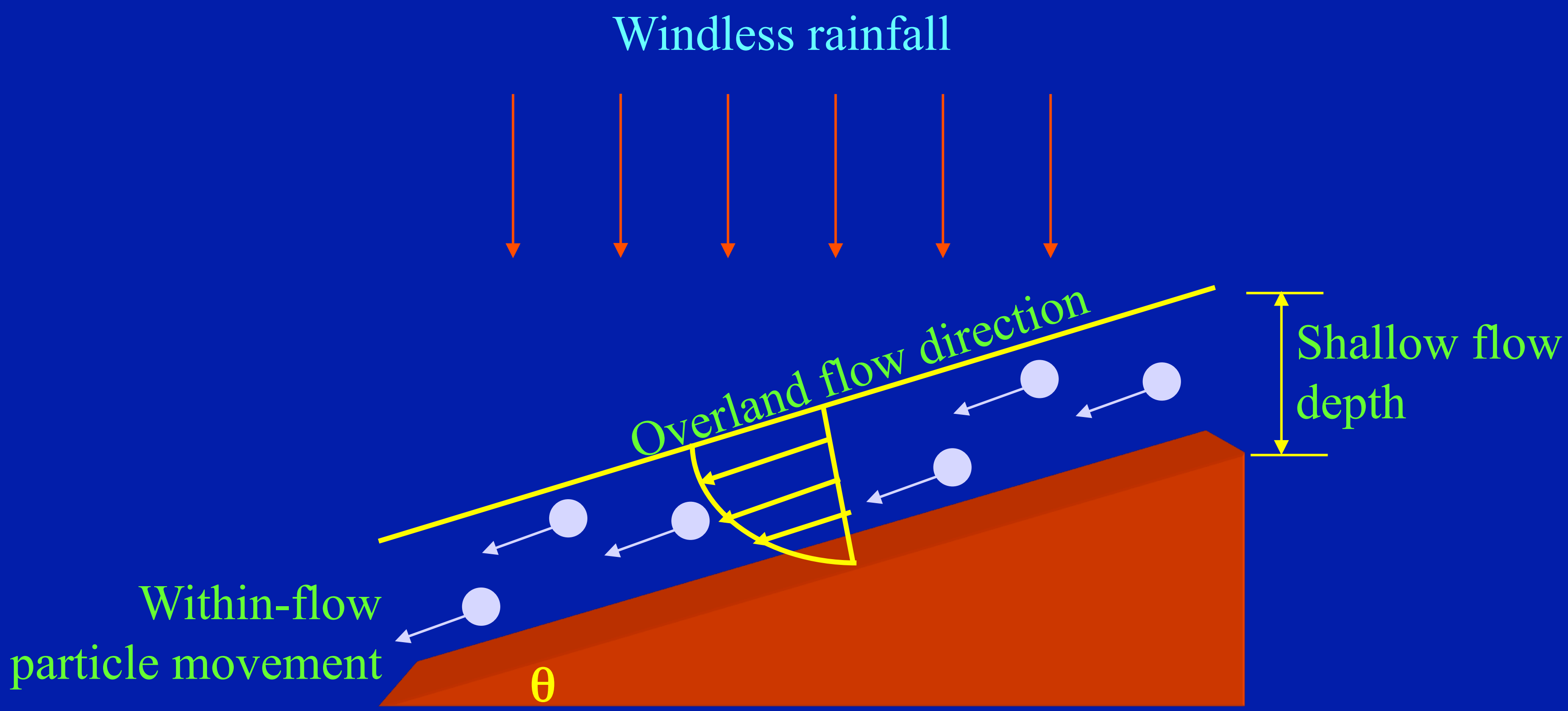
Radial splashes with much more compressional forces & compensatory lateral forces

WFR-Assumption

Splashed particles, either submerged or not, by raindrop impact move downslope or downslope particle movement is more important than the upslope particle movement irrespective of the slope aspect.



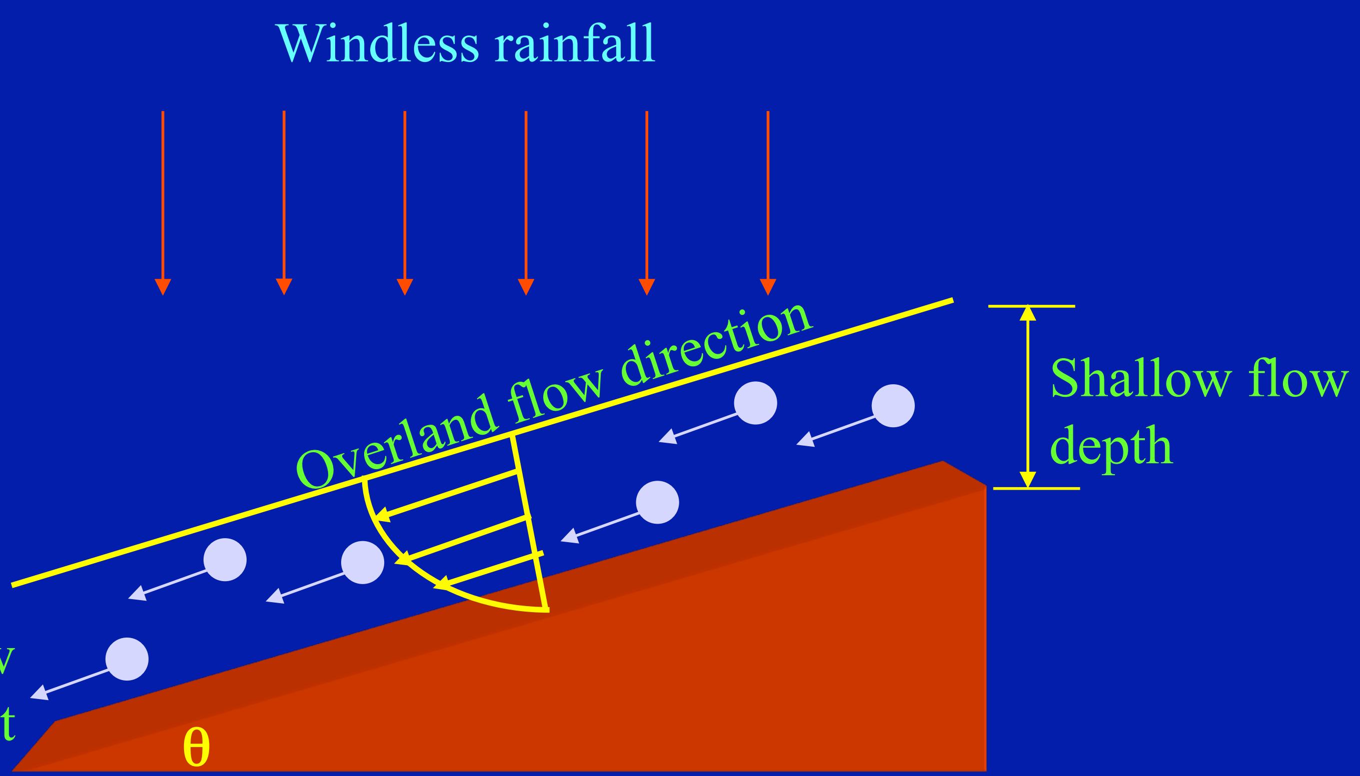
The splash asymmetry of the detached soil particles occurs such that more momentum is transferred in the downslope direction and thus the difference between upslope and downslope transport increases as the slope gradient increases.



In this case, lateral raindrop stress is in the same direction as the shallow flow direction.
Only compressional stress produces resistance against downward flow (raindrop-induced flow resistance (Shen and Li, 1973; Katz et al., 1995)

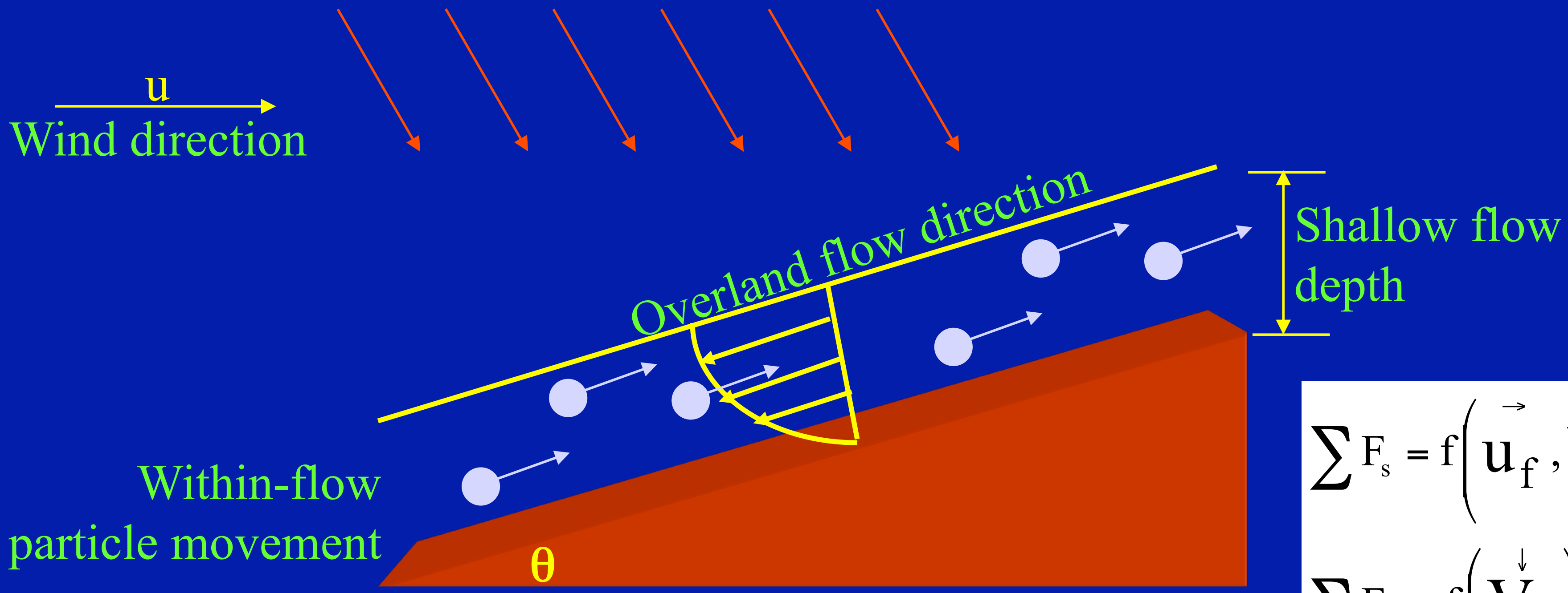
$$\sum F_s = f\left(\vec{u}_f, \vec{V}_s\right)$$

$$\sum F_n = f\left(\overset{\downarrow}{V}_n\right)$$



What changes occur in Sediment Transport by Raindrop Impacted Shallow Flow under WDR when compared to that under WFR?

Wind-driven rainfall incidental on a windward slope



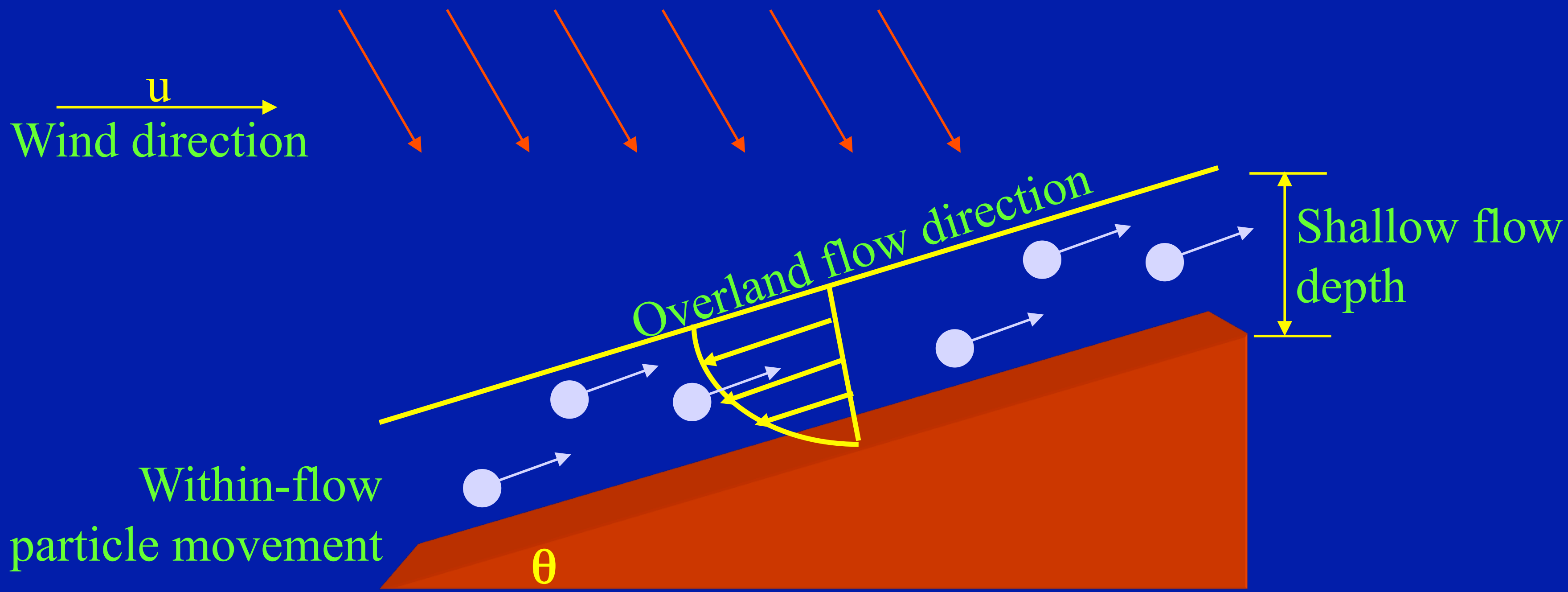
$$\sum F_s = f\left(\overrightarrow{u}_f, \overleftarrow{V}_s\right)$$

$$\sum F_n = f\left(\overset{\downarrow}{V}_n\right)$$

Unidirectional upslope splashes with less compressional forces & more lateral forces induced by wind shear stress

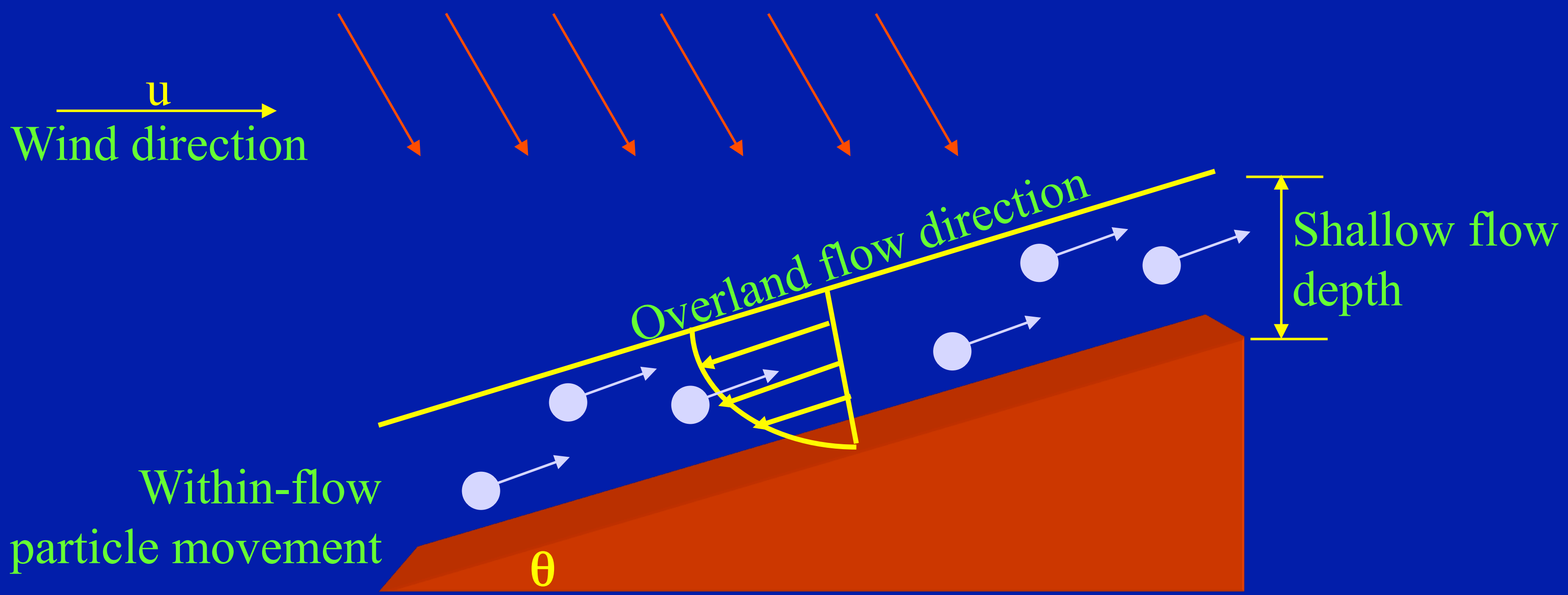
In wind-driven rains incident on the windward slopes, the particles splashed by the inclined raindrops are directed upslope, and there is only upslope movement at the threshold, and these particles are captured by the shallow flow running downslope.

Wind-driven rainfall incidental on a windward slope

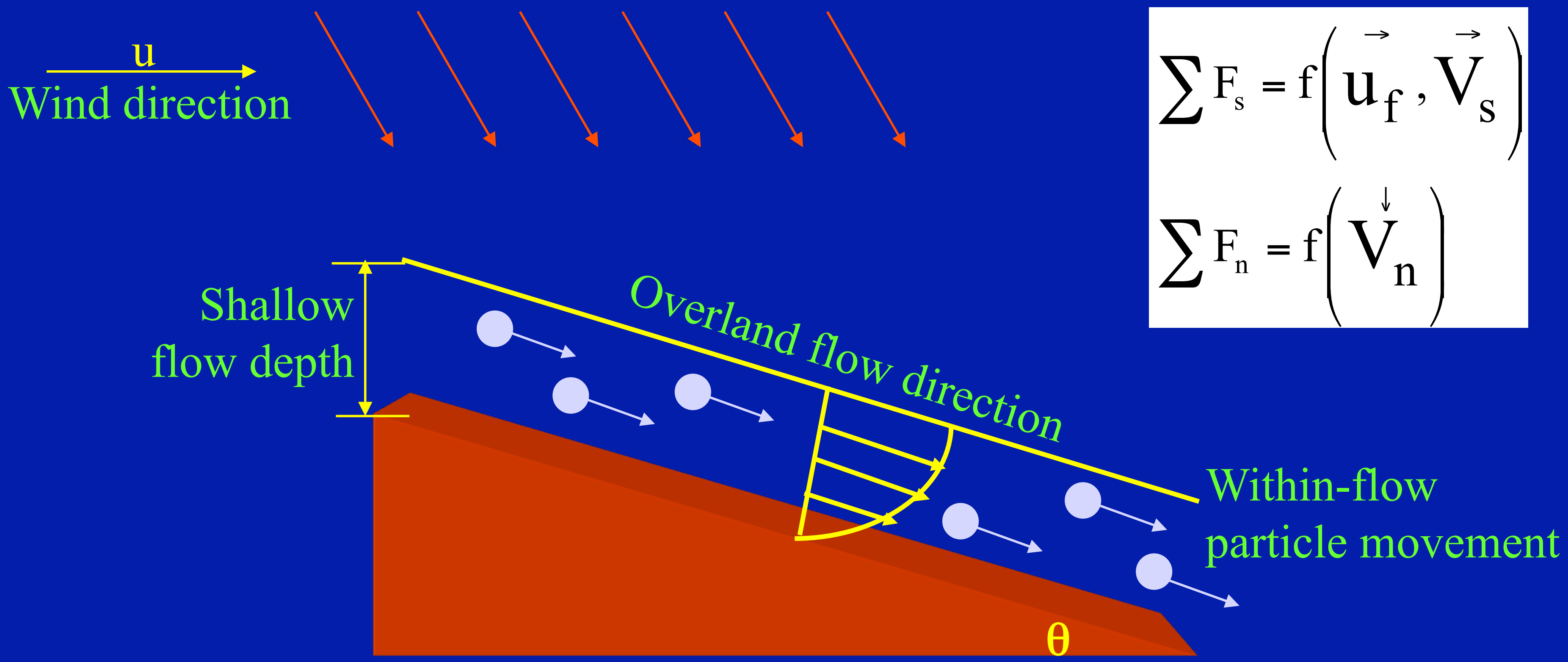


Reverse splashes at impact with respect to the shallow flow direction occur, and this, together with contrary lateral raindrop stress that increases as the horizontal wind velocity increases Not only compressional stress but also lateral raindrop stress produces resistance against downward flow.

Wind-driven rainfall incidental on a windward slope



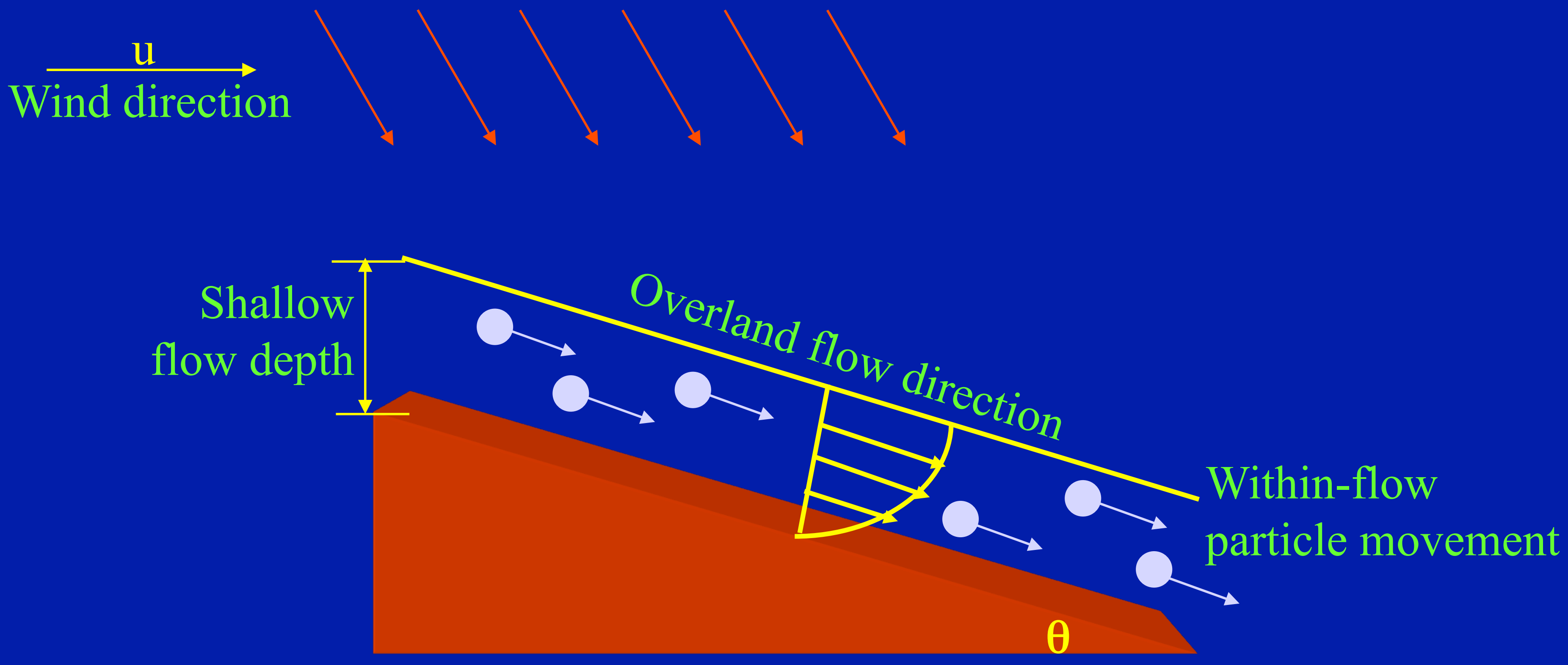
Wind-driven rainfall incidental on a leeward slope



Unidirectional downslope splashes with much much less compressional forces & much more lateral forces induced by wind shear forces

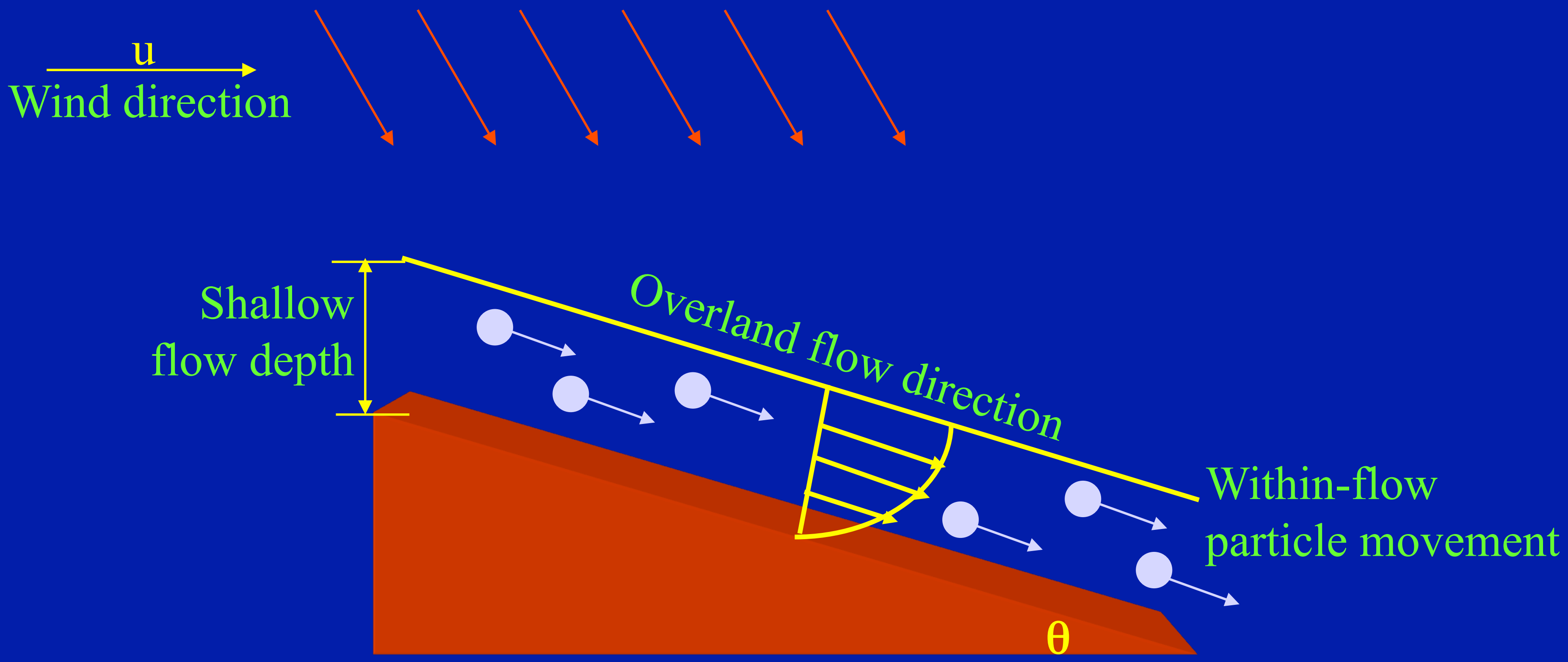
In the wind-driven rains incident on the leeward slopes, the particles splashed by the inclined raindrops are directed downslope and thus, being in the same direction as the shallow flow direction.

Wind-driven rainfall incidental on a leeward slope



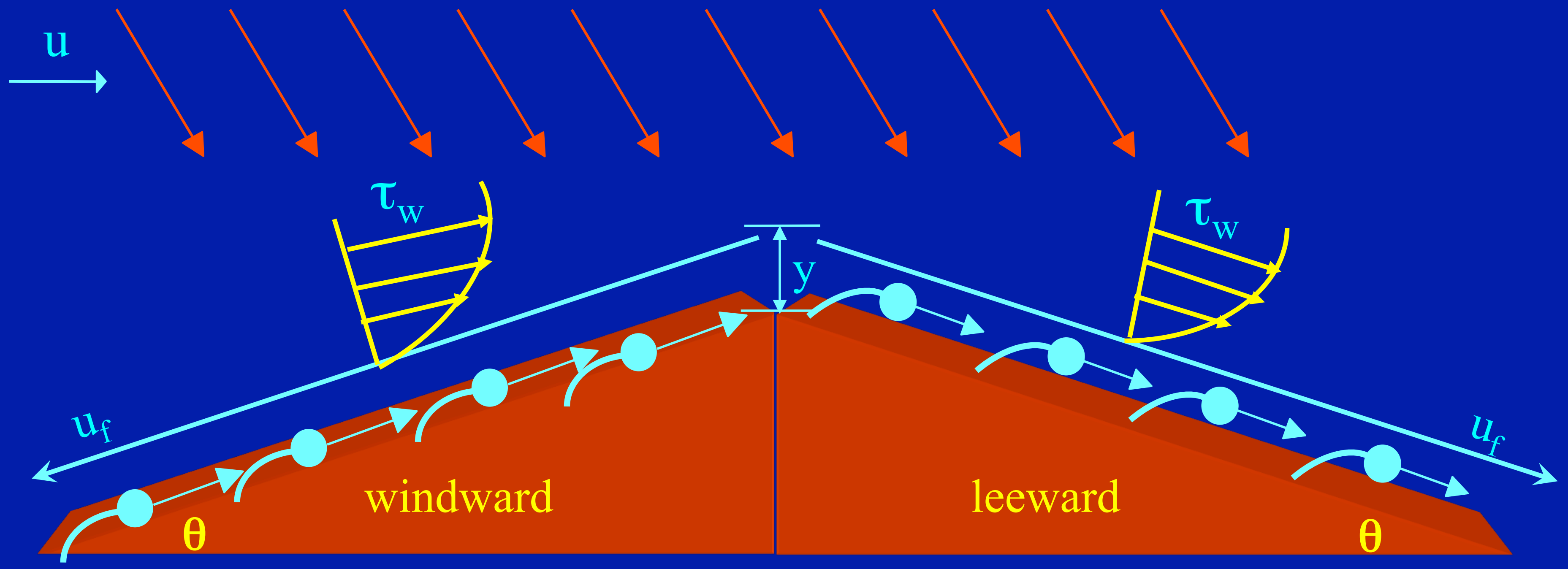
The lateral raindrop stress is also in the same direction as the shallow flow. Only compressional stress, which is relatively much less, produces resistance against downward flow (raindrop-induced flow resistance).

Wind-driven rainfall incidental on a leeward slope



- Conclusion
  - The distribution of forces or partition of compressional and lateral forces of impacting raindrops over wide shallow overland flow significantly varies with slope aspect under WDR.

- Conclusion
  - Shallow flow sediment transport capacity will depend mainly on distribution of raindrop forces over flow under WDR.



Thank you