

Wet-range physical realism in a full-range model of soil water retention

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Importance of the wet range: *nearly* saturated soil and rock

- Control of macropore/matrix domain exchange
- Dynamics of water content affected by a fluctuating water table
 - Capillary fringe
 - Specific yield
- Timing and circumstances of transition from unsaturated to field-saturated conditions
 - Initiation of ponding
 - Triggering of landslides
 - Initiation of preferential flow
- Processes of tension infiltrometers
- Infiltration/runoff partitioning

Goals for water retention model

- Represent wet range realistically
- Base the math on the dominant physical processes, to the extent possible
- Develop parameters with strong physical interpretation
- Maintain practical usability
- Ensure applicability to media with a finite maximum pore size (e.g. soil matrix)

Consider matric-potential range in three parts, and dominant process in each

Dry range

Films and crevices

Adsorption

Middle range

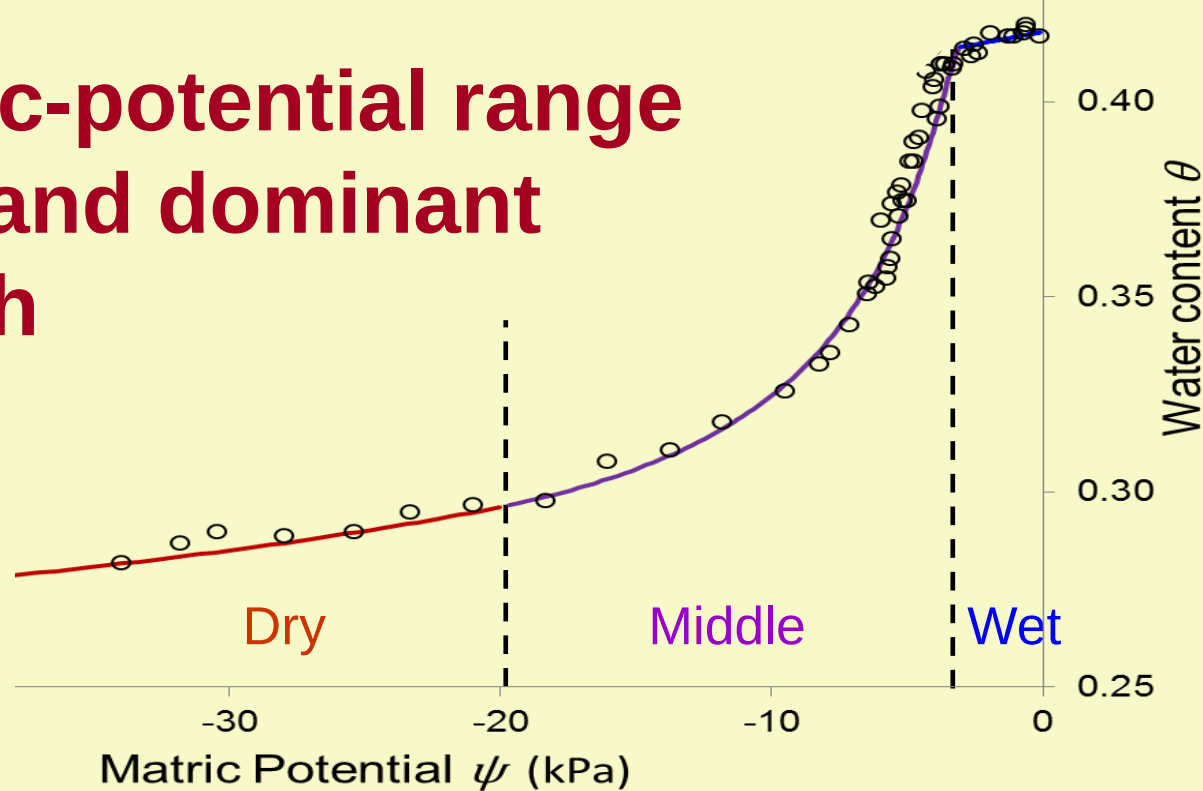
Some pores water-filled; air phase remains connected

Capillary filling and emptying

Wet range

All pores water-filled except where air is trapped

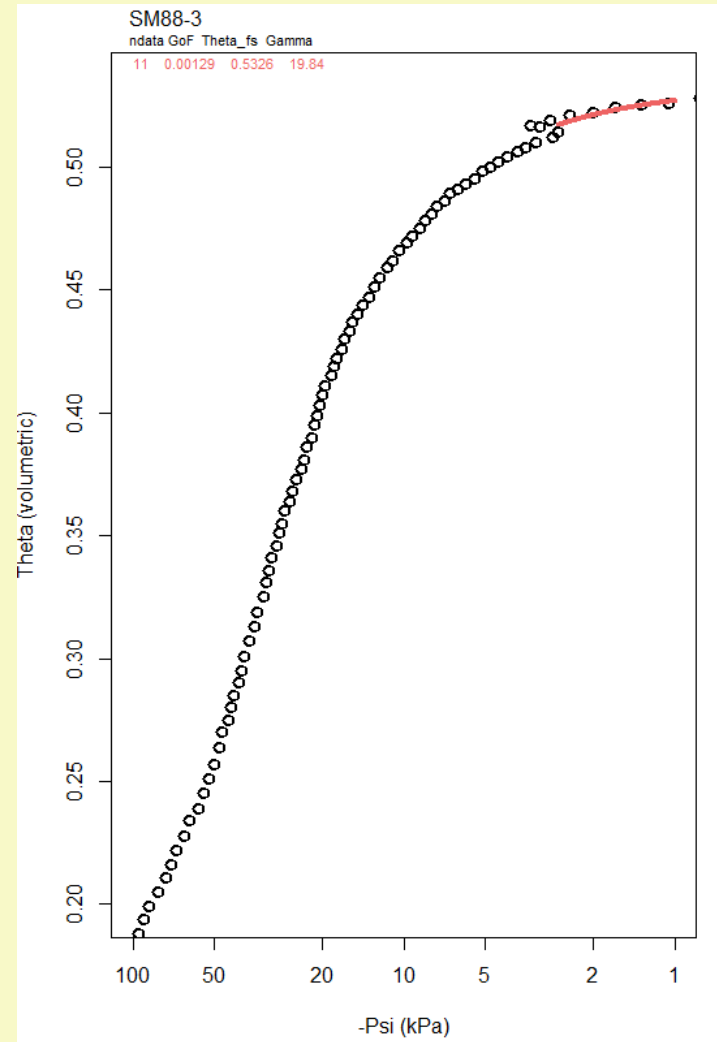
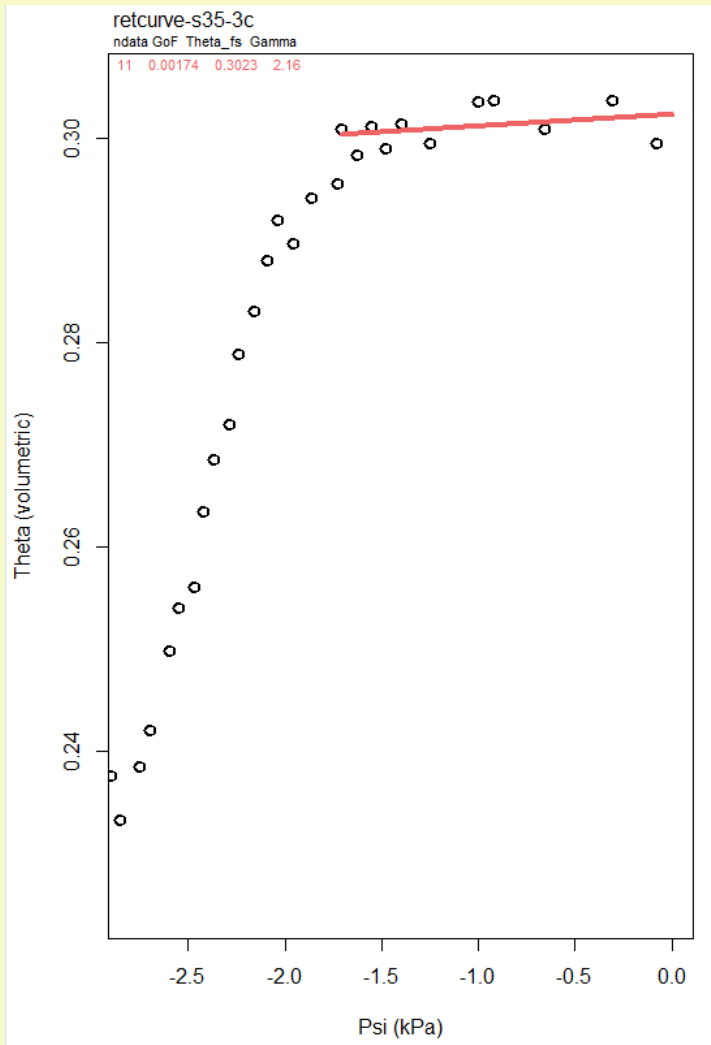
Expansion/contraction of trapped air, plus secondary effects such as coalescence of trapped bubbles



Wettest portion of full-range water retention

- Models have been developed that have a dry range based on adsorption processes and a middle range based on capillary processes
- Wet range
 - Between the air-entry value and saturation
 - Models typically treat it by default as an extension of the capillary range, or simply as a straight, flat line
- The air phase is trapped
 - No capillary emptying and filling
 - Water content *does* change with matric potential because of dynamic trapped-air processes

Examples: Data show a distinct nonzero slope in the wet range



Develop wet-range formula

Start with the effect of Boyle's law on trapped air (TA)

$$(\text{TA pressure}) \times (\text{TA volume}) = \text{constant}$$

$$p_o (\phi - \theta_{fs}) = (p_o + \psi)(\phi - \theta)$$

Diagram illustrating the variables in the Boyle's law equation for trapped air (TA):

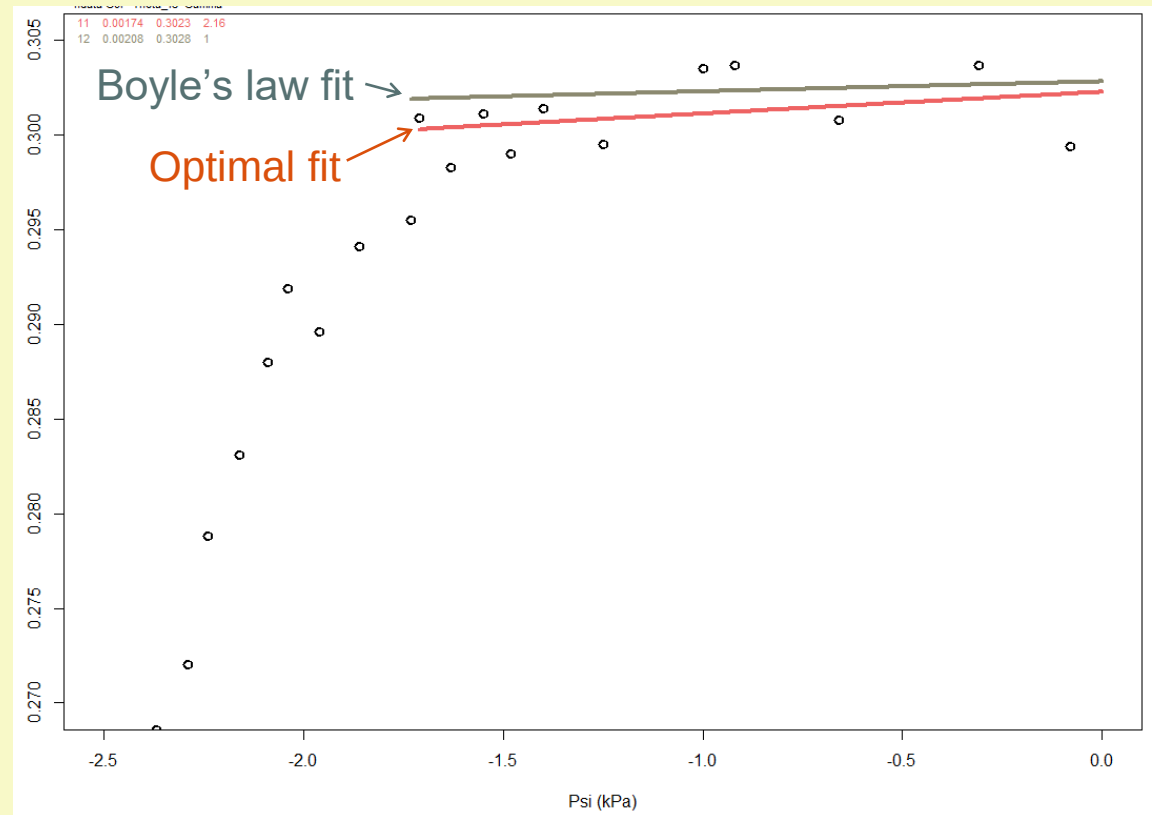
- p_o : TA pressure at $\psi = 0$
- ϕ : porosity
- θ_{fs} : field saturated water content
- ψ : matric potential
- θ : water content

Rearrange to get:

$$\theta_B(\psi) = \frac{p_o \theta_{fs} + \phi \psi}{p_o + \psi}$$

Testing of Boyle's law formula

Many data sets show that Boyle's law underestimates the rate of change of water content as matric potential decreases:



Among other possibilities, a likely contributing factor is that within the medium, liquid bridges separating bubbles of trapped air may break or reform with changes in bubble volume caused by pressure variations (Stonestrom and Rubin, 1989a, WRR).

Augmented Boyle's law formula for wet range

Amplify the effect of Boyle's law volume changes with an empirical enhancement factor γ

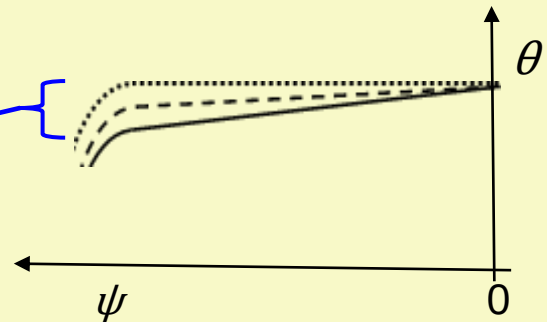
$$\theta(\psi) = \theta_{fs} + \underbrace{\gamma(\phi - \theta_{fs})}_{\text{Boyle's law}} \frac{\psi}{p_o + \psi}$$

Enhancement factor γ (indicated by an arrow pointing to the γ in the equation)

Volume of trapped air ϕ (indicated by an arrow pointing to the ϕ in the equation)

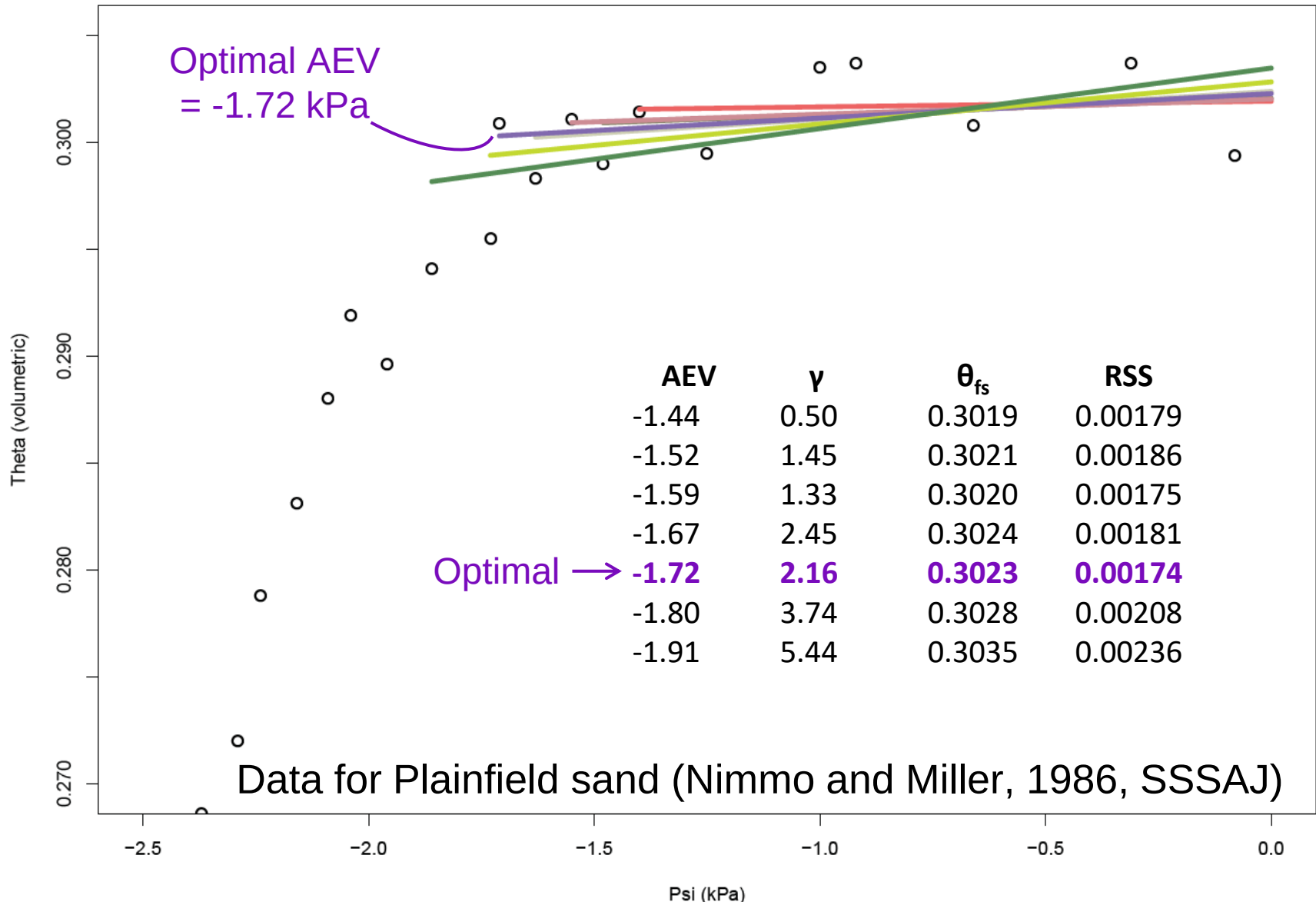
Boyle's law (indicated by a bracket under the term $\gamma(\phi - \theta_{fs})$)

Effect of different γ values



Test new wet-range model

Fits with various air-entry values (AEVs)



Combine into full-range model with three sub-ranges

Wet range: Augmented Boyle's law

$$\theta(\psi) = \theta_w + \gamma(\phi - \theta_w) \frac{\psi}{p_o + \psi} \quad \text{for } \psi_w \leq \psi$$

Mid range: lognormal distribution

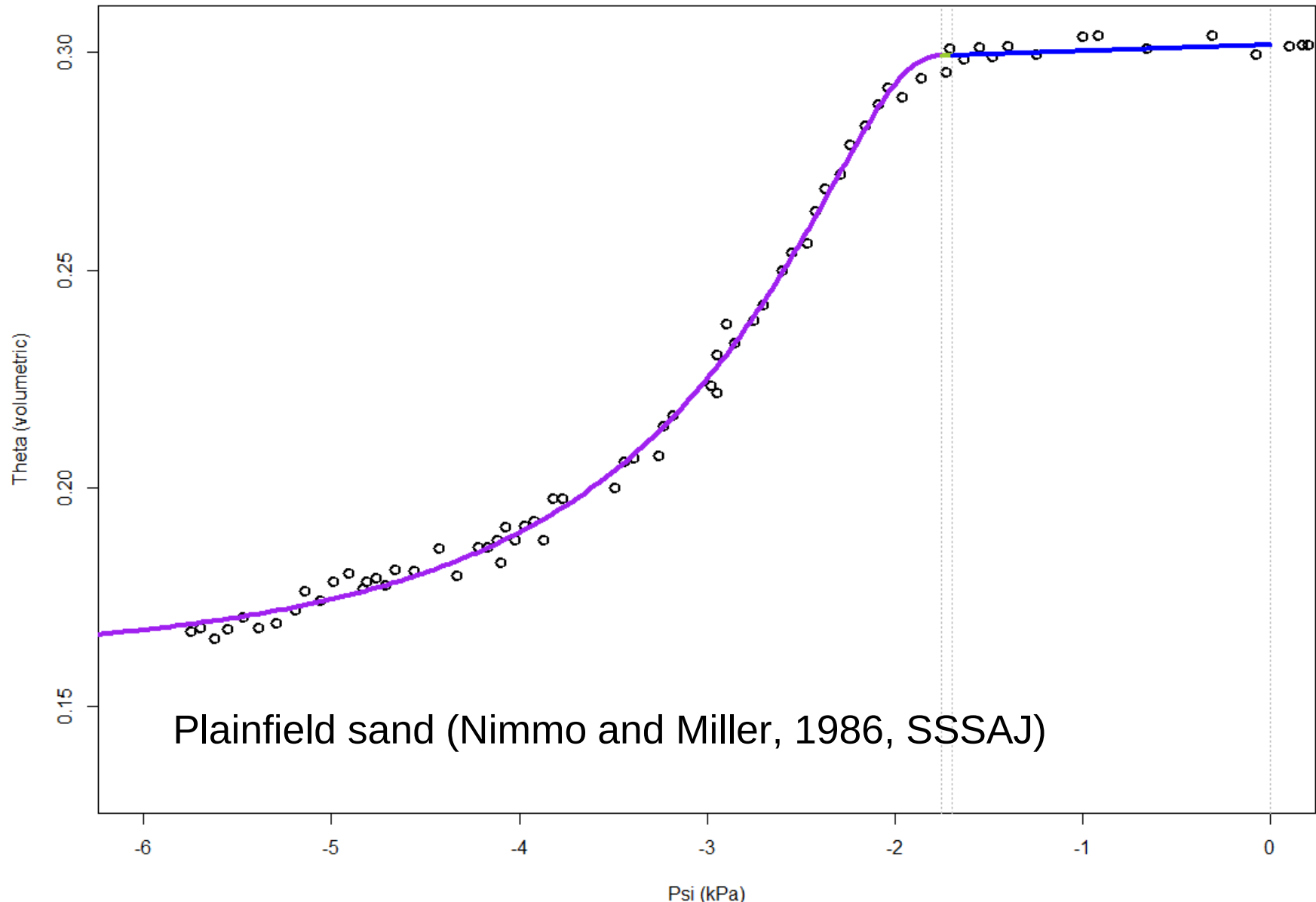
$$\theta(\psi) = \theta_m + \left(\frac{\theta_w - \theta_m}{2} \right) \left[1 + \operatorname{erf} \left(\frac{v(\psi) - \mu}{\sigma\sqrt{2}} \right) \right] \quad \text{for } \psi_m < \psi < \psi_w$$
$$v = \ln \left[\frac{\psi_w(\psi - \psi_m)}{\psi_m(\psi_w - \psi)} \right]$$

Dry range: logarithmic in $1/\psi$

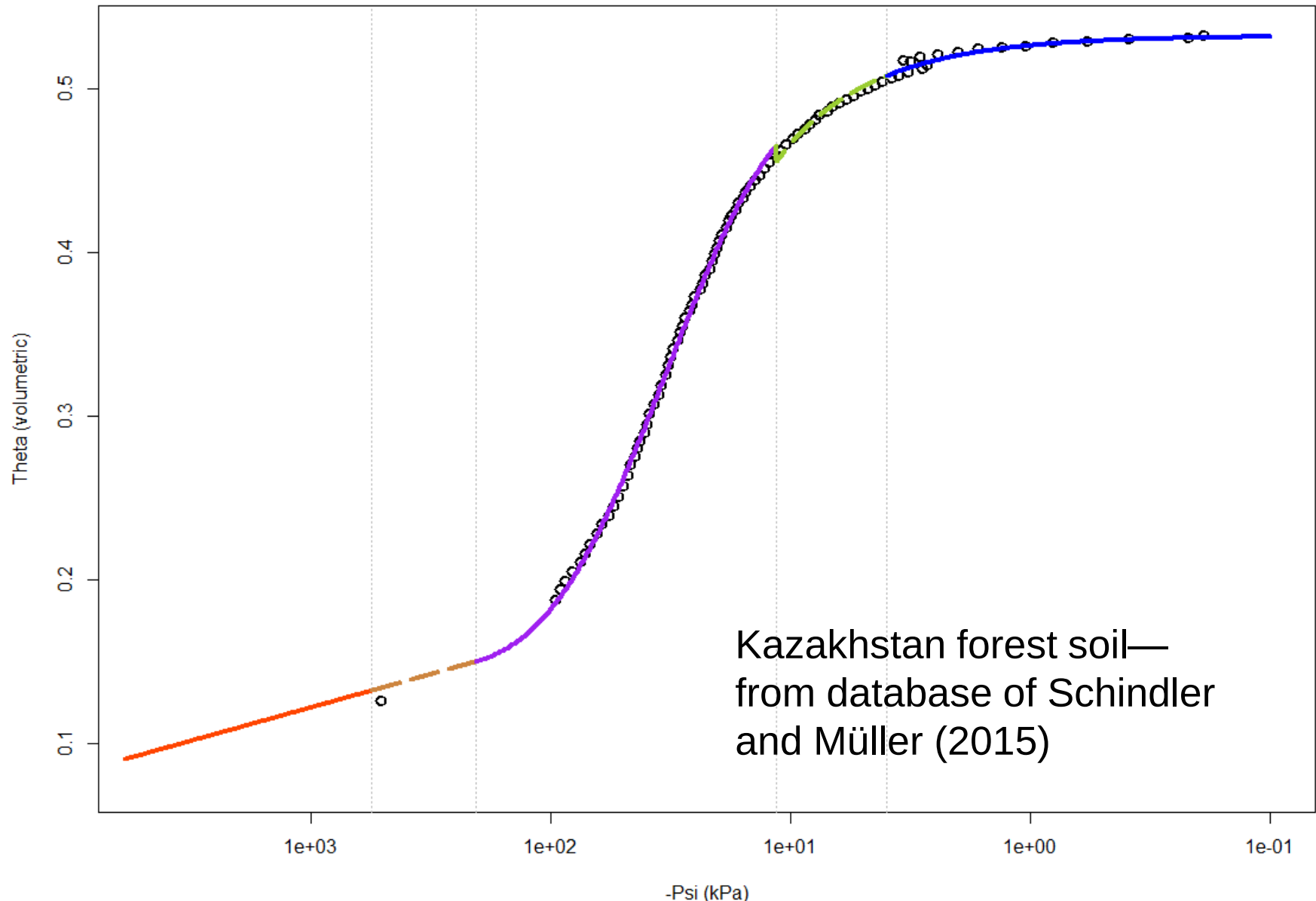
$$\theta(\psi) = \alpha \ln \left(\frac{\psi_d}{\psi} \right) \quad \text{for } \psi \leq \psi_m$$

Join segments at points (ψ_m, θ_m) and (ψ_w, θ_w) , equating derivatives to achieve smoothness

Full-range model example 1



Full-range model example 2



Interpretation of parameters

α ~ approximately proportional to specific surface

ψ_m ~ transition from adsorption to capillary dominance

μ_ψ ~ median capillary pore size

σ ~ geometric standard deviation of capillary pore size

ψ_w ~ transition from capillary to trapped-air dominance

γ ~ susceptibility to trapped-air coalescence, etc.

Conclusions

- The new model realistically fits the full range of soil water retention
- Novel features
 - Enhanced Boyles'-law representation of wet range
 - Lognormal fit between two finite ψ values
- Advantages can outweigh sacrifices of simplicity
 - Improved realism
 - Strong physical interpretation of parameter values
 - Realistic wet-range quantification facilitates investigation of macropore-matrix interaction and other near-saturated processes