Overland Flow Simulation in ParFlow

ParFlow Short Course

Module 5

Learning Objectives:

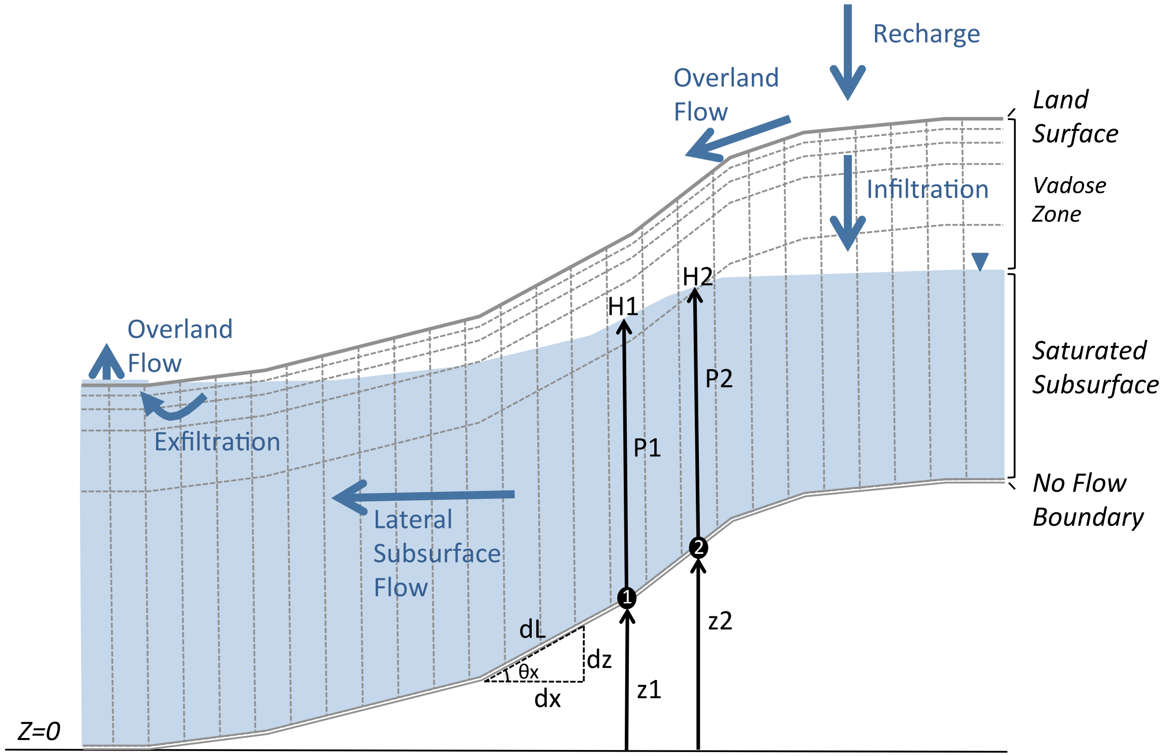
At the end of this module students will understand:

- How subsurface and overland flows are integrated with ParFlow
- What is meant by a free surface overland flow boundary condition in ParFlow
- What equations are being solved for overland flow and what parameters control them.
- The difference between the different overland flow modules in ParFlow
- The different runoff mechanisms and how ParFlow can handle them.
- The difference between this approach and a flow routing model

We solve the mixed form of Richards' and Shallow Water equations

$$S_S S_W(h)\frac{\partial h}{\partial t}+\theta\frac{\partial S_W(h)}{\partial t}=\nabla\bullet\mathbf{q}+q_r(\mathbf{x},z)$$

Mixed form of Richards' we solve for h



We solve the mixed form of Richards' and Shallow Water equations

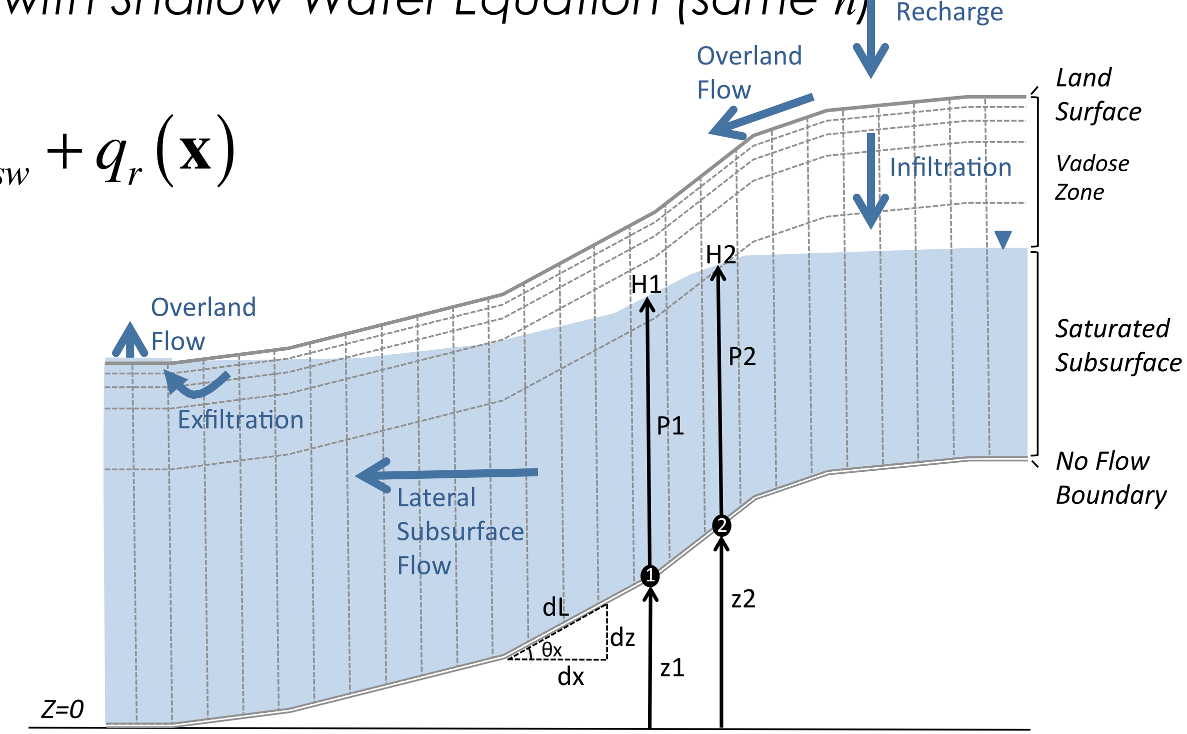
$$S_S S_W(h)\frac{\partial h}{\partial t}+\theta\frac{\partial S_W(h)}{\partial t}=\nabla\bullet\mathbf{q}+q_r(\mathbf{x},z)$$

Mixed form of Richards' we solve for h

Upper boundary condition (Neumann type) combined with Shallow Water Equation (same h)

$$\mathbf{k}\bullet\left(-\mathbf{K}_S(\mathbf{x})k_r(h)\bullet\nabla(h+z)\right)=\frac{\partial\|h,0\|}{\partial t}-\nabla\bullet\|h,0\|v_{sw}+q_r(\mathbf{x})$$

$$v_x=-\frac{\sqrt{S_{f,x}}}{n}\psi_s^{2/3}$$



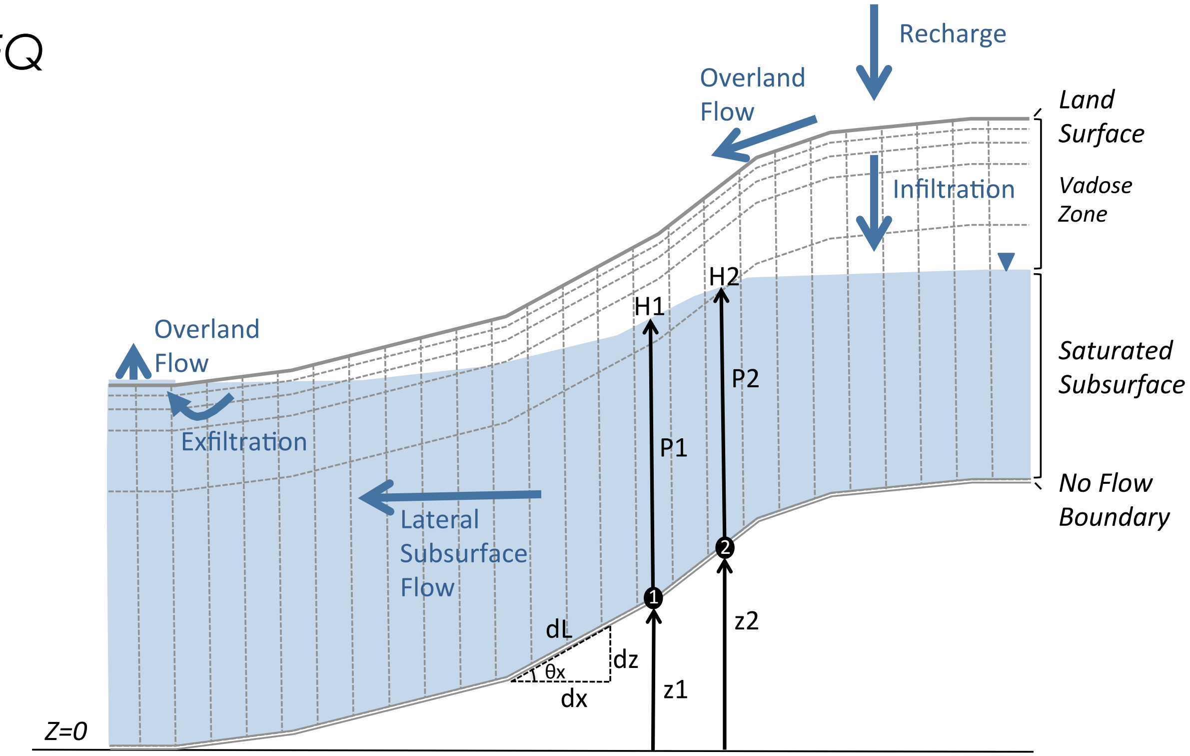
We solve the mixed form of Richards' and Shallow Water equations

$$S_S S_W(h)\frac{\partial h}{\partial t} + \theta \frac{\partial S_W(h)}{\partial t} = \nabla \bullet \mathbf{q} + q_r(\mathbf{x}, z)$$

Mixed form of Richards' we solve for h

Flux Relationships from modified Darcy and Mannings EQ

$$\mathbf{q} = -\mathbf{K}_S(\mathbf{x})k_r(h)\left[\nabla(h+z)\cos\beta_x + \sin\beta_x\right]$$



We solve the mixed form of Richards' and Shallow Water equations

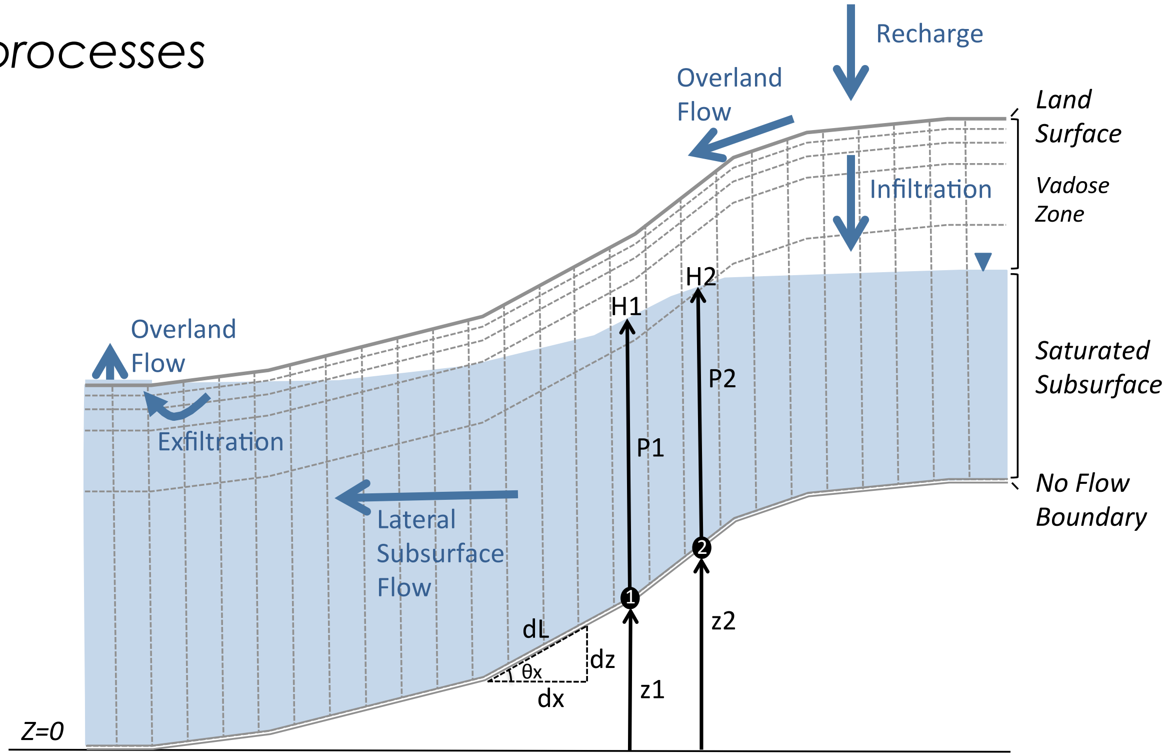
$$S_S S_W(h)\frac{\partial h}{\partial t}+\theta\frac{\partial S_W(h)}{\partial t}=\nabla\bullet\mathbf{q}+q_r(\mathbf{x},z)$$

Mixed form of Richards' we solve for h

Boundary source/sink, from weather and land surface processes

$$q_r(x,z)=-E_T(x,z)$$

$$q_r(x)=P(x)-E(x)$$



We solve the mixed form of Richards' and Shallow Water equations

$$S_S S_W(h)\frac{\partial h}{\partial t}+\theta\frac{\partial S_W(h)}{\partial t}=\nabla\bullet\mathbf{q}+q_r(\mathbf{x},z)$$

Mixed form of Richards' we solve for h

Upper boundary condition (Neumann type) combined with Shallow Water Equation (same h)

$$\mathbf{k}\bullet\left(-\mathbf{K}_S(\mathbf{x})k_r(h)\bullet\nabla(h+z)\right)=\frac{\partial\|h,0\|}{\partial t}-\nabla\bullet\|h,0\|v_{sw}+q_r(\mathbf{x})$$

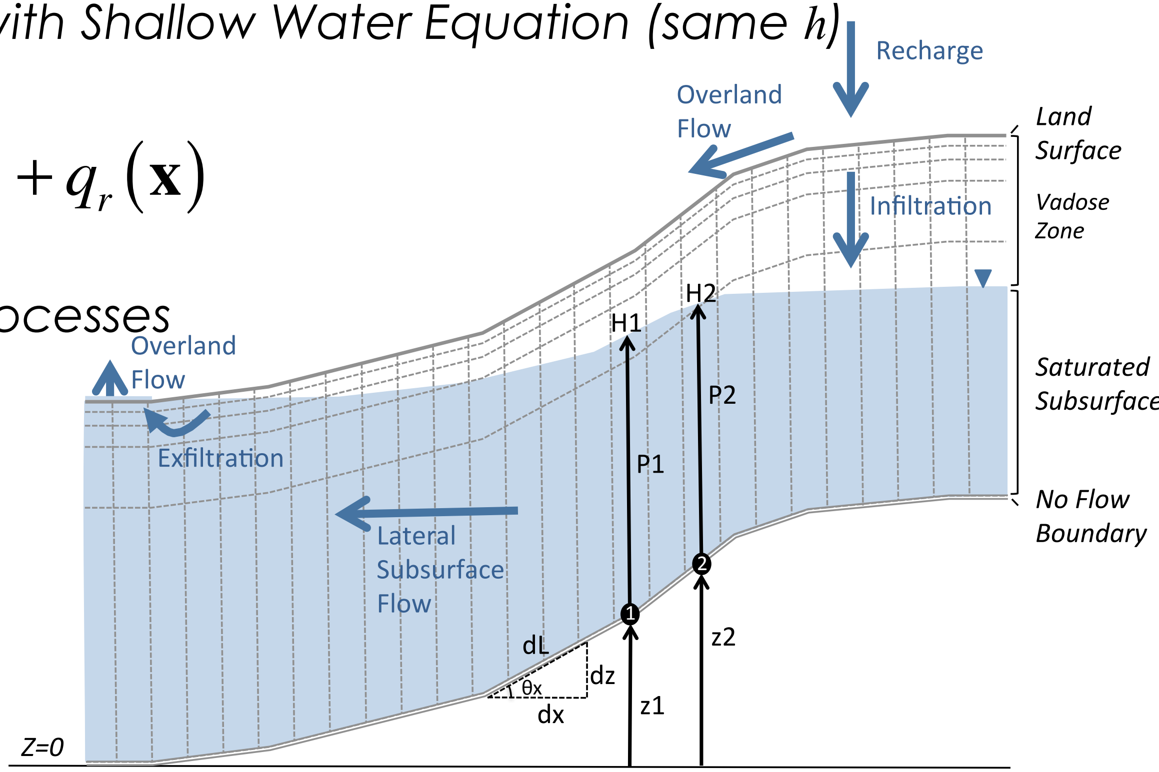
Boundary source/sink, from weather and land surface processes

$$q_r(x)=P(x)-E(x)\qquad q_r(x,z)=-E_T(x,z)$$

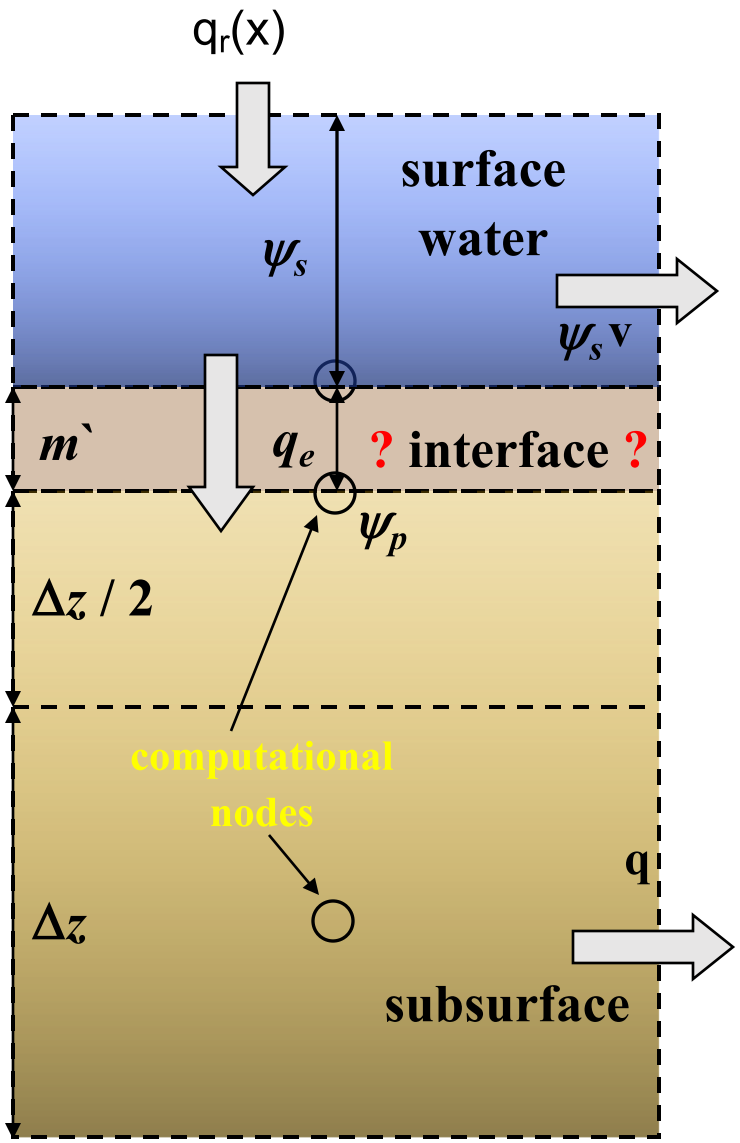
Flux Relationships from modified Darcy and Mannings EQ

$$\mathbf{q}=-\mathbf{K}_S(\mathbf{x})k_r(h)\left[\nabla(h+z)\cos\beta_x+\sin\beta_x\right]$$

$$v_x=-\frac{\sqrt{S_{f,x}}}{n}\psi_s^{2/3}$$



Overland Flow: The Conductance Concept



Kinematic wave eq

$$\frac{\partial \psi_s}{\partial t} = \nabla \cdot \psi_s \mathbf{v} - q_r(x) - q_e(x)$$

$$q_e(x) = \lambda(x)\left(\psi_s - \psi_p\right)$$

Exchange Flux

$$S_s S_w \frac{\partial \psi_p}{\partial t} + \phi \frac{\partial S_w(\psi_p)}{\partial t} = \nabla \cdot \mathbf{q} + q_s + m' q_e$$

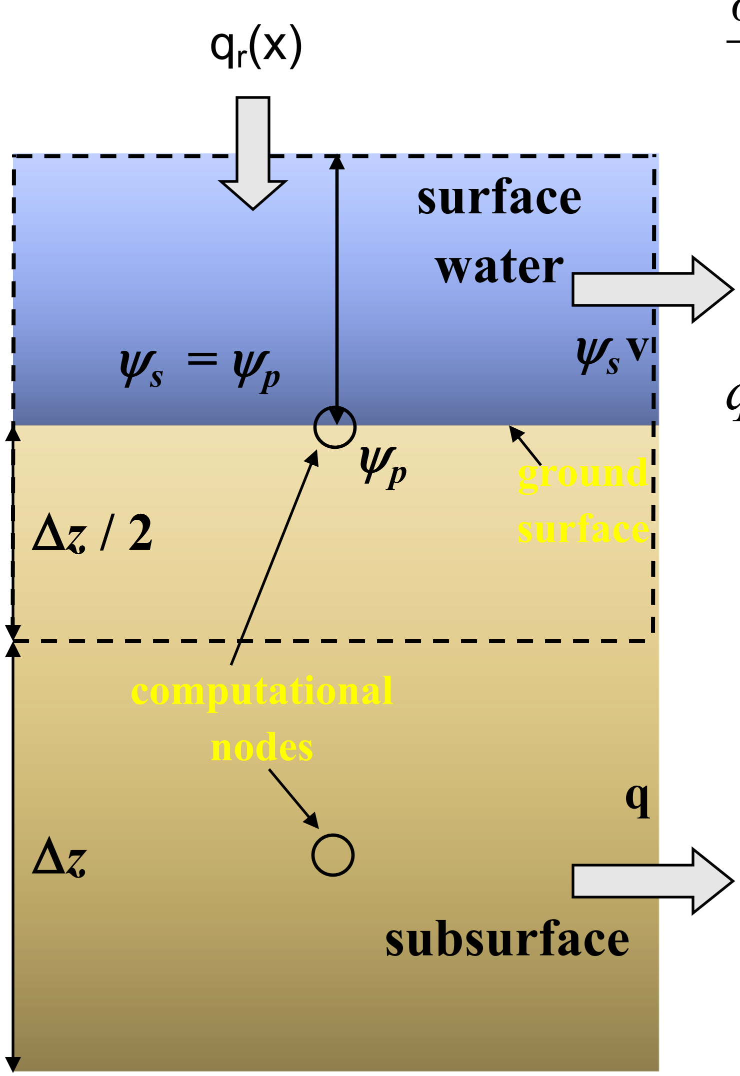
Richards' eq

e.g. VanderKwaak and Loague (2001); Panday and Huyakorn (2004)

Problems

- Conceptual
  - Distinct interface?
  - Interface properties?
  - Interface dynamics?
- Technical
  - Different time scales
  - Iterative solution?
  - Numerical instability
  - Mass balance
  - Uncertainty in parameter estimates

Overland Flow: General Pressure Formulation



$$\frac{\partial \psi_s}{\partial t} = \nabla \cdot \psi_s \mathbf{v} - q_r(x) - q_e(x)$$ Kinematic wave eq

$$\psi_s = \psi_p = \psi$$

The greater of ψ and 0

$$q_e(x) = \frac{\partial \|\psi, 0\|}{\partial t} - \nabla \cdot \|\psi, 0\| \mathbf{v} - q_r(x)$$

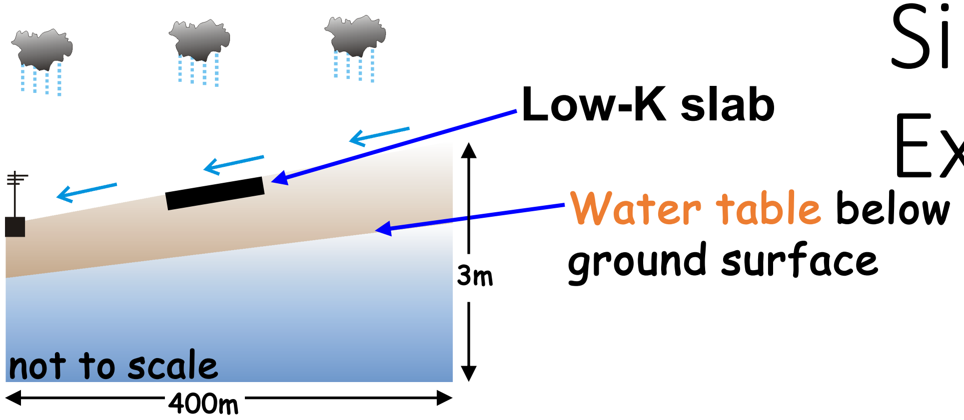
$$q_{bc} = -\mathbf{K}_s k_r(\psi) \nabla(\psi - z)$$ Neumann type BC

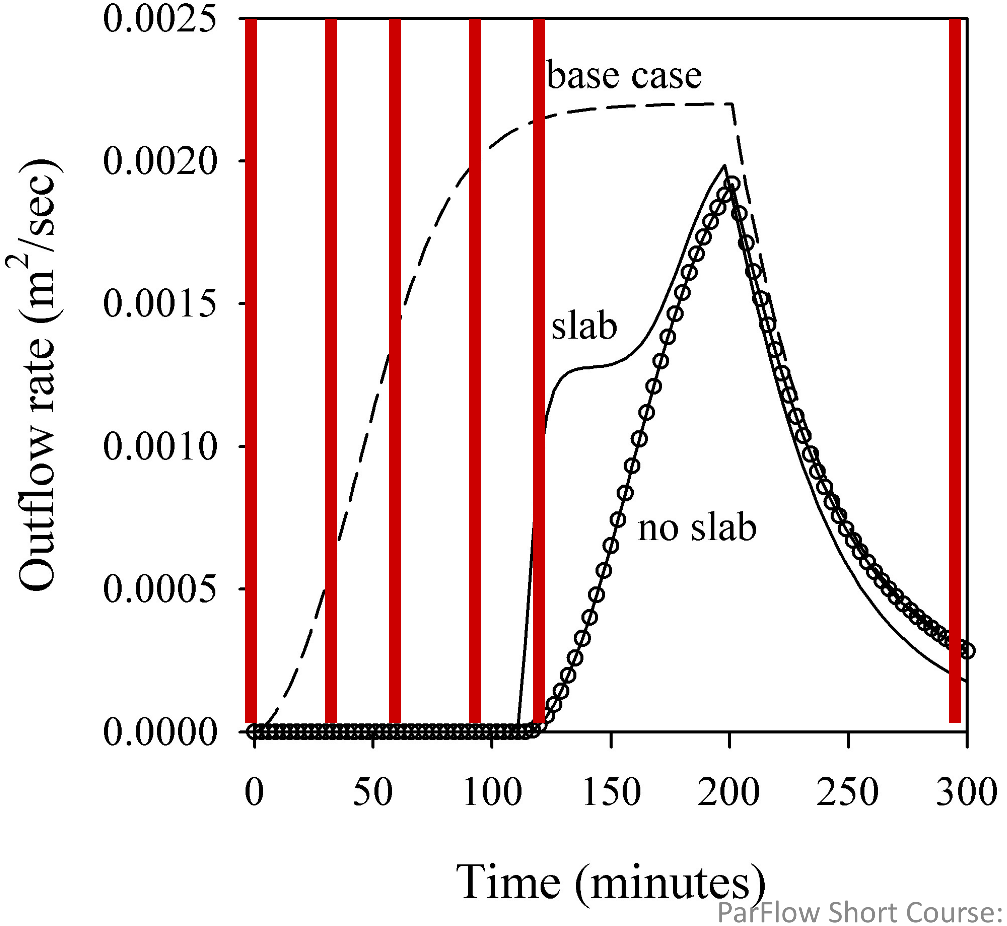
$$q_{bc} = q_e$$

$$\boxed{-\mathbf{K}_s k_r(\psi) \nabla(\psi - z) = \frac{\partial \|\psi, 0\|}{\partial t} - \nabla \cdot \|\psi, 0\| \mathbf{v} - q_r(x)}$$

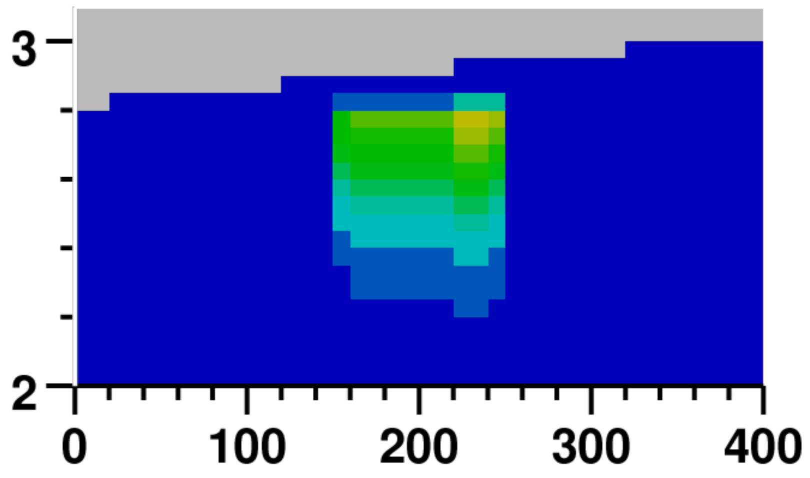
Kollet and Maxwell, AWR (2006)

Simulation Example





t = 300 min



Kollet & Maxwell, AWR, 2006

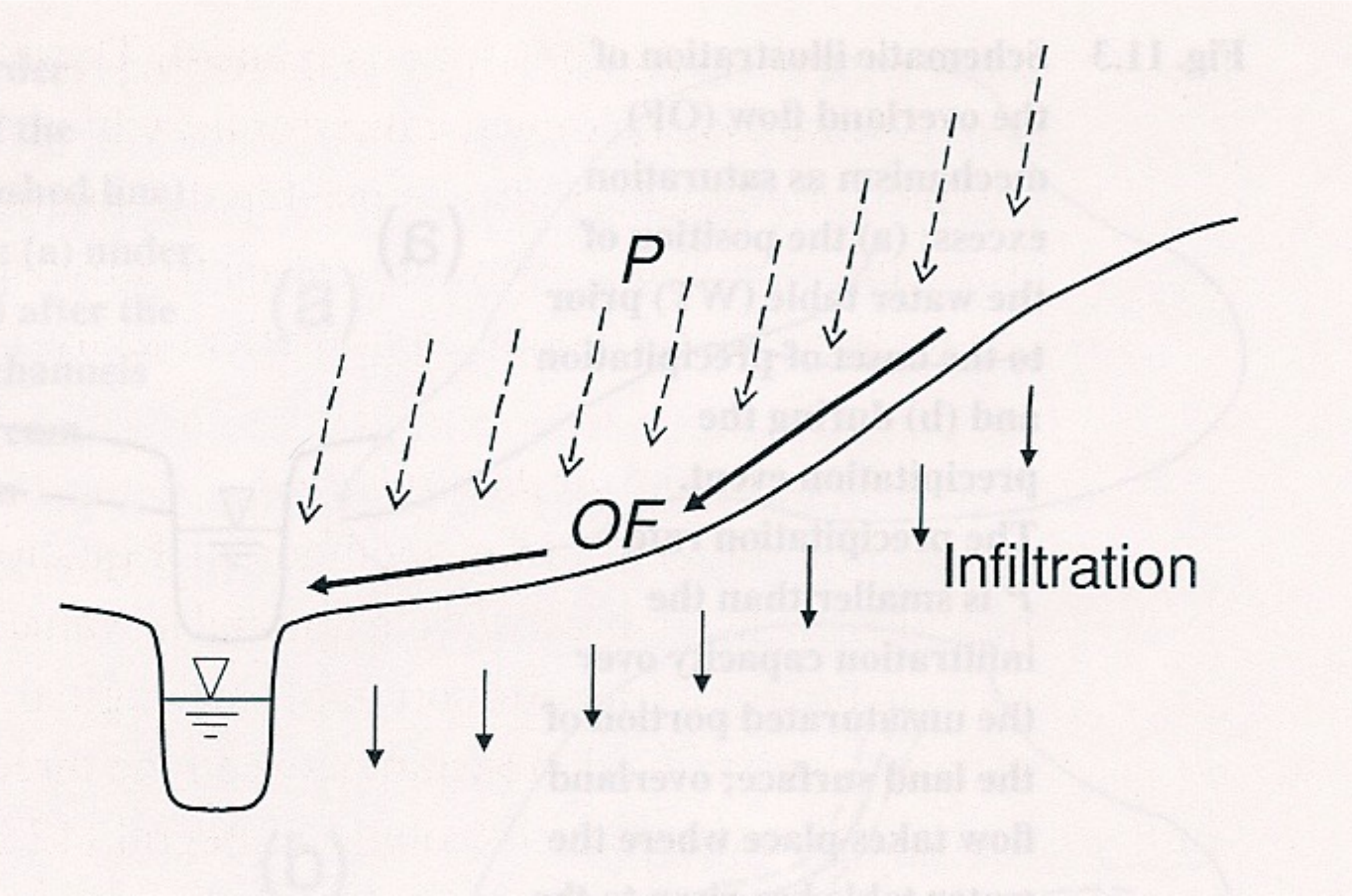
How do we turn on overland flow?

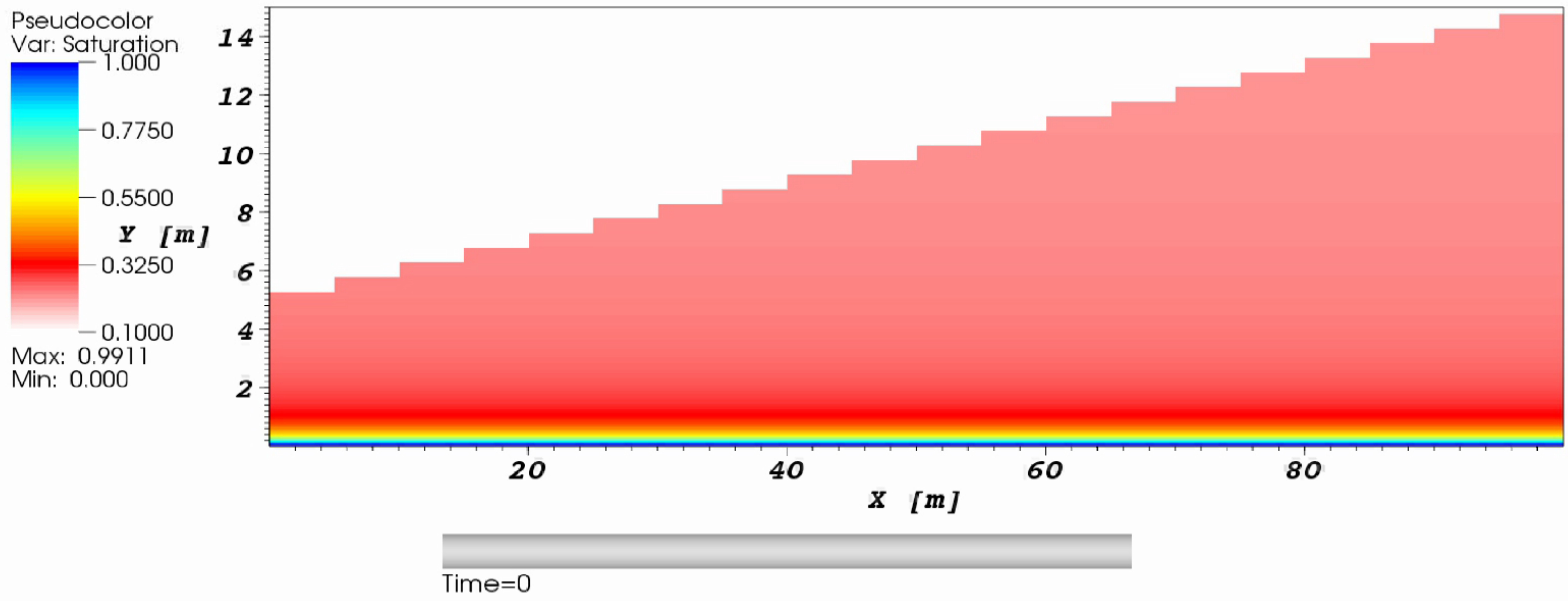
```
model.BCPressure.PatchNames = "top bottom side"


model.Patch.top.BCPressure.Type = "OverlandKinematic"
model.Patch.top.BCPressure.Cycle = "rainrec"
model.Patch.top.BCPressure.rain.Value = -0.05
model.Patch.top.BCPressure.rec.Value = 0.0
```

Runoff Generation Mechanisms

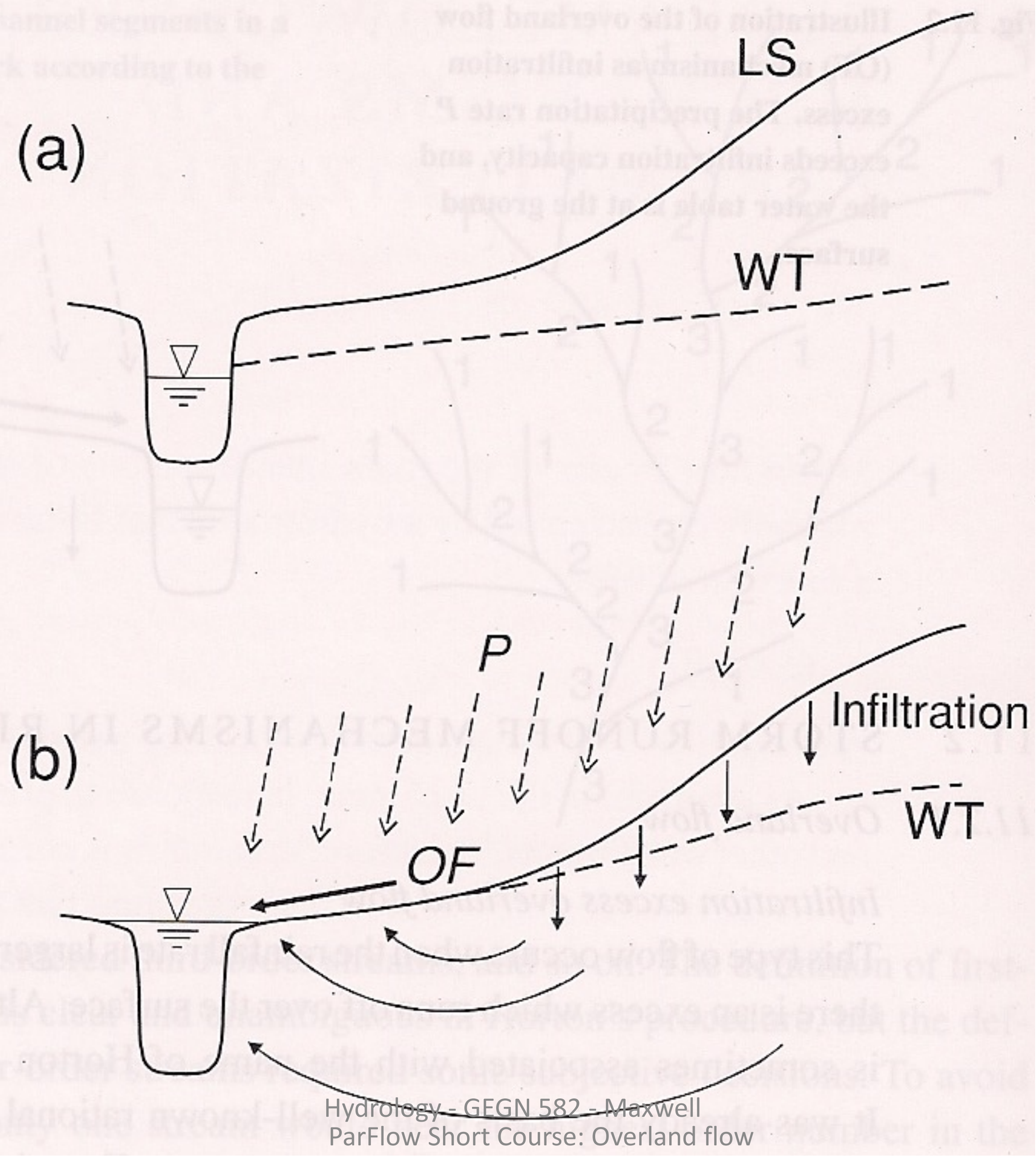
- Runoff is commonly thought to be generated via three different mechanisms:
  - Infiltration Excess
  - Saturation Excess
  - Subsurface Stormflow

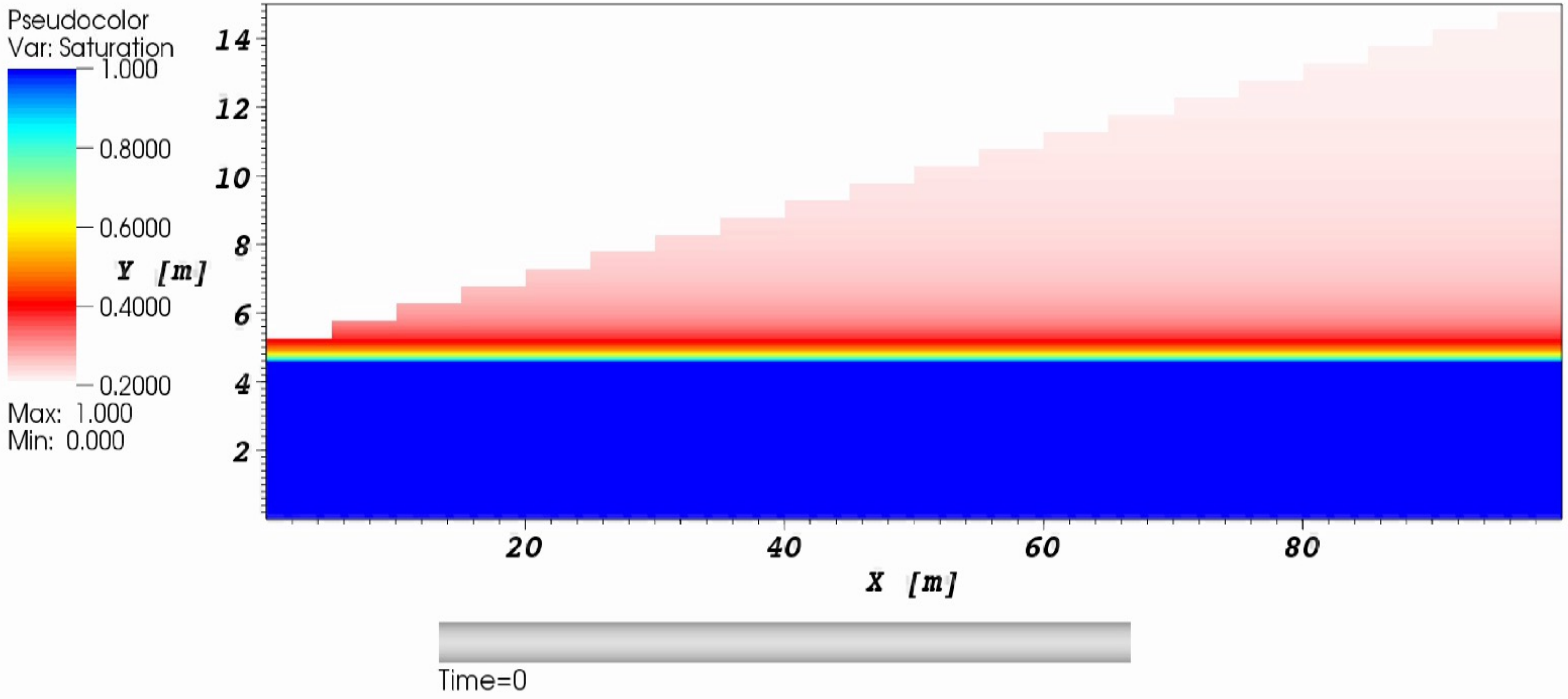
Infiltration Excess- “Hortonian” flow



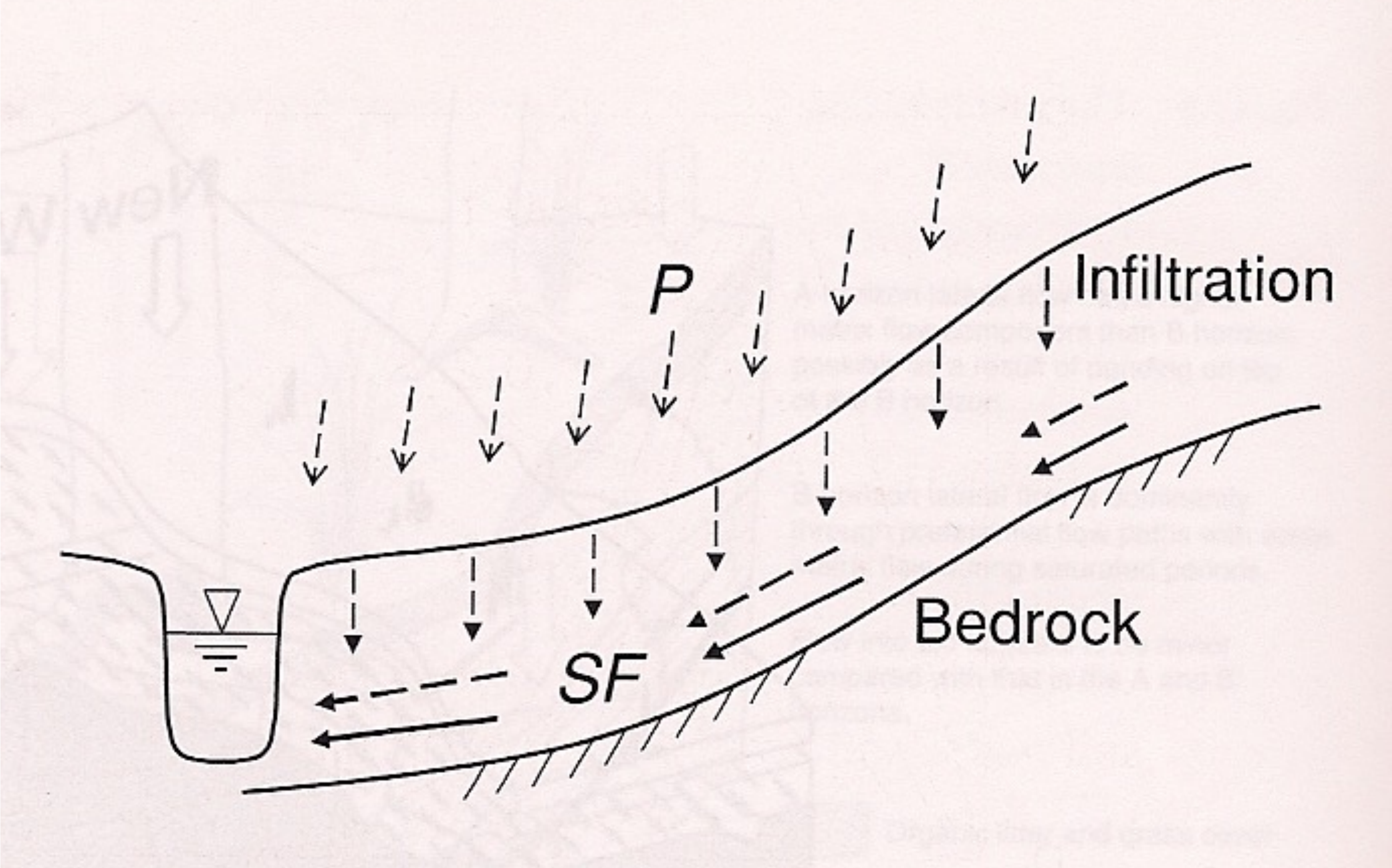

Pseudocolor
Var: Saturation
1.000
0.7750
0.5500
0.3250
0.1000
Max: 0.9911
Min: 0.000
14
12
10
8
6
4
2
Y [m]
20
40
60
80
X [m]
Time=0

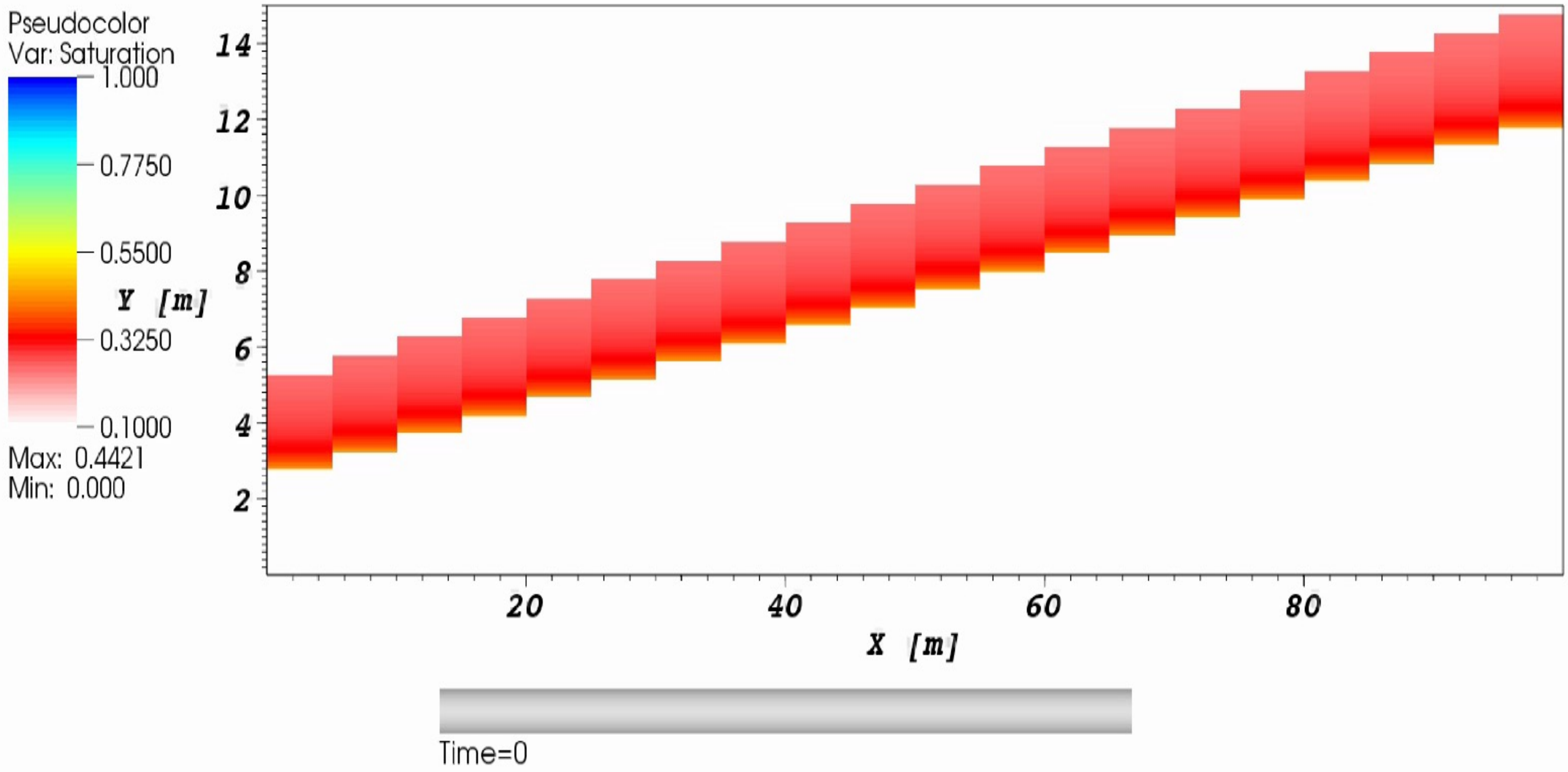
Saturation Excess- “Dunne” flow

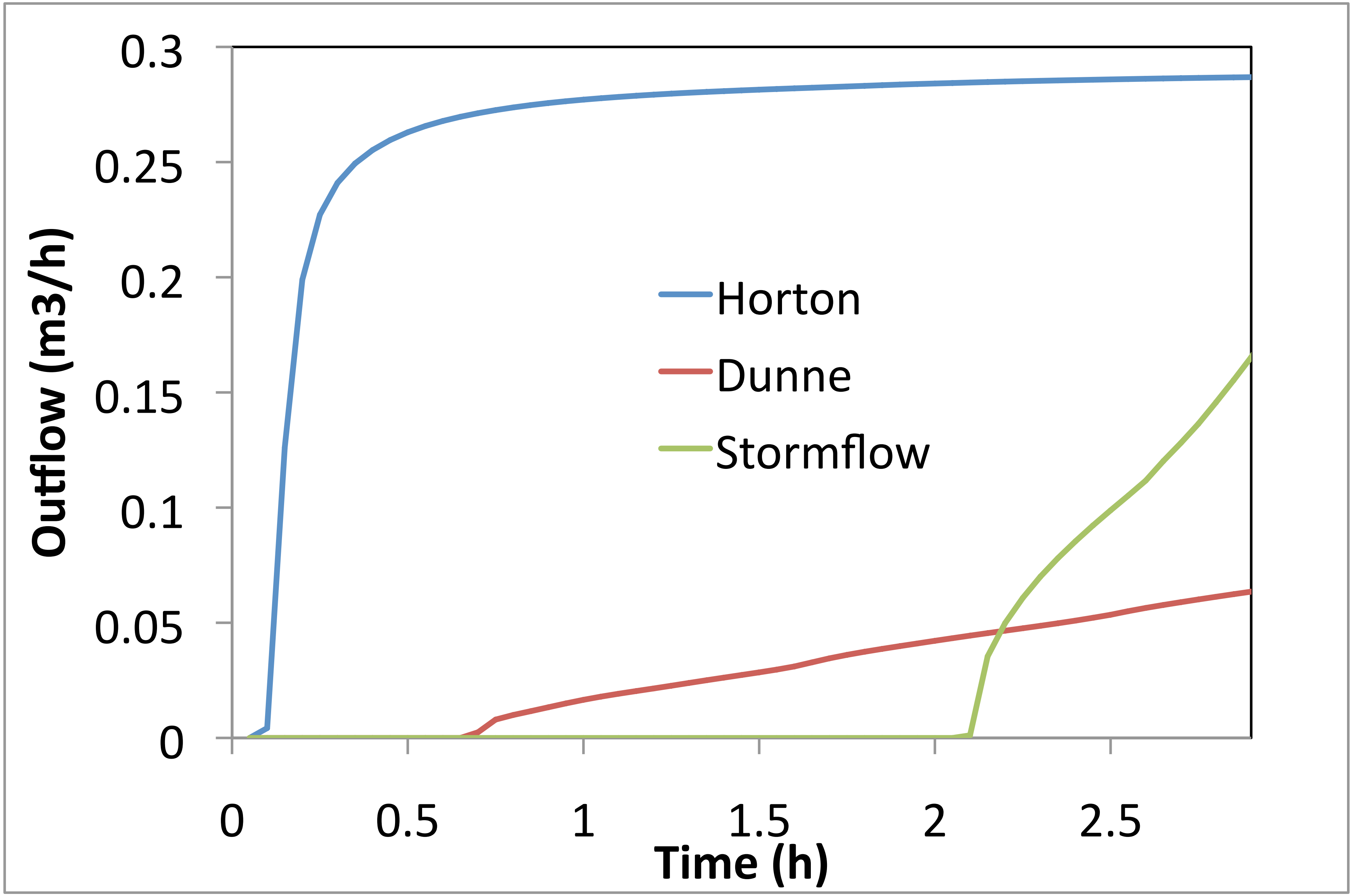


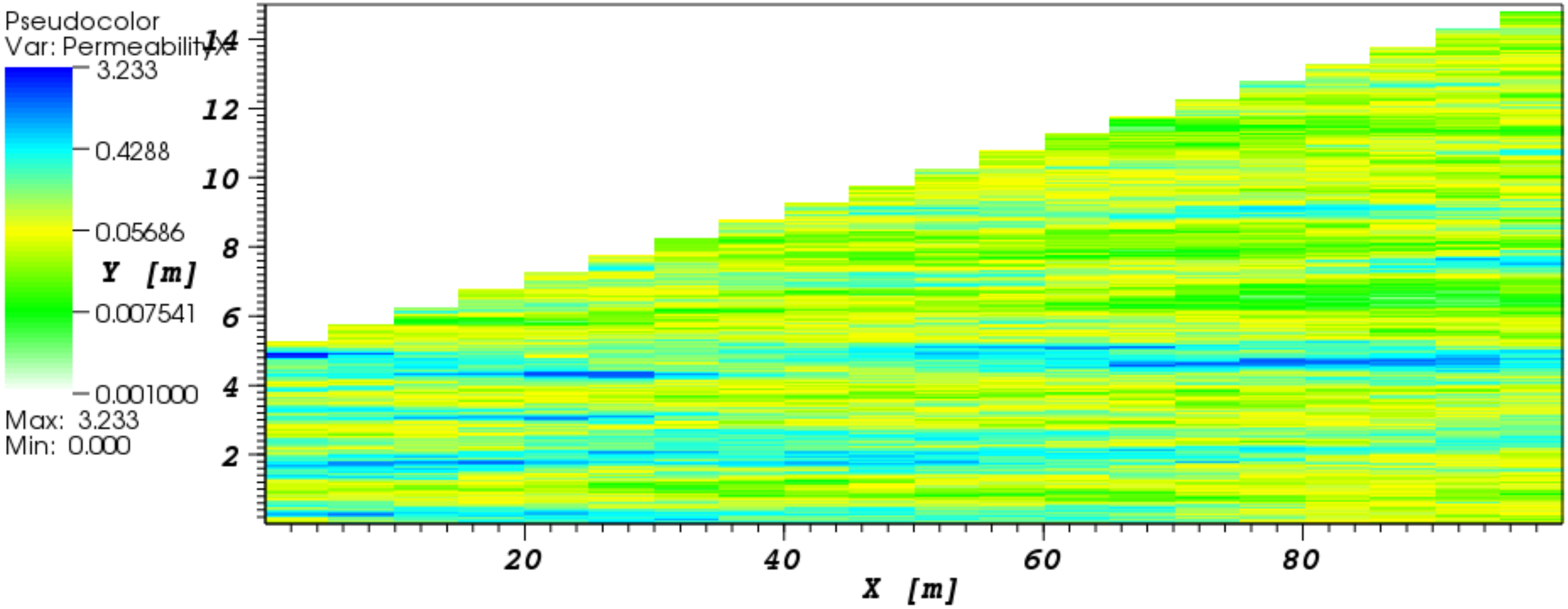

Pseudocolor
Var: Saturation
1.000
0.8000
0.6000
0.4000
0.2000
Max: 1.000
Min: 0.000
Y [m]
14
12
10
8
6
4
2
20
40
60
80
X [m]
Time=0

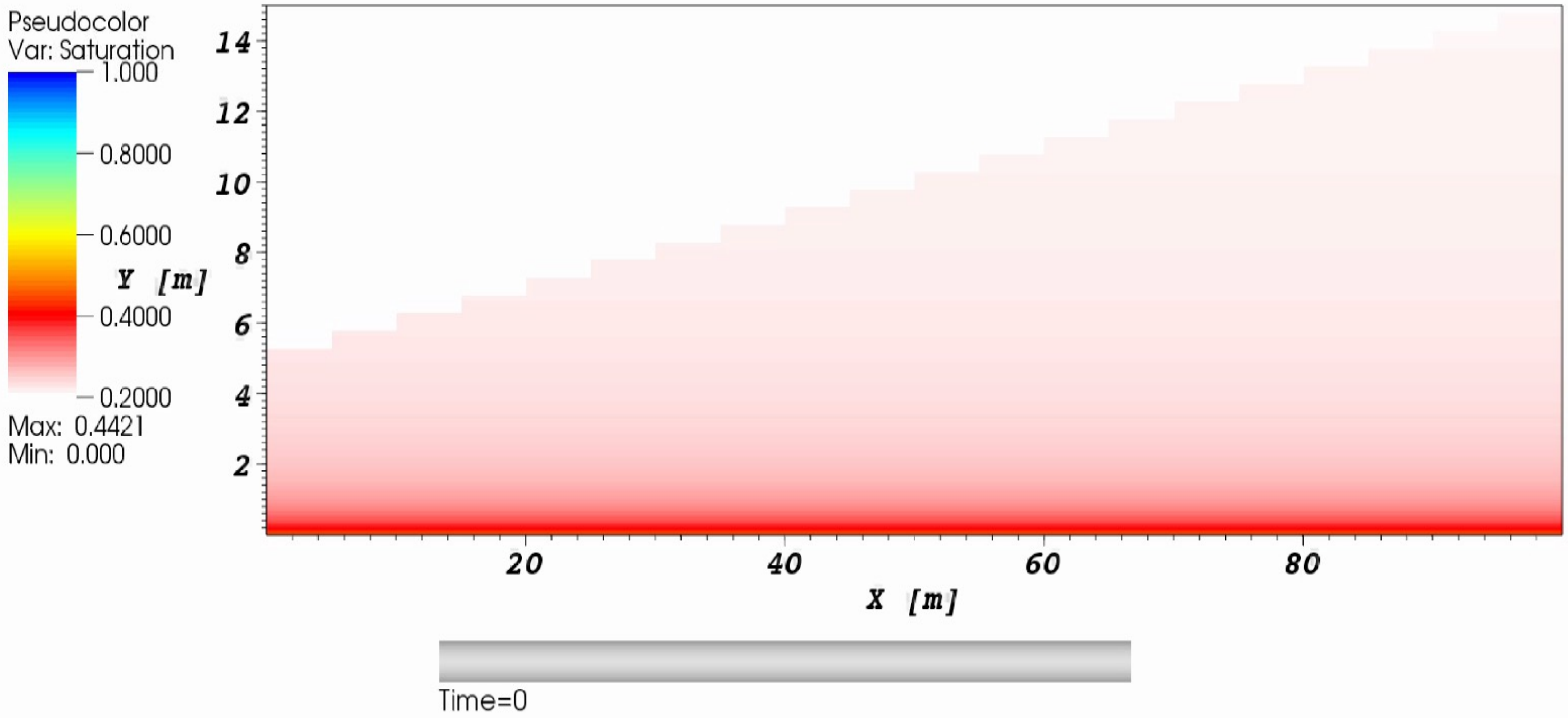
Subsurface Stormflow

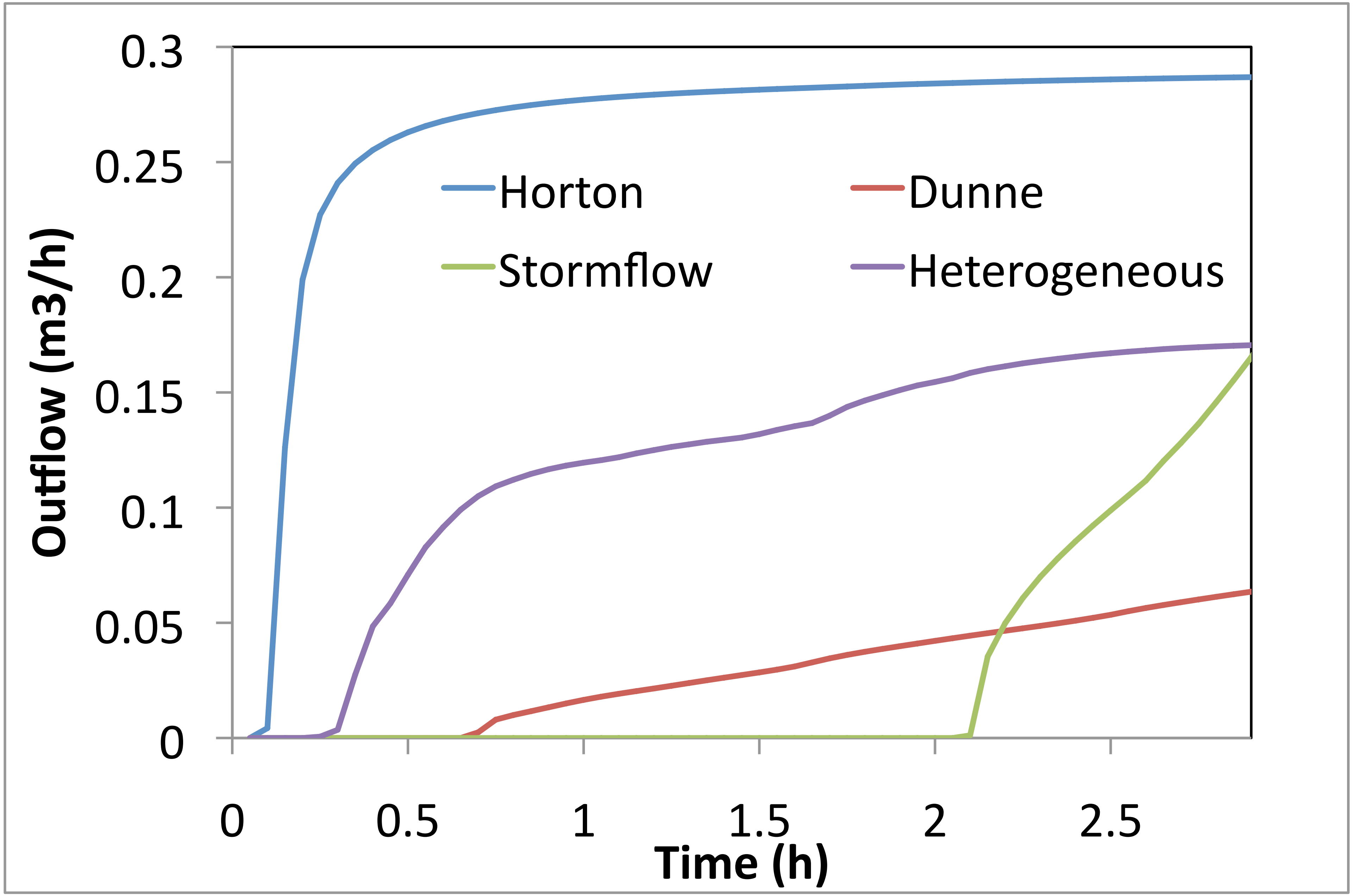


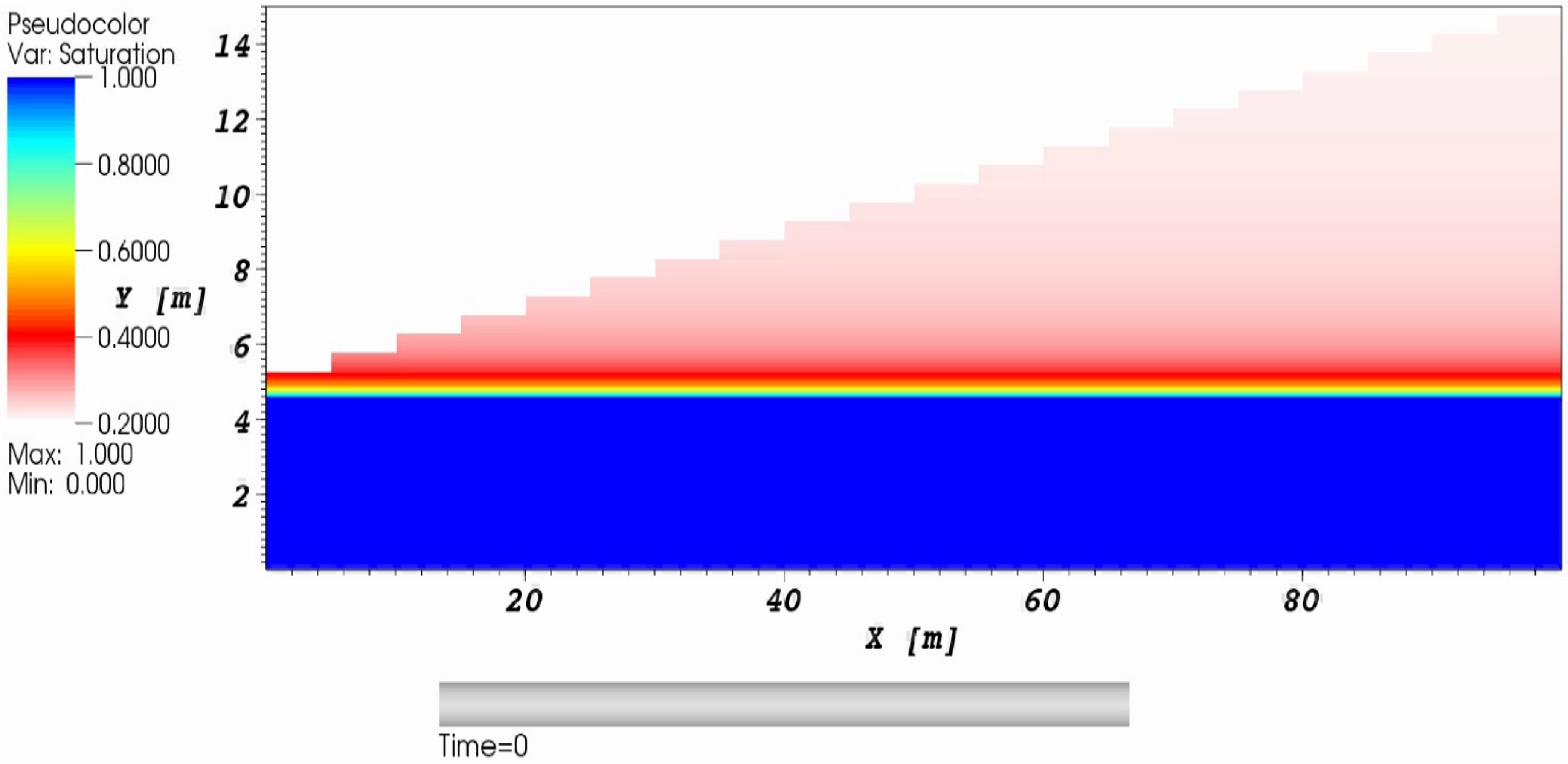

Pseudocolor
Var: Saturation
1.000
0.7750
0.5500
0.3250
0.1000
Max: 0.4421
Min: 0.000
Y [m]
14
12
10
8
6
4
2
20
40
60
80
X [m]
Time=0

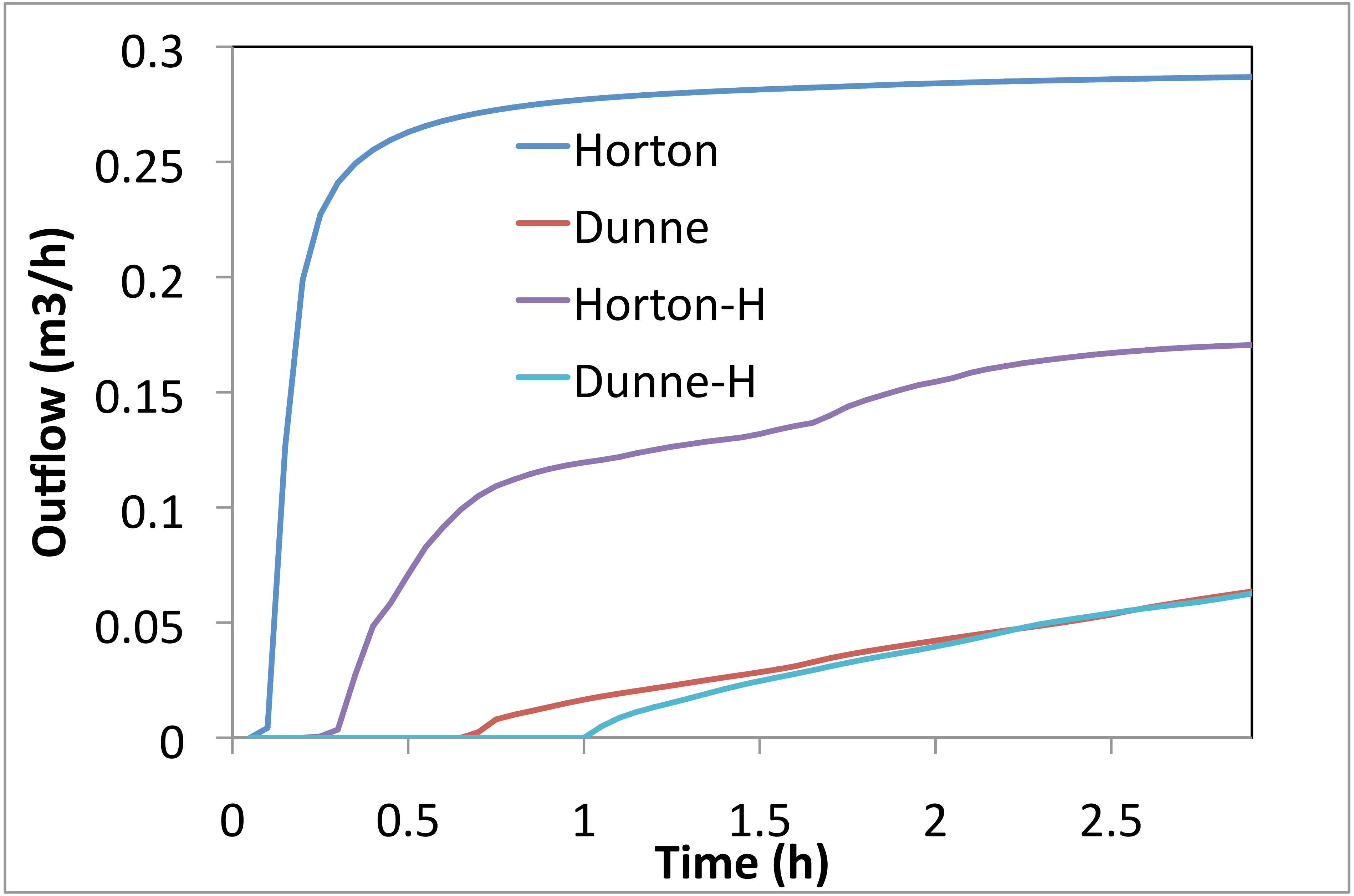

0.3
0.25
0.2
0.15
0.1
0.05
0
Outflow (m3/h)
0
0.5
1
1.5
2
2.5
Time (h)
Horton
Dunne
Stormflow


Pseudocolor
Var: PermeabilityX
3.233
0.4288
0.05686
0.007541
0.001000
Max: 3.233
Min: 0.000
Y [m]
14
12
10
8
6
4
2
20
40
60
80
X [m]


Pseudocolor
Var: Saturation
1.000
0.8000
0.6000
0.4000
0.2000
Max: 0.4421
Min: 0.000
Y [m]
14
12
10
8
6
4
2
20
40
60
80
X [m]
Time=0


Outflow (m3/h)
0.3
0.25
0.2
0.15
0.1
0.05
0
Horton
Dunne
Stormflow
Heterogeneous
0
0.5
1
1.5
2
2.5
Time (h)


Pseudocolor
Var: Saturation
1.000
0.8000
0.6000
0.4000
0.2000
Max: 1.000
Min: 0.000
Y [m]
14
12
10
8
6
4
2
20
40
60
80
X [m]
Time=0


0.3
0.25
0.2
0.15
0.1
0.05
0
Outflow (m3/h)
0
0.5
1
1.5
2
2.5
Time (h)
Horton
Dunne
Horton-H
Dunne-H

The **Tilted V catchment is** a **standard benchmark** problem in hydrology

- The Tilted V is the simplest **representative watershed** type domain
- Two hillslopes drain into a central channel
- Long history as a **benchmark problem** in hydrology