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A comparison between the DrainFlow and SCS-CN methods in rainfall-runoff modelling

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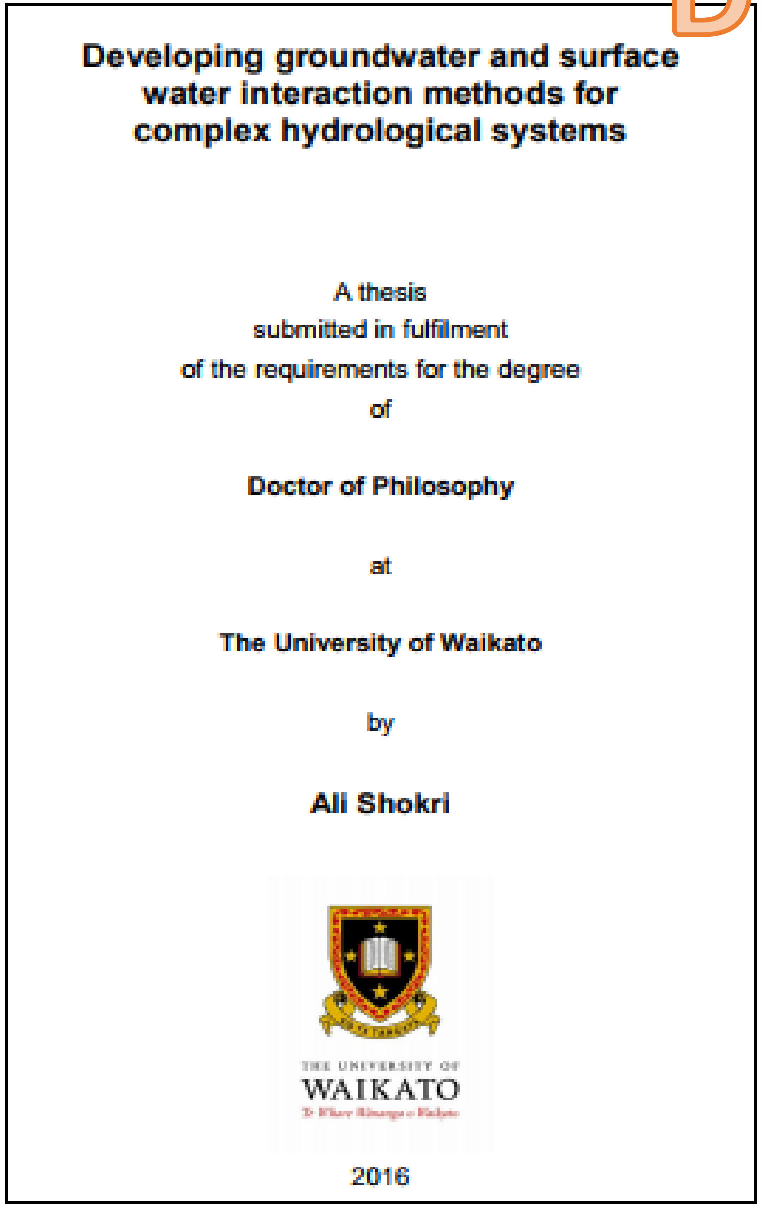
Lecturer at WINTEC

Wednesday 20 Sep 2017

DrainFlow



Developing groundwater and surface water interaction methods for complex hydrological systems

A thesis
submitted in fulfilment
of the requirements for the degree
of

Doctor of Philosophy

at

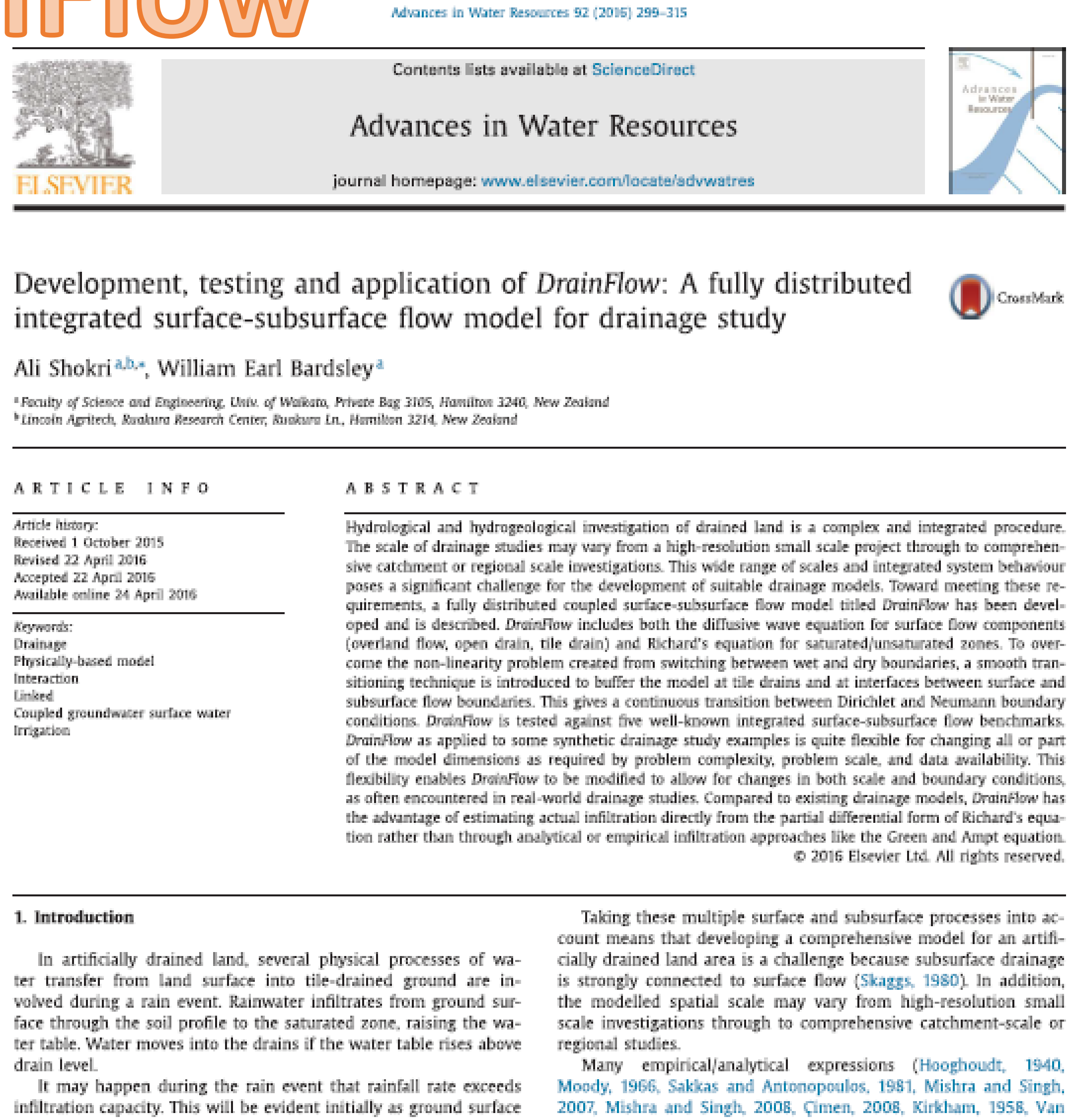
The University of Waikato

by

Ali Shokri

THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

2016



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Development, testing and application of *DrainFlow*: A fully distributed integrated surface-subsurface flow model for drainage study

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ABSTRACT

Hydrological and hydrogeological investigation of drained land is a complex and integrated procedure. The scale of drainage studies may vary from a high-resolution small scale project through to comprehensive catchment or regional scale investigations. This wide range of scales and integrated system behaviour poses a significant challenge for the development of suitable drainage models. Toward meeting these requirements, a fully distributed coupled surface-subsurface flow model titled *DrainFlow* has been developed and is described. *DrainFlow* includes both the diffusive wave equation for surface flow components (overland flow, open drain, tile drain) and Richard's equation for saturated/unsaturated zones. To overcome the non-linearity problem created from switching between wet and dry boundaries, a smooth transitioning technique is introduced to buffer the model at tile drains and at interfaces between surface and subsurface flow boundaries. This gives a continuous transition between Dirichlet and Neumann boundary conditions. *DrainFlow* is tested against five well-known integrated surface-subsurface flow benchmarks. *DrainFlow* as applied to some synthetic drainage study examples is quite flexible for changing all or part of the model dimensions as required by problem complexity, problem scale, and data availability. This flexibility enables *DrainFlow* to be modified to allow for changes in both scale and boundary conditions, as often encountered in real-world drainage studies. Compared to existing drainage models, *DrainFlow* has the advantage of estimating actual infiltration directly from the partial differential form of Richard's equation rather than through analytical or empirical infiltration approaches like the Green and Ampt equation.

1. Introduction

In artificially drained land, several physical processes of water transfer from land surface into tile-drained ground are involved during a rain event. Rainwater infiltrates from ground surface through the soil profile to the saturated zone, raising the water table. Water moves into the drains if the water table rises above drain level.

It may happen during the rain event that rainfall rate exceeds infiltration capacity. This will be evident initially as ground surface

Taking these multiple surface and subsurface processes into account means that developing a comprehensive model for an artificially drained land area is a challenge because subsurface drainage is strongly connected to surface flow (Skaggs, 1980). In addition, the modelled spatial scale may vary from high-resolution small scale investigations through to comprehensive catchment-scale or regional studies.

Many empirical/analytical expressions (Hooghoudt, 1940, Moody, 1966, Sakkas and Antonopoulos, 1981, Mishra and Singh, 2007, Mishra and Singh, 2008, Çimen, 2008, Kirkham, 1958, Van

Drainflow: a fully distributed integrated surface/subsurface flow model for drainage studies

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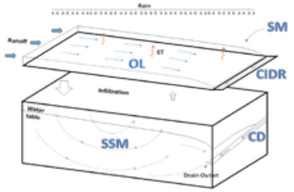
Introduction

The scale of drainage studies may vary from high-resolution small scale investigations through to comprehensive catchment or regional-scale studies. This wide range of scales poses a significant challenge for the development of a suitable drainage model.

The purpose of the study is to develop a fully distributed surface/subsurface interactive flow model specialized in drainage study named henceforth **Drainflow.**



Drainflow Modules:

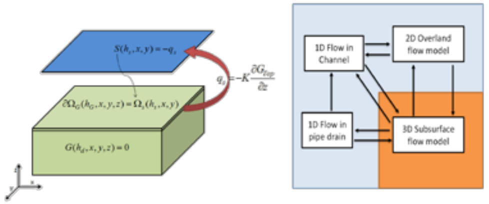
- Overlandflow (OL)
- Channel flow (CIDR)
- Tile drain (CD)
- Subsurface flow for saturated/unsaturated zones (SSM)

Methodology

Drainflow uses both the Saint-Venant equations for surface flow components and the Richards equation for saturated and unsaturated zones

To develop the model, surface and subsurface flow modules are formulated separately, then each component is connected to the other parts. All modules simultaneously interact to calculate water level and discharge in tile drains, channel networks, and overland flow. In the subsurface domain, the model also yields soil moisture and water table elevation.

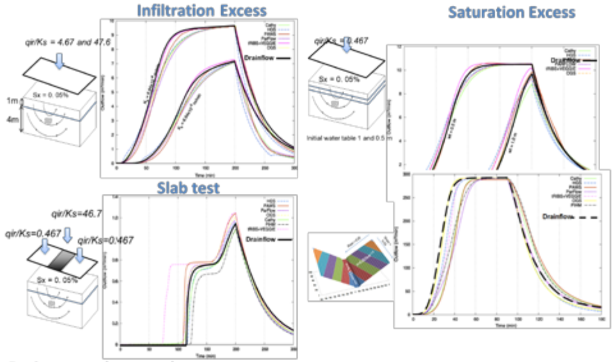
In addition, a smoothed Heaviside function is introduced to give a continuous transition of the model between Dirichlet and Neumann boundary conditions for tile drains and surface/subsurface flow interface boundaries.



Boundary condition coupling concept

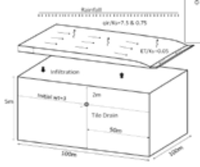
Results

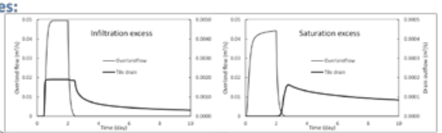
To test the model's accuracy, comparisons are made between **Drainflow** and a range of surface/subsurface flow models for five published integrated surface and subsurface problems. The comparison indicates **Drainflow** has a reasonably good agreement with the other integrated models.
Furthermore, it is shown that the smoothed Heaviside functions technique is a very effective method to overcome the non-linearity problem created from switching between dry and wet boundary conditions



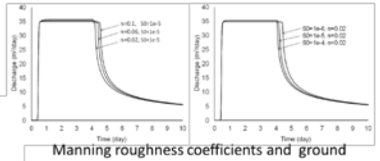
Drainage study examples:

Example 1:
one tile drain

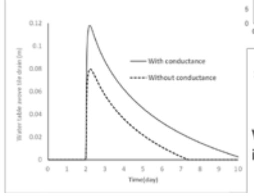




Overland-flow and tile drain flux hydrographs



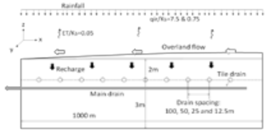
Manning roughness coefficients and ground surface flow slope affect on tile drain hydrographs.

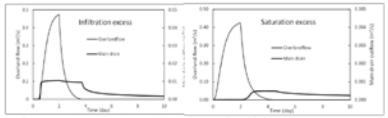


Water table above tile drain with and without tile drain iterance conductance influence.

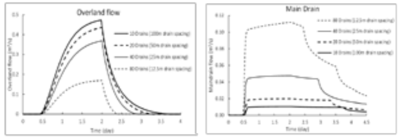
Example 2: Upscaling

Drainflow is tested in some drainage study examples. This is found that Drainflow is fairly flexible in terms of changing all or part of the model dimensions if required because of problem complexity, scale, and data availability.
Drainflow can be easily simplified dimensionally and methodologically to a less comprehensive and complex model if required.
This flexibility gives **Drainflow** the capacity to meet the specific requirements of the varying scale and boundary conditions that often encountered in drainage studies.





Overland flow and Main-drain hydrographs for saturated and infiltration excess scenarios for 10 tile drain .

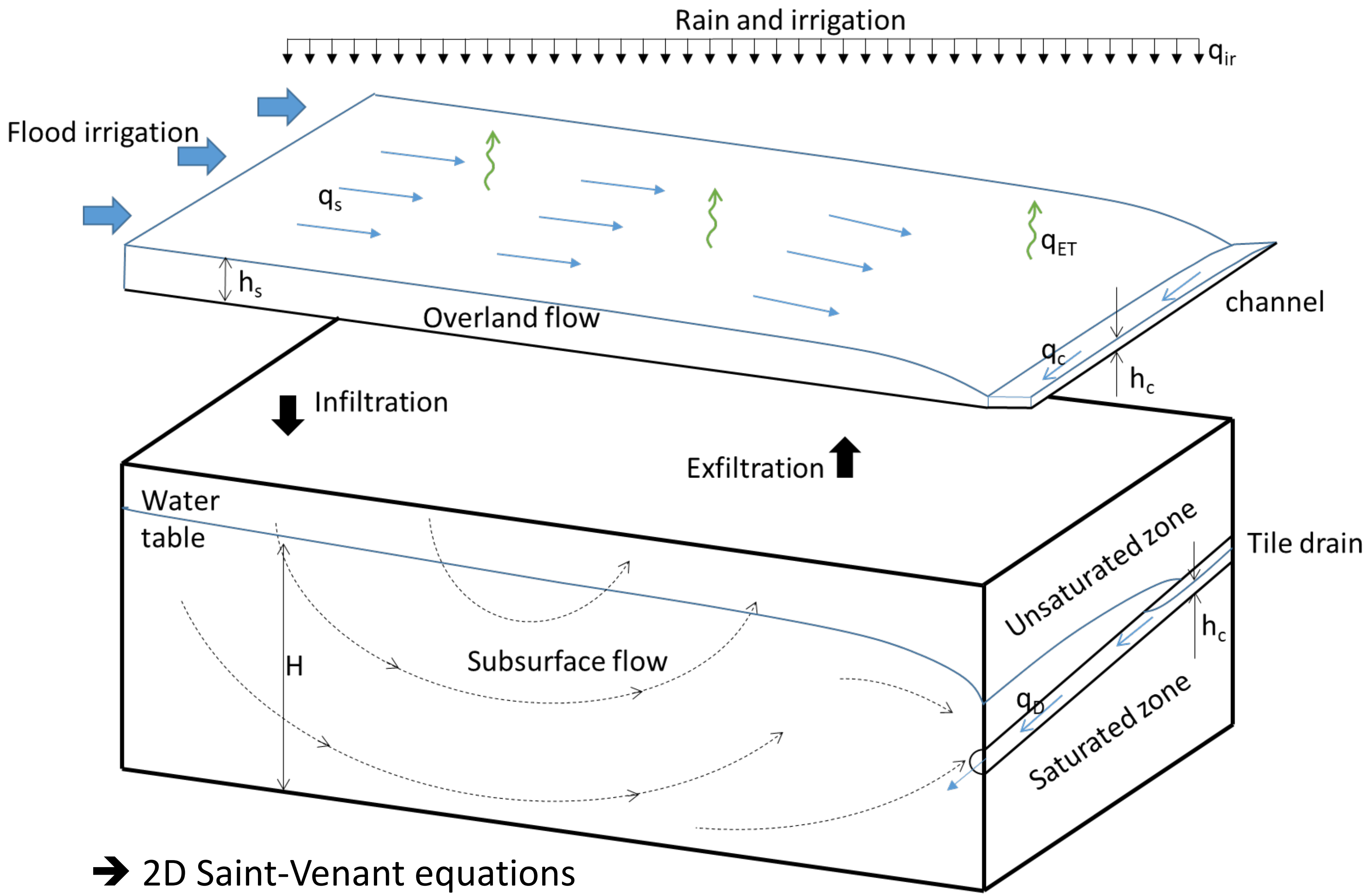


Comparing overlandflow and maindrain Hydrographs when 10, 20, 40 and 80 tile drain applies to the same field area.

Conclusions

- A comprehensive surface/subsurface interaction flow model specialized in drainage study is developed. The model tested against some well-known published benchmarks.
- Model utilized in some simple drainage studies. Results shows the developed model could give a better understanding of drainage study process like:
  - Pipe drain and main drain discharge
  - Land Surface Recharge (LSR)
  - The lag time
  - Runoff
  - water table
- The developed model might be applicable for a larger scale study (catchment or regional scale) by applying simplification assumptions.

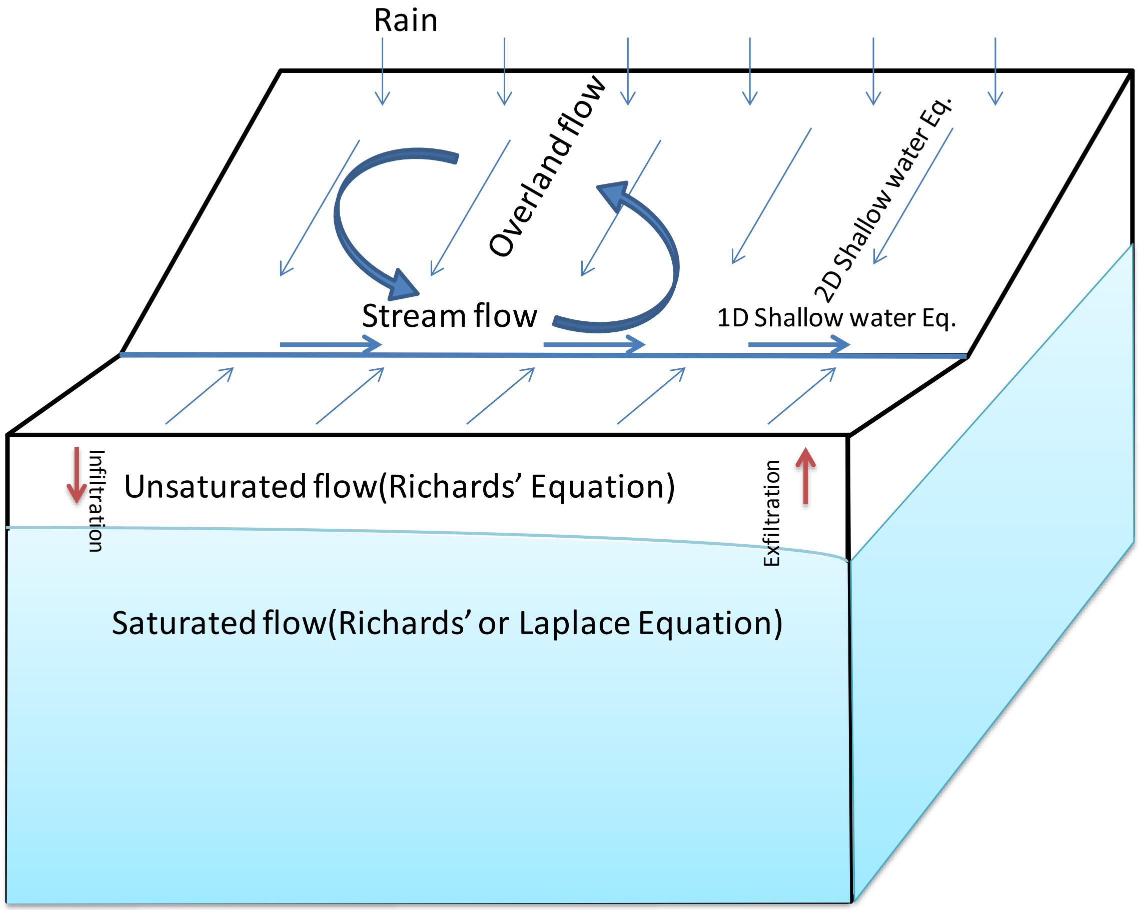
DrainFlow

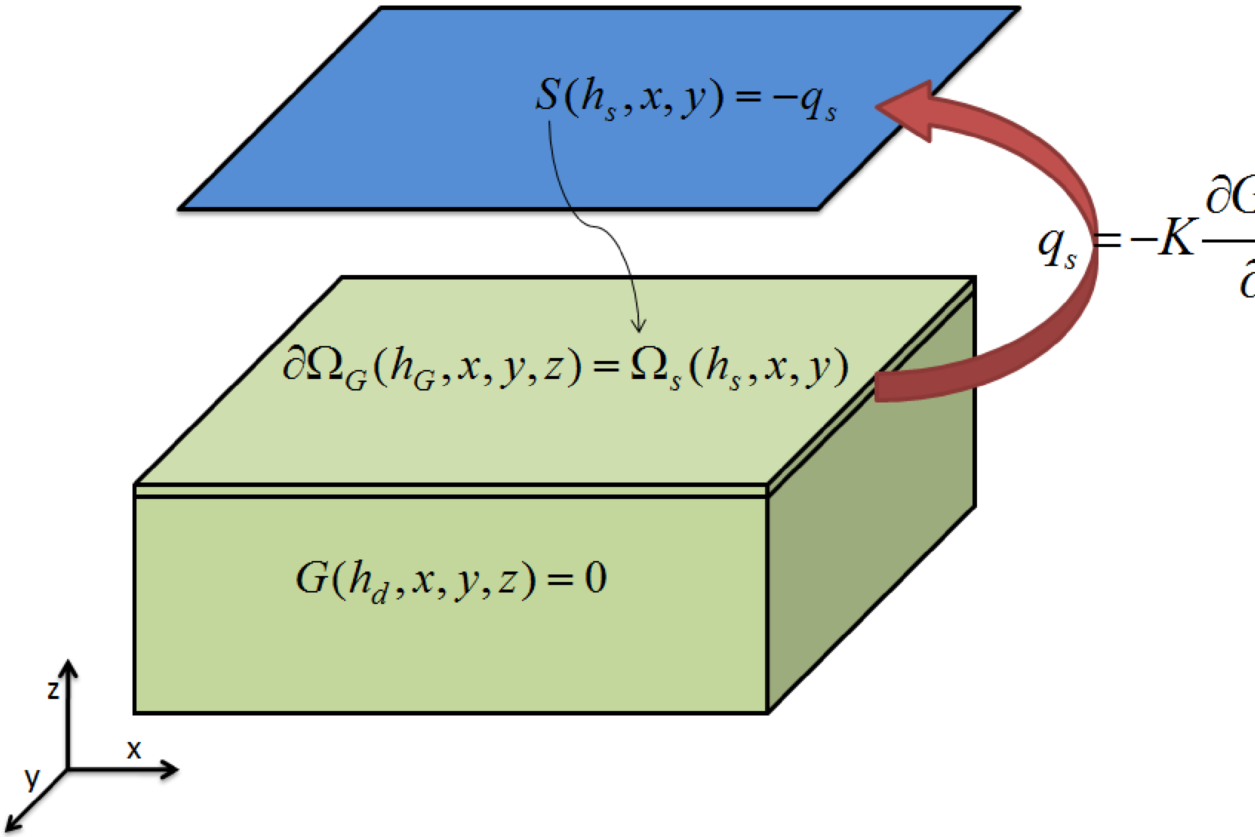


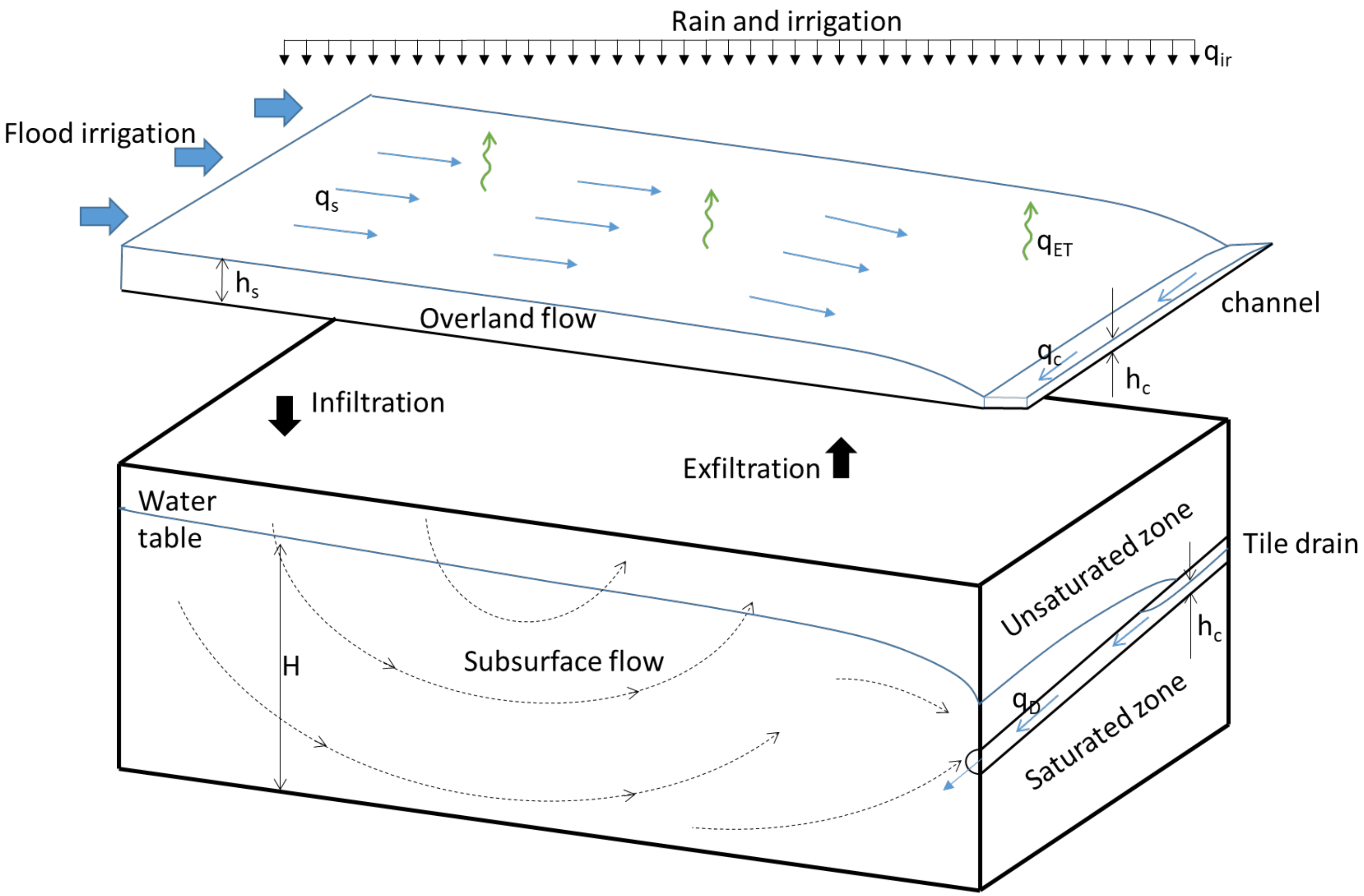
Modules:

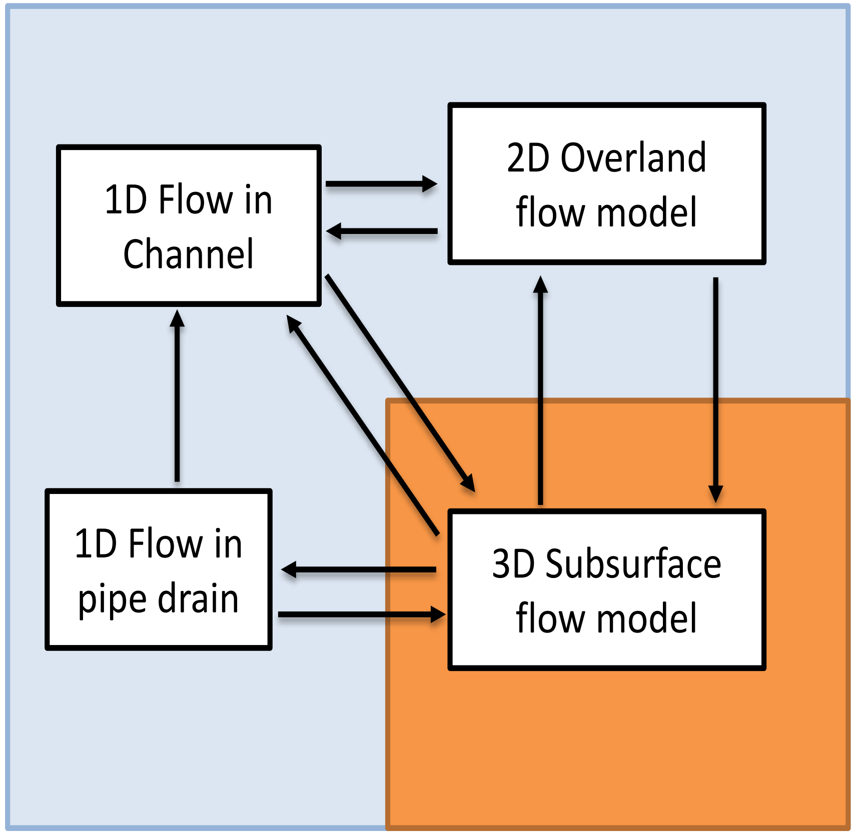
- Overlandflow → 2D Saint-Venant equations
- Channel flow (CIDR) → 1D Saint-Venant equations
- Subsurface flow (SSM) → 3D Richards equation
- Tile drain (CD) → 1D Saint-Venant equations

Coupling method





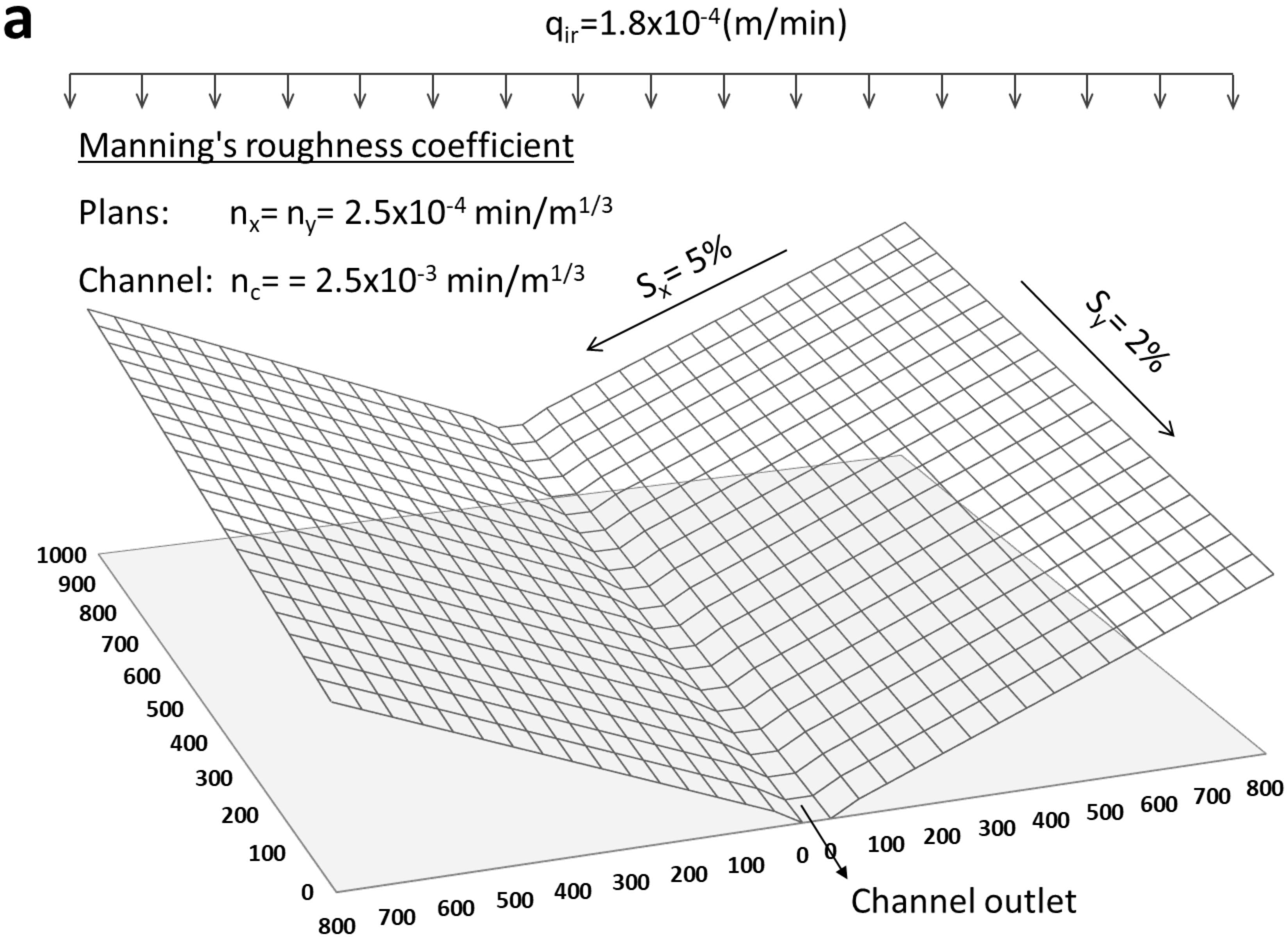



1D Flow in Channel

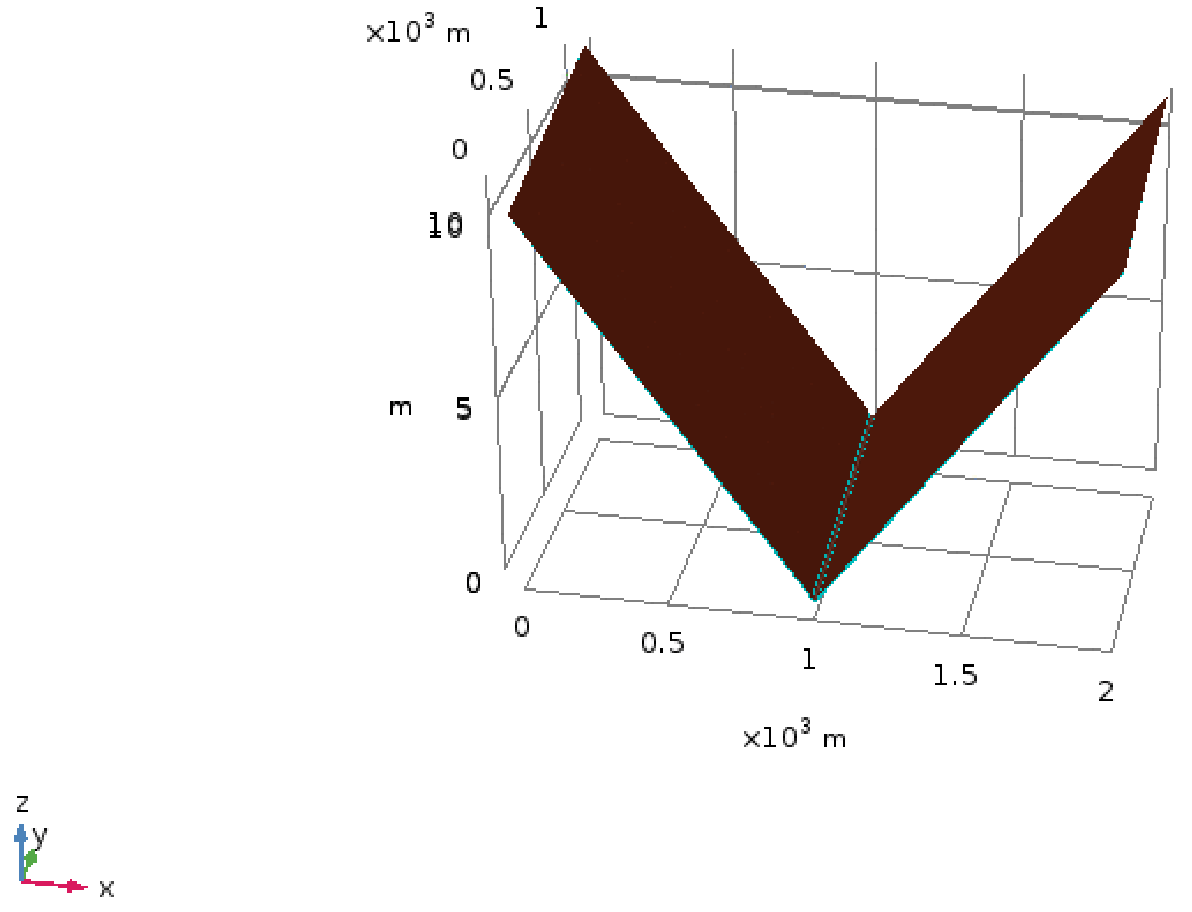
2D Overland flow model

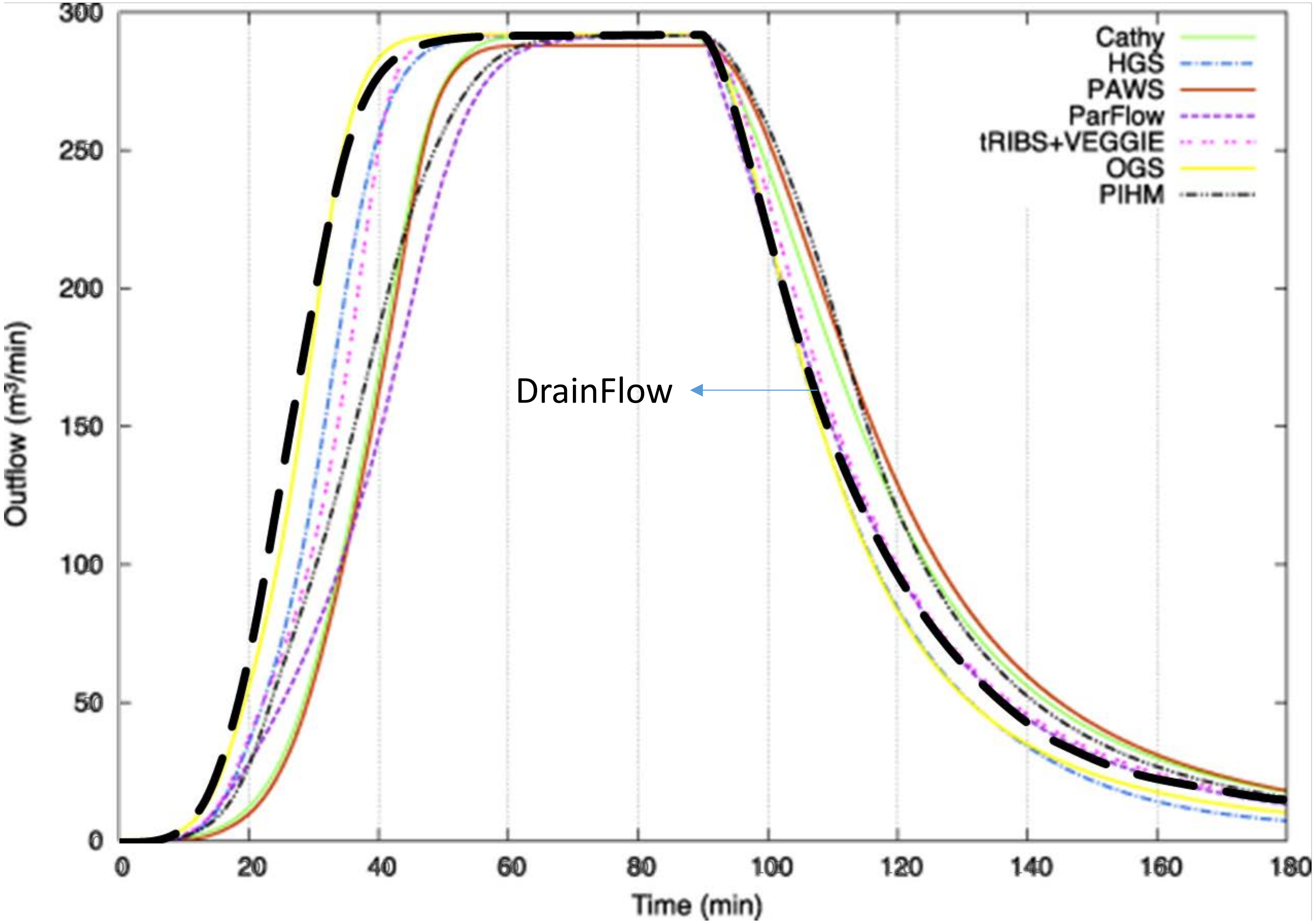
1D Flow in pipe drain

3D Subsurface flow model


a
q_{ir}=1.8x10^{-4}(m/min)
Manning's roughness coefficient
Plans: $n_x = n_y = 2.5 \times 10^{-4}$ min/m$^{1/3}$
Channel: $n_c = = 2.5 \times 10^{-3}$ min/m$^{1/3}$
$S_x = 5\%$
$S_y = 2\%$
1000
900
800
700
600
500
400
300
200
100
0
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
Channel outlet

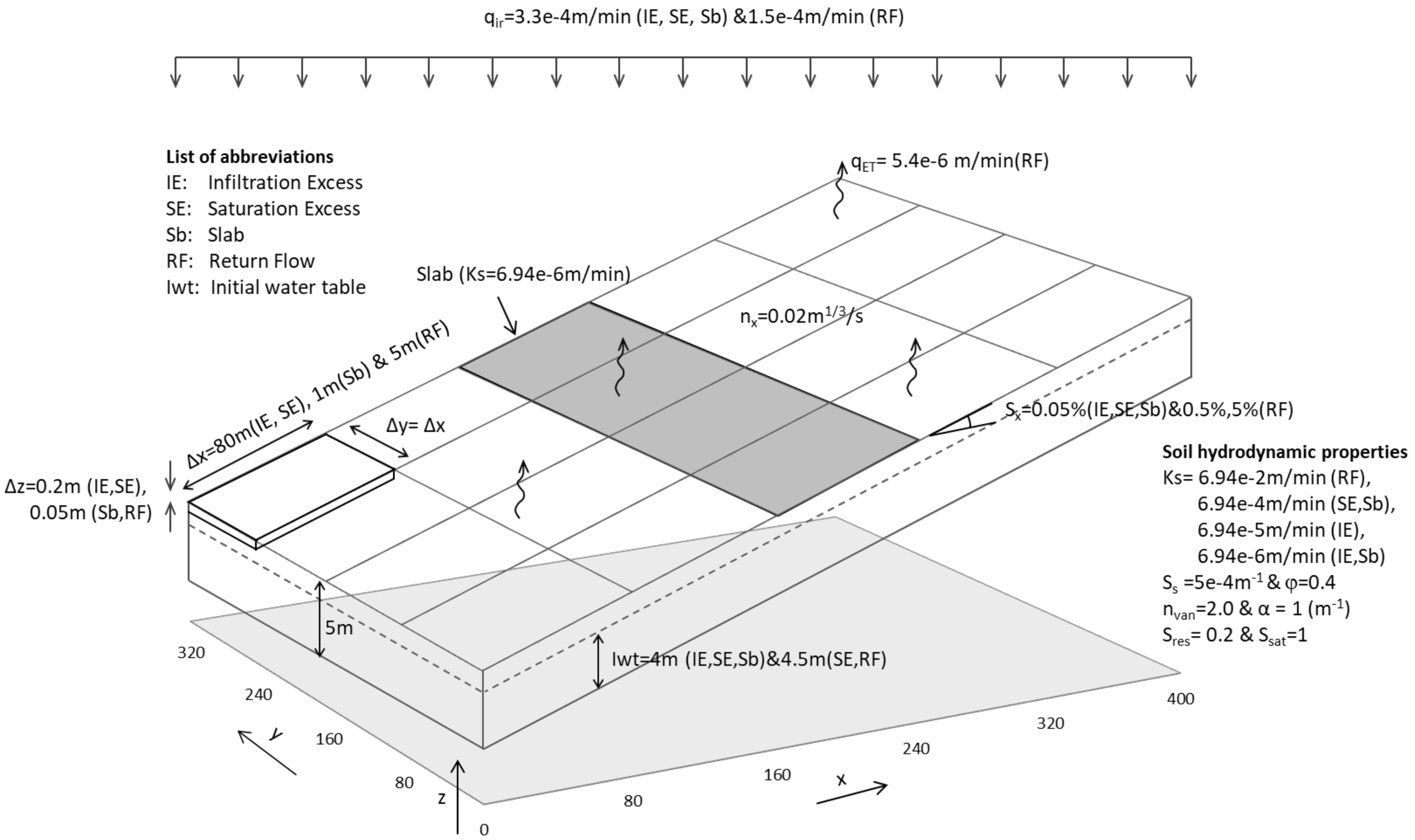
Simple V-Catchment simulation




Cathy
HGS
PAWS
ParFlow
tRIBS+VEGGIE
OGS
PIHM
Outflow (m^3/min)
0
50
100
150
200
250
300
Time (min)
0
20
40
60
80
100
120
140
160
180

DrainFlow

Some other Examples to test the DrainFlow



q_{ir}=3.3e-4m/min (IE, SE, Sb) &1.5e-4m/min (RF)

List of abbreviations
IE: Infiltration Excess
SE: Saturation Excess
Sb: Slab
RF: Return Flow
Iwt: Initial water table

q_{ET}= 5.4e-6 m/min(RF)

Slab (Ks=6.94e-6m/min)

n_x=0.02$m^{1/3}$/s

Δx=80m(IE, SE), 1m(Sb) & 5m(RF)

Δy= Δx

S_x=0.05%(IE,SE,Sb)&0.5%,5%(RF)

Δz=0.2m (IE,SE),
0.05m (Sb,RF)

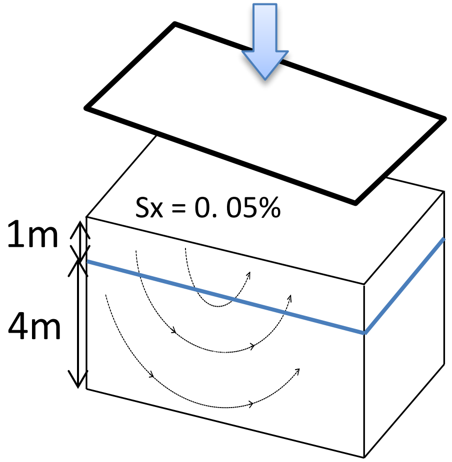
5m

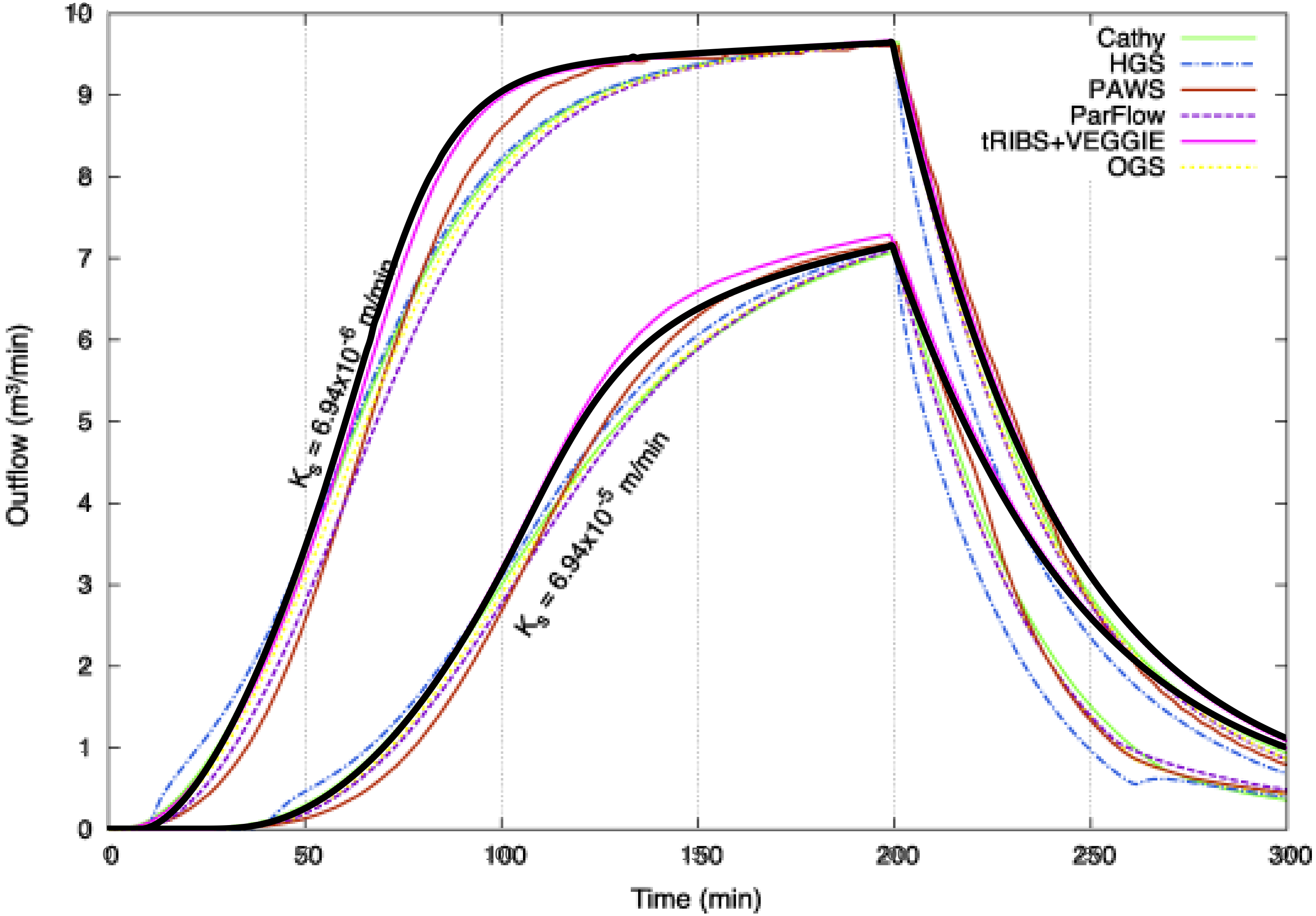
Iwt=4m (IE,SE,Sb)&4.5m(SE,RF)

Soil hydrodynamic properties
Ks= 6.94e-2m/min (RF),
6.94e-4m/min (SE,Sb),
6.94e-5m/min (IE),
6.94e-6m/min (IE,Sb)
S_s =5e-4m^{-1} & φ=0.4
n_{van}=2.0 & α = 1 (m^{-1})
S_{res}= 0.2 & S_{sat}=1

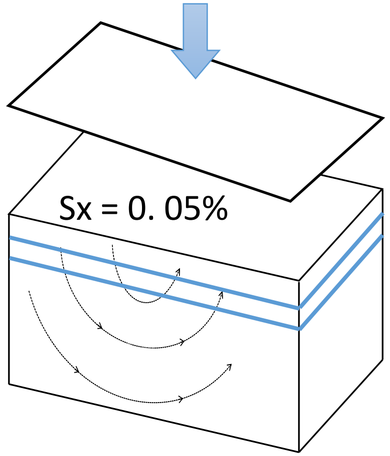
Infiltration excess runoff benchmark
(low hydraulic conductivity)

qir/Ks = 4.67 and 47.6

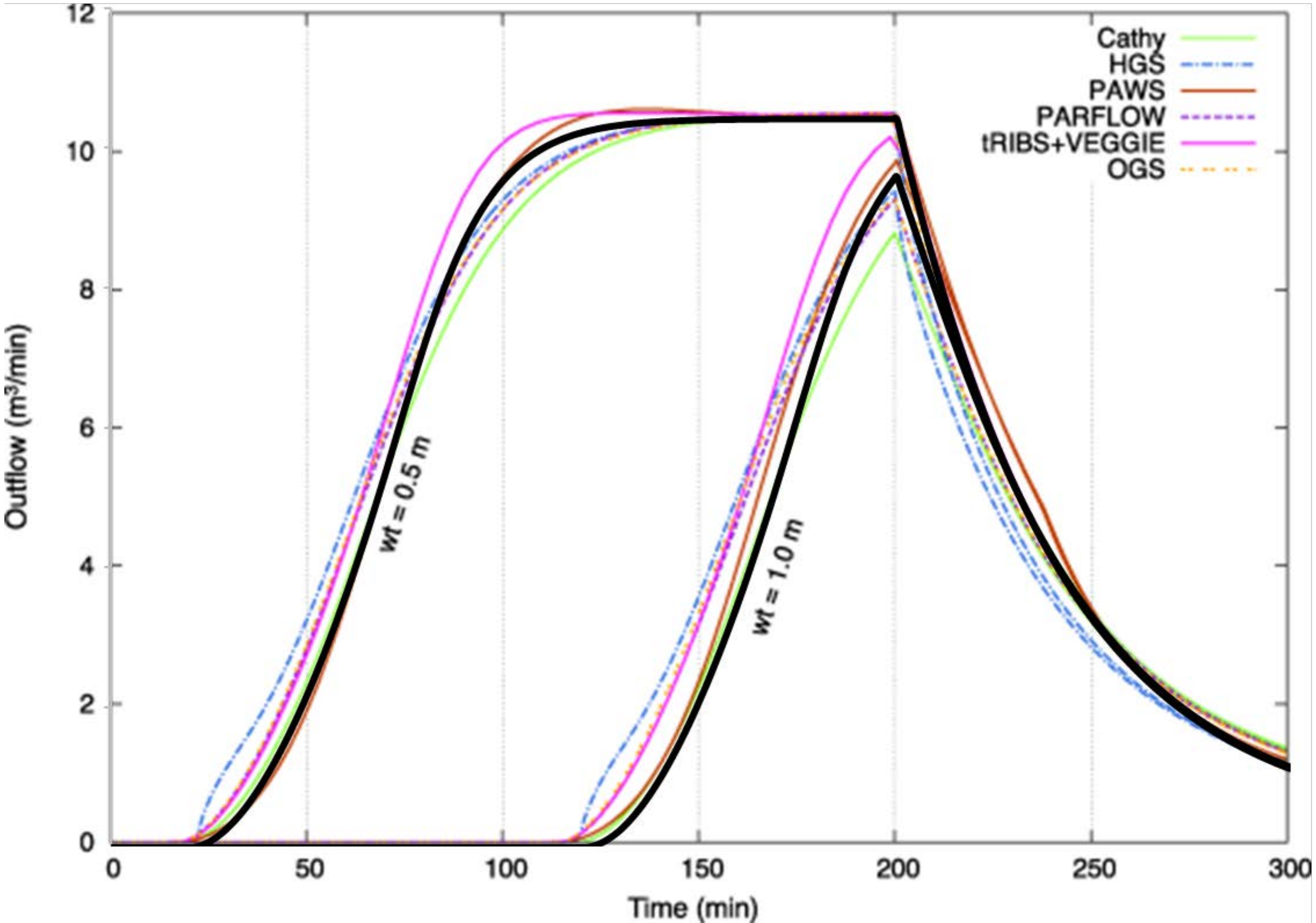




Saturation excess runoff benchmark (high permeability)



Initial water table 1 and 0.5 m



Application of *DrainFlow* to synthetic tile drainage examples

Slopes

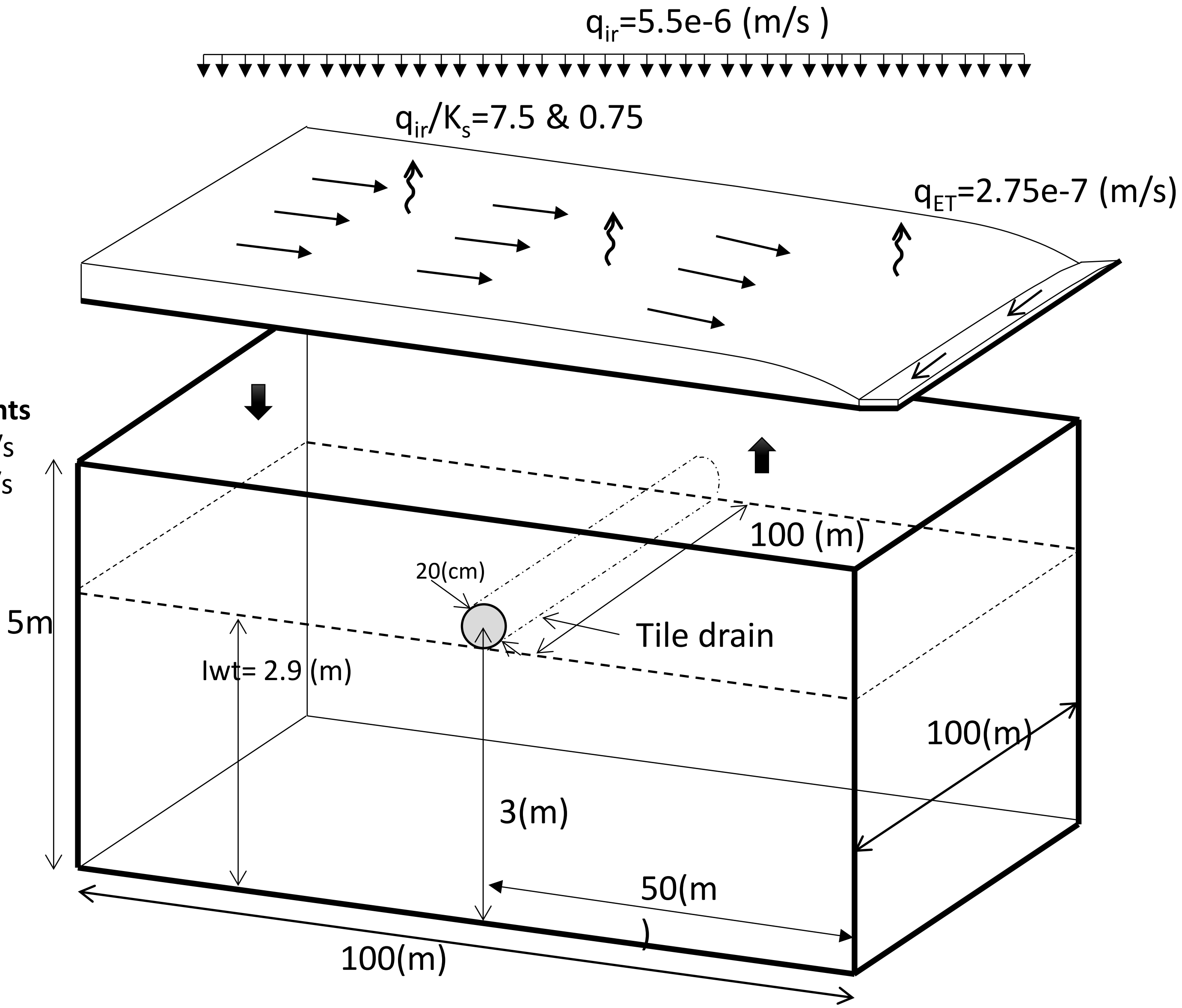
Ground surface:	0.001%
Tile drain:	0.01%

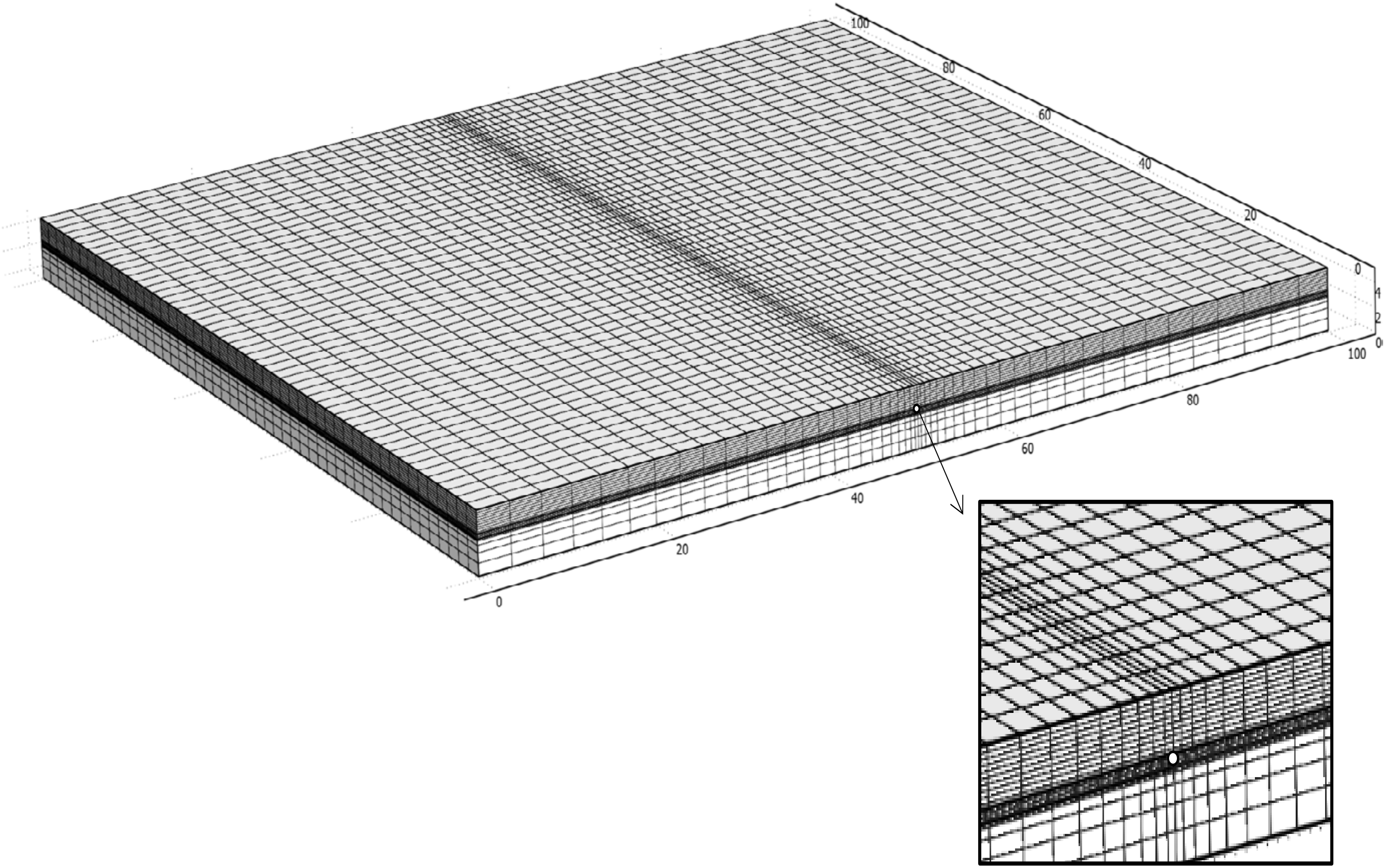
Manning's roughness coefficients

Ground surface:	0.059 $m^{1/3}/s$
Tile drain:	0.025 $m^{1/3}/s$

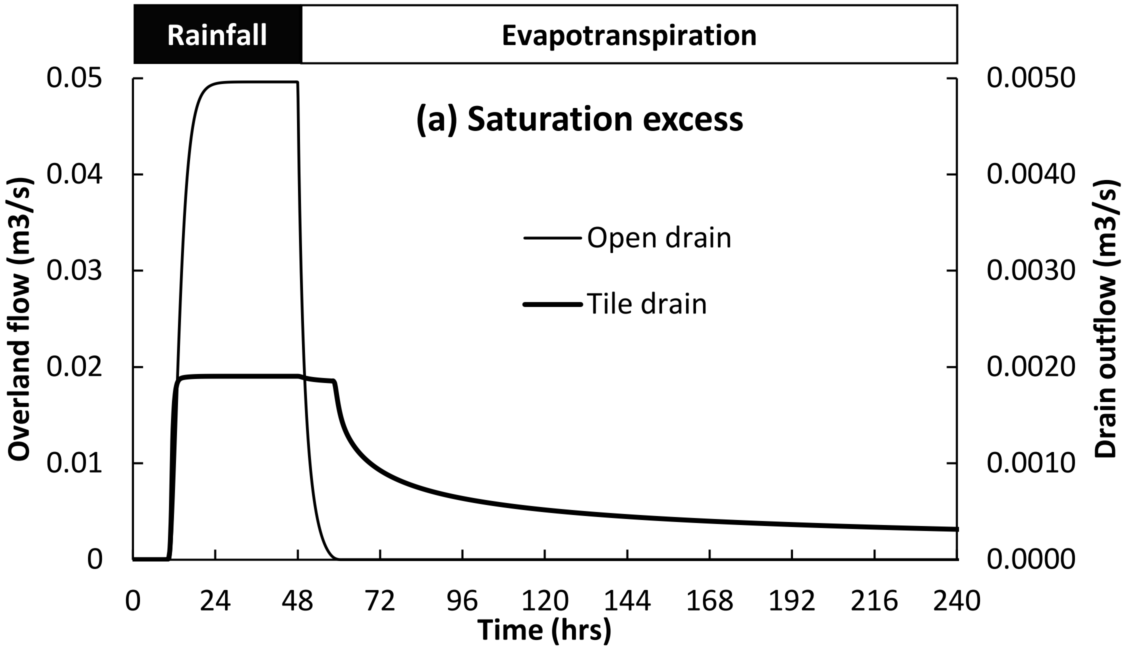
Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)
S_s =5e-4m^{-1} & φ=0.4
n_{van}=2.0 & α = 1 (m^{-1})
S_{res}= 0.2 & S_{sat}=1

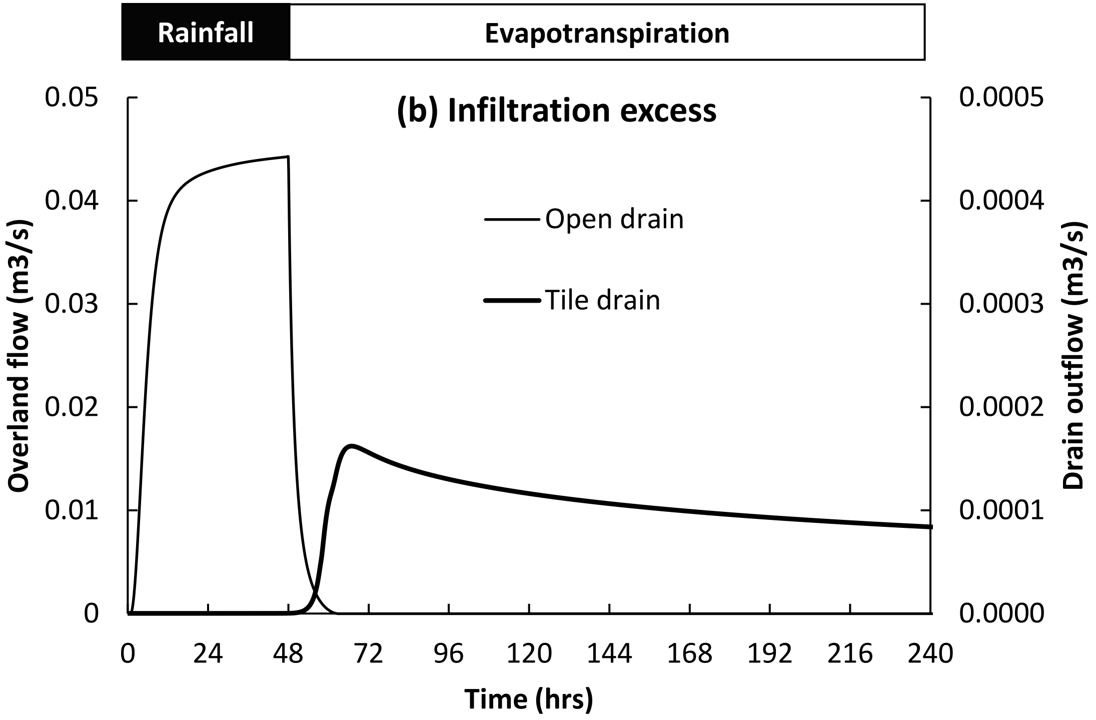



100
80
60
40
20
0
4
2
0
100
80
60
40
20
0

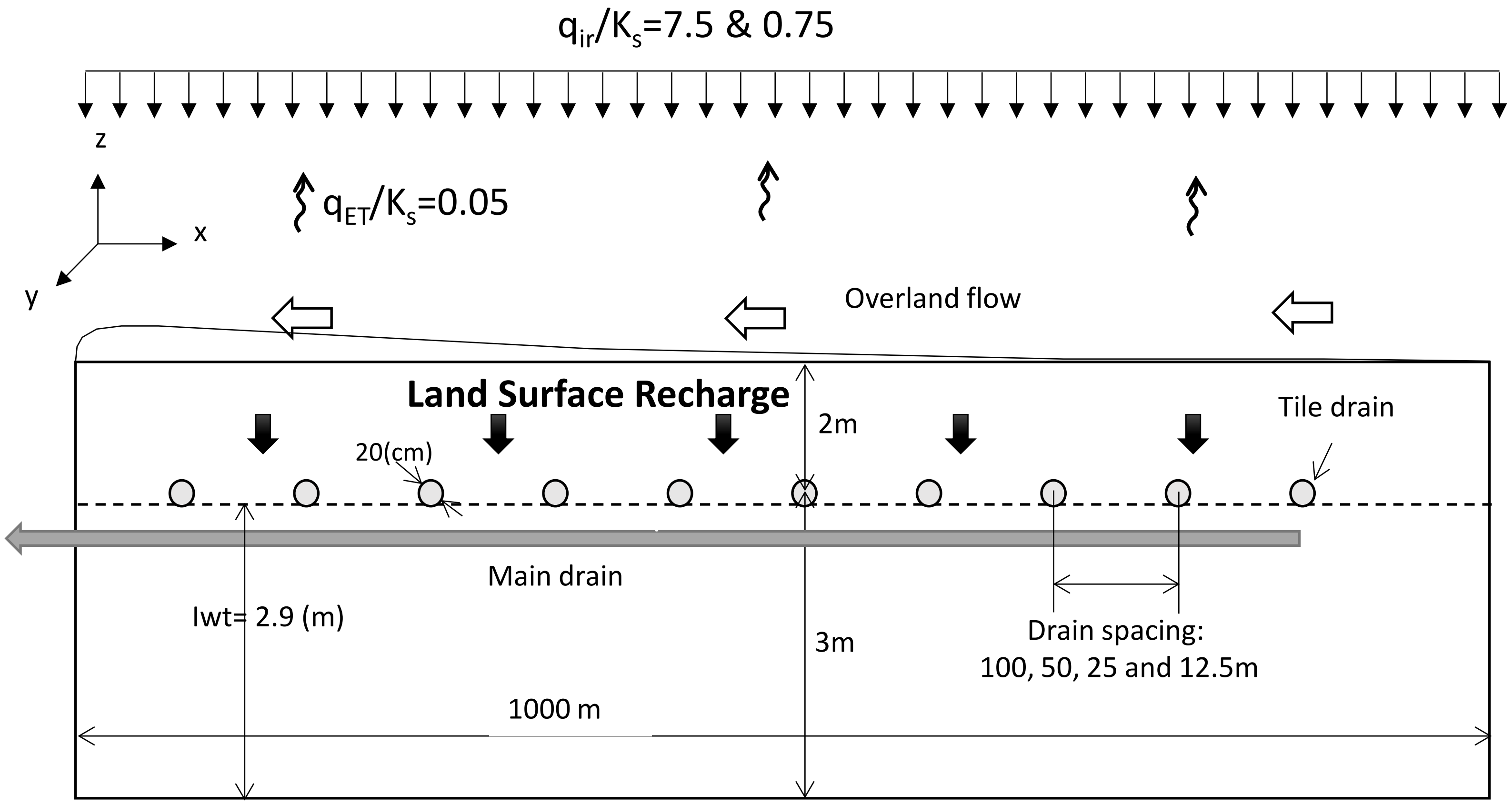
*O*verland flow and tile drain hydrographs



Saturated excess scenario



Infiltration excess scenario



Slopes

Ground surface:	0.001%
Tile drain:	0.01%

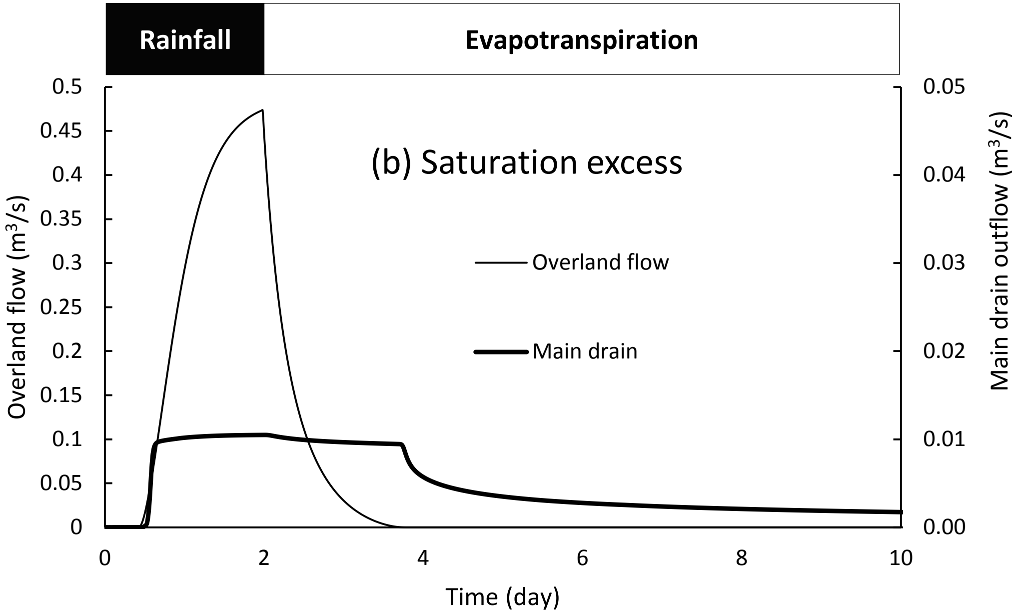
Manning's roughness coefficients

Ground surface:	0.059 $m^{1/3}/s$
Tile drain:	0.025 $m^{1/3}/s$
Main drain:	0.018$m^{1/3}/s$

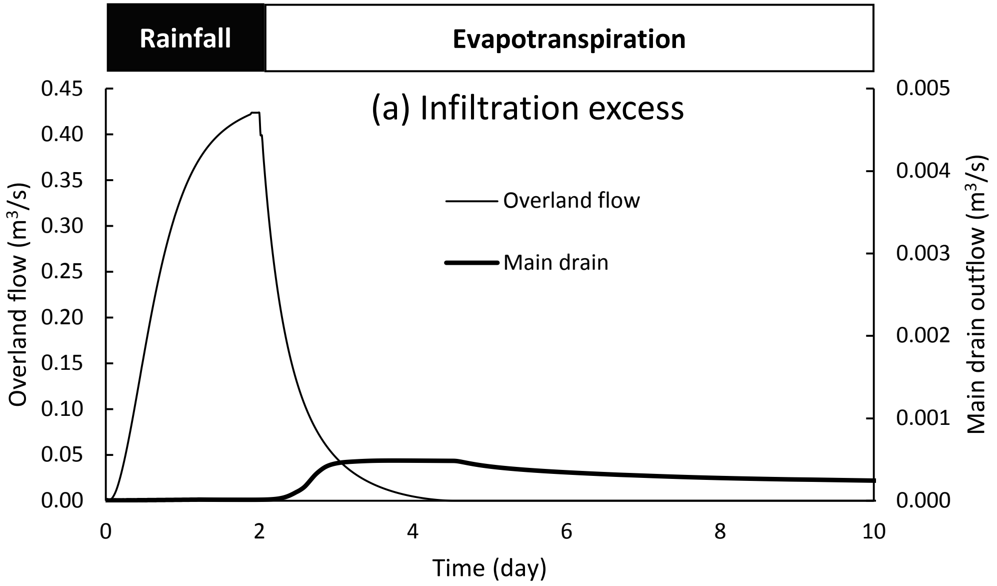
Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)
S_s =5e-4m^{-1} & φ=0.4
n_{van}=2.0 & α = 1 (m^{-1})
S_{res}= 0.2 & S_{sat}=1

Overland flow and main-drain hydrographs for the 10 tile drains

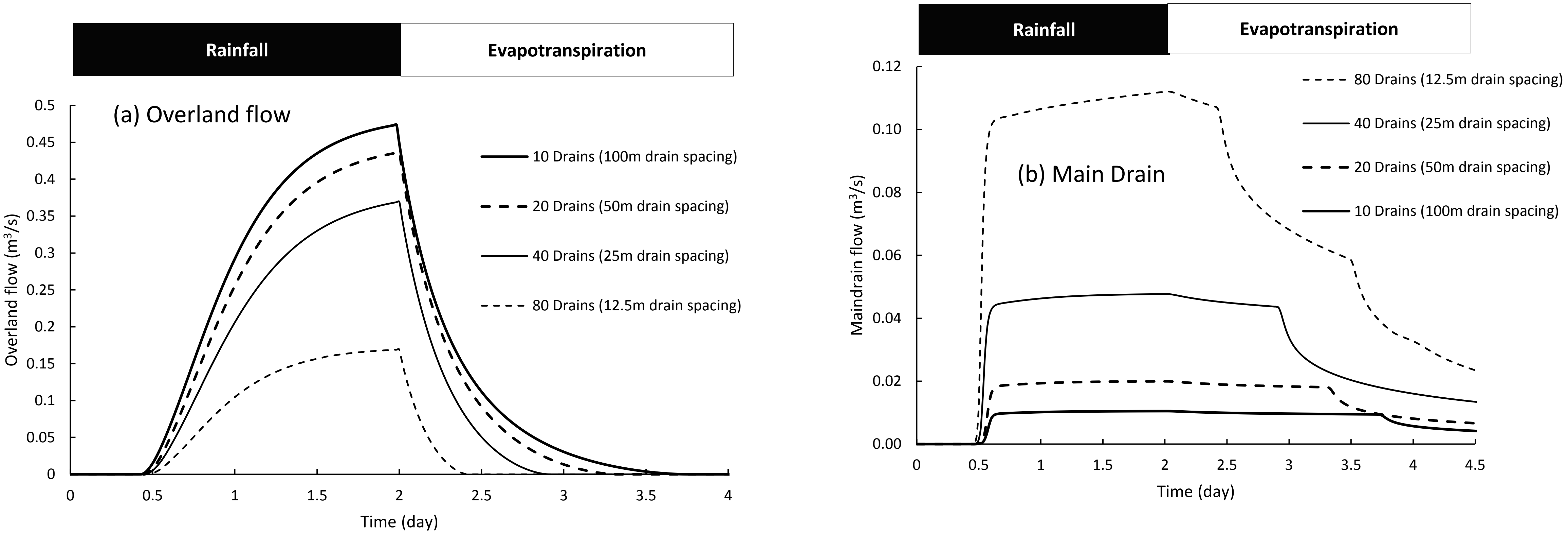


Saturated excess scenario

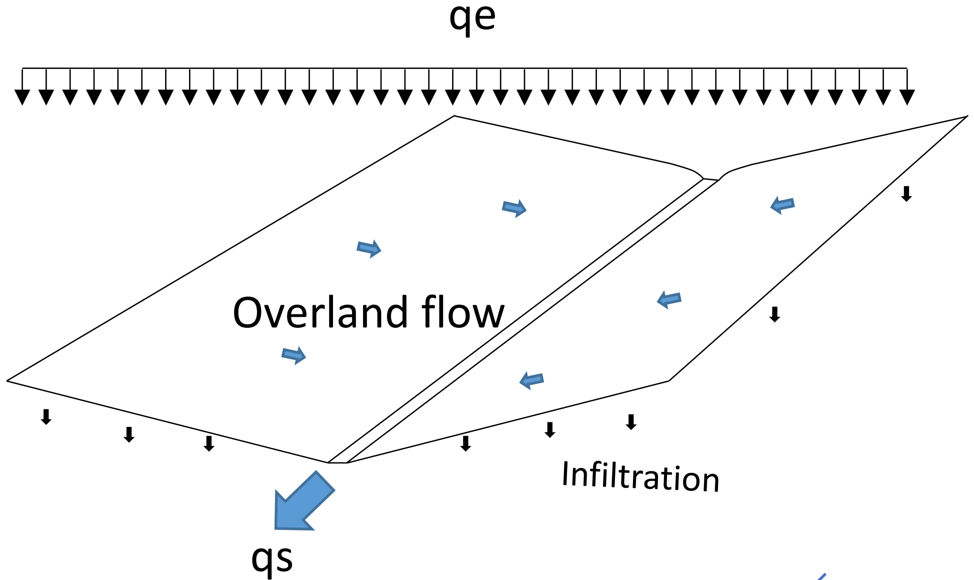


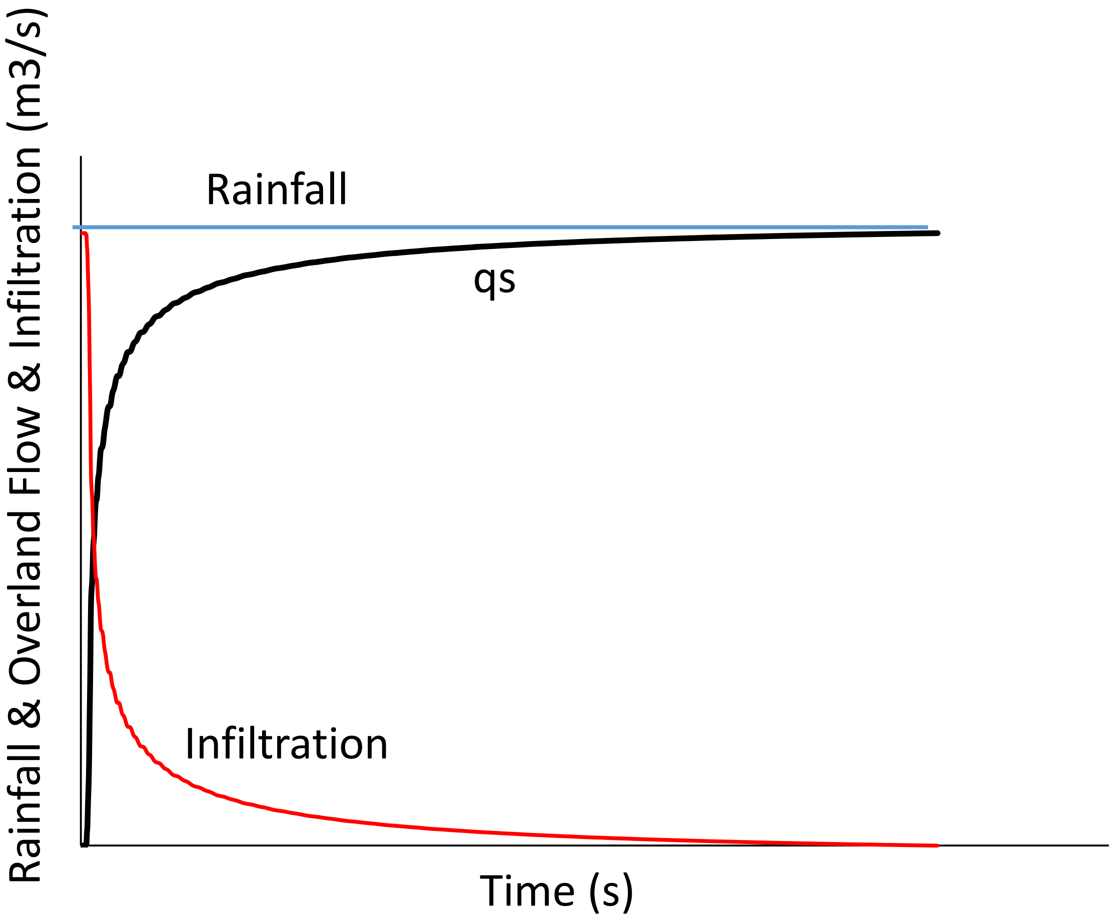
Infiltration excess scenario

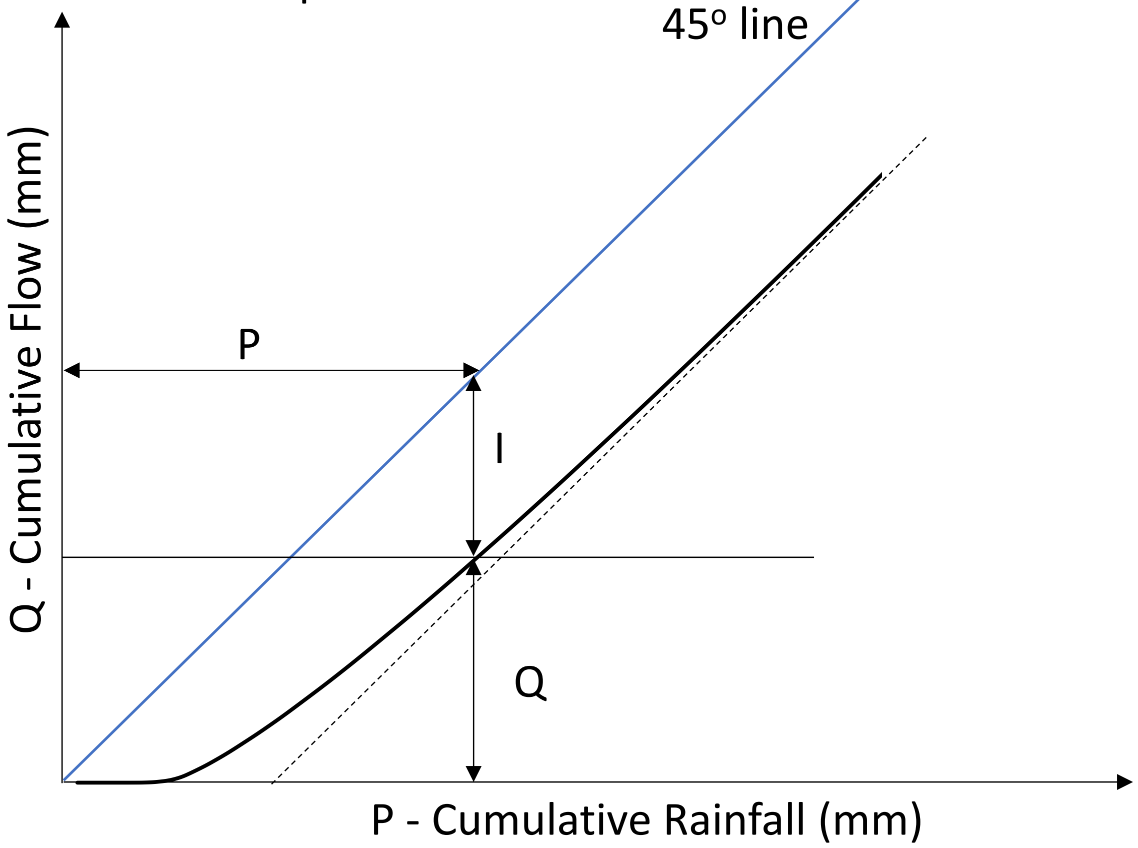
Comparisons between DrainFlow results for (a) overland flow and (b) tile drain hydrographs for **saturation excess runoff condition**, for various tile drain spacings.



SCS-CN methodology







SCS-CN methodology

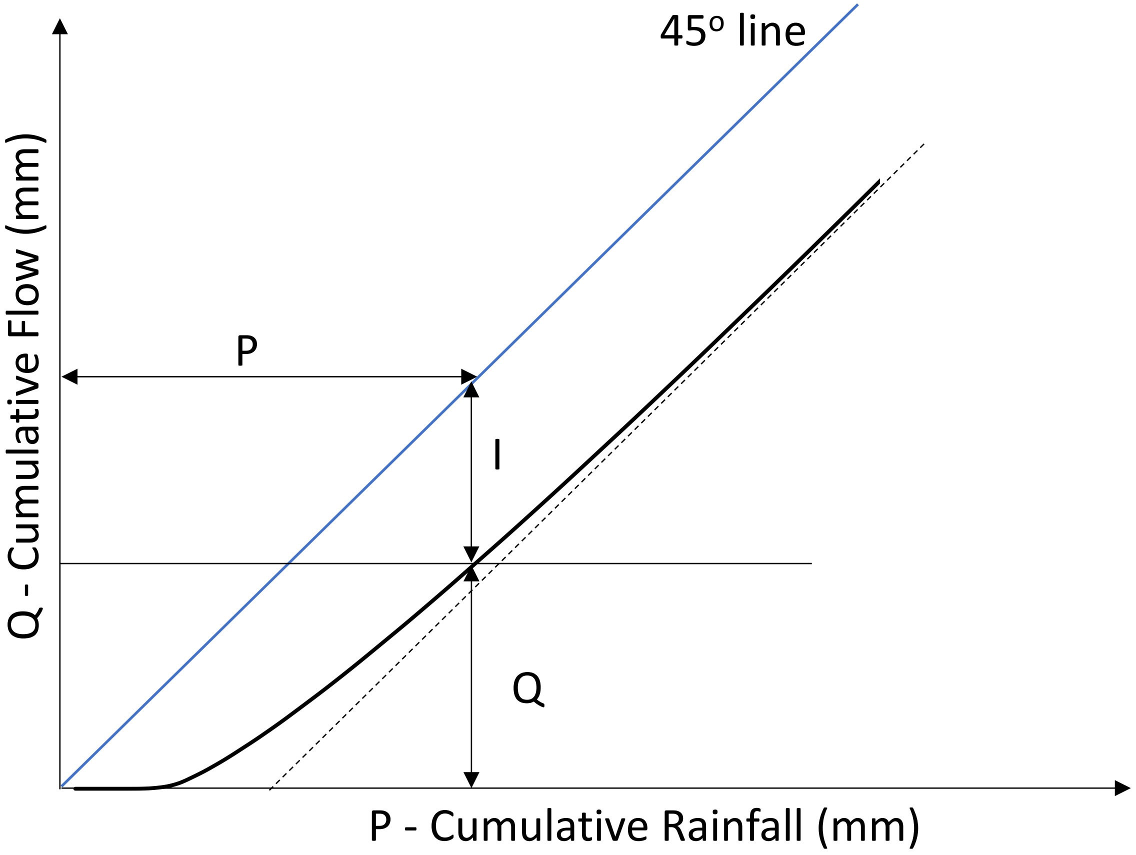
- The SCS-CN formula is a lumped based approach that calculates the total direct runoff from a storm event.

$$\boldsymbol{Q} = \frac{(\boldsymbol{P}-\boldsymbol{Ia})^2}{(\boldsymbol{P}-\boldsymbol{Ia}+\boldsymbol{S})} \quad \text{when} \quad P \geq Ia,$$

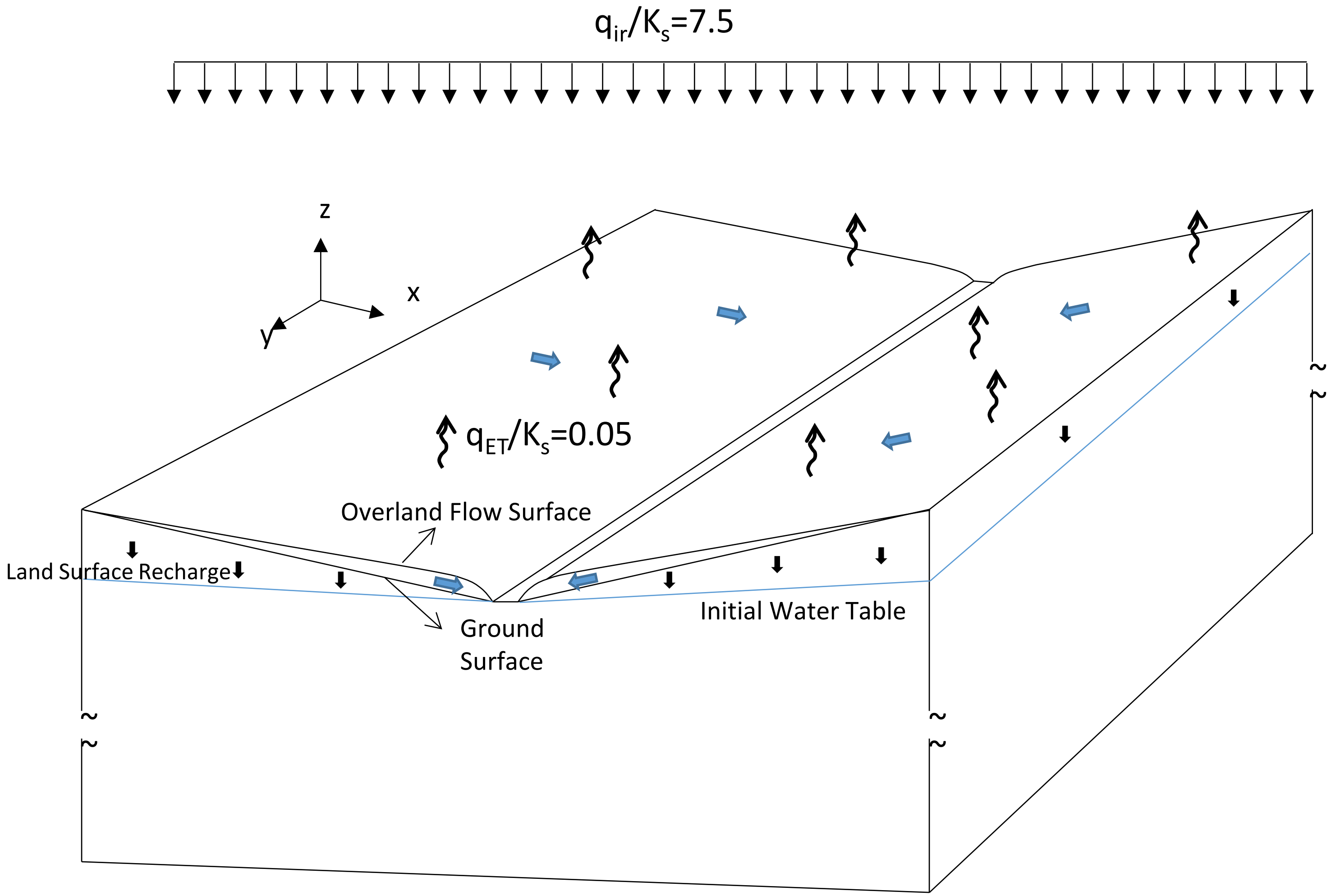
$$\boldsymbol{Q} = 0 \qquad \text{otherwise}$$

Where $\boldsymbol{S} = \frac{\boldsymbol{25400}}{\boldsymbol{CN}} - \boldsymbol{254}$

$$\boldsymbol{I_a} = \boldsymbol{\lambda S} \quad \longrightarrow \quad \boldsymbol{\lambda} = \boldsymbol{0.2}$$



A comparison between the DrainFlow and SCS-CN methods in a hypothetical V-catchment



Manning's roughness coefficients

Ground surface: 0.059 $m^{1/3}/s$

Channel 0.025 $m^{1/3}/s$

Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)

S_s =5e-4m^{-1} & φ=0.4

n_{van}=2.0 & α = 1 (m^{-1})

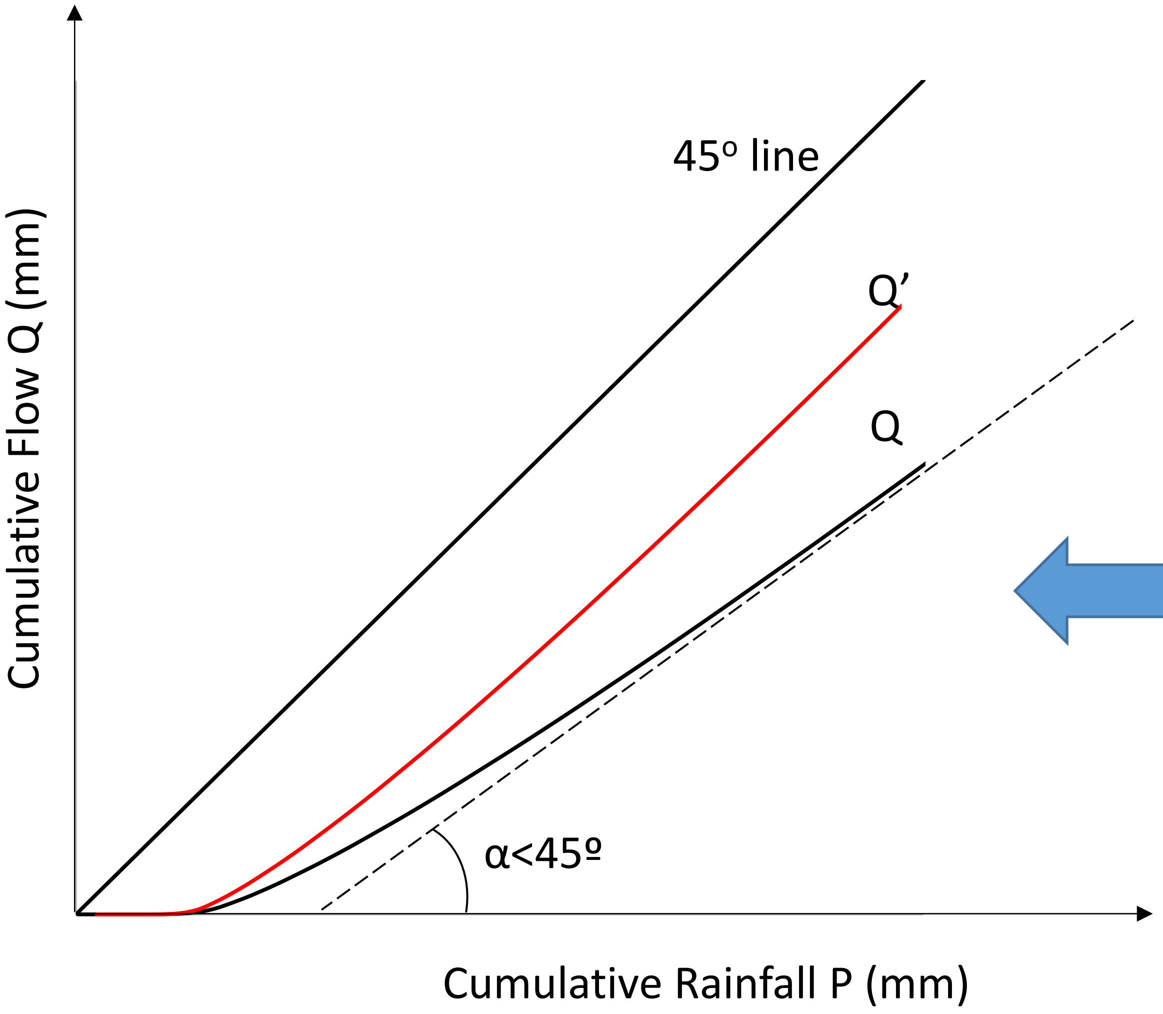
S_{res}= 0.2 & S_{sat}=1

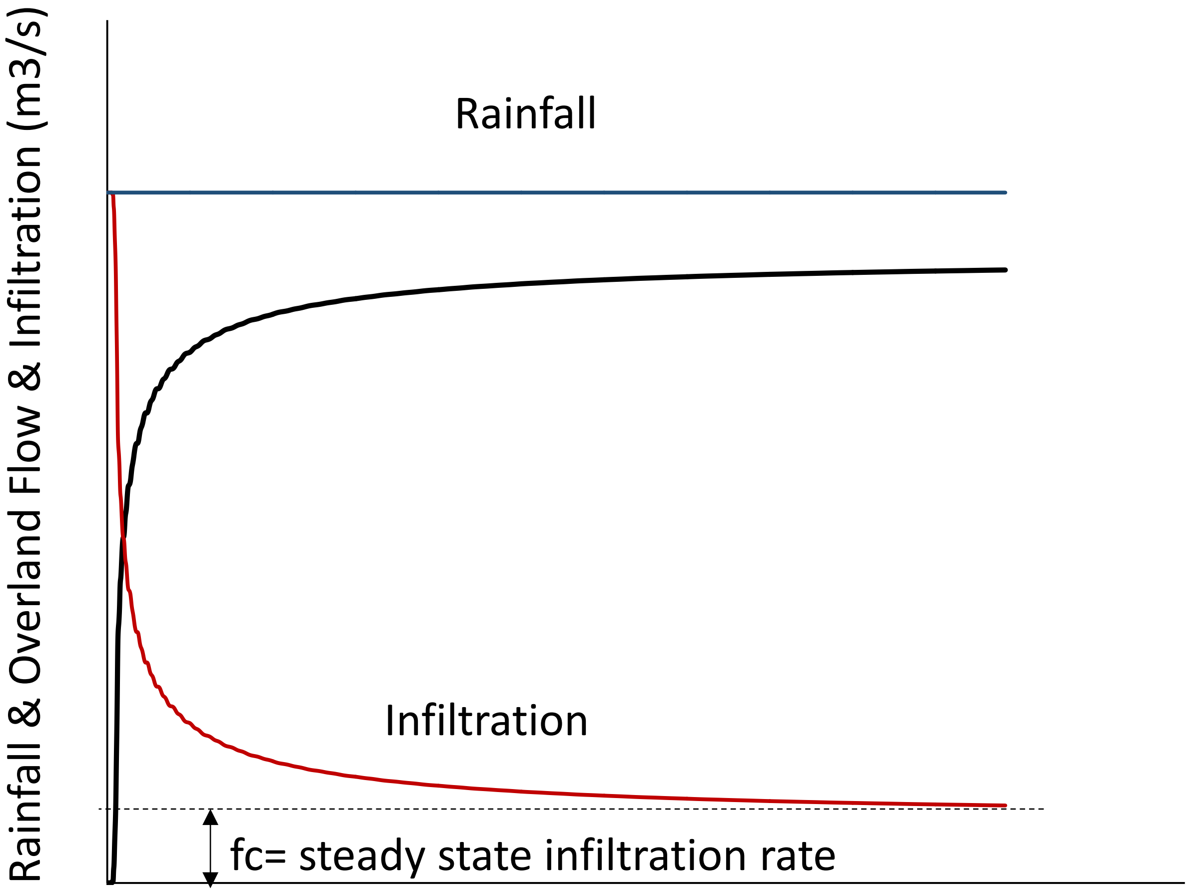
Ground Slopes

Sx: 0.001%

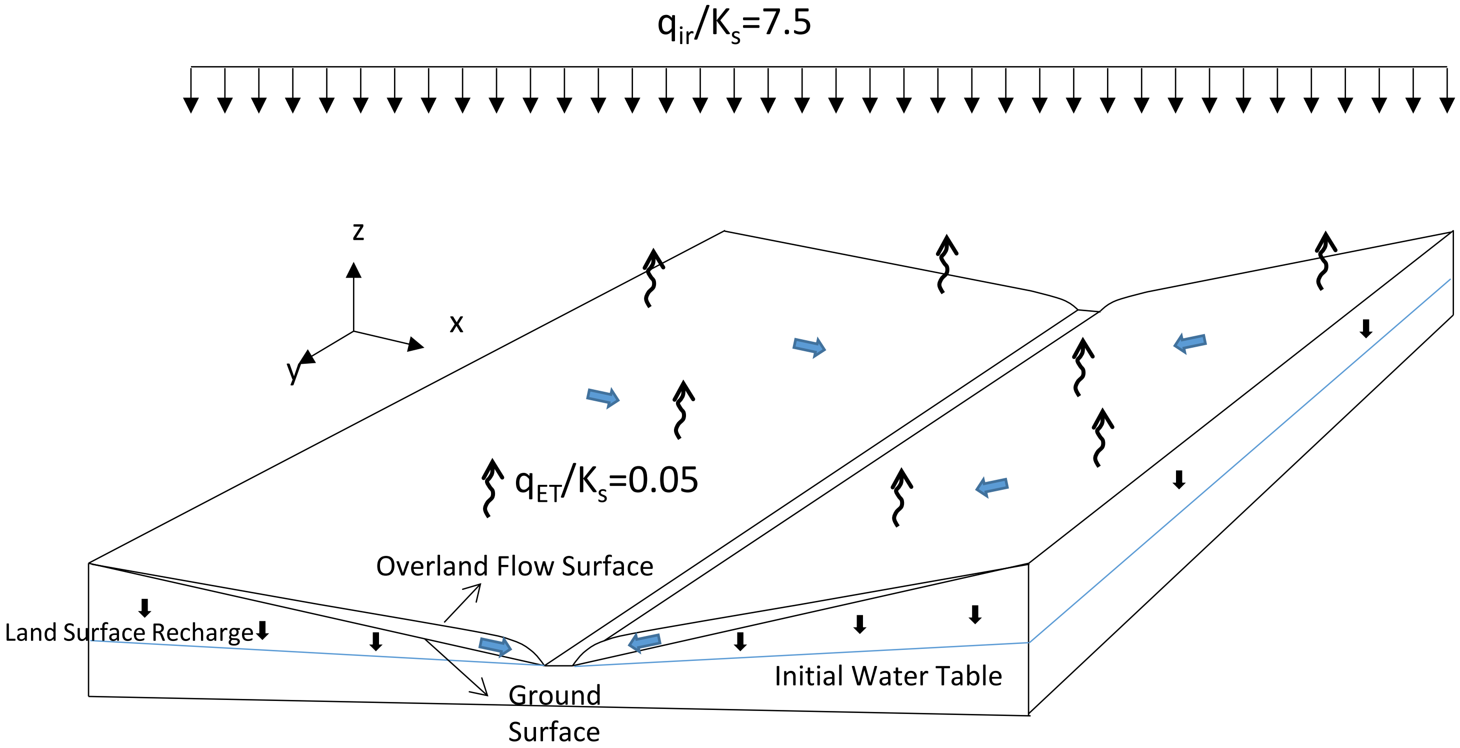
Sy: 0.01%

DrainFlow results





Possible cases with a zero steady state infiltration rate fc=0



Manning's roughness coefficients

Ground surface: 0.059 $m^{1/3}/s$

Channel 0.025 $m^{1/3}/s$

Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)

S_s =5e-4m^{-1} & φ=0.4

n_{van}=2.0 & α = 1 (m^{-1})

S_{res}= 0.2 & S_{sat}=1

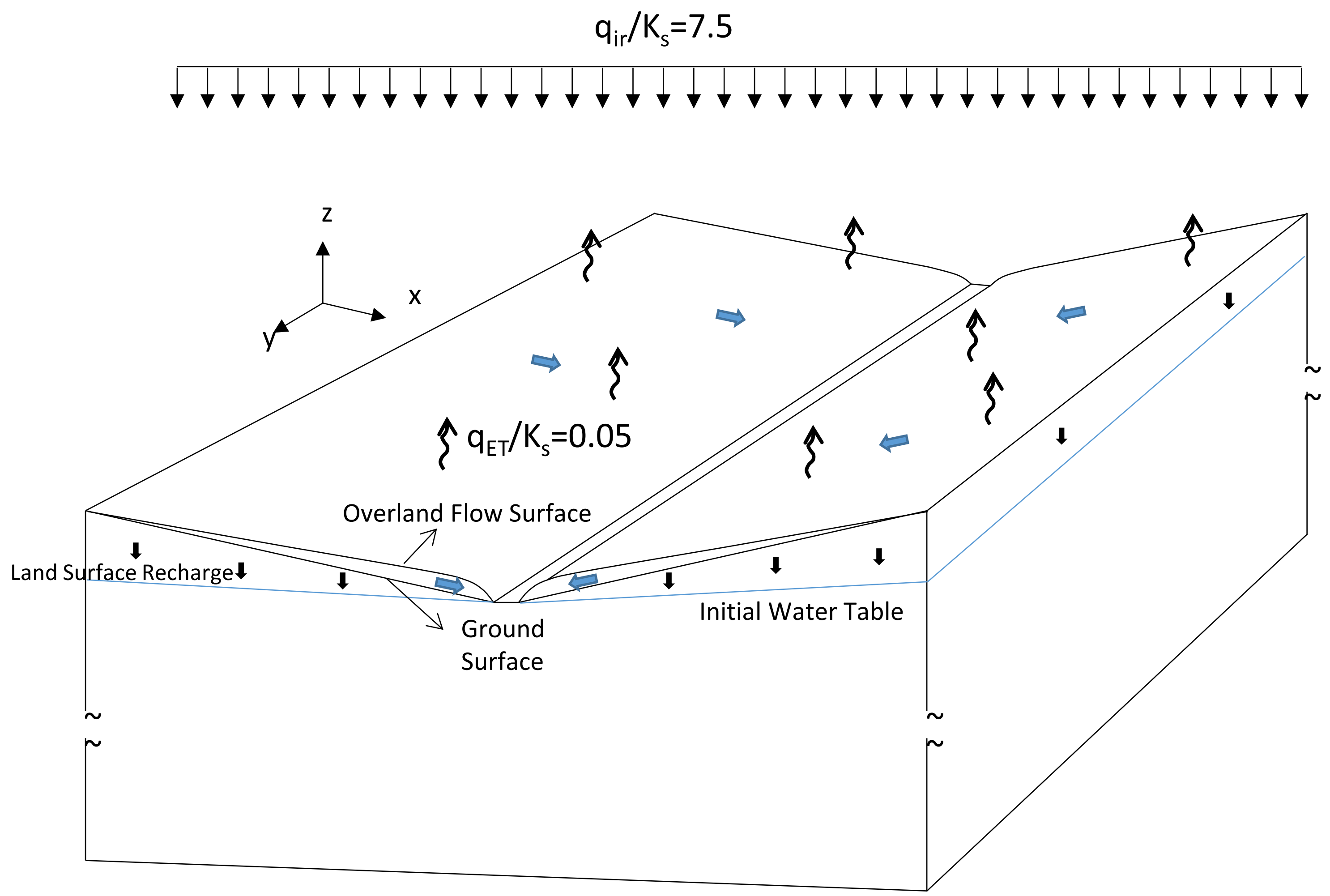
Ground Slopes

Sx: 0.001%

Sy: 0.01%

Possible cases with a non-zero steady state infiltration rate

$fc \neq 0$



Manning's roughness coefficients

Ground surface: 0.059 $m^{1/3}/s$

Channel

0.025 $m^{1/3}/s$

Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)

S_s =5e-4m^{-1} & φ=0.4

n_{van}=2.0 & α = 1 (m^{-1})

S_{res}= 0.2 & S_{sat}=1

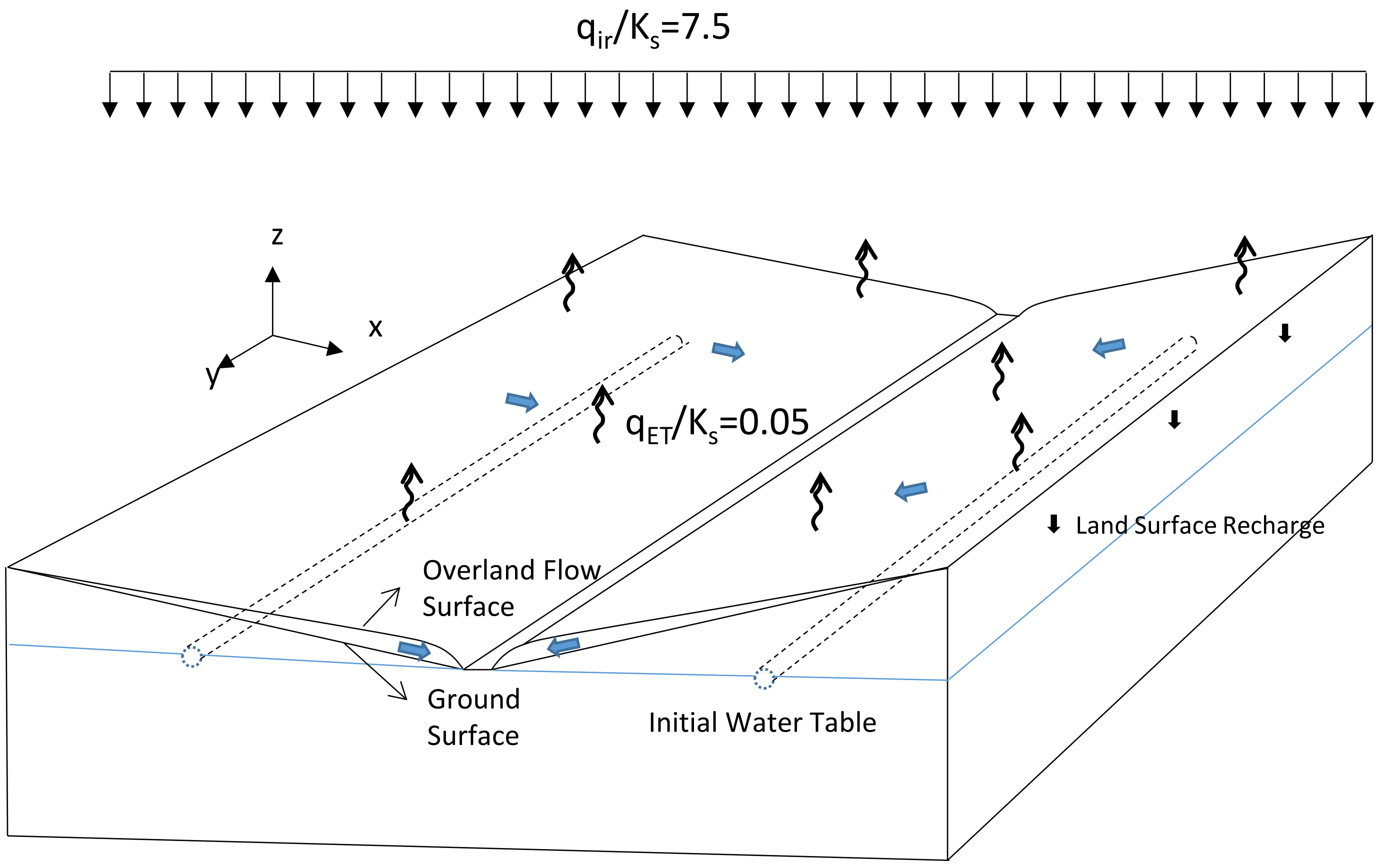
Ground Slopes

Sx: 0.001%

Sy: 0.01%

Possible cases with a non-zero steady state infiltration rate

fc≠0



Manning's roughness coefficients

Ground surface: 0.059 $m^{1/3}/s$

Channel

0.025 $m^{1/3}/s$

Soil hydrodynamic properties

K_s= 7.71e-6 and 7.71e-7 (m/s)

S_s =5e-4m^{-1} & φ=0.4

n_{van}=2.0 & α = 1 (m^{-1})

S_{res}= 0.2 & S_{sat}=1

Ground Slopes

Sx: 0.001%

Sy: 0.01%

SCS-CN generalisation

Thanks

$$\boldsymbol{Q} = \frac{\boldsymbol{A}(\boldsymbol{P}-\boldsymbol{Ia})^2}{(\boldsymbol{P}-\boldsymbol{Ia}+\boldsymbol{S})} \quad \text{when} \quad P \geq Ia,$$

$$\boldsymbol{Q} = 0 \qquad \text{otherwise}$$

A=1 When fc=0

0<A<1 otherwise