Catchment and climate hydrology

Lowland hydrology

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Where is this?

Topics

- Differences between mountainous and lowland catchments (freely draining and polder catchments): landscape, hydrological processes and consequences for rainfall-runoff modelling
- Effect of shallow groundwater on land-surface interactions and rainfall-runoff processes
- Hydrological modelling in lowland catchments

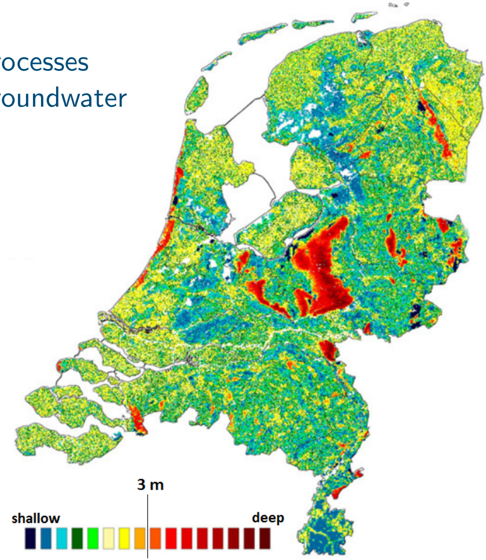
Lecture set-up

- Introducing lowland catchments
- Groundwater-unsaturated zone coupling
- Wetness-dependent flowroutes
- Groundwater-surface water feedback
- Application of WALRUS

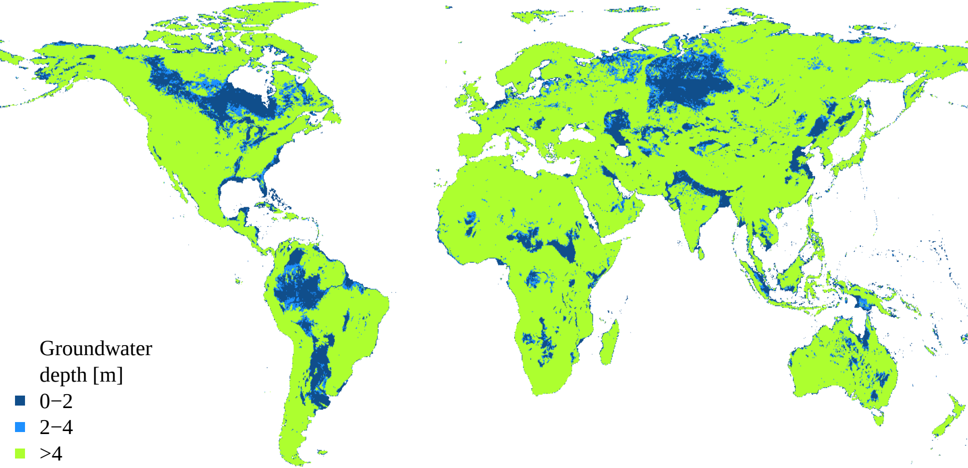
Introducing lowland catchments

Lowland catchments

Areas where hydrological processes
are influenced by shallow groundwater



Areas with shallow groundwater worldwide

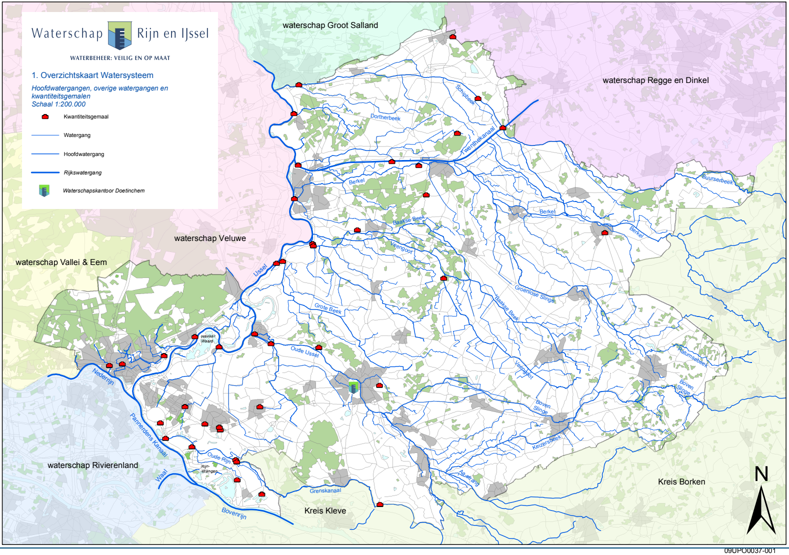


Freely draining lowlands and polders: differences

Freely draining	Polder
Slightly sloping	Flat
Drained by brooks	Water discharged by pumps
Brooks have natural origin	Man-made channels; sometimes (not always) reclaimed from sea or swampy land

Freely draining lowlands: surface water network

Water board Rijn and IJssel

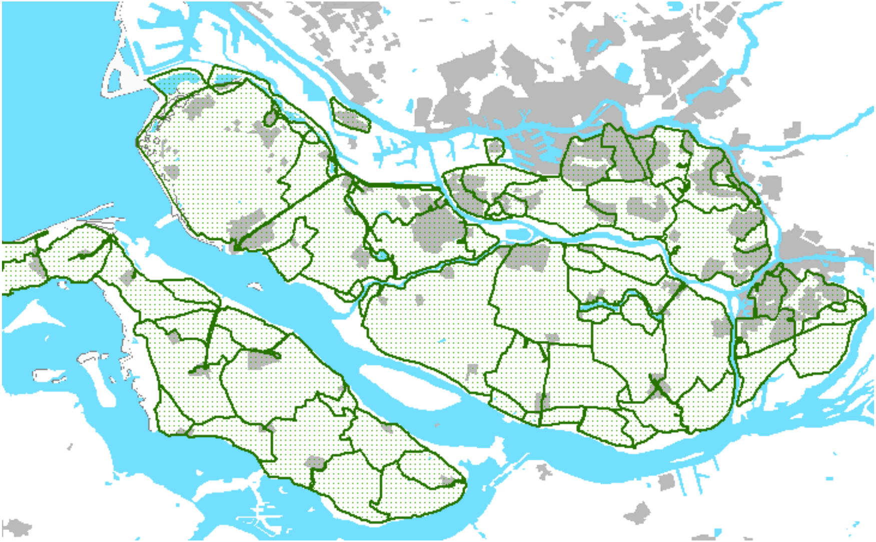


Polders: surface water network

Water board Hollandse Delta

Polders can be seen as catchments too

Water board Hollandse Delta



Polders around the world

30 km east of Tokyo

Freely draining lowlands and polders: similarities

- Limited slope
- Often located in river deltas
- Shallow groundwater
- Agriculturally productive
- Attractive for settlement

Challenges in lowland catchments

Advantages lead to challenges:

- Floods
- Climate change
- Land use change
- Water quality detoriation
- Land subsidence
- Increasing demand for information

Commonly used models in lowland catchments

- surface water-based: MIKE-SHE, HEC-RAS, SOBEK
- soil-column based: HYDRUS, SWAP
- groundwater-based: MODFLOW
- combinations: SHE, HydroGeosphere, SIMGRO, NHI

These are all “physically-based”.

Remember the model types:

- black-box models
- conceptual (parametric) models
- physically-based models

(Dis)advantages of parametric models

Advantages:

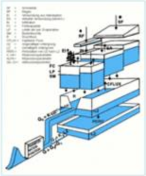
- smaller risk of overparameterisation than physically-based models
- physical representation clearer and parameter identification easier than black-box models
- more practical (faster) than physically-based models

Disadvantages:

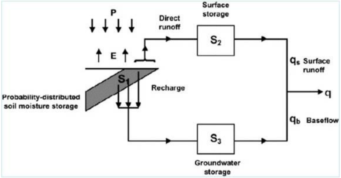
- no spatial information
- needs calibration

Model choice depends on aim of the study, catchment characteristics and data availability

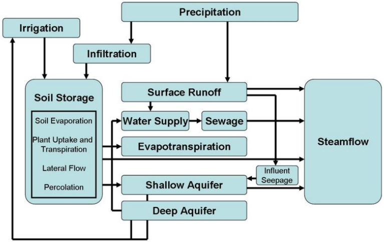
Examples of parametric models



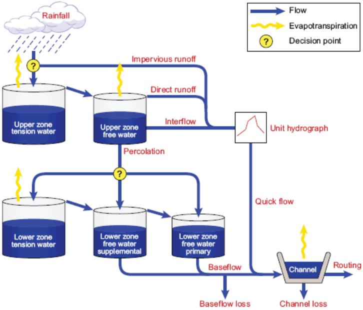
HBV



PDM



SWAT



Sacramento Model

Problem

Until 2013:

complex, spatially distributed models for lowland catchments

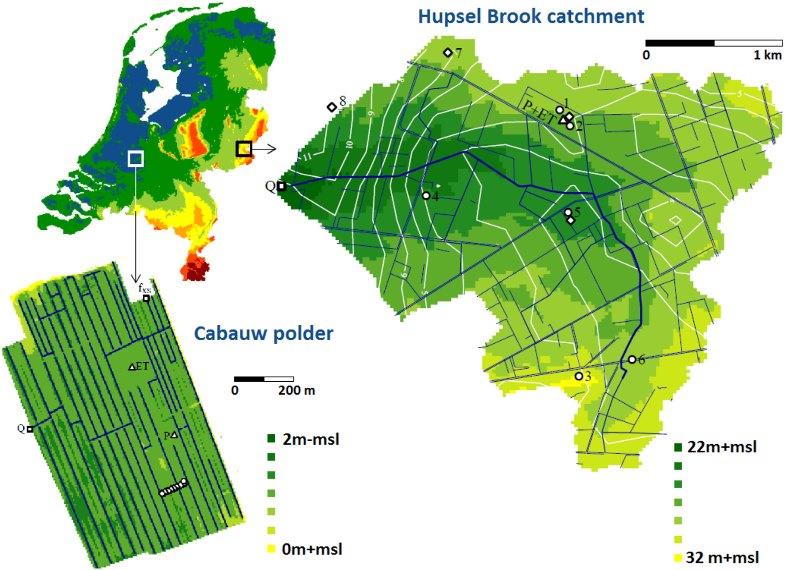
OR

simple, parametric models for sloping catchments

$\downarrow$

Fill the gap: a simple, parametric model for lowland catchments:
Wageningen Lowland Runoff Simulator

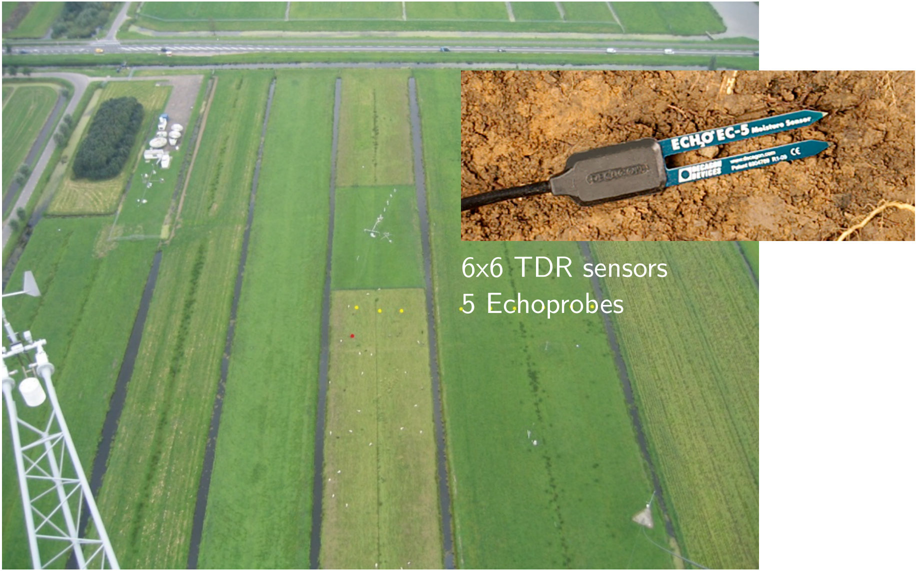
Two contrasting experimental catchments



Learning from the field for model development

Groundwater-unsaturated zone coupling

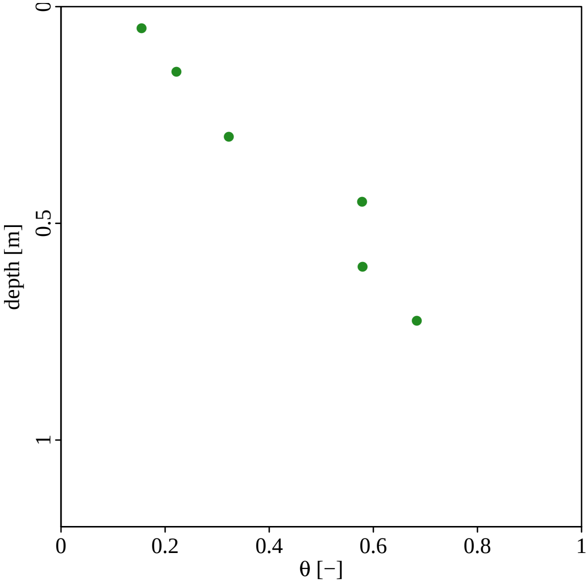
Soil moisture measurements



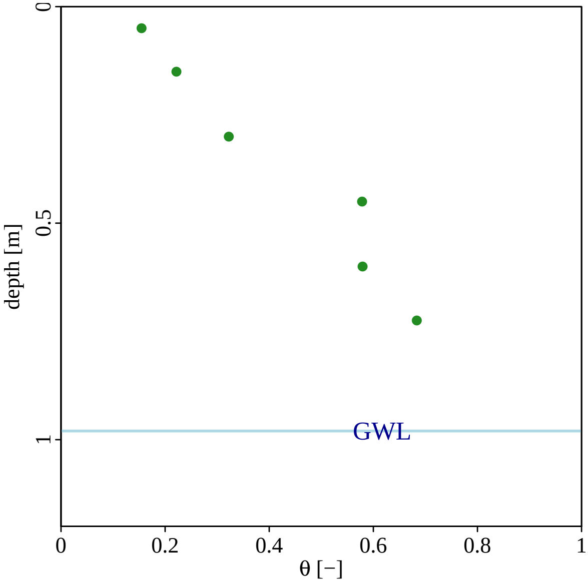
6x6 TDR sensors

5 Echoprobes

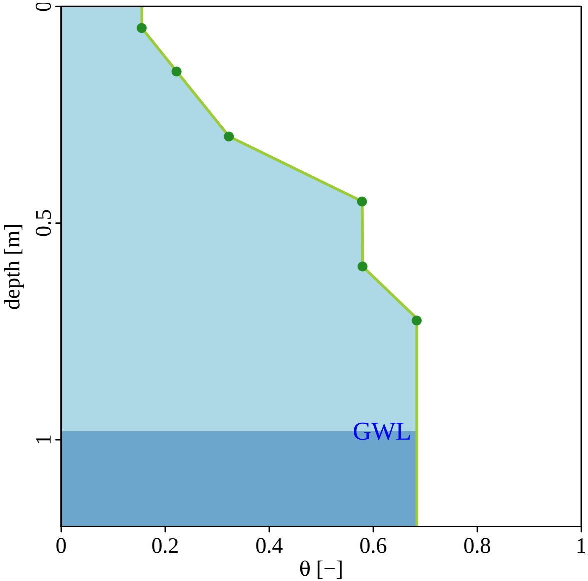
Soil moisture observations



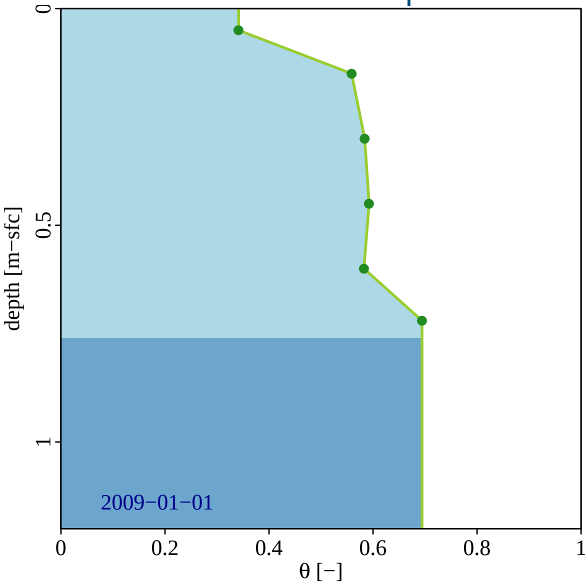
Soil moisture and groundwater observations



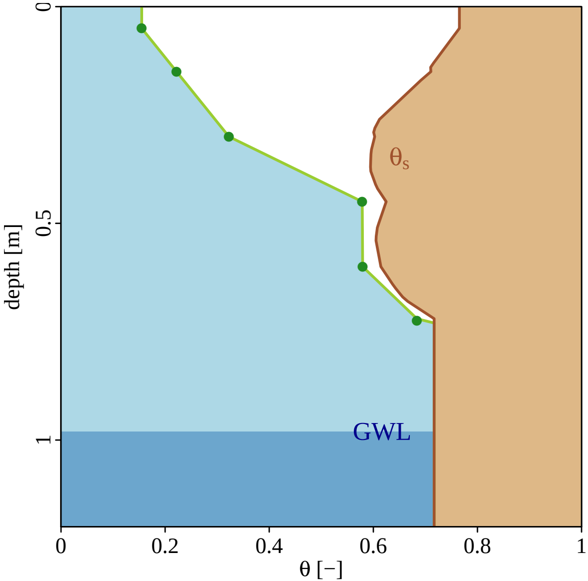
Interpolation soil moisture profile



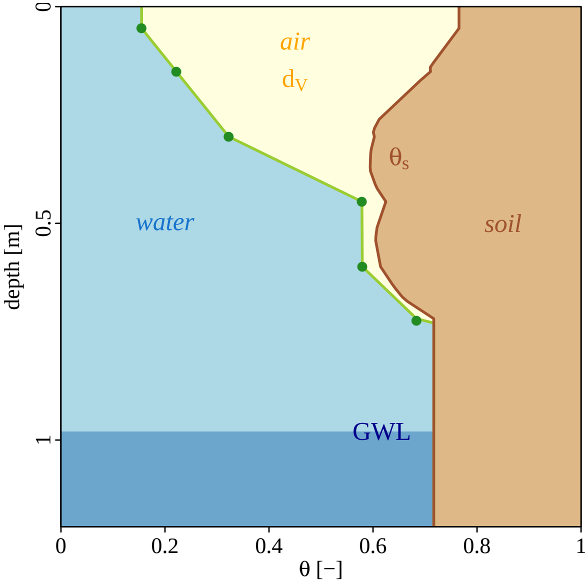
Temporal variation soil moisture profile



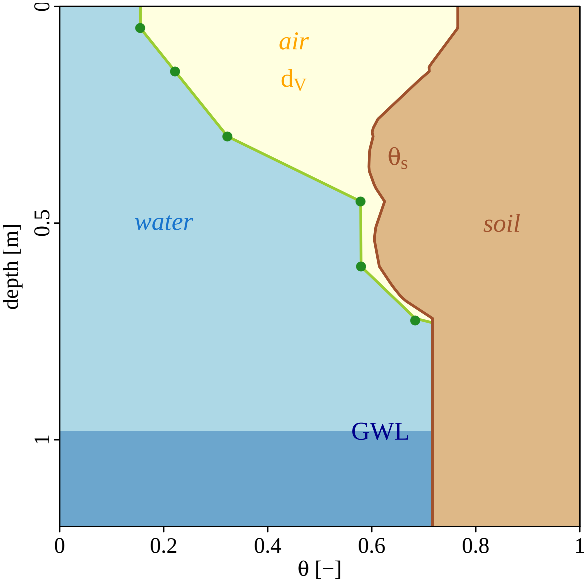
Maximum soil moisture content



Storage deficit

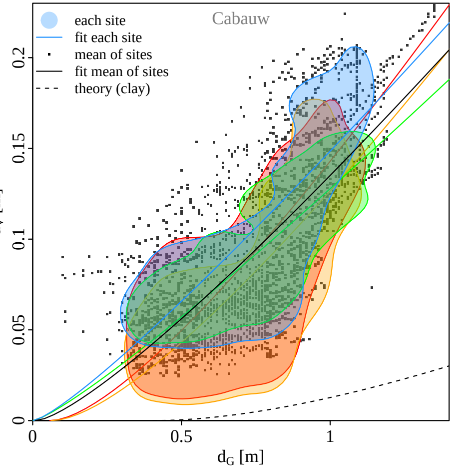


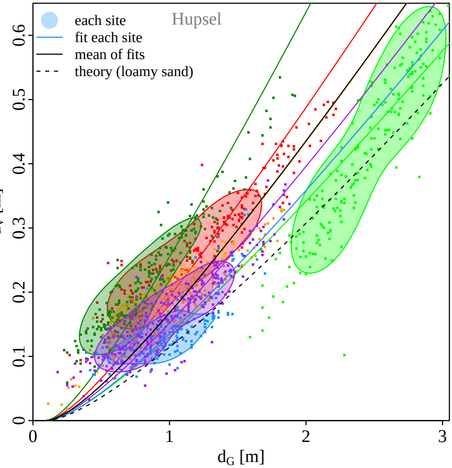
Exercise



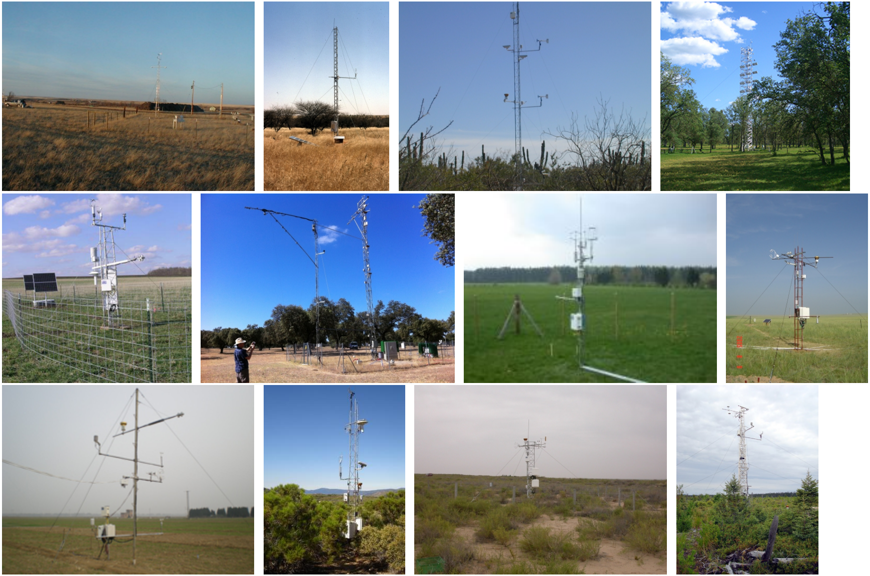
- If you're online:
  Go to Brightspace →
  7. Human impact →
  Open `dV-dG-sketch.png`
  in paint (or similar)
- Choose one day
- Draw soil moisture profile
- Draw soil moisture profile at saturation (θ_s)
- Estimate d_V graphically: (each square is 0.01 m)
- Draw one point in the (d_G,d_V)-plot on the blackboard

Relation storage deficit and groundwater depth





Some FLUXNET sites



“Our” FLUXNET site in Cabauw

What is the influence of the water system on meteorological fluxes?

Evapotranspiration measurements (by KNMI)

Global radiation + temperature
→ potential evapotranspiration

Bowen ratio from eddy
covariance set-up
to close energy balance →
actual evapotranspiration

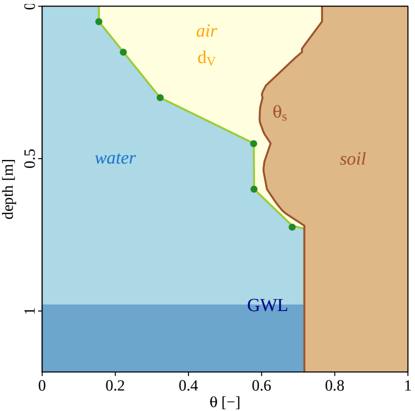
Difference: water stress

Evapotranspiration reduction

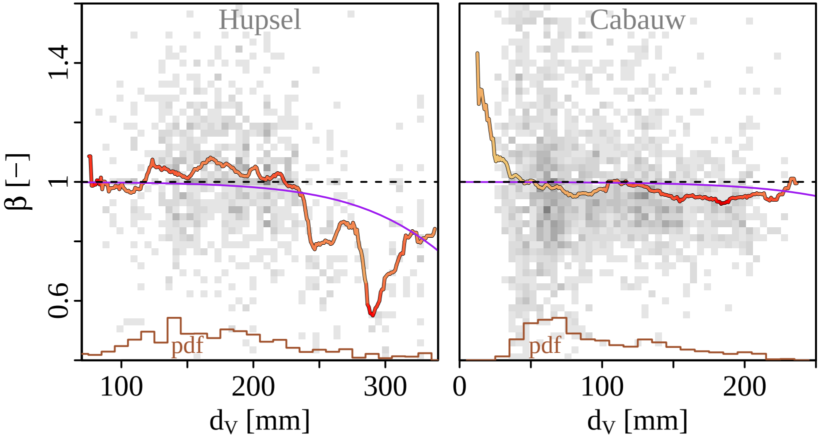
$$ET_{\mathrm{act}} = \beta \times ET_{\mathrm{pot}}$$

β = evapotranspiration reduction factor to account for water stress

$$\frac{ET_{\mathrm{act}}}{ET_{\mathrm{pot}}} = func(d_{\mathrm{V}})$$



Evapotranspiration reduction



In this figure, β is computed from independent measurements of ET_{act} and ET_{pot} (that's why $\beta > 1$ is possible).

Lesson 1: groundwater-unsaturated zone coupling

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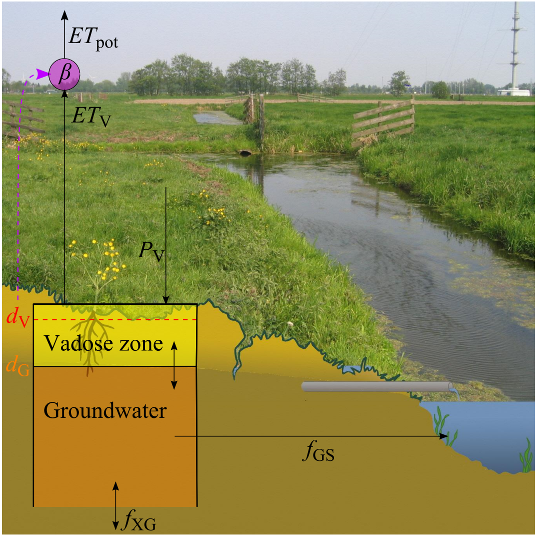
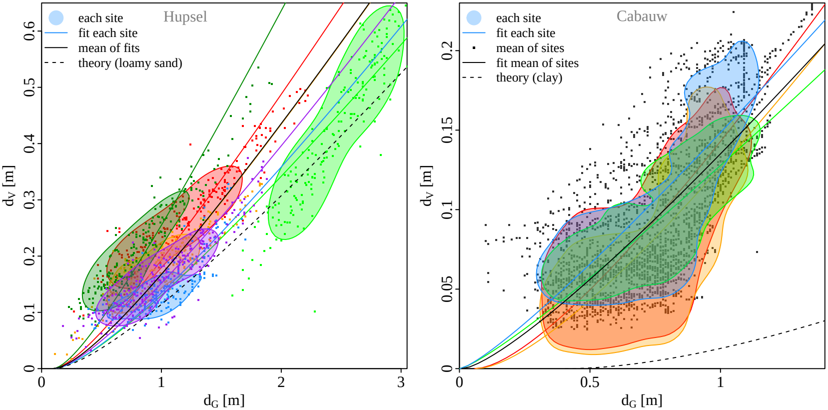


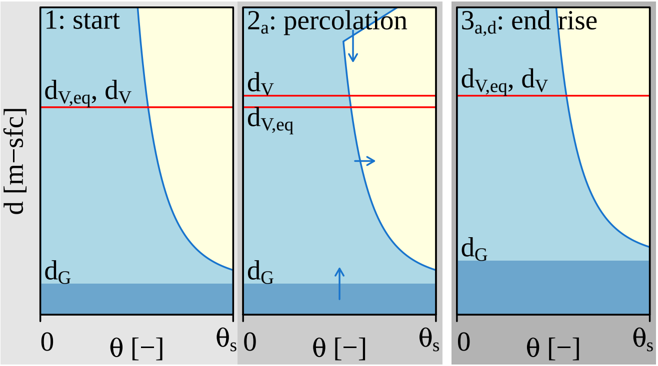
Relation storage deficit and groundwater depth



Standard option for relation based on power law soil moisture profile:

$$d_{\mathrm{V,eq}} = \int_{\psi_{\mathrm{ae}}}^{d_{\mathrm{G}}} \left[\theta_{\mathrm{s}} - \theta_{\mathrm{s}} \left(\frac{h}{\psi_{\mathrm{ae}}}\right)^{-1/b}\right] \mathrm{d}h = \theta_{\mathrm{s}} \left(d_{\mathrm{G}} - \frac{d_{\mathrm{G}}^{1-1/b}}{(1-\frac{1}{b})\psi_{\mathrm{ae}}^{-1/b}} - \frac{\psi_{\mathrm{ae}}}{1-b}\right)$$

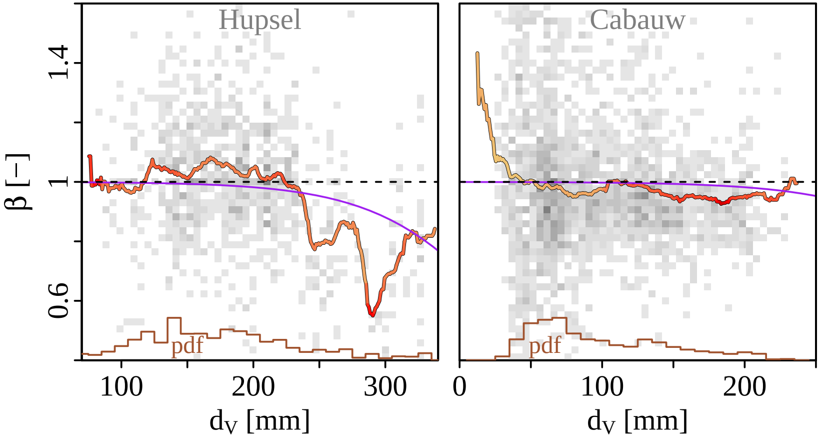
Percolation, capillary rise, drainage, infiltration



Change in groundwater depth depends on the difference between storage deficit and equilibrium storage deficit belonging to the current groundwater depth:

$$\frac{\mathrm{d}d_{\mathrm{G}}}{\mathrm{d}t} = \frac{d_{\mathrm{V}} - d_{\mathrm{V,eq}}}{c_{\mathrm{V}}}$$

Storage deficit determines evapotranspiration reduction



$$\beta = \frac{ET_{\mathrm{act}}}{ET_{\mathrm{pot}}} = \frac{1-\exp[\zeta_1(d_{\mathrm{V}}-\zeta_2)]}{1+\exp[\zeta_1(d_{\mathrm{V}}-\zeta_2)]} \cdot \frac{1}{2} + \frac{1}{2}$$

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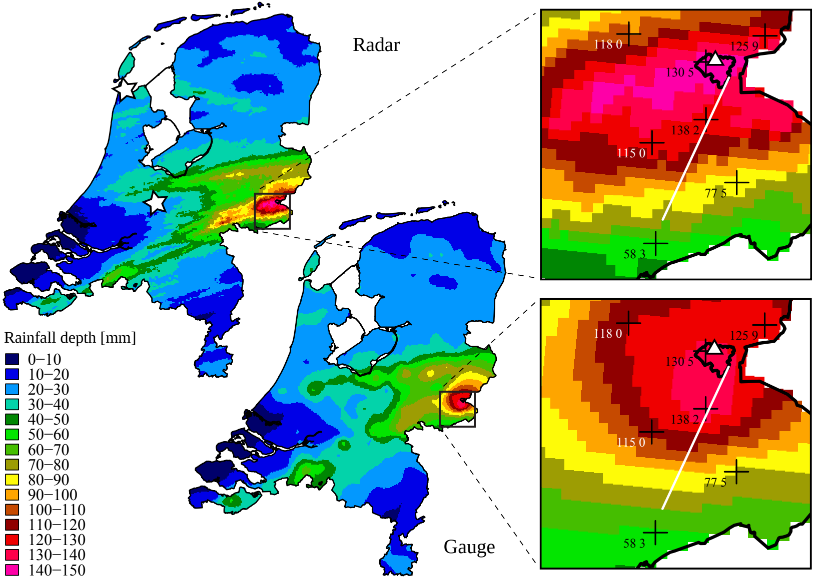
Wetness-dependent flowroutes

Extreme rainfall event (26 Aug. 2010)



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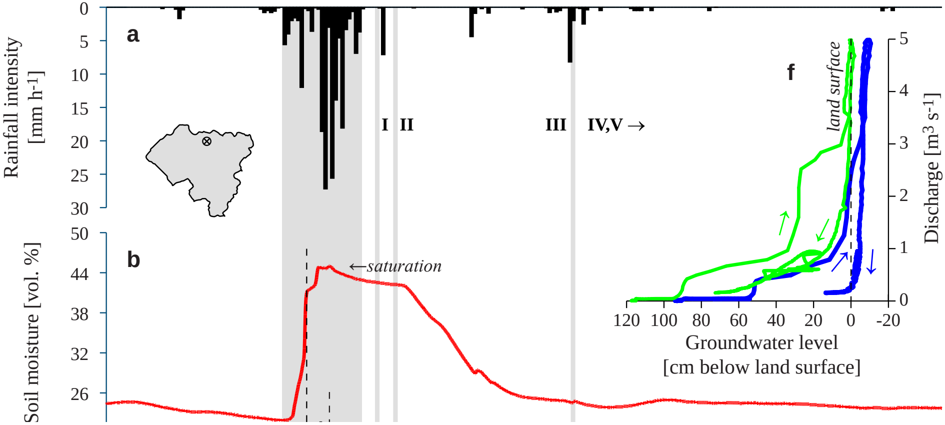
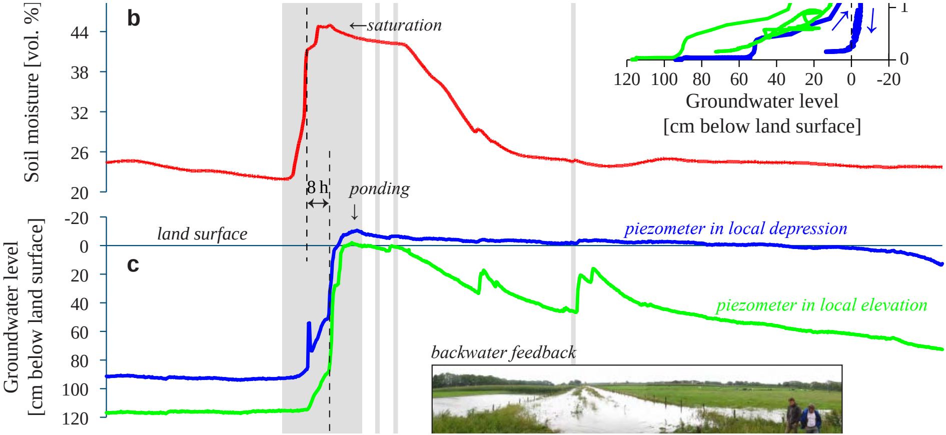
Phase I: Soil moisture increase



Dry initial conditions prevented more extreme response

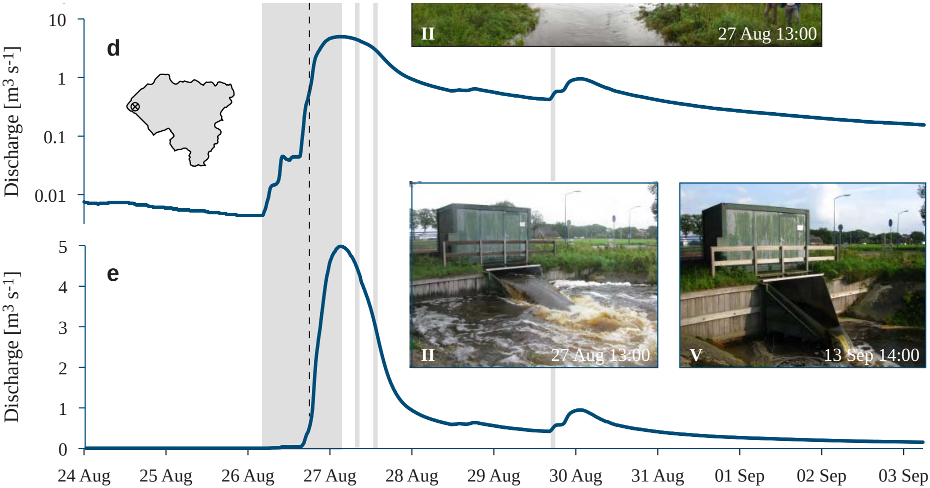
II: Groundwater rise and III: ponding & surface runoff



Groundwater rise quick when soil almost saturated

Spatial differences groundwater observations

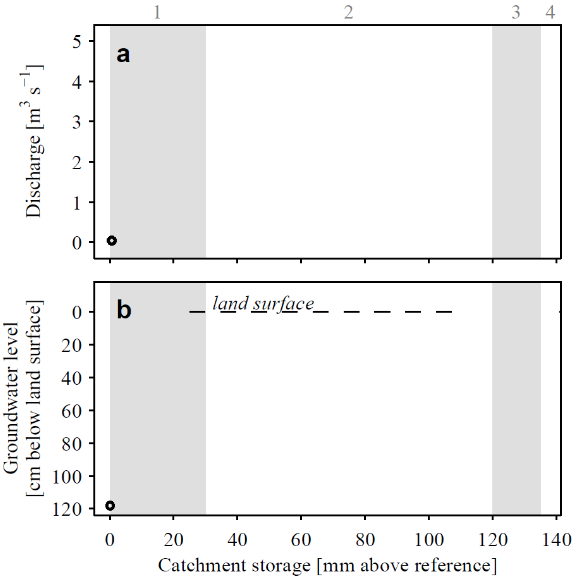
Discharge



Discharge peak topped off

IV: Backwater feedback (post-event field survey)

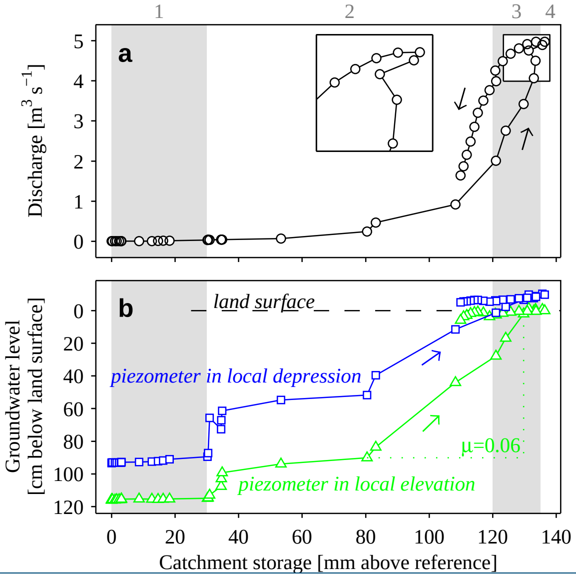
Exercise: storage-discharge relation



$$S = S_0 + \int_{t=t_0}^{t} (P - Q)\mathrm{d}t.$$

Thresholds (fill and spill): different flowroutes with varying wetness

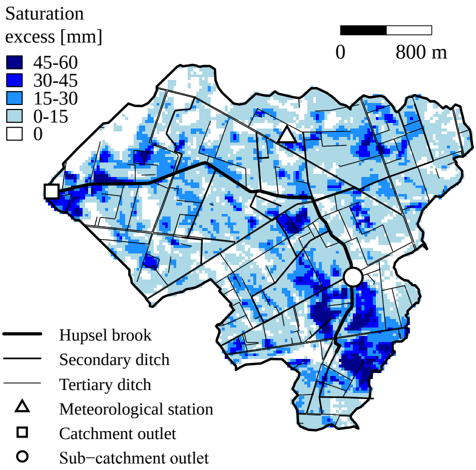
Storage-discharge relation



$S = S_0 + \int_{t=t_0}^{t} (P - Q)\mathrm{d}t.$

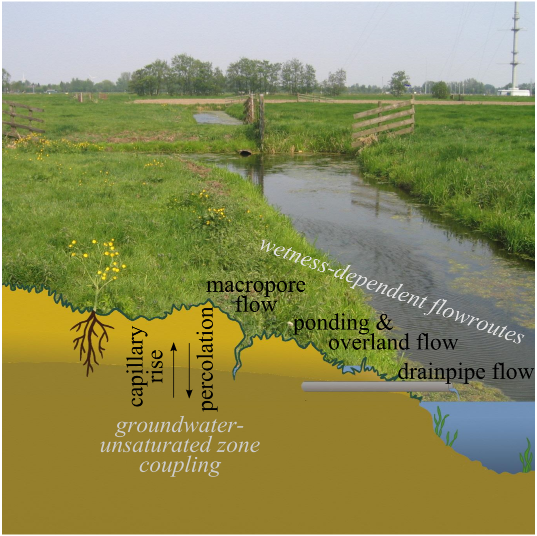
Thresholds (fill and spill):
different flowroutes
with varying wetness

Spatial variation

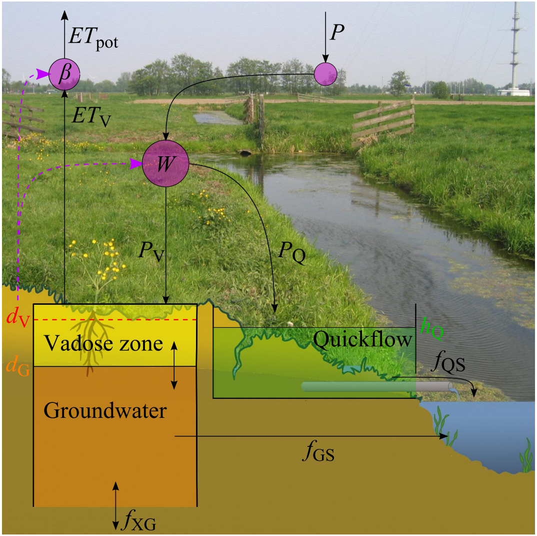


Thresholds exceeded in different locations at different moments → discharge response gradual, not stepwise

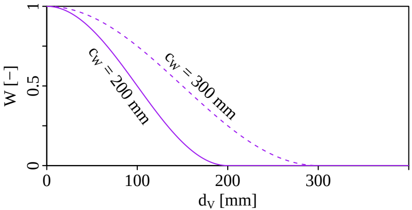
Lesson 2: wetness-dependent flowroutes

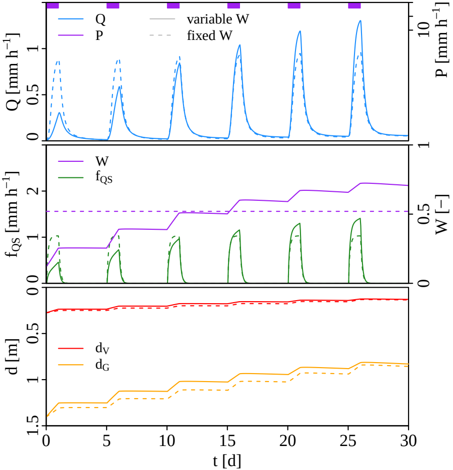


Lesson 2: wetness-dependent flowroutes



Dynamic flow route divider





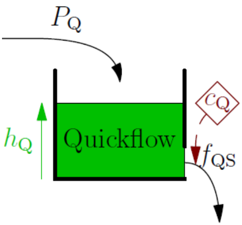
Wetness index (W) is the fraction of rain that is led into the quickflow reservoir. Depends on storage deficit.

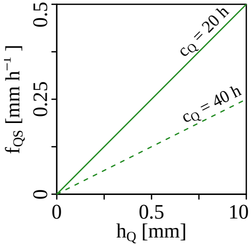
Default relation: $W = \frac{1}{2} + \frac{1}{2} \cdot \cos\left(\frac{\max(\min(d_V, c_W), 0) \cdot \pi}{c_W}\right)$

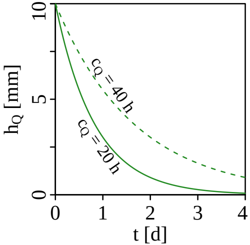
Quickflow

Depends on water level in (linear) quickflow reservoir

$$f_{QS} = \frac{h_Q}{c_Q} \cdot a_G$$







Lowland hydrology

Groundwater-surface water feedback



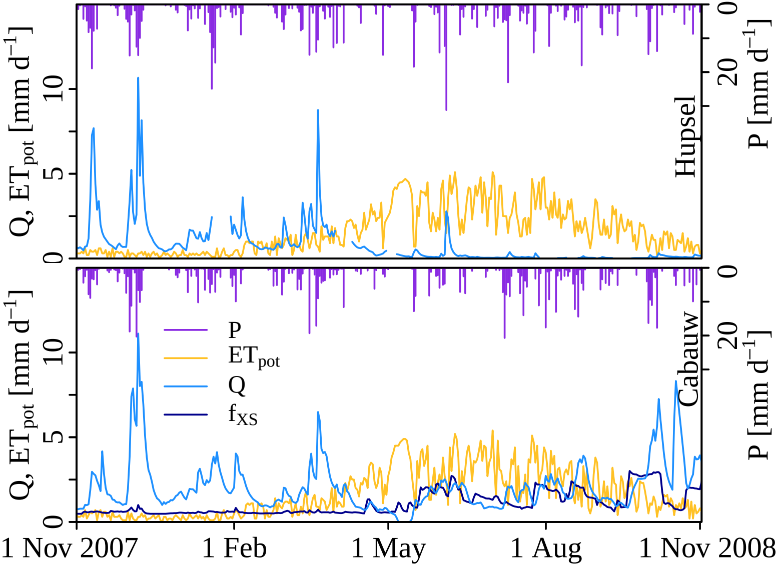


Surface water level management

Surface water supply

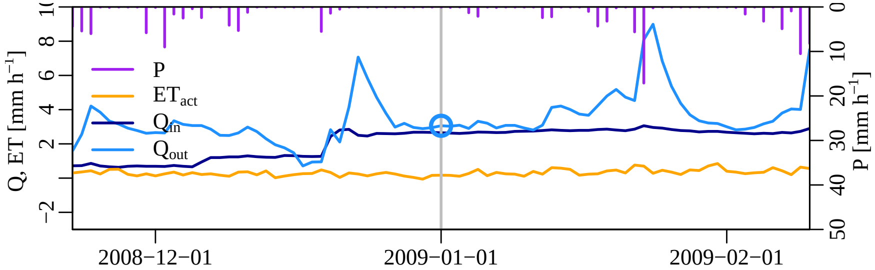
Changing weir elevations

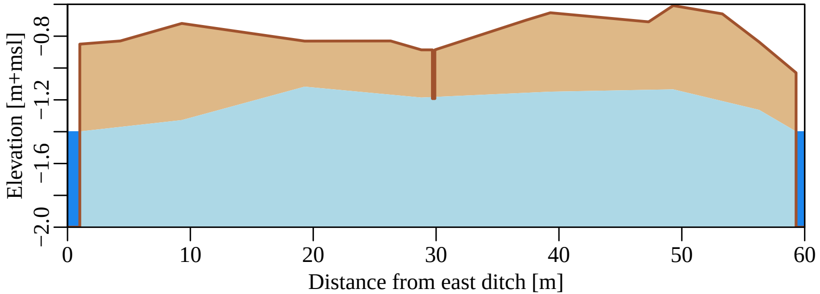
Effect of surface water supply on discharge



Groundwater measurements

Variation of groundwater in space and time

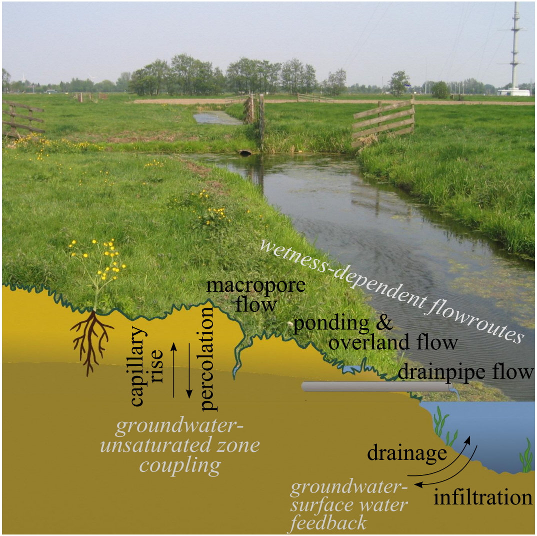




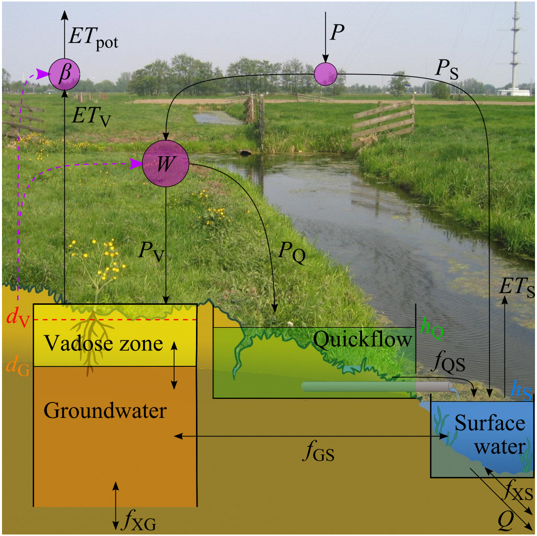
Effect of water level management

Surface water levels maintained by water authorities
↓
Groundwater levels high year-round
↓
Soil moisture content high; always saturated below $\sim$50 cm
↓
Evapotranspiration reduction hardly occurs

Lesson 3: groundwater-surface water feedback



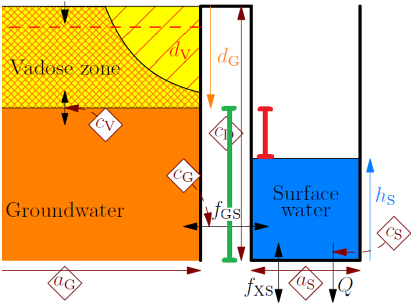
Lesson 3: groundwater-surface water feedback

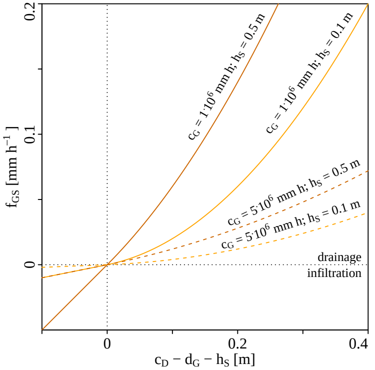


Groundwater drainage/infiltration

Flow depends on difference between groundwater and surface water levels (left term; red) and contact surface (right term; green):

$$f_{\mathrm{GS}} = \frac{(c_{\mathrm{D}} - d_{\mathrm{G}} - h_{\mathrm{S}}) \cdot \max((c_{\mathrm{D}} - d_{\mathrm{G}}), h_{\mathrm{S}})}{c_{\mathrm{G}}} \cdot a_{\mathrm{G}}$$

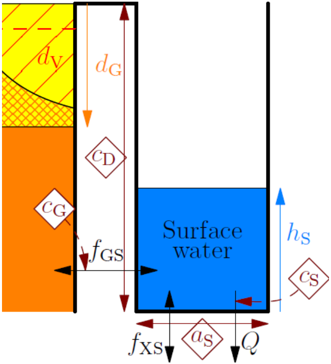


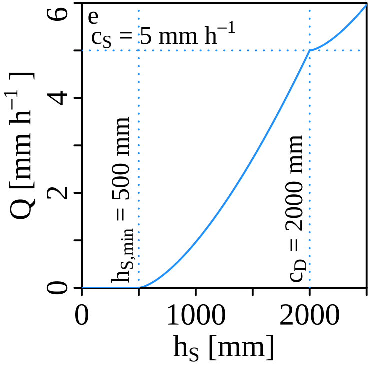


Note that water can flow both ways (drainage/infiltration)

Depends on surface water level.
Supply stage-discharge relation or use default:

$$Q = c_S \left(\frac{h_S - h_{S,min}}{c_D - h_{S,min}} \right)^{x_S}$$

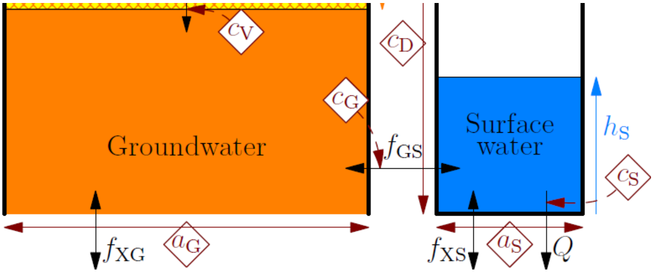




External fluxes

f_{XG} Upward (positive) or downward (negative) seepage

f_{XS} Surface water supply (positive) or extraction (negative)



Application of WALRUS

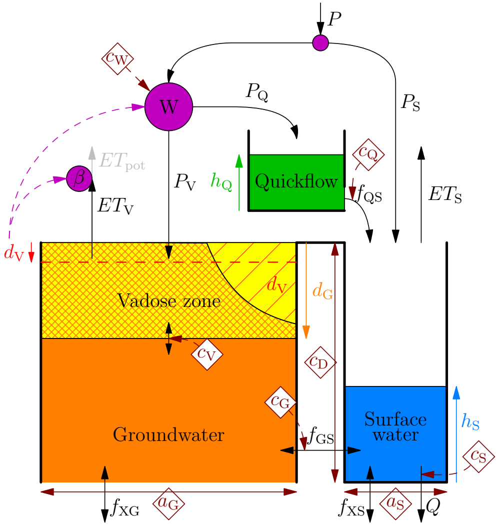
Parameters and initial conditions

Parameters

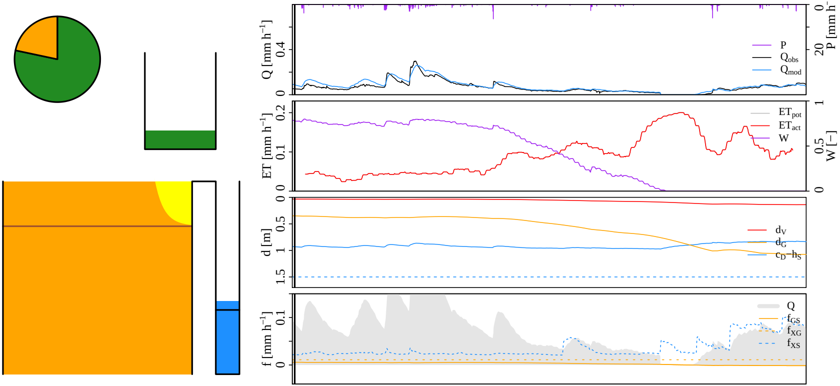
- a_{S}, c_{D}, soil type, (c_{S})
  estimate from catchment characteristics
- c_{W}, c_{G}, c_{Q}, (c_{V})
  calibrate

Initial conditions

- $d_{\mathrm{V},0}$, $d_{\mathrm{G},0}$, $h_{\mathrm{Q},0}$, $h_{\mathrm{S},0}$
- *not specified*
  equilibrium – all discharge from groundwater
- G_{frac}
  fraction of discharge from groundwater



Model runs



Q [mm h^{-1}]
P [mm h^{-1}]
P
Q_{obs}
Q_{mod}
ET [mm h^{-1}]
W [−]
ET_{pot}
ET_{act}
W
d [m]
d_V
d_G
$c_D - h_S$
f [mm h^{-1}]
Q
f_{GS}
f_{XG}
f_{XS}

Applications

- Flood/drought forecasting
  $\rightarrow$ operationally used by Dutch water boards
- Real-time control
- Input for hydraulic model
  $\rightarrow$ implemented as rainfall-runoff module in SOBEK
- Risk analyses
- Scenario analyses
- Infrastructure design
- Gap filling

More information

- WALRUS package, tutorial, information, publications, etc: `www.github.com/ClaudiaBrauer/WALRUS`.
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