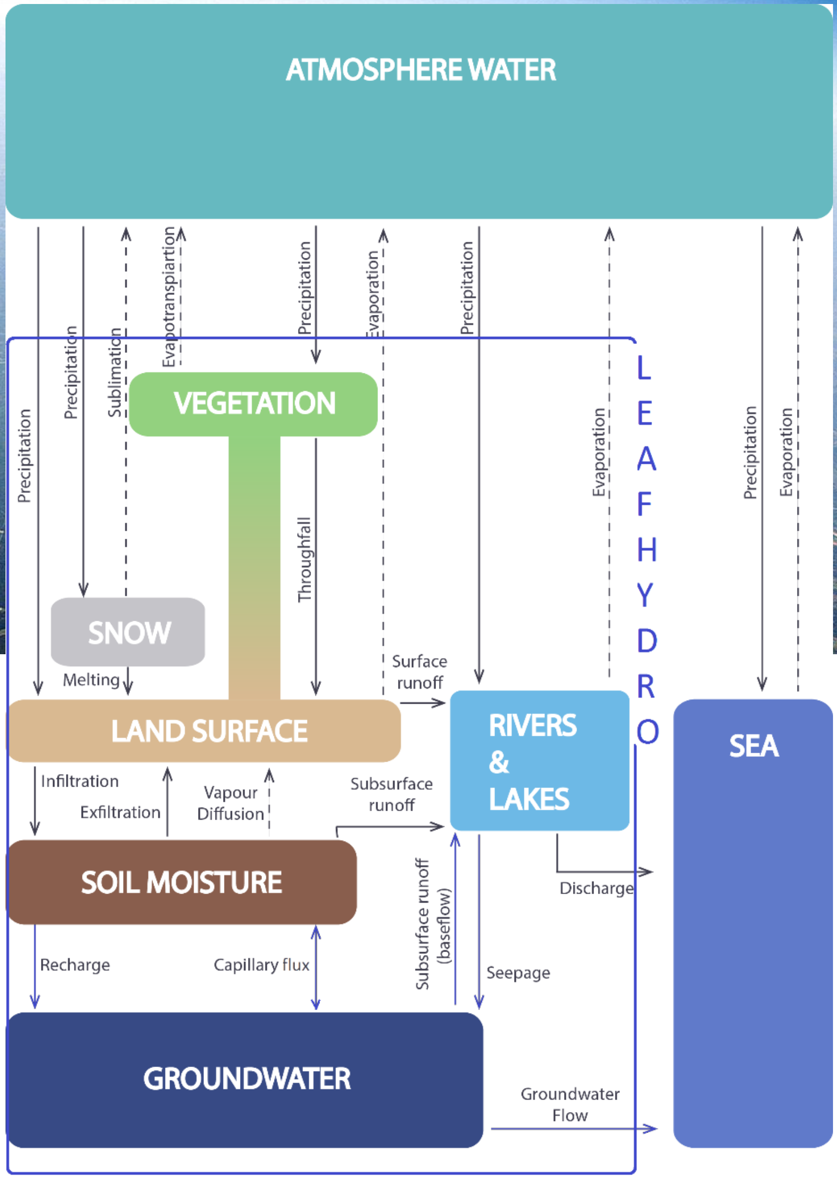
Groundwater interactions with the land surface: introduction of a dynamic groundwater scheme into the JULES LSM



Sarah Collins (BGS)
Alberto Martínez-de la Torre (UKCEH)
Andrew Hughes (BGS)

UK Centre for Ecology & Hydrology

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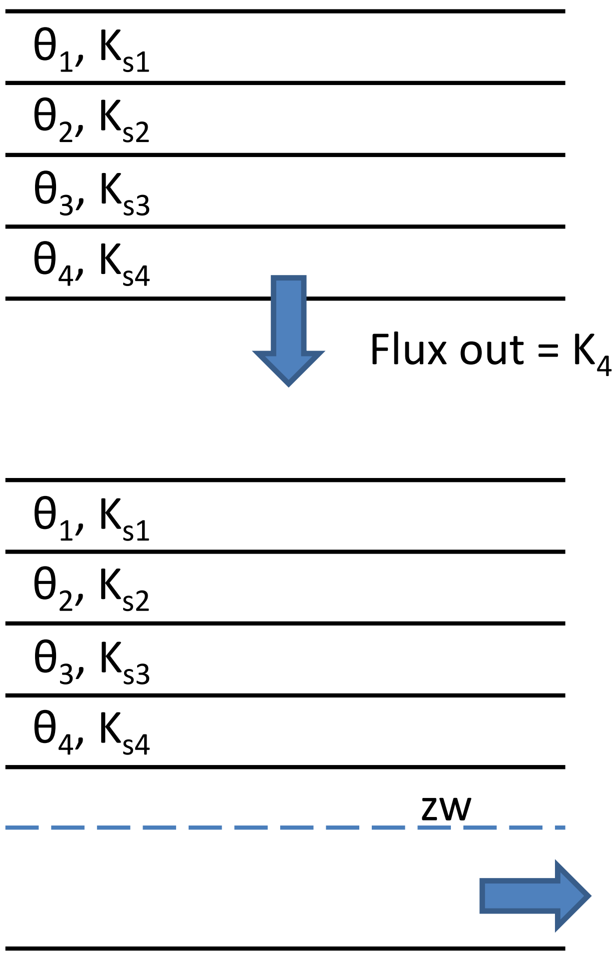
Hydro-JULES

JULES subsurface flow

- In the "base" JULES model subsurface flow is the gravitational drainage from the lowest soil layer.

- If "TOPMODEL" is used, the groundwater table depth (zw) is estimated from the soil moisture deficit. Subsurface flow is dependent on transmissivity and zw (as well as other parameters, Clark and Gedney, 2008). There is no lateral flow between cells.



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When do we need lateral flow?

The TOPMODEL approach in JULES may be suitable for a range of catchments, particularly those with a low baseflow index.

However, an explicit groundwater model can, for example:

- Improve process representation (e.g. surface water−groundwater interaction) and simulated streamflow in groundwater-dominated catchments
- Allow us to incorporate a more complex geology and determine a more realistic water table depth
- Allow us to include groundwater abstraction, which can be a significant component of the catchment water balance (e.g. in India)
- Include capillary rise from the water table back into the soil layers (which increases evapotranspiration)

Groundwater scheme: key components

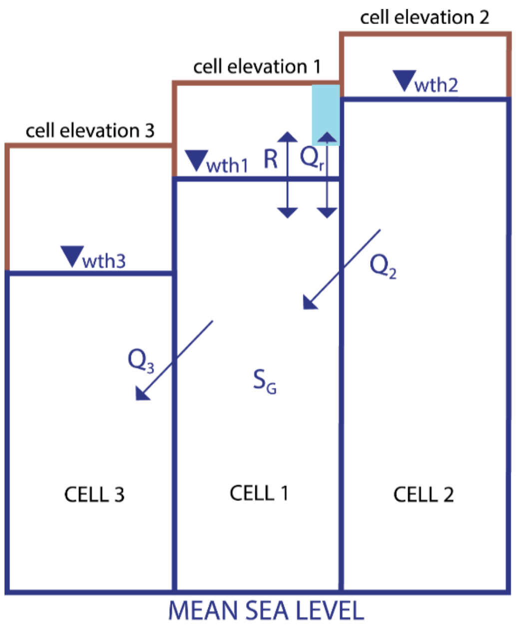
$\Delta x \Delta y R$ **Groundwater recharge**: Water flux between the groundwater reservoir and the soil. Depending on the soil wetness and the atmosphere demands, the recharge can be downwards, causing the water table to rise, or upwards, causing the water table to deepen.

$\sum_{n=1}^{8} Q_n$ **Lateral groundwater flow**: Water flux to or from neighbour cells within the saturated groundwater reservoir. This flux is governed by the water table head elevation and hydraulic conductivity.

Q_r **Groundwater−river flow**: It can occur as groundwater discharge (subsurface runoff) into the streams when the water table head is above the river bed, maintaining the streams baseflow, or as river infiltration to the groundwater reservoir when the water table head is below the river bed.

Q_{abs} **Groundwater abstraction**: Removal of water from the aquifer. It can be very difficult to estimate the rate of groundwater abstraction, if the local authority does not keep a record.

$$\frac{dS_G}{dt} = \Delta x \Delta y R + \sum_{n=1}^{8} Q_n - Q_{abs} - Q_r$$



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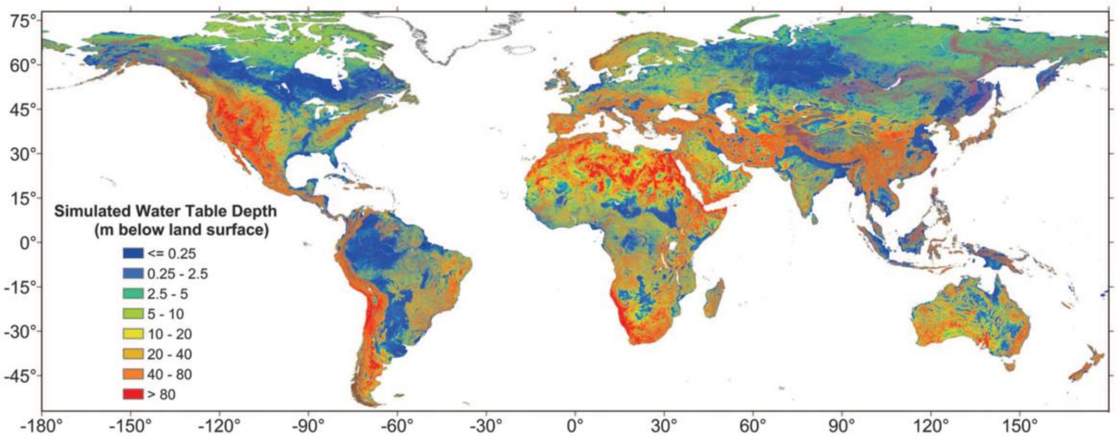
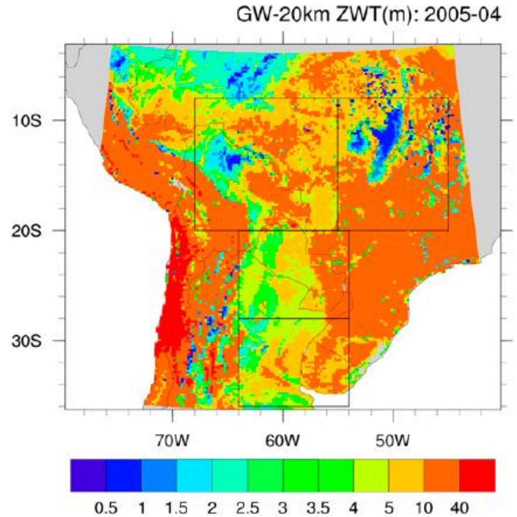
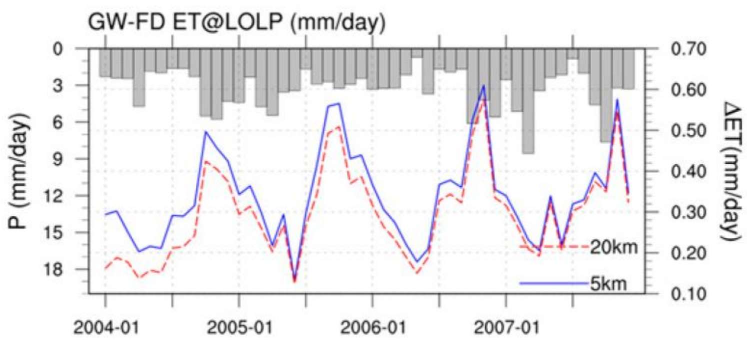
Groundwater in LSMs

A number of land surface models now include a groundwater scheme with lateral flow:

- LEAFHYDRO (Fan et al 2013)
- Common Land Model + ParFlow (Maxwell and Miller 2005)
- JULES-GFB (Batelis et al 2020)
- ISBA Land Surface Scheme (Vergnes et al 2014)







Martínez, 2016 (*Journal of Hydrometeorology*): full integration with the DGW scheme into Noah-MP over Southern SA at 5/20km resolution

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Groundwater in LSMs

However, there is much more to modelling groundwater than the model code:

- Parameterisation of a groundwater model is difficult given the lack of hydrogeological data in many areas
- Validation of a groundwater model requires long-term groundwater level data

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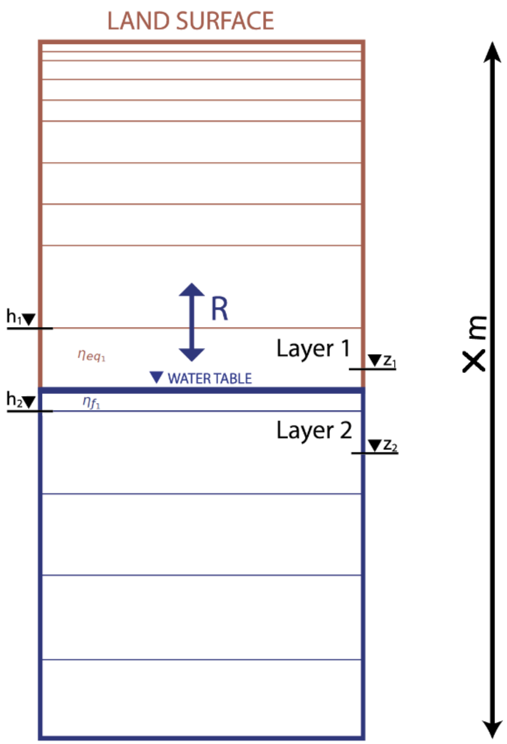
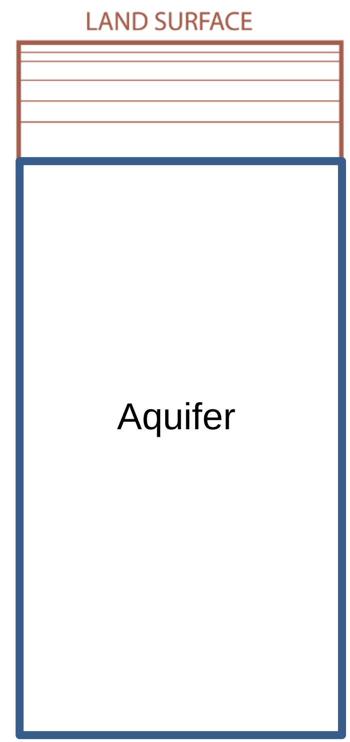
Groundwater Recharge

Calculate position of water table by assuming equilibrium (no vertical flux) between saturated portion of layer 1 and saturated layer 2

Introduce aquifer layer below the soil column.



Impermeable layer

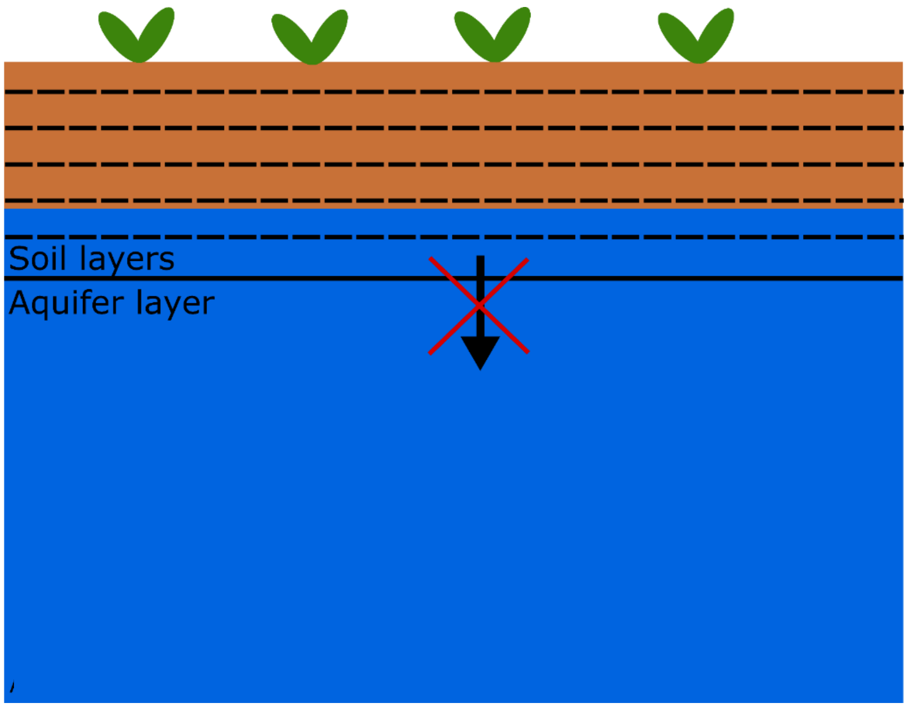


Impermeable layer

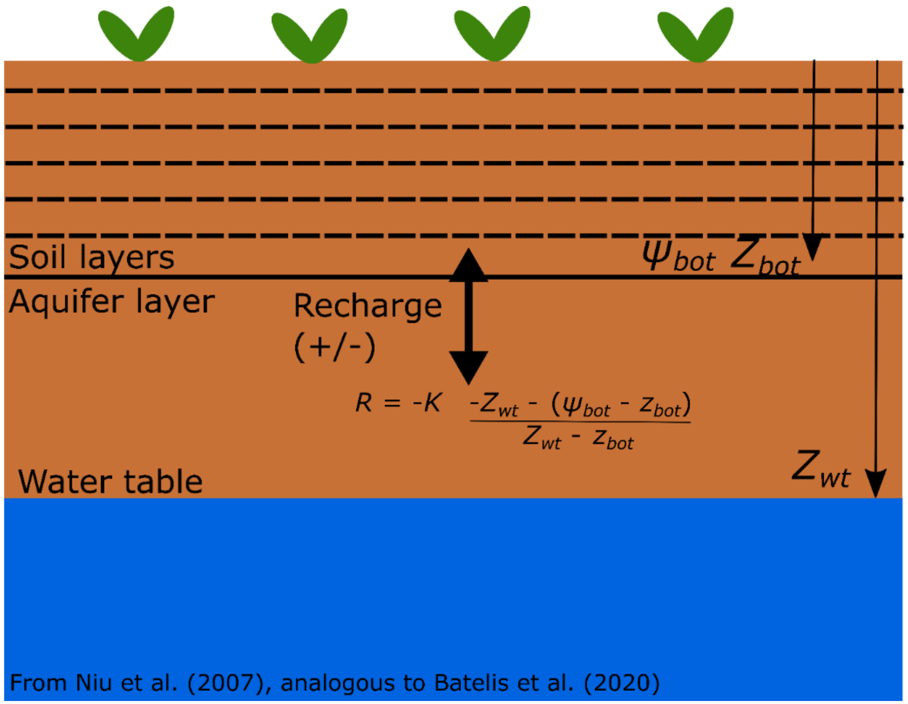
Issues: computational expense (especially with deep water table)

Groundwater Recharge

Water table within soil layers



Water table below soil layers



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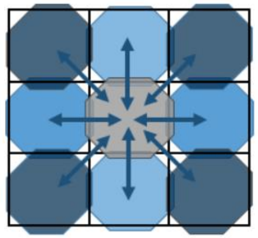
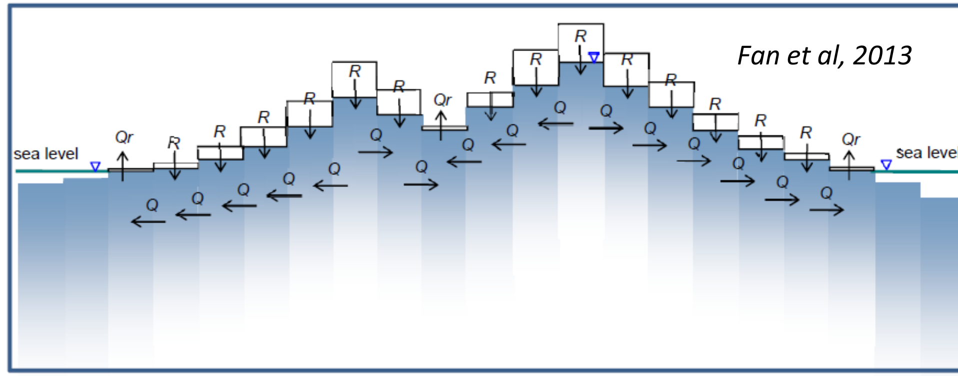
Groundwater Lateral flow

Lateral flow from the nth neighbour applying Darcy's law

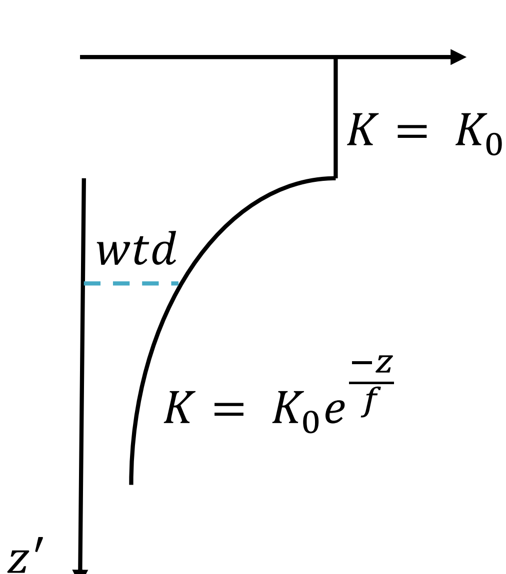
$$Q_n = cT\left(\frac{wtd_n - wtd}{l}\right)$$

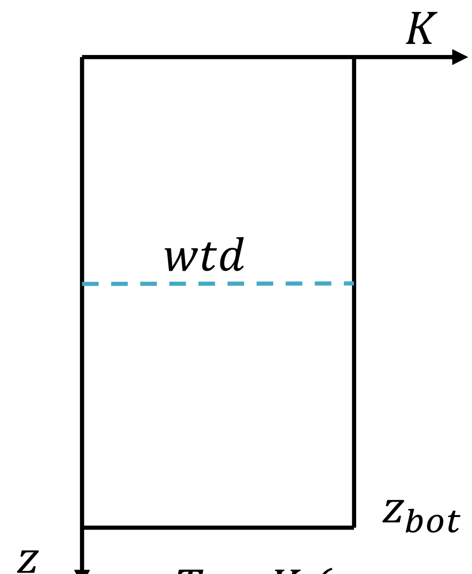




Transmissivity $$T = \int_{-wtd}^{\infty} K_{L_f}\, dz'$$

Exponential decrease in K with depth derives from TOPMODEL and is widely used by hydrologists for catchments with low baseflow index. In catchments with permeable geology, K will generally remain high to much greater depths.





$$T = K\,(z_{bot} - wtd)$$

K vs. depth

Exponential decrease in K with depth works well for weathered basement aquifers

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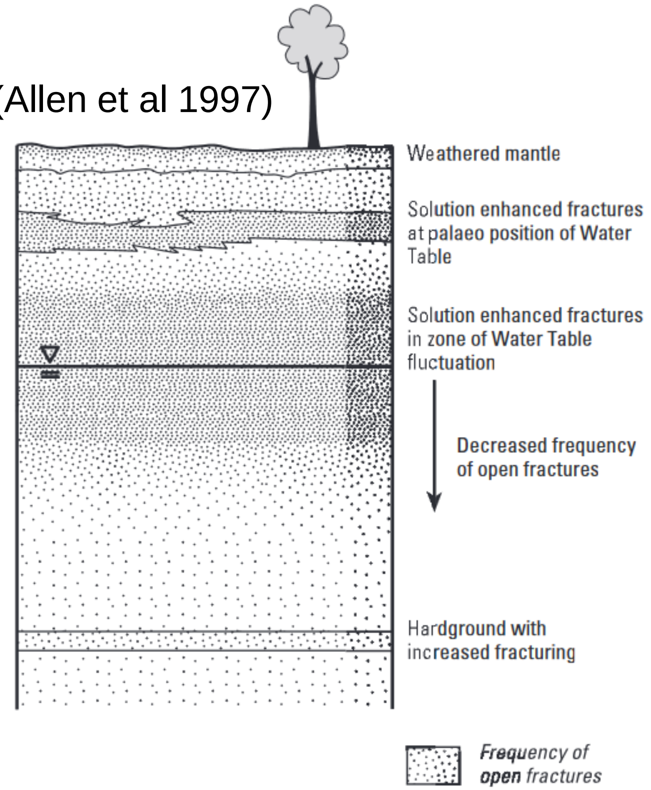
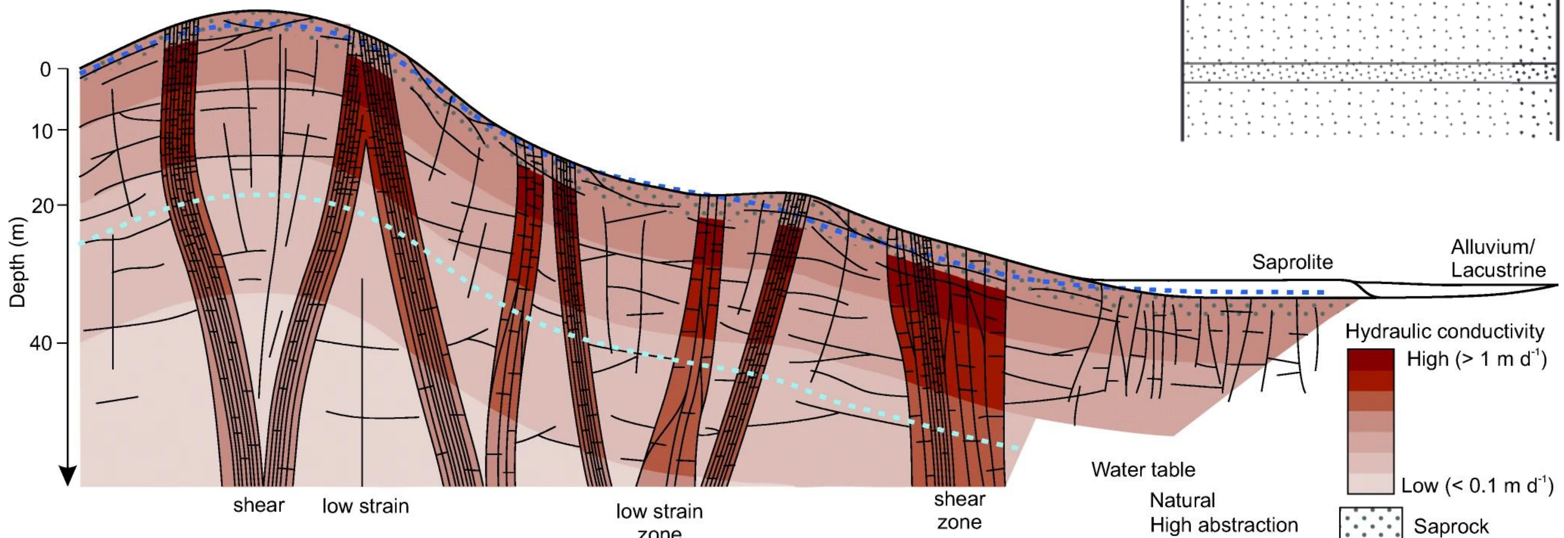
K vs. depth

- In the chalk aquifers of the UK, K is largely controlled by the density and size of fractures. Deeper within the chalk, the frequency and aperture of fractures decline due to increasing overburden and a general reduction in circulating groundwater and hence dissolution.
- Weathered basement aquifers of tropical and sub-tropical regions (e.g. sub-Saharan Africa and south Asia) also have rapidly declining fracture frequency (and thus K) with depth.

Chalk (Allen et al 1997)





Gneiss, Peninsular India (Collins et al 2020)

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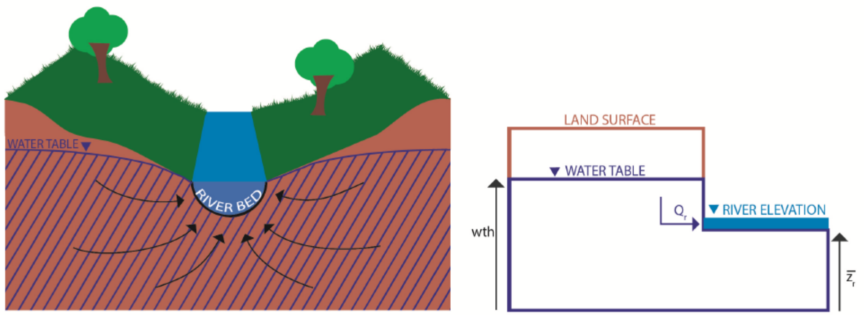
Groundwater-river flow

- Gaining streams, applying Darcy's law

$$Q_r = \left(\frac{\bar{K_{rb}}}{\bar{b_{rb}}}\right)\left(\bar{w}_r \sum L_r\right)(wth - \bar{z}_r)$$

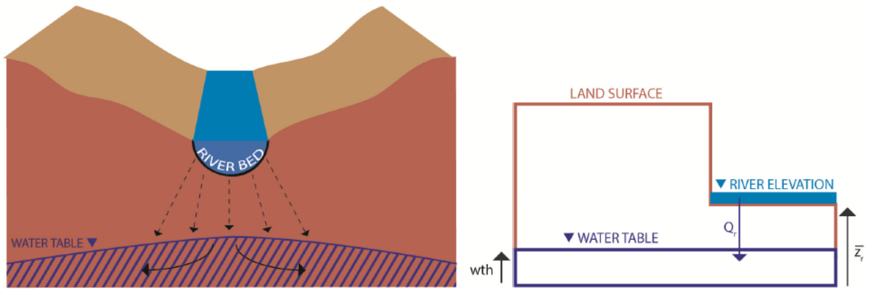
- Define river conductance → $RC = \dfrac{\bar{K_{rb}} \bar{w}_r \sum L_r}{\bar{b_{rb}}}$



- which is the standard representation used in groundwater models (e.g. MODFLOW)

- Losing streams, b_{rb} and the distance between riverbed and water table cancel each other:

$$Q_r = -K_{rb} \bar{w}_r \sum L_r$$



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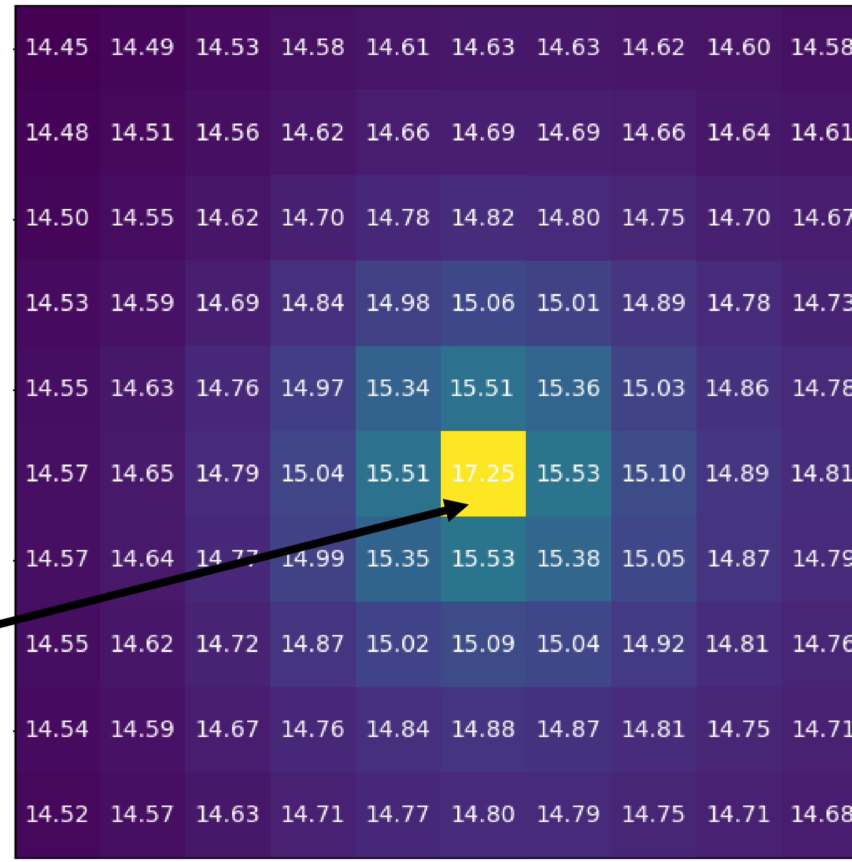
Abstraction

Depth to groundwater (m)



Drawdown from extraction well(s)

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Implementation into JULES, 1 point runs

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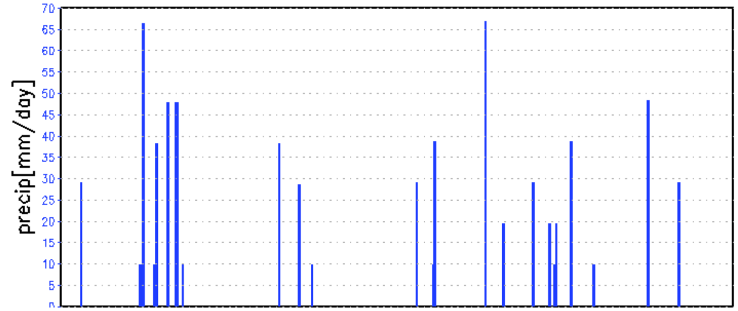

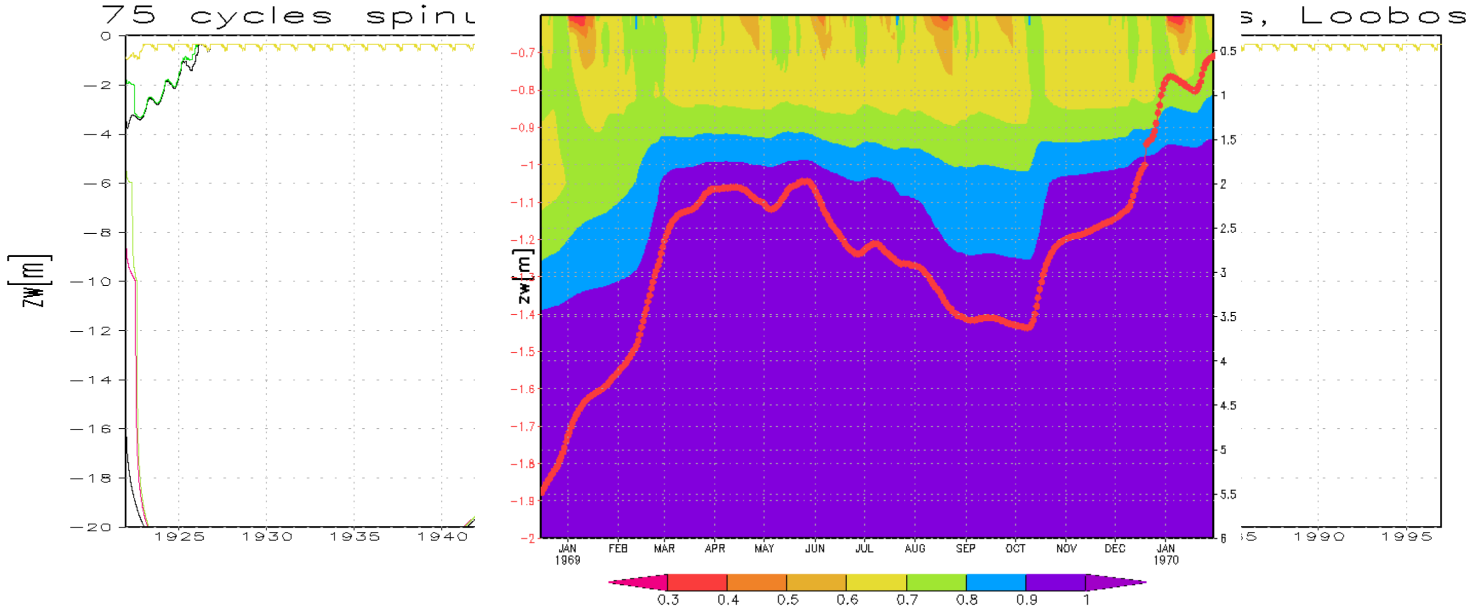

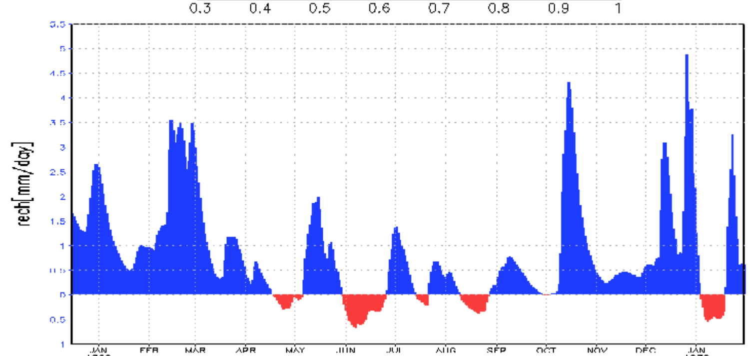

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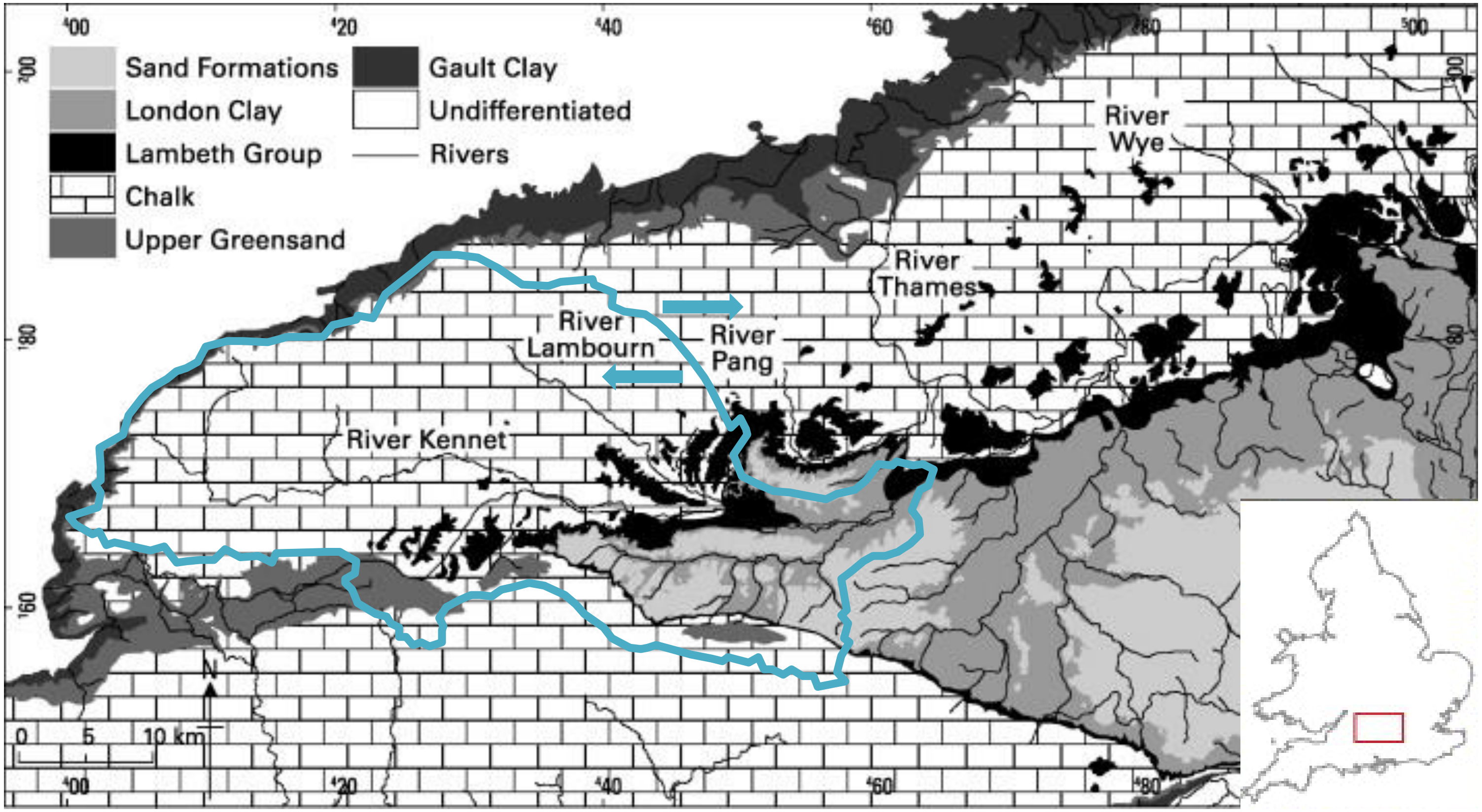
Implementation into JULES, Kennet run

Surface water catchment boundaries do not always match groundwater catchment boundaries. The groundwater divide between the Pang and Lambourn varies seasonally by >3 km.



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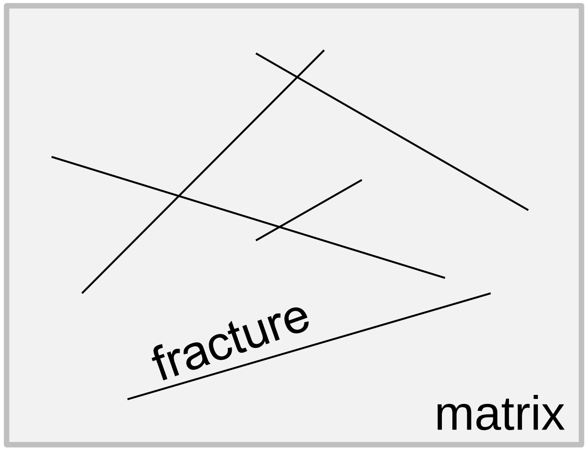
Implementation into JULES, Kennet run

The bulk conductivity model
(Rahman and Rosolem 2019)

- The matrix stores water, but transmits water very slowly in the unsaturated zone (very low K)
- In winter, flux into the unsaturated zone increases. The fractures “wet up”, hugely increasing the transfer of water through the unsaturated zone to the water table



$$K_{\mathrm{sb}} = K_{\mathrm{s}} + K_{\mathrm{s}} f_{\mathrm{m}} \frac{S - S_0}{1 - S_0} \text{ if } S > S_0,$$

$$K_{\mathrm{sb}} = K_{\mathrm{s}} \text{ if } S <= S_0,$$

with

$$S = \frac{\theta - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}},$$

S_0 threshold saturation
f_m parameter
K_{sb} bulk saturated K
K_s saturated K

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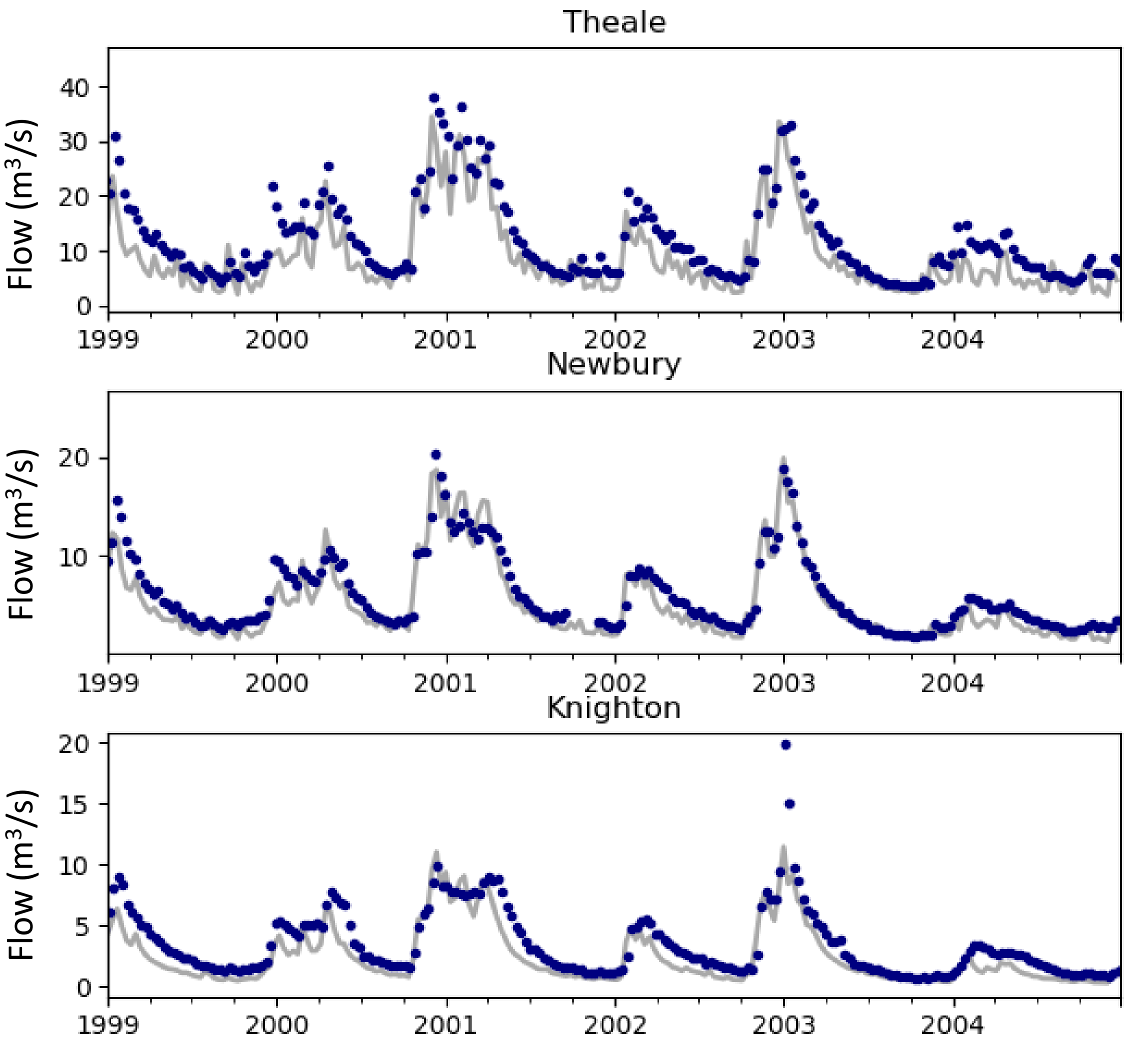
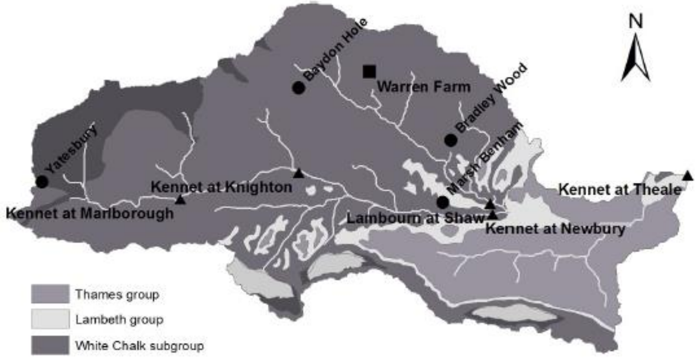
Implementation into JULES, Kennet run





Observed river flow

Simulated river flow

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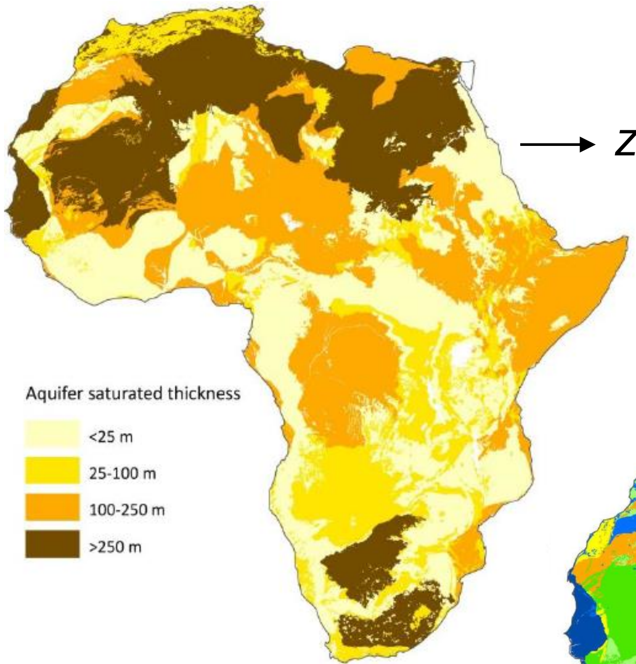
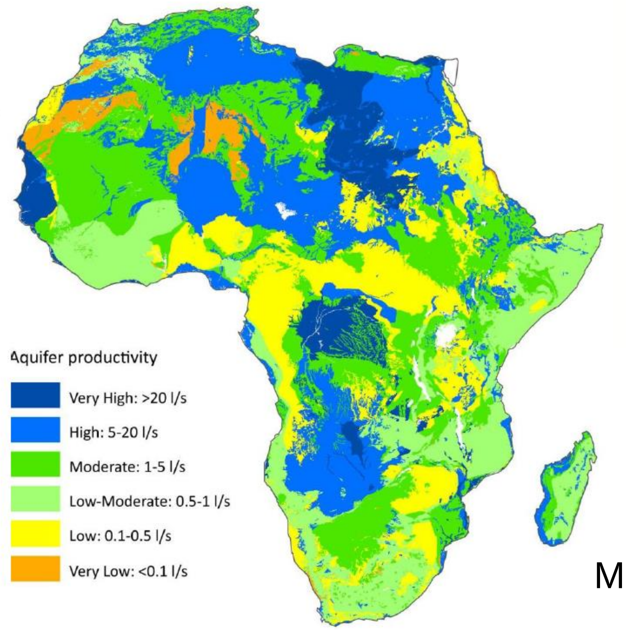
Working on an Africa instance

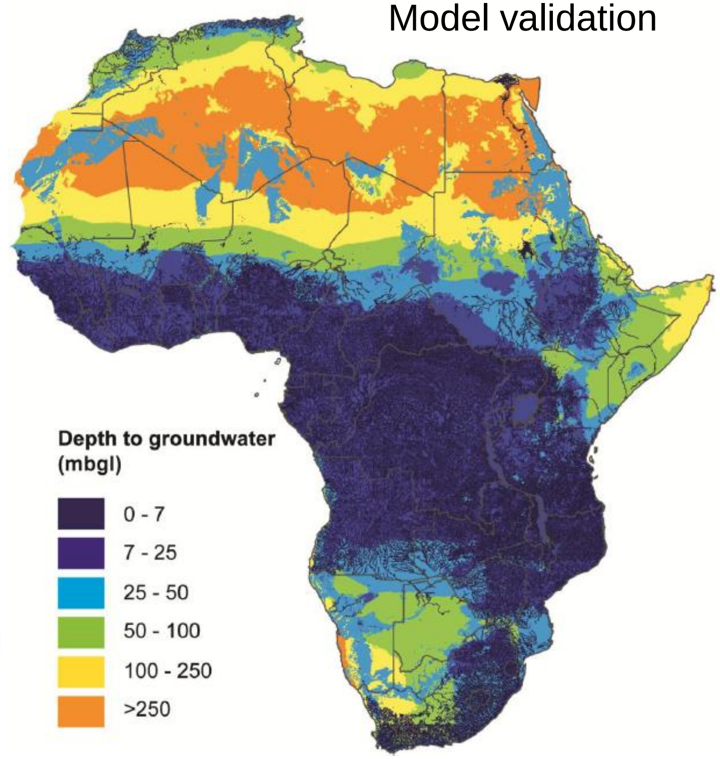


→ z_{bot}



→ K

Model validation



MacDonald et al (2011)

Compilation of a huge amount of work over many years.

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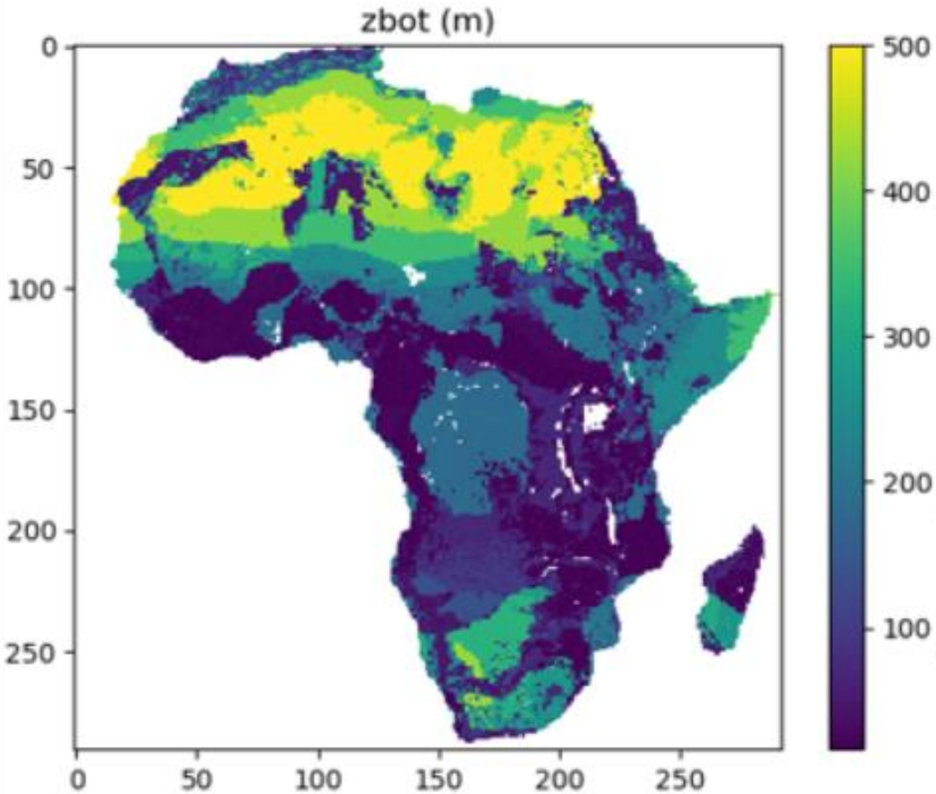
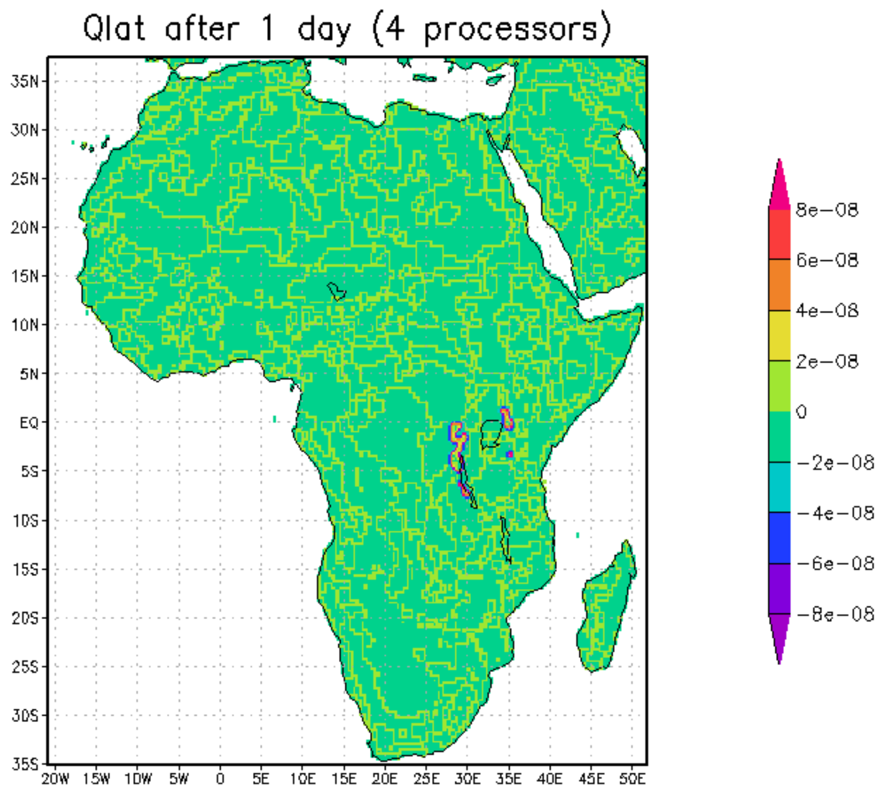
Working on an Africa instance





Testing the code for the Africa domain driven by e2o data at 0.25deg resolution, MPI works!

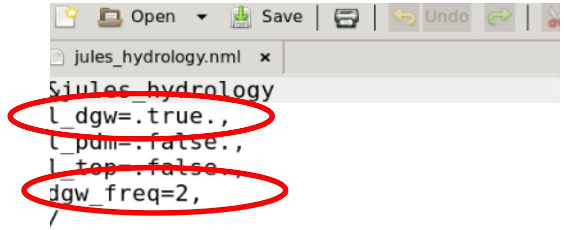
Implementation into JULES

Opened ticket #532 to implement the Dynamic Groundwater scheme from in JULES.

Branches:
https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/albertomartinez/vn5.2_dgw_leafhydro

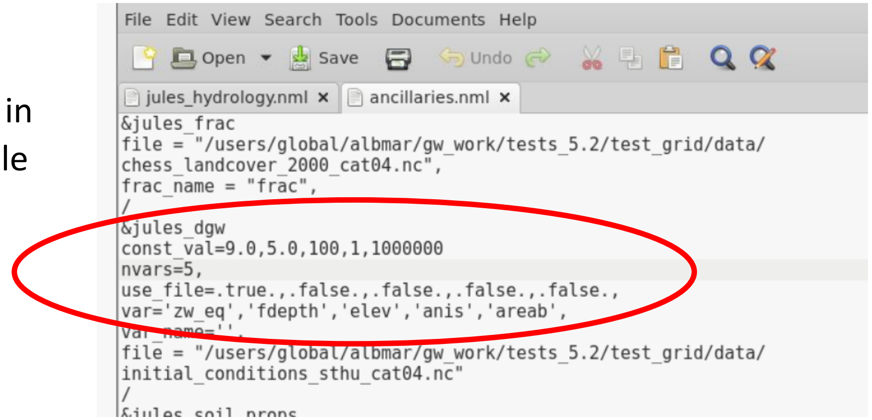
https://code.metoffice.gov.uk/trac/jules/browser/main/branches/dev/albertomartinez/vn5.2_dgw_leafhydro_bgs

- New flag **l_dgw** to activate the scheme and new variable **dgw_freq** in jules_hydrology.nml



- Read in zw_eq_gb, fdepth_gb and other ancillary datasets from a gridded file or as constant values in a new namelist **jules_dgw** in the ancillaries.nml file

- Added **zwd, gwrech, qlat** to possible **outputs**



Working with MetOffice to improve the code and make it to the trunk

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THANKS

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