A MUlti-scale Soil moisture-Evapotranspiration Dynamics study (AMUSED)

Influence of Chalk Hydrology on Land Surface Processes in the UK

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Research article

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The effect of chalk representation in land surface modelling

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Review status
This discussion paper is under review for the journal Hydrology and Earth System Sciences (HESS).

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Abstract. Modelling and monitoring of hydrological processes in the unsaturated zone of the chalk, which is a porous medium with fractures, is important to optimize water resources assessment and management practices in the United Kingdom (UK). However, efficient simulations of water movement through chalk unsaturated zone is difficult mainly due to the fractured nature of chalk, which creates high-velocity preferential flow paths in the subsurface. Complex hydrology in the chalk aquifers may also influence land surface mass and energy fluxes because processes in the hydrological cycle are connected via non-linear feedback mechanisms. In this study, it is hypothesized that explicit representation of chalk hydrology in a land surface model influences land surface processes by affecting water movement through the shallow subsurface. In order to substantiate this hypothesis, a macroporosity parameterization is implemented in the Joint UK Land Environment Simulator (JULES), which is applied on a study area encompassing the Kennet catchment in the Southern UK. The simulation results are evaluated using field measurements and satellite remote sensing observations of various fluxes and states in the hydrological cycle (e.g., soil moisture, runoff, latent heat flux) at two distinct spatial scales (i.e., point and catchment). The results reveal the influence of representing chalk hydrology on land surface mass and energy balance components such as surface runoff and latent heat flux via subsurface processes (i.e., soil moisture dynamics) in JULES, which corroborates the proposed hypothesis.

Short summary
Modelling water flow through chalk (a fine grained porous medium traversed by fractures) is important for optimizing...
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Assessing water flow through chalk unsaturated zone is essential for the most important aquifer units in the United Kingdom

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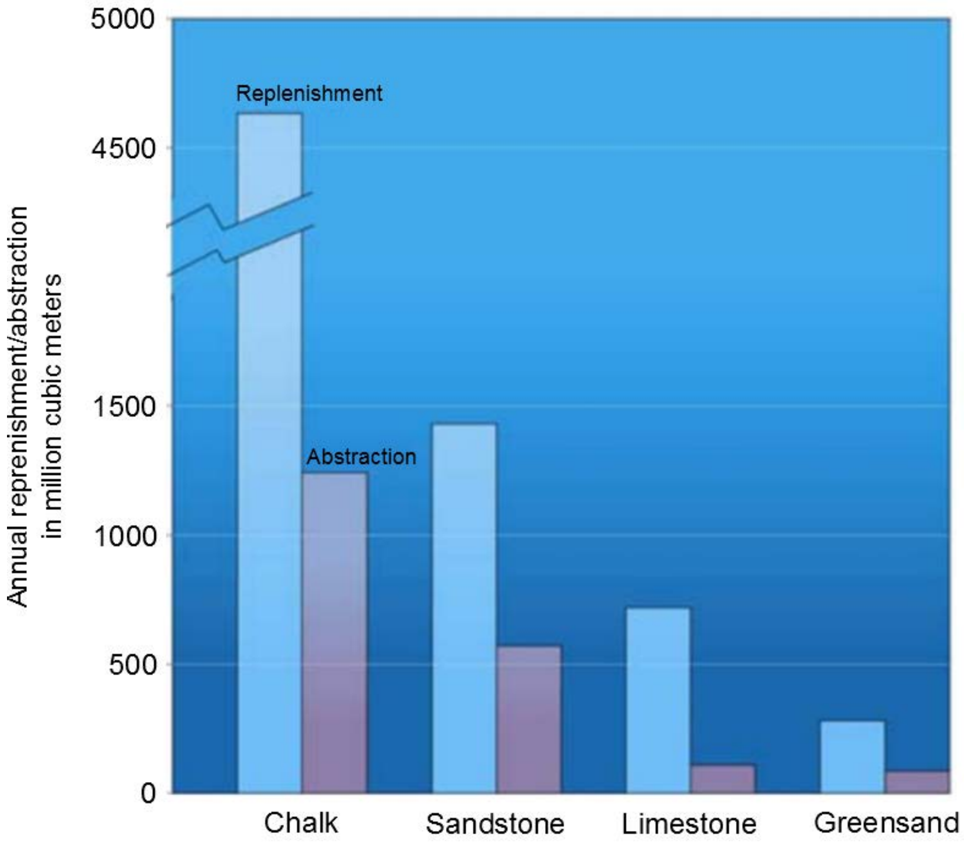
UK Groundwater Forum



Comparison of replenishment and abstraction of groundwater for the principal aquifers of the UK.

British Geological Survey

"The Chalk Group forms the most important aquifer unit within the Thames Basin, supplying water for drinking water public consumption and supporting river flows …"

Ireson et al. (2009)

"The unsaturated zone in such systems plays a crucial role in the hydrological cycle, determining the timing and magnitude of recharge …"

Complex physical properties of chalk makes efficient simulation of water flow through the unsaturated zone challenging

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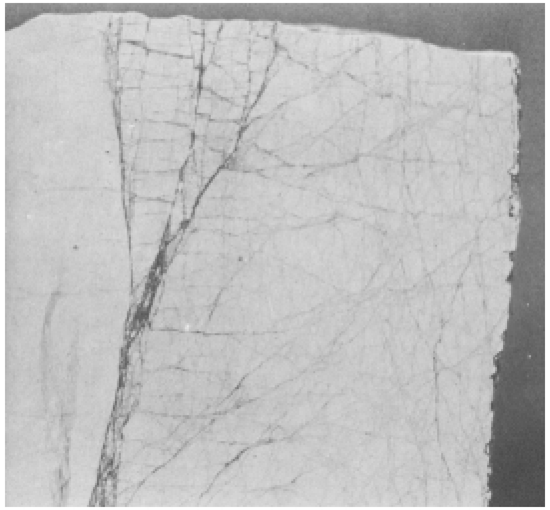
Chalk = Matrix + Fractures

Permeability 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} (ms^{-1})

Porosity 0.3-0.4 10^{-7} (-)



Brown et al. (2016)

- Water flow through chalk matrix is relatively slow.
- Through the chalk fractures, water movement is substantially faster.
- Fracture flow in chalk is activated when saturation is relatively high.

Hypothesis: Complex hydrology in the chalk unsaturated zone affects land surface mass and energy fluxes

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WATER RESOURCES RESEARCH, VOL. 44, W02402, doi:10.1029/2007WR006004, 2008

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Subsurface hydrology can affect land surface mass and energy fluxes

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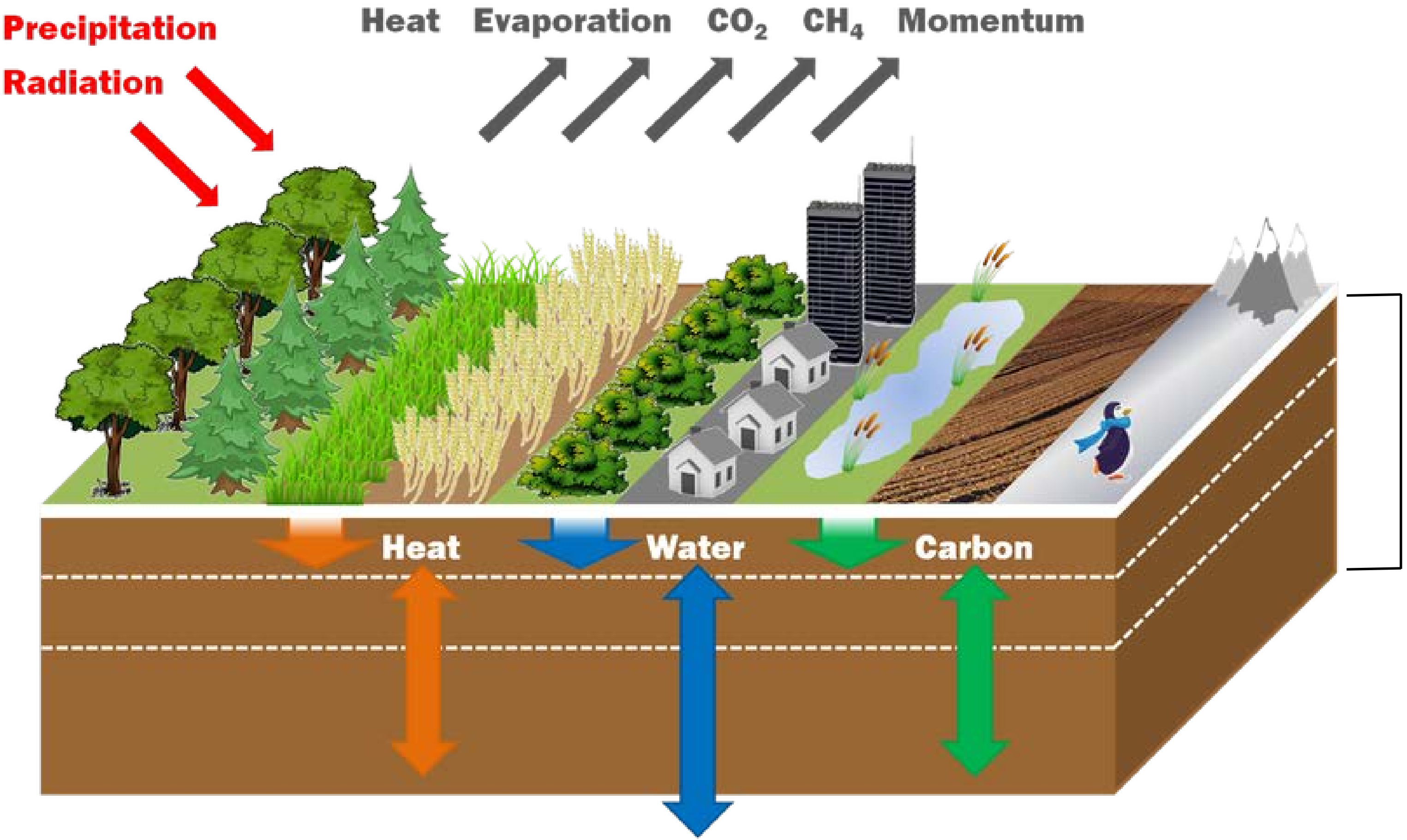
Citation:
Rahman, M., M. Sulis, and S. J. Kollet (2014), The concept of dual-boundary forcing in land surface-subsurface interactions of the terrestrial hydrologic and energy cycles, *Water Resour. Res.*, *50*, 8531–8548, doi:10.1002/2014WR015738.

In this study, the concept of a dual-boundary forcing is proposed that connects the variability of atmospheric (upper boundary) and subsurface (lower boundary) processes to the land surface mass and energy balance components. According to this concept, the space-time patterns of land surface mass and energy fluxes can be explained by the variability of the dominating boundary condition for the exchange processes, which is determined by moisture and energy availability. A coupled subsurface-land surface model is applied on the Rur catchment, Germany, to substantiate the proposed concept. Spectral and geostatistical analysis on the observations and model results show the coherence of different processes at various space-time scales in the hydrological cycle. The spectral analysis shows that atmospheric radiative forcing generally drives the variability of the land surface energy fluxes at the daily time scale, while influence of subsur-

JULES is modified to represent explicitly represent chalk hydrology in the subsurface

JULES



(Relatively) simple parametrization to represent chalk hydrology

Previous efforts of simulating chalk hydrology in the UK

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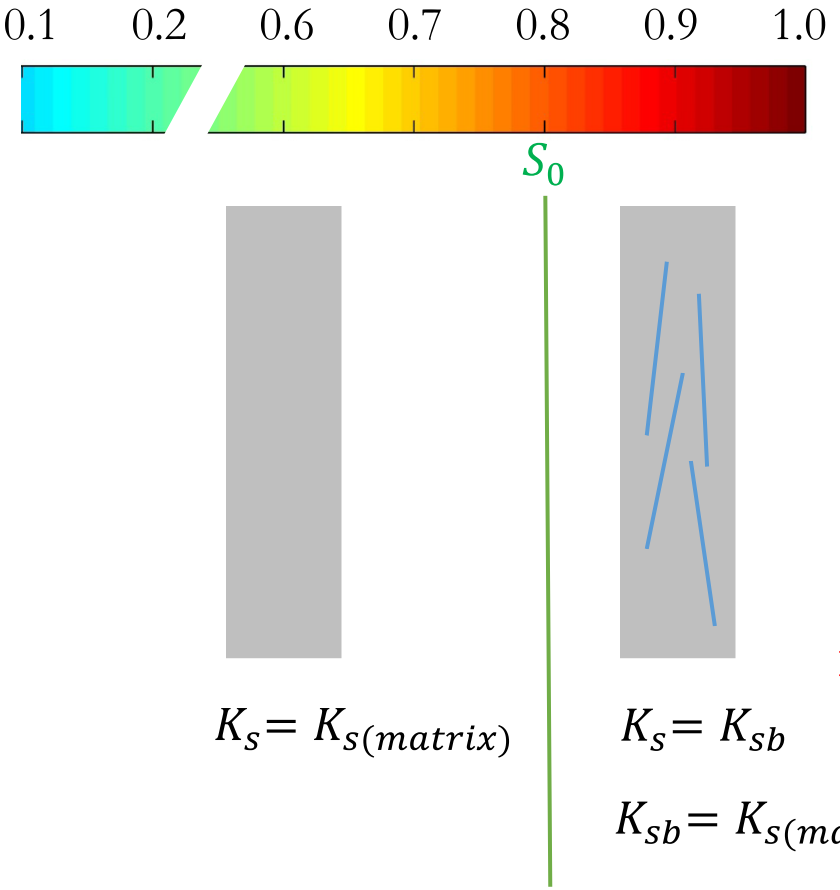
- Finch and Haria, 2006: Dual permeability modeling approach can be used to simulate the hydrological processes in Chalk.
- Matthius et al., 2006: Overlying soil and weathered chalk layers are likely to affect the hydrological processes in a Chalk aquifer.
- Ireson et al., 2009: Groundwater recharge in Chalk occurs predominantly through matrix; fast recharge pathway through fracture is highly dependent on rainfall intensity.
- Ireson and Butler, 2011: Considering matrix and fracture flow is necessary to simulate recharge in a Chalk aquifer.
- Le Vine et al., 2016: Significant efficiency enhancement in simulating Chalk hydrology using a land surface model can be achieved by improving physical representation of Chalk in the model.
- …

A new approach of representing chalk hydrology in JULES: The Bulk Conductivity (BC) model

- A macroporosity parameterization based on *Zehe et al.* (2001).

Relative saturation (S)

$$S = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$



$K_s = K_{s(matrix)}$

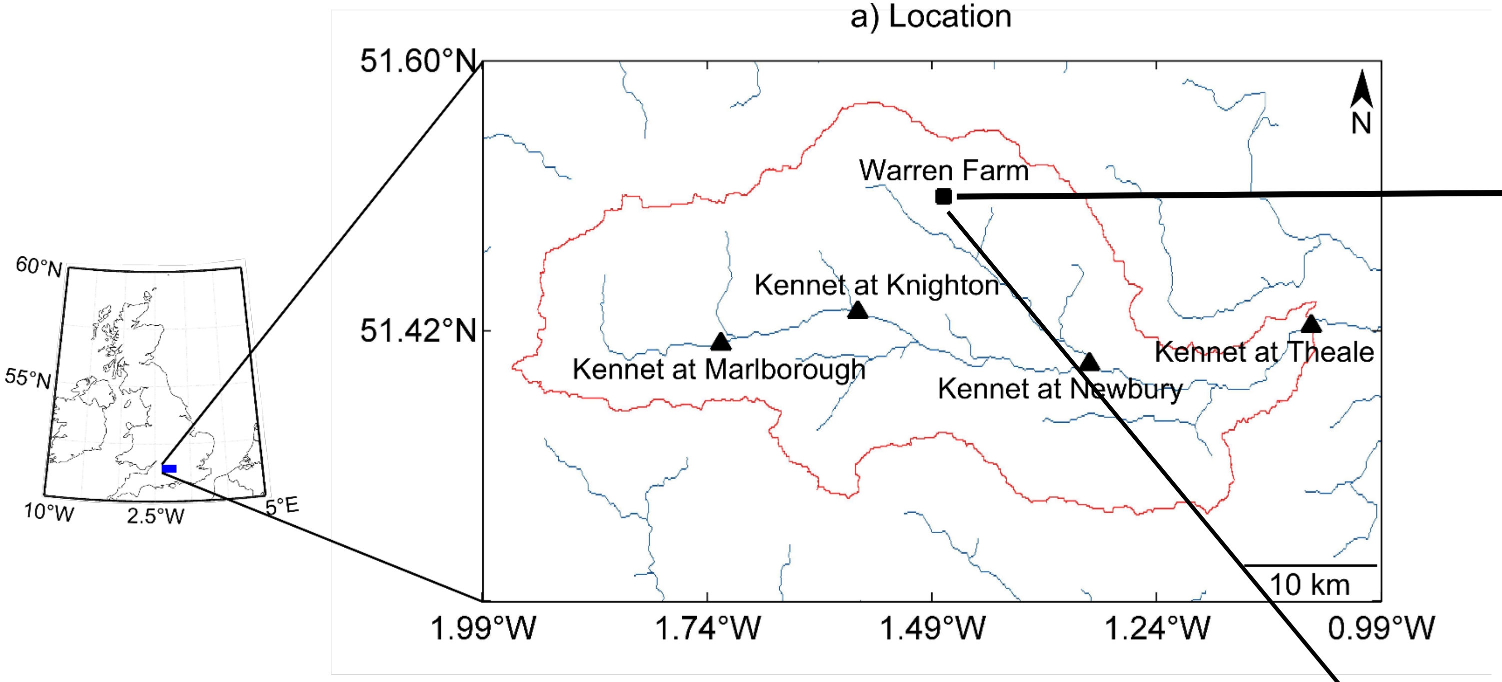
$K_s = K_{sb}$

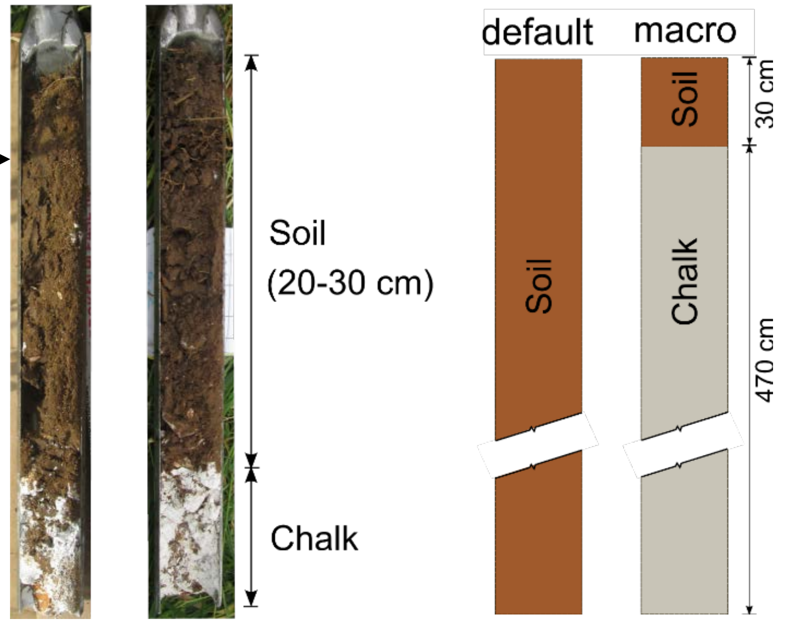
threshold

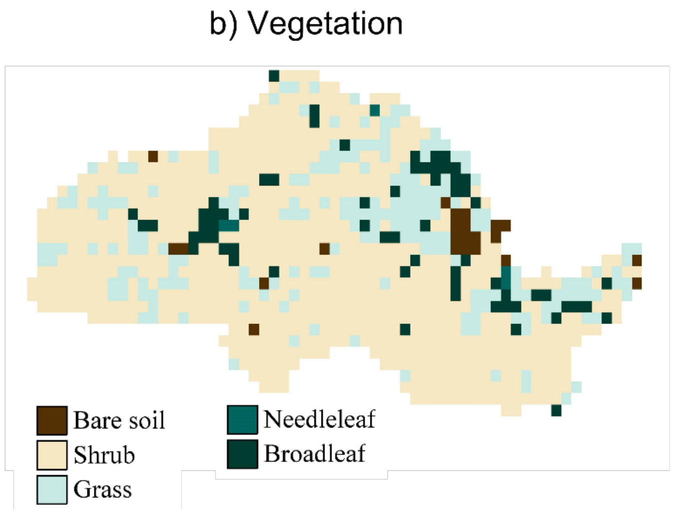
macroporosity factor

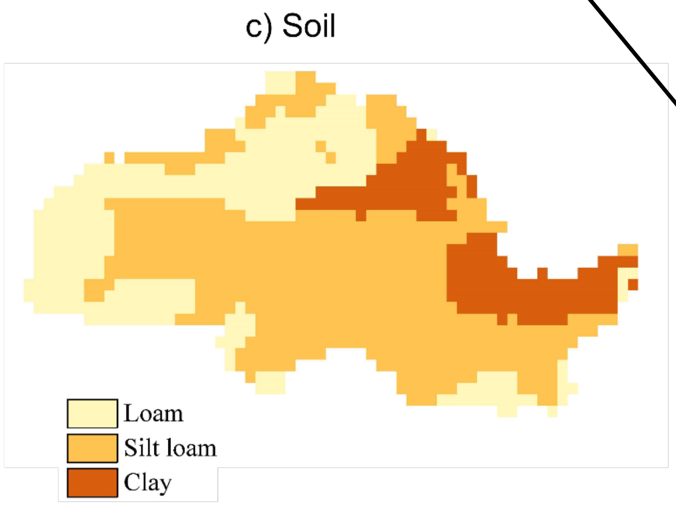
$$K_{sb} = K_{s(matrix)} + K_{s(matrix)} f_m \frac{S - S_0}{1 - S_0}$$

The modified JULES model was applied over the Kennet catchment in the Southern UK



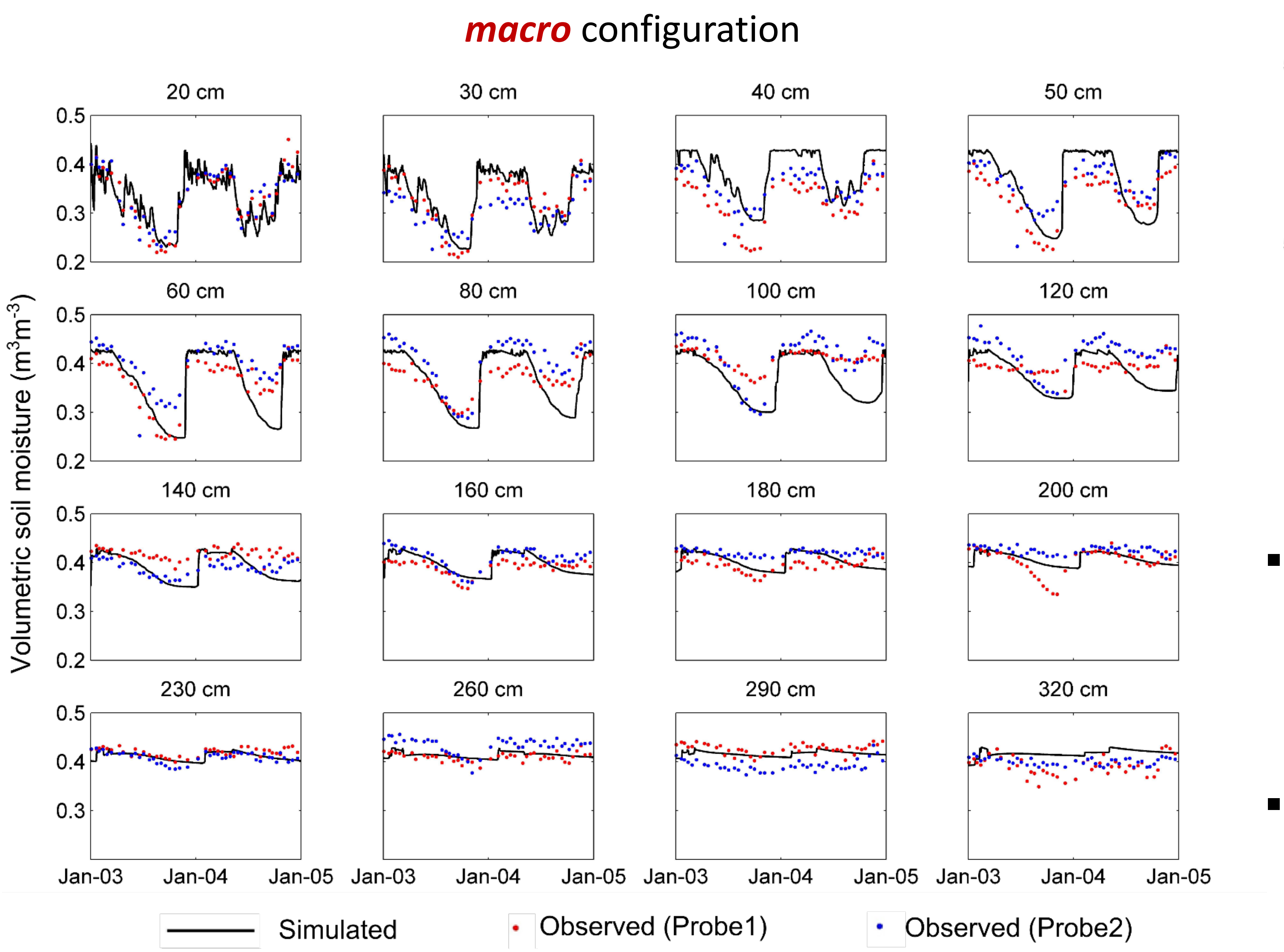


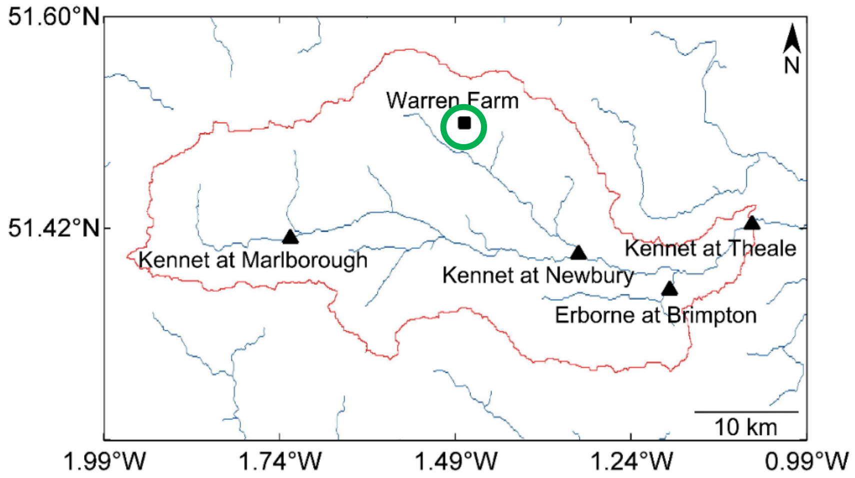




AMUSED instruments

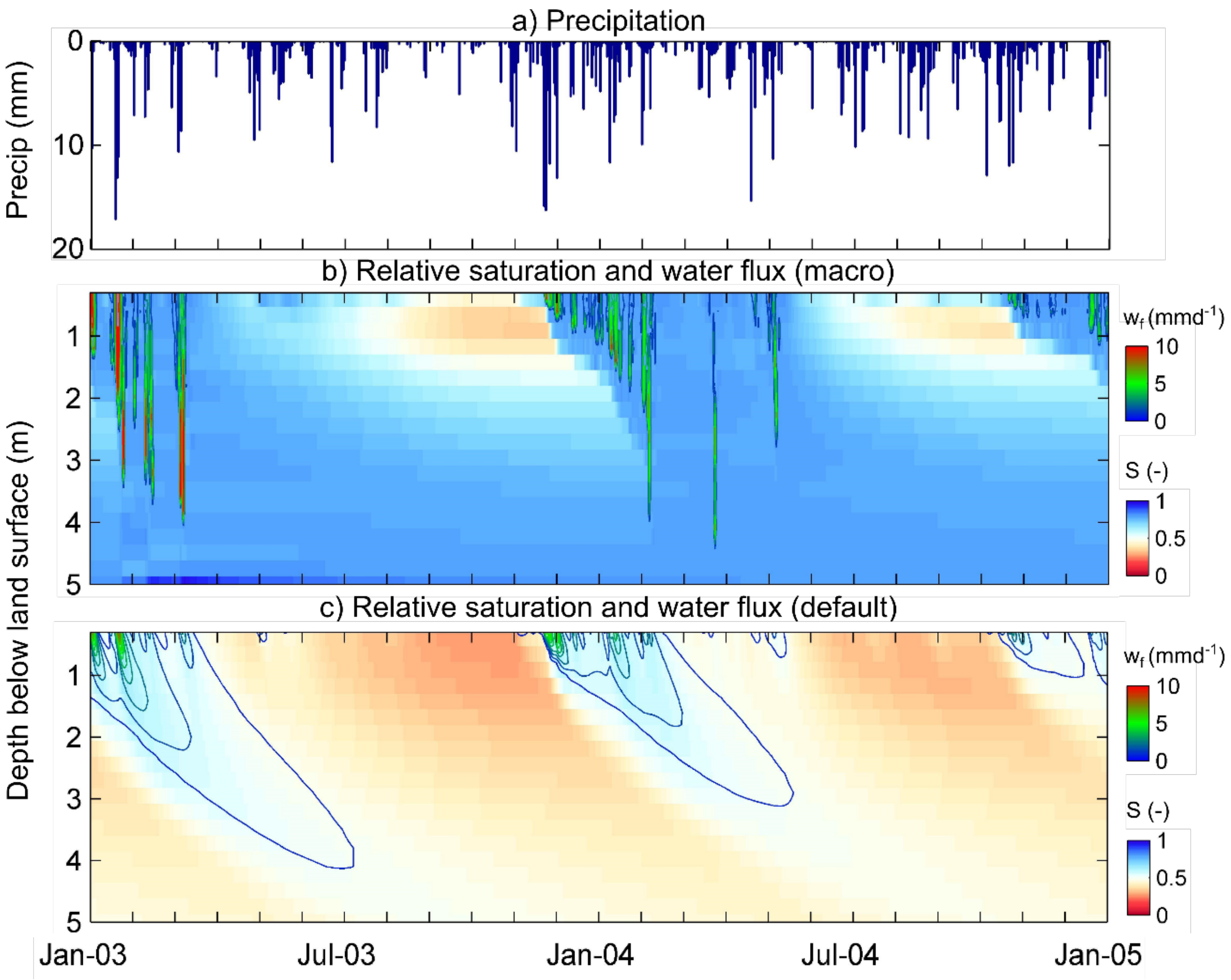
Explicit representation of chalk hydrology improves soil moisture prediction at the point scale



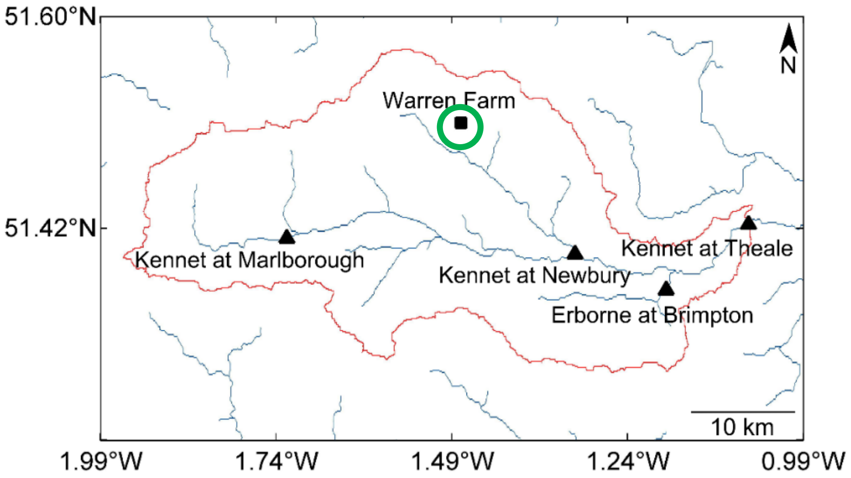


- Without a consistent representation of chalk hydrology, the JULES model (*default* configuration) generally underestimates soil moisture.
- Chalk representation remarkably improves the prediction of soil moisture (*macro* configuration).

There are distinct differences between *default* and *macro* configurations in terms of water movement through subsurface



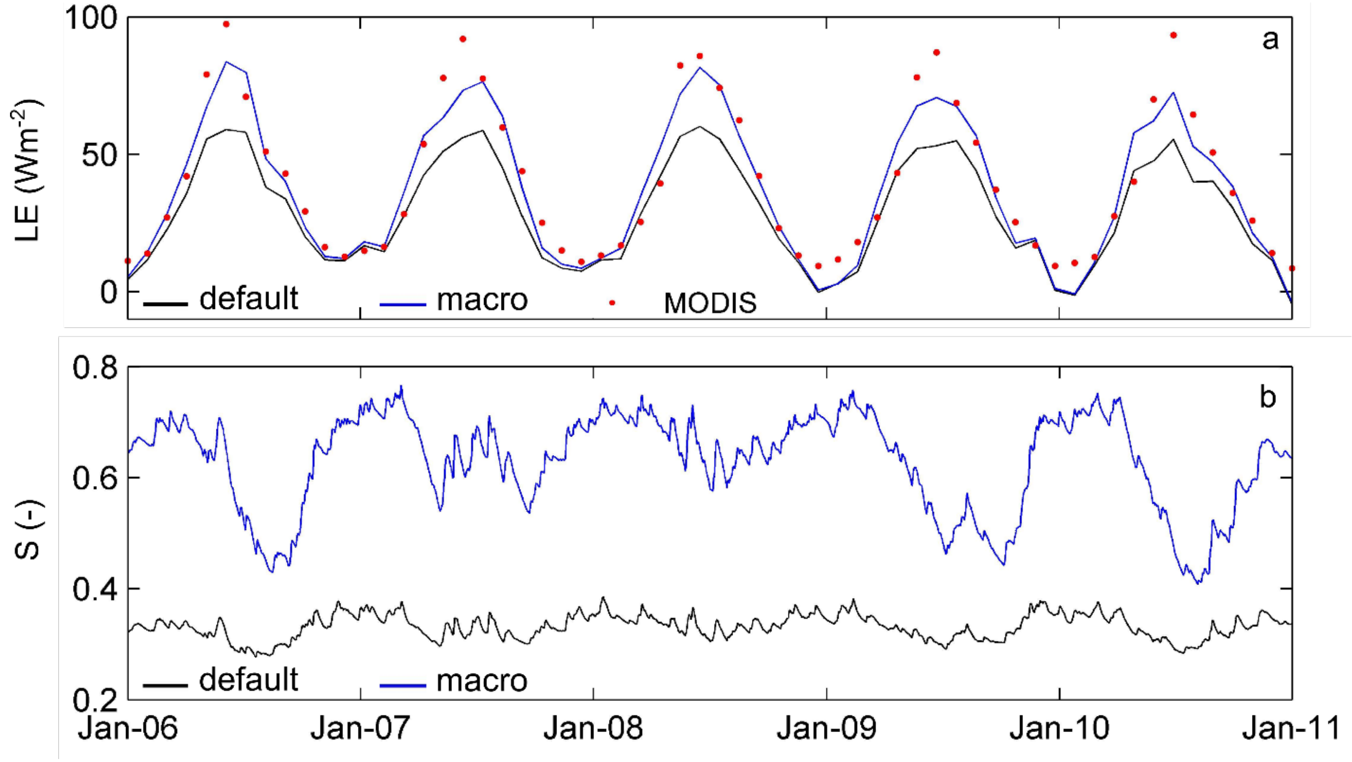
S = relative saturation, w_f = water flux



- The *macro* configuration shows higher water flux through the profile during wet periods compared to *default*.
- The *default* configuration simulates drier conditions compared to *macro*.

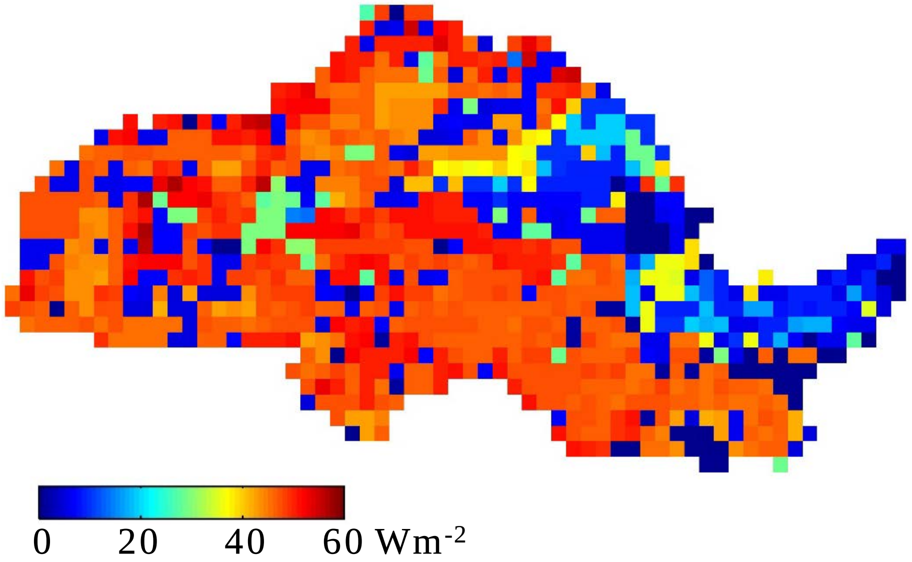
Explicit representation of chalk hydrology improves LE prediction at the catchment scale

Catchment average LE from MODIS is compared against *default* and *macro* predictions.



S = Relative saturation at the root zone

Differences between average LE from *macro* and *default* configurations (2006-2011)

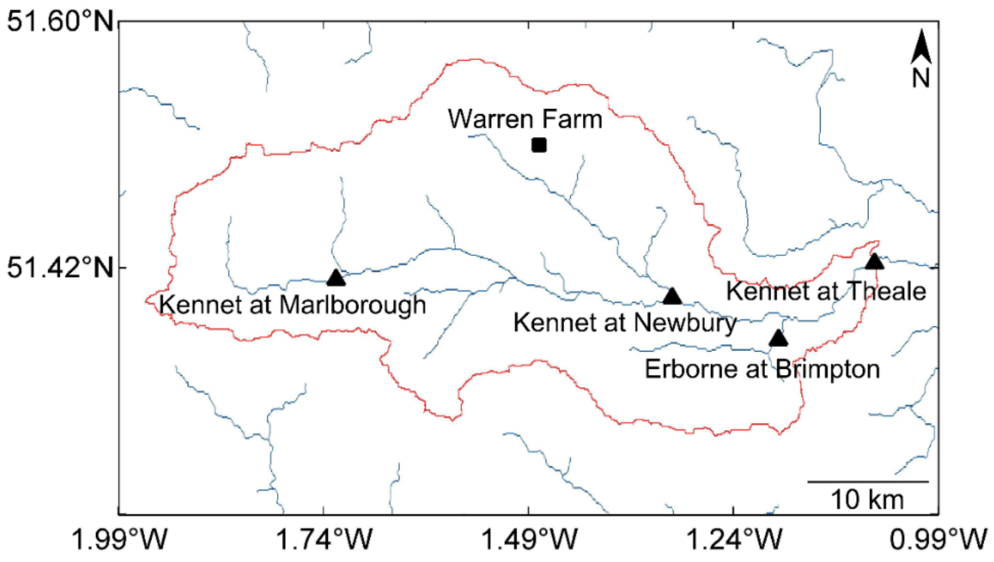


- The *macro* configuration substantially improves LE prediction especially in the warmer months of the year.

Explicit representation of chalk hydrology improves runoff prediction at the catchment scale

Metric	Observed	Simulated (default)	Simulated (macro)
RR	0.40	0.82	0.38
Δμ	-	1.04	-0.07
Δσ	-	2.04	0.56

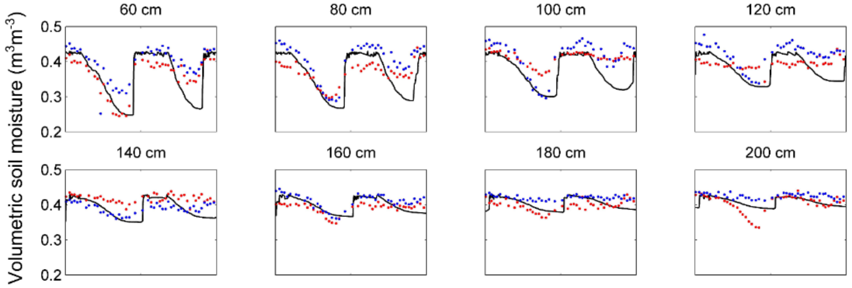
RR = Runoff Ratio (mean runoff/mean rainfall)
Δμ = relative bias
Δσ = relative difference in std. dev.



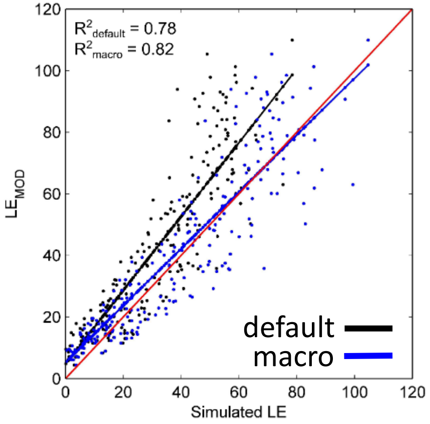
- The RR indicates that the *macro* configuration improves the overall water balance simulated by JULES compared to *default*.
- Inclusion of chalk hydrology (*macro*) also reduces overall bias and differences in variability between observed and simulated runoff.

Conclusions

- Explicit representation of chalk hydrology improved soil moisture predicted by JULES at Warren Farm.



- Catchment average LE and runoff predictions by JULES was substantially improved after including the BC model to represent chalk hydrology.



Metric	Observed	Simulated (default)	Simulated (macro)
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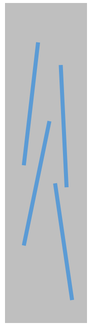
- The proposed BC model involves only two parameters that can be estimated from the physical properties of chalk.



$$K_s = K_{sb}$$

$$K_{sb} = K_{s(matrix)} + K_{s(matrix)} f_m \frac{S - S_0}{1 - S_0}$$

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