On the use of a physically-based baseflow timescale in land surface models

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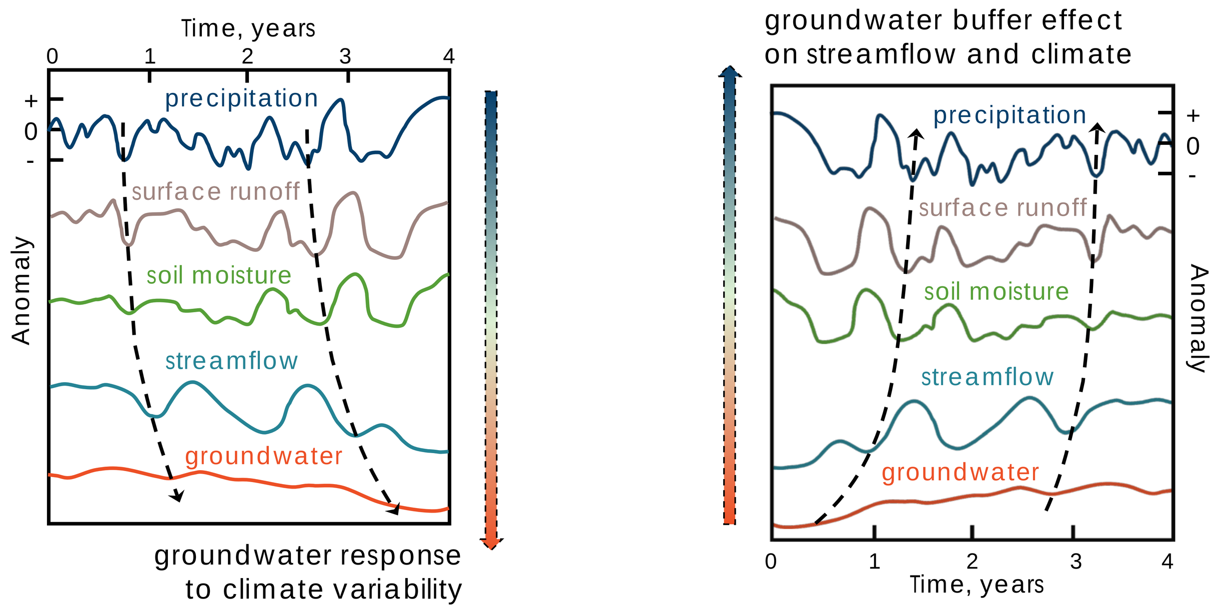
1. Introduction

The response time of groundwater (GW) discharge to fluctuations in recharge is essential to predict impacts of land-use and climate change on catchment water yield. Aquifers impose a time-lag between changes in recharge and discharge to streams and have a large capacity to buffer surface water variability, depending on the scale of the system and its physical attributes. Over shallow water table (WT) regions, groundwater also influences soil moisture memory and evapotranspiration (Fig. 1).

Fig. 1 – Buffering effects of groundwater (adapted from Lo & Entekhabi *et al.* 1996)

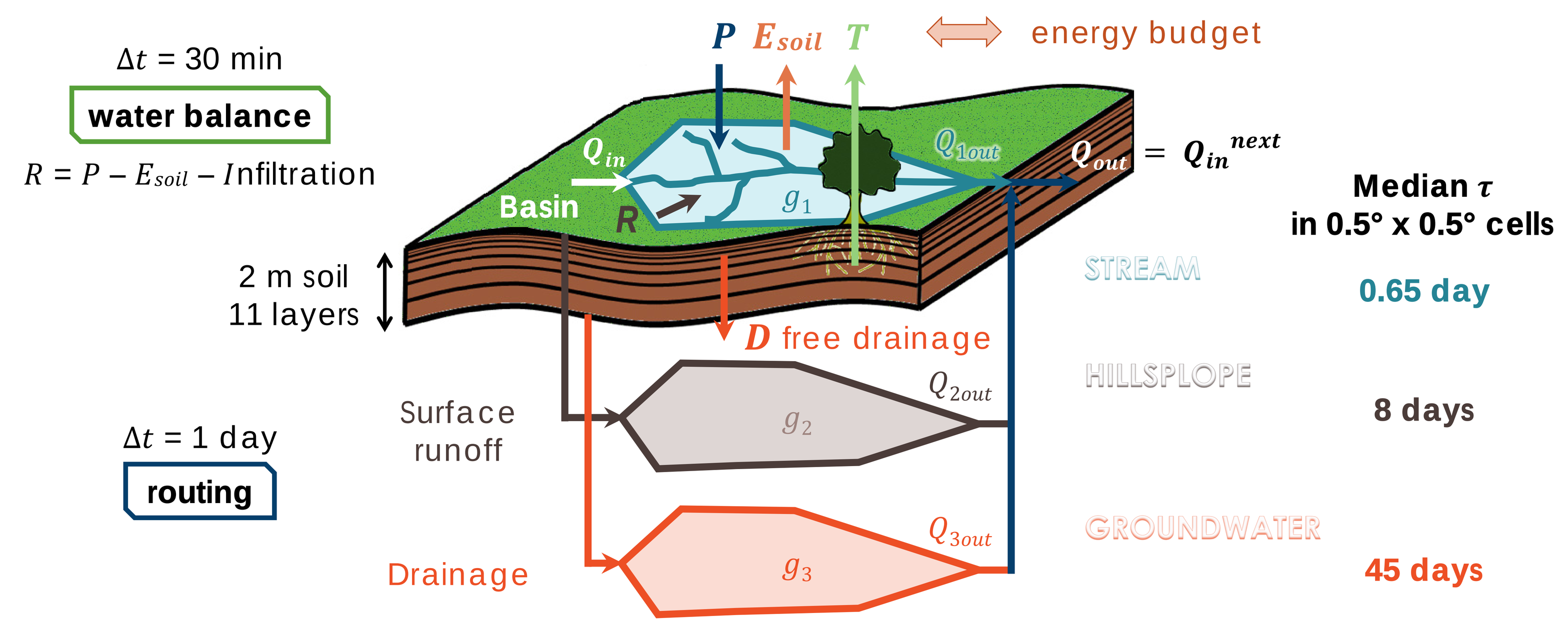


Land surface models (LSMs) provide a suitable environment to quantitatively estimate these feedback mechanisms. A first-order representation of groundwater as a single linear storage element is frequently used in LSMs **(2)**. Hydraulic groundwater theory provides an analytical framework to allow the parametrization of this reservoir, in terms of a baseflow characteristic timescale τ **(3)**. **Here we evaluate to what degree the use of this physically-based time constant in the routing scheme affects simulated river discharges across large catchments (4).** On this basis, we discuss the reliability of such a global scale estimate of GW response times in land surface hydrology modelling **(5)**.

2. Groundwater representation in land surface models

ORCHIDEE (Krinner *et al.* 2005) is a land surface model developed in Institut Pierre Simon Laplace that allows the simulation of the terrestrial water and energy balances. In the routing scheme, each successive sub-basin in grid cells includes three linear reservoirs for stream, hillslope and groundwater (Fig. 2).

Fig. 2 – Soil hydrology and routing scheme in ORCHIDEE



Q_i (kg.s^{-1}) is the flux out of each reservoir
V_i (kg) is water amount in the reservoir i

$$Q_{iout} = \frac{V_i}{\tau_i}$$

τ_i (s) is the characteristic timescale of travel time within each reservoir i

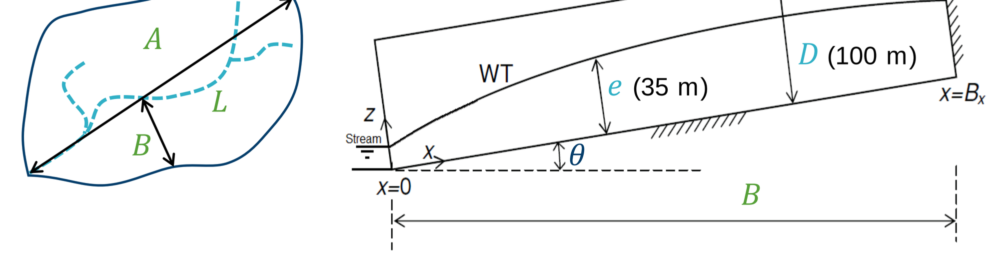
d (m) is the river length from one subgrid basin to the next one
θ is the height lost over river path / river path length
g_i (s.m^{-1}) is a reservoir property estimated empirically using observed discharge of the Senegal River (Ngo-Duc *et al.* 2007) and assumed constant over the globe

$$\tau_i = g_i \frac{d}{\sqrt{\theta}}$$

3. Estimation of a physically-based baseflow timescale

We use the long-time solution of the linearized Boussinesq equation (Brutsaert 2005) to estimate τ as a function of catchment descriptors (Fig. 3) at global scale (Fig. 4).

Fig. 3 – τ formulation



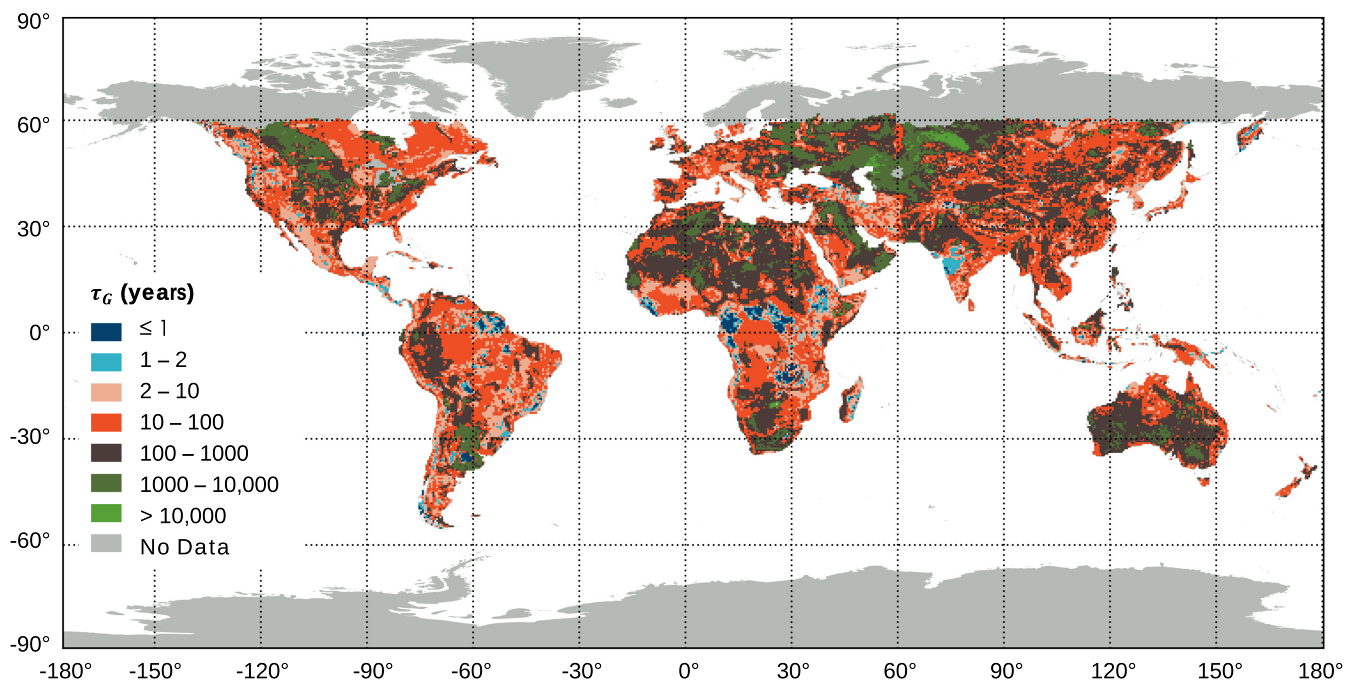
$$\tau_G = \frac{n_e}{\pi^2 T \delta^2 \cos^2\theta + \frac{\pi^2}{2} K \delta \sin\theta}$$

δ drainage density: $\delta = A / \sum L = 1/(2B)$ (m^{-1})
T transmissivity: $T = K \cdot e$ (m^2.s^{-1})
n_e effective porosity (-)
θ aquifer slope: ~water table slope (-) from Fan *et al.* (2013)

T and n_e derived from **GLHYMPS** high-resolution datasets (Gleeson *et al.* 2014) & literature values (n_e, Morris & Johnson 1967)
B derived from an estimation of δ using the **GRIN** global river network (Schneider *et al.* 2017)
δ_{mean} = 0.74 km^{-1}

Fig. 4 – Physically-based baseflow time constant τ_G at global scale (0.5° resolution)

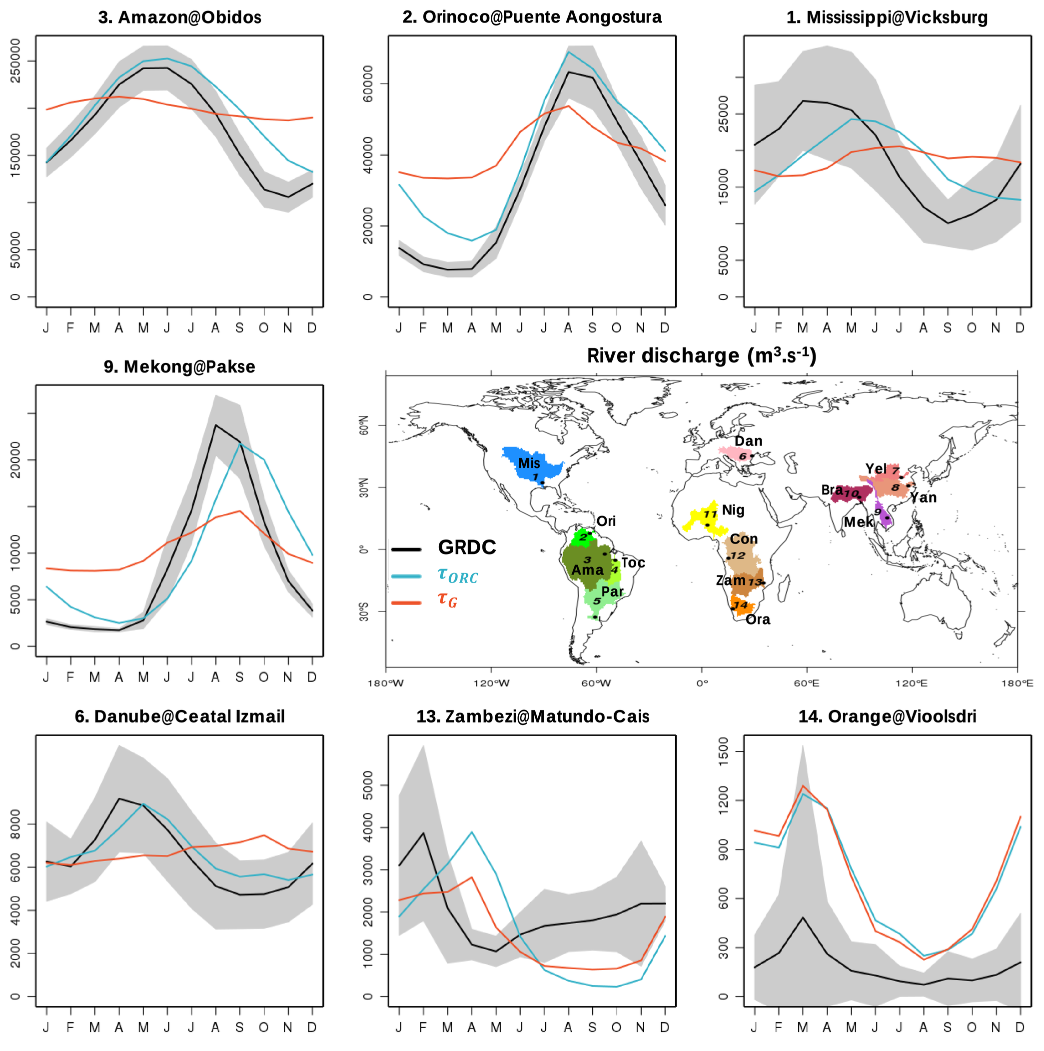
τ_{G_Q50} = 65 years



4. ORCHIDEE simulated river discharge

ORCHIDEE is run globally in offline mode at 0.5° under a WFDEI GPCC forcing (Weedon *et al.* 2014). Results using τ_G **(3)** are compared to a reference simulation using the initial almost spatially constant topographic-dependent τ_{ORC} **(2)** (Fig. 5).

Fig. 5 – Evaluation of the simulated against observed river discharge (m³.s⁻¹) from GRDC between 1985-2010.



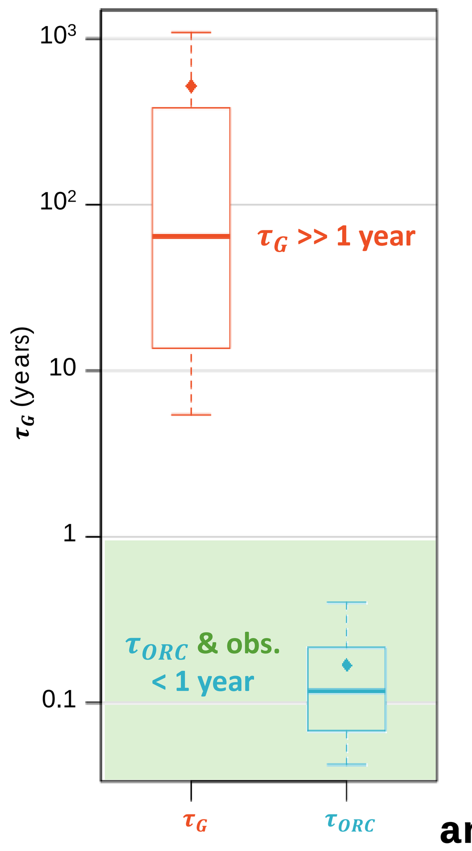


Fig. 6 – Baseflow timescale τ_G against τ_{ORC} and a reference range from recession analysis.

✓ Increased buffering of river discharge variability ∝ drainage

✓ τ_G is largely overestimated when compared to references at the basin scale (Fig. 6) and not suitable for parametrization of a shallow linear groundwater reservoir.

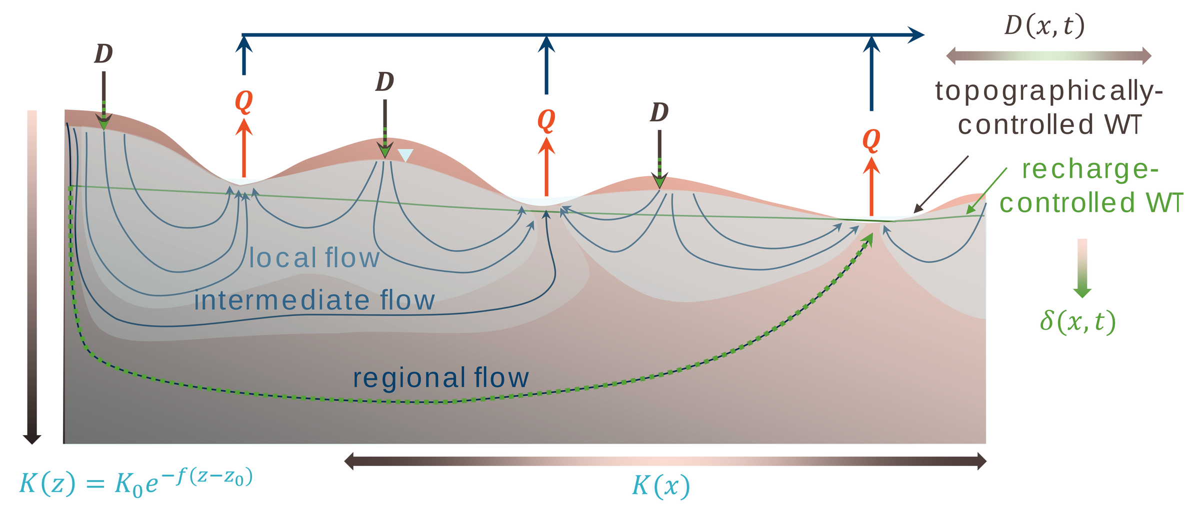
5. Discussion

✓ Relevance and accuracy of global estimates of aquifer hydraulic properties

δ: from GRIN, a river network describing natural heterogeneities and in agreement with observations
e, θ, n_e: uncertain but expected variations of about one order of magnitude
K: a mean value per hydrolithology class, varies up to 6 orders of magnitude, a higher range than in soil hydraulic conductivity databases (e.g. USDA) or LSMs with groundwater model (e.g. Vergnes *et al.* 2012)

✓ Underlying assumptions in the analytical method: quasi-steady state approach, shallow unconfined aquifer with small depth to length ratio, homogeneous isotropic aquifers

Fig. 7 – Multiscale groundwater flow (adapted from Schaller & Fan 2009)

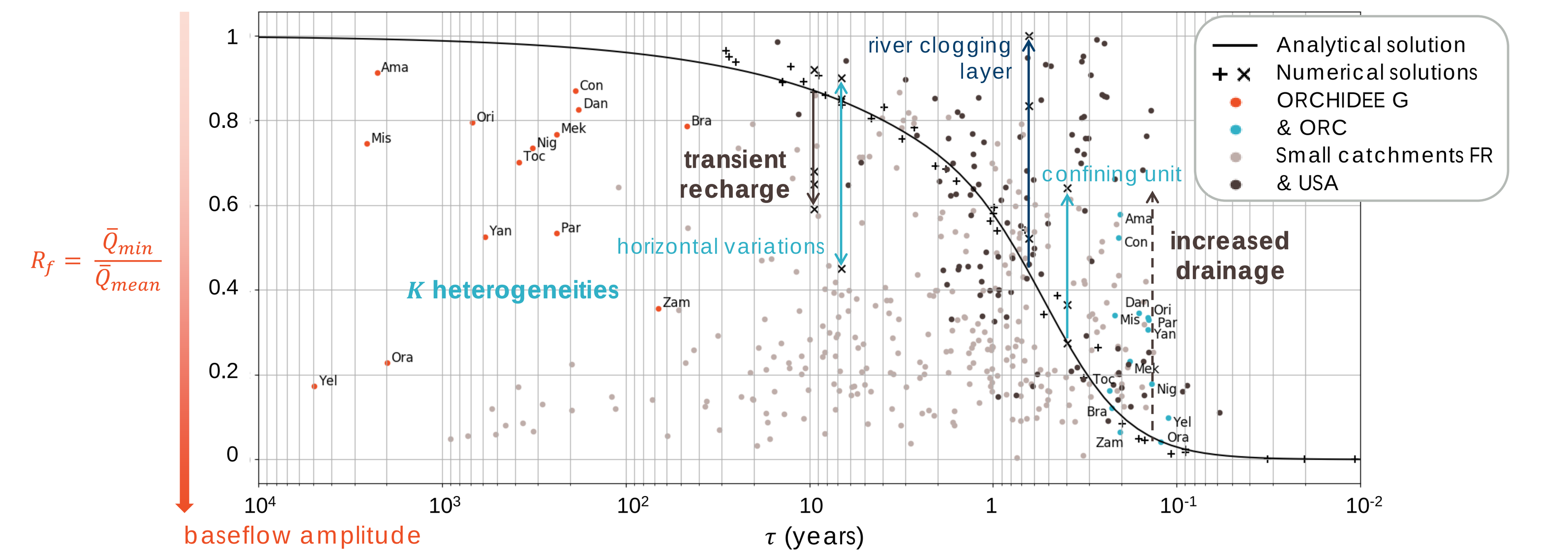


Preferential flow pathways due to natural heterogeneities in aquifers (Fig. 7) strongly influence groundwater recharge and discharge.

✓ Relationships between the groundwater outflow rate and the controlling physical and hydrologic parameters of the basin (Fig. 8)

Analytical approach: minimum baseflows in the annual cycle (R_f) as function of the aquifer response time (Erskine & Papaioannou 1997)
Numerical modelling: idealised 1-D solutions using MODFLOW (Harbaugh & McDonald 1996) considering subsurface heterogeneity and transient recharge
Real small catchments (Falcone 2011, Poncelet 2016): land slope and drainage density of the watersheds, effective porosity and hydraulic conductivity of the underlying shallow aquifers

Fig. 8 – R_f - τ relationships



6. Conclusion and perspectives

✓ The use of a physically-based τ in ORCHIDEE deteriorates river discharge simulation due to a strong buffering effect → rapid local flow is dominant.

✓ A more appropriate description of the physical properties of near-surface aquifers (T & n_e) is required to provide better agreement with observations.

✓ Future research may investigate (i) how to take into account spatial heterogeneity and climate variability in τ formulation (ii) the implementation of a nonlinear storage groundwater reservoir in ORCHIDEE.

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Acknowledgements

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