What control transit times versus Q relationships at the hillslope scale ? Implications for solute vs Q relationships

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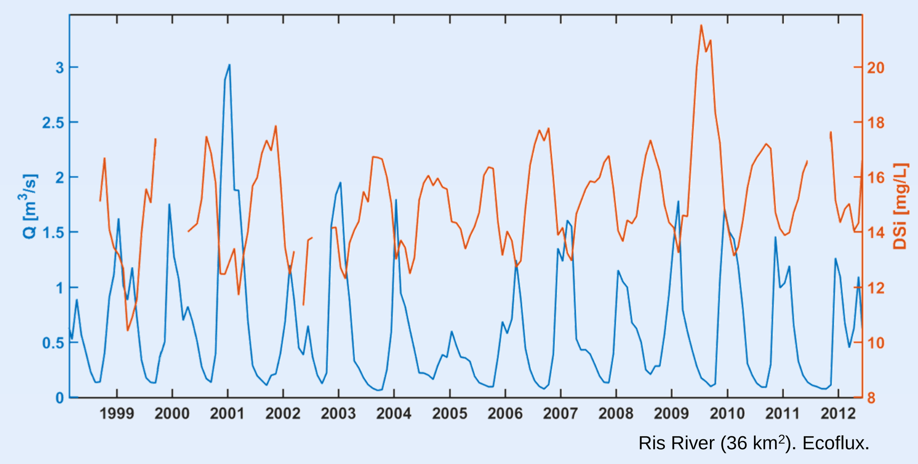
1. ABSTRACT

C/Q relationships illustrate how catchments retain, release and degrade different nutrients. They have been intensively used to classify the ways watersheds export nutrients. Yet, it is not clear how these hydro-biogeochemical signatures inform catchment scale processes relatively to nutrient storage, degradation and way of release. A lot of processes have been invoked to account for the chemostasy of the majority of catchments relatively to geogenic solutes.

Here we propose to study numerically the mean transit times (mTT) versus Q relationships at the hillslope scale as an intermediary before C/Q relationships. mTT is indeed a pivotal quantity between flux and transport processes. It has the advantage to depend only on hydrological processes but to synthetically illustrate key flux and transport controls relatively to nutrient processes. To do that, we build numerical experiments with the hs1D model, a groundwater flow model taking into account groundwater interactions with the land surface through seepage and saturation excess overland flow generation. hs1D also displays a Lagrangian particle tracking component, enabling to delineate transient transit times distributions (TTD).

We show that mTT vs Q relationships arising from this model are always characterized by dilution or chemostatic characteristics, illustrating the rejuvenation of water ages when discharge increases. We further show that the chemodynamic behavior of mTT vs Q relationships is observed when the transient TTDs display an important coefficient of variation (CV=σ/μ). High CV of the TTD indeed reflects a wide diversity of short and long flowpaths. In the hs1D model, this flowpaths diversity is triggered by the interactions of the water table with the land surface, generating saturation excess overland flows (ie short flowpaths), seepage flows (intermediate flowpaths) in conjunction with return flow (ie long flowpaths). Besides, break in the mTT vs Q slopes can arise at different critical discharge levels, reflecting changes in the sollicated critical zone compartments (e.g. soil vs aquifer) supplying discharge. These different processes signature unraveled in the mTT vs Q relationships could be used to infer the different nitrate sources location (soil vs aquifer). This call for a renewed understanding of event-based C versus Q relationships.

2. RATIONALE ON C/Q RELATIONSHIPS: WHY CATCHMENTS DISPLAY SUCH CHEMOSTATIC PROPERTIES?

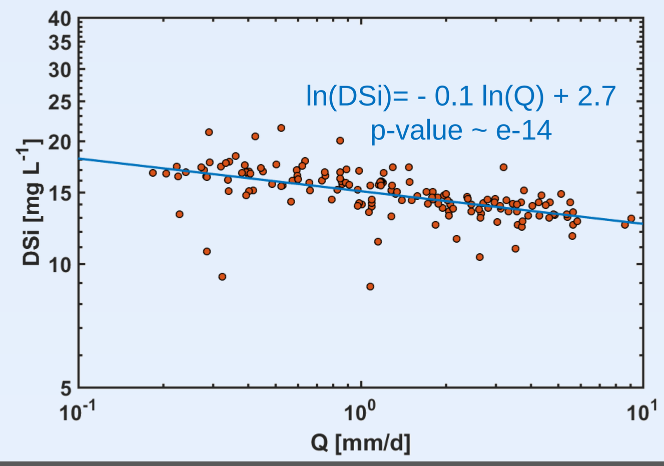


Can transient transit time distributions be informative for C/Q relationships?

What can trigger chemostatic versus chemodynamic relationships ?

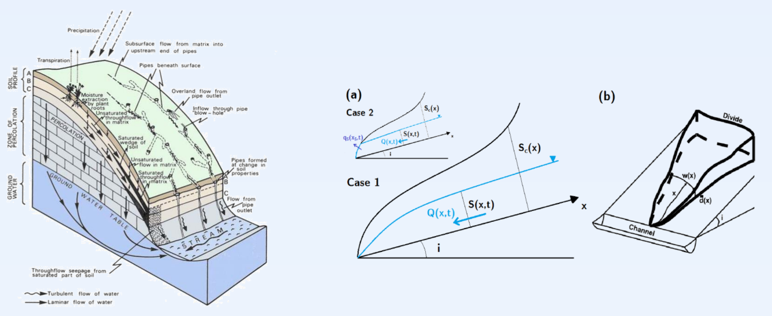
Hillslope geology & geomorphology influences the water flowpaths, their transit times. How does this translate on C vs Q relationships ?

► *Study the mTT vs Q relationships.*



3. HS1D MODEL: HILLSLOPE SCALE GROUNDWATER MODEL

A. Flux Model

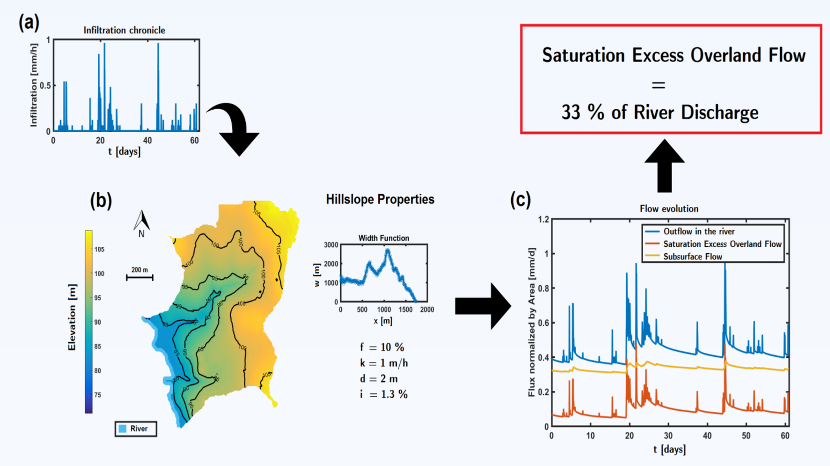


Hillslope storage Boussinesq models

- *Regularized DAE system*

$$\begin{cases} \frac{\partial S}{\partial t}(x,t) + q_S(x,t) = -\frac{\partial Q}{\partial x}(x,t) + N(t)\,\omega(x) \\ q_S(x,t) = \mathscr{G}\left(\frac{S(x,t)}{S_c(x)}\right)\mathscr{R}\left(-\frac{\partial Q}{\partial x}(x,t) + N(t)\,\omega(x)\right) \\ Q(x,t) = -\frac{kS(x,t)}{\phi_d}\left(\cos\theta\,\frac{\partial}{\partial x}\left(\frac{S}{\phi_d\,w}\right)(x,t) + \sin\theta\right) \\ S(x,t) = \phi_d\,\omega(x)h(x,t) \\ 0 \le S(x,t) \le S_c(x) = \phi_d\omega(x)d(x). \end{cases}$$

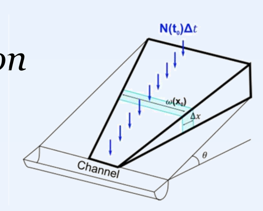
- *Partition groundwater vs saturation excess overland flows contributions to the river*



B. Transport Model

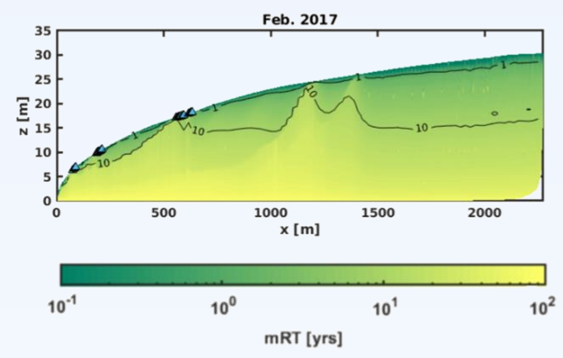
Lagrangian particle tracking

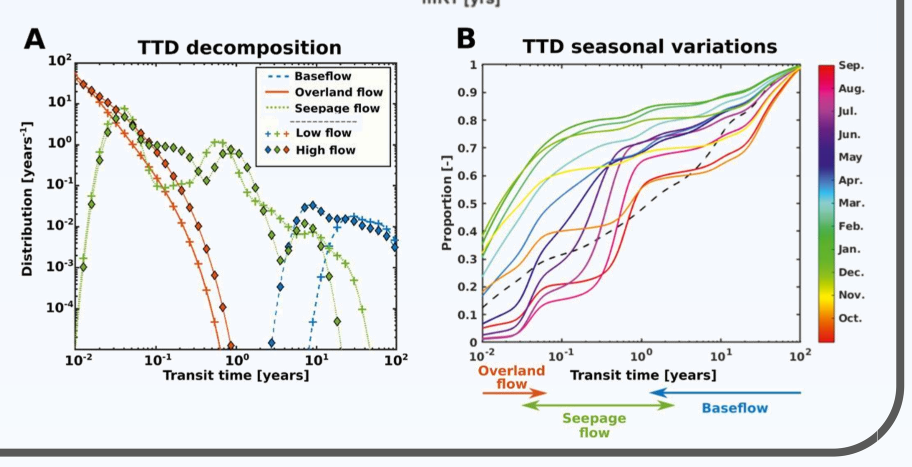
- *Flux weighted particle injection*



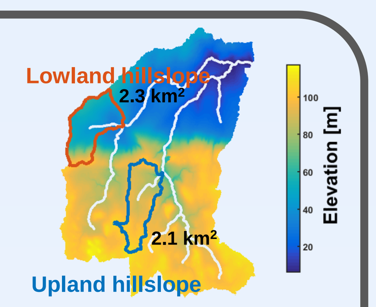
$$\begin{cases} S(x(t),t)\frac{dx}{dt}(t) = \frac{\phi_d}{\phi_{tot}}Q(x(t),t) \\ \frac{dz}{dt}(t) = -z(t)\frac{\phi_d}{\phi_{tot}}\left(\frac{d}{dx}\left(\frac{Q(x(t),t)}{S(x(t),t)}\right) + \frac{1}{w}\frac{dw}{dx}\frac{Q(x(t),t)}{S(x(t),t)}\right) \\ x(t_0) = x_0 \\ z(t_0) = z_0 = h(x_0,t_0) \end{cases}$$

- *Retrieve the transient transit time & residence time distributions and decompose it following the water flowpath (eg base flow, overland flow).*

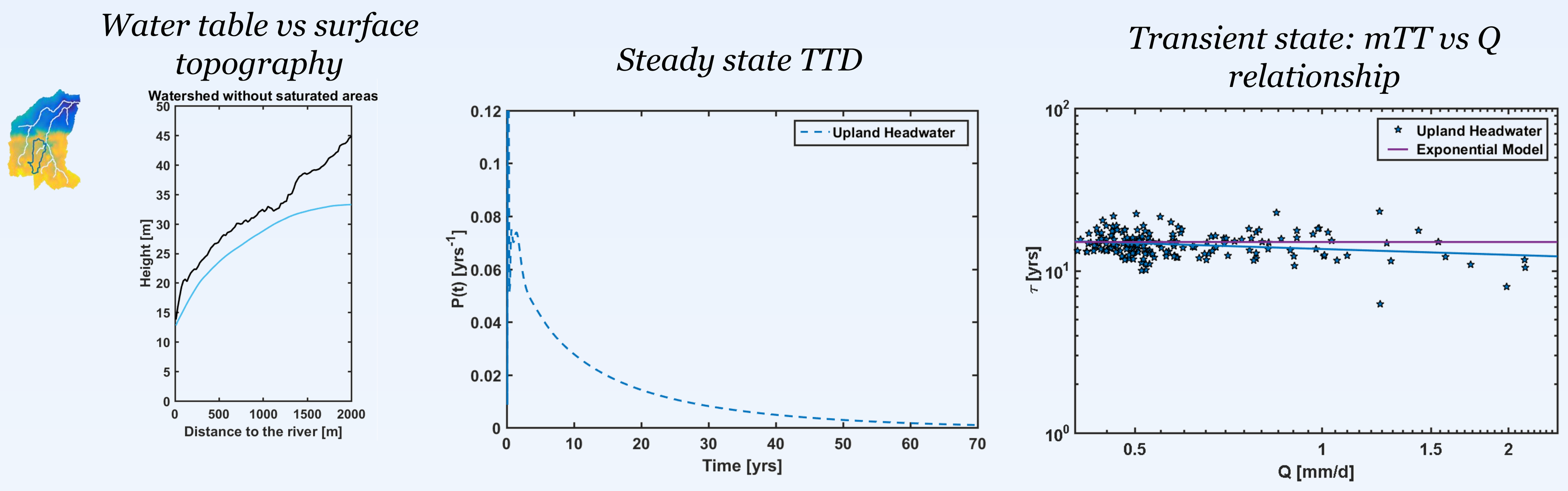




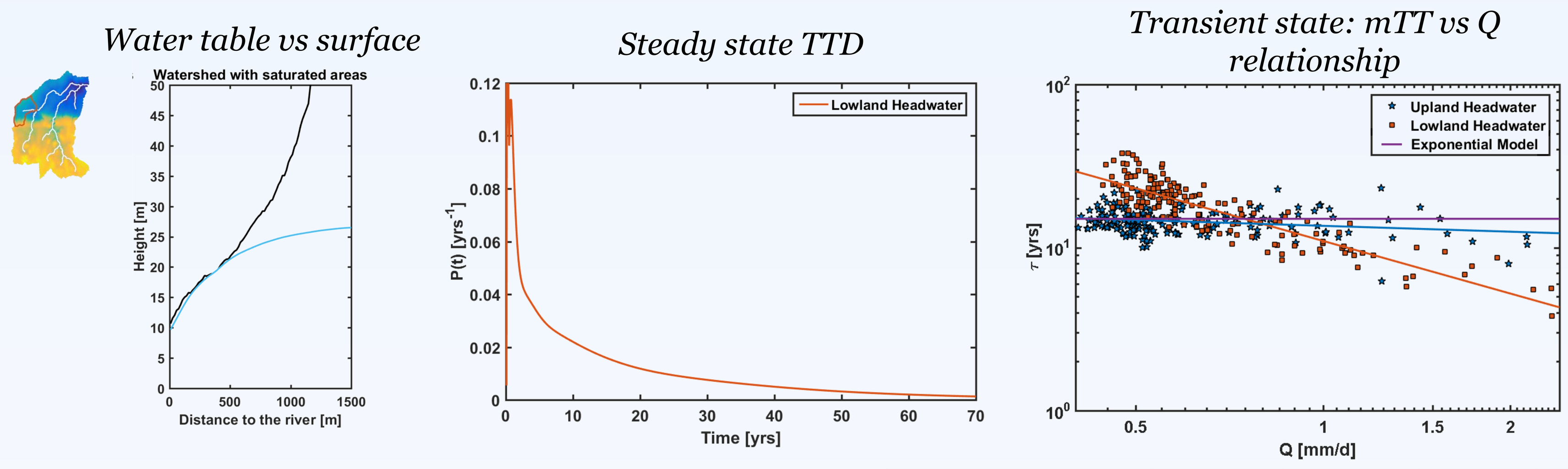
4. NUMERICAL EXPERIMENTS CARRIED ON TWO CONTRASTED HILLSLOPES



A. Upland headwater: no saturated areas



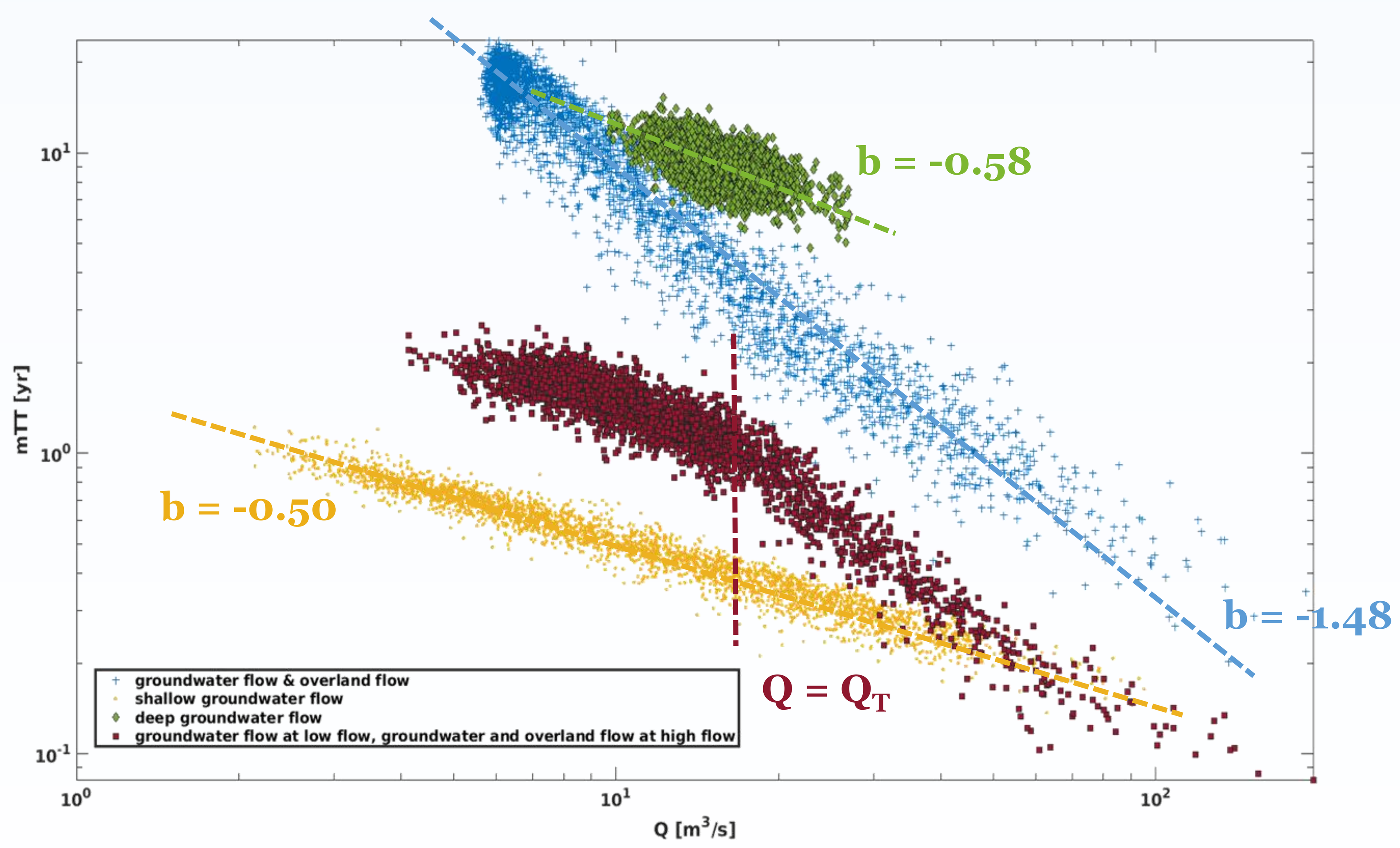
B. Lowland headwater: saturated areas



C. Comparison of the moments of the TTD with the b exponent in the mTT vs Q relationships (mTT=aQ^b)

	τ [years]	σ [years]	CV [-]	b
Exponential	15	15	1	0
Upland Headwater	15	17	1,1	-0,1
Lowland Headwater	16	22	1,4	-1,1

5. INVESTIGATE THE RELATIONSHIP BETWEEN THE FLOW PROCESS AND THE b EXPONENT



- Deep groundwater flow is more chemostatic that shallow groundwater flow processes (longer tail).
- Saturation excess overland flow process leads to the most chemodynamic diluting processes (b<-1).
- Threshold at Q=Q_T between the main contributing processes can shape mTT vs Q relationships with varying b for different range of Q.

CONCLUSION & PERSPECTIVES

- All the investigated processes lead to chemostatic – b=0 (e.g. perfectly mixed reservoir), slightly chemodynamic (Boussinesq groundwater flow) or chemodynamic – b<0 (saturation excess overland flow generation) diluting patterns for the mTT vs Q relationships.
- Presence and absence of saturated areas trigger changes in the overlying processes and can dynamically modify the mTT vs Q relationship. This results in having mTT vs Q relationships not described by only one b exponent.
- Chemodynamic with concentration relationships (b>0) could be attained with unsaturated zone processes acting as a piston flow process although it is hard to imagine this process relevant at hillslope or catchment scale.
- Overall, event-based mTT vs Q relationships could be more informative relatively to the overlying fine hillslope processes. This opens new perspective for revisiting solute vs Q relationships observed at catchment scale.

References:

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