Evapotranspiration in green stormwater infrastructure systems (GIS): analysis from observations and modeling

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TEAM : Transferts et interactions liés à l'eau en milieu construit

laboratoire eau environnement systemes urbains

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(1) Background: Sustainable management of the urban stormwater

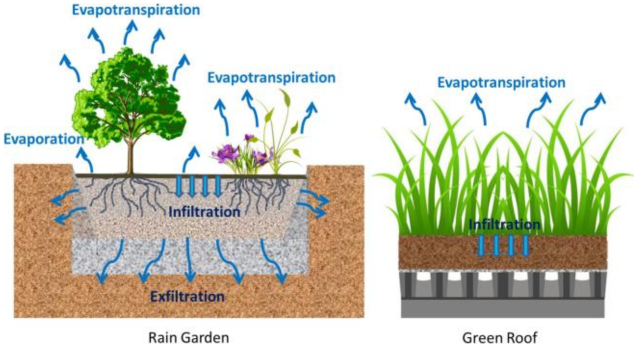
- **Traditional sewerage system (canalisation, underground basins, pipes, etc.**

- **Green infrastructure systems (green roofs, rain gardens, rain trees, etc.)** → **Promotes infiltration and evapotranspiration**

a) traditional retention basin (waterproof); b) multifunctional basin used for football practice; c) infiltration ditch

(Source : F. Rodriguez et al. (2017)

Understanding and reproducing evapotranspiration is identified as a major challenge for urban hydrology (Fletcher et al.,(2013), McGrane (2016), etc…)



Ebrahimian et al. (2019)

— **the contribution of the ET process to the reduction of runoff volume**

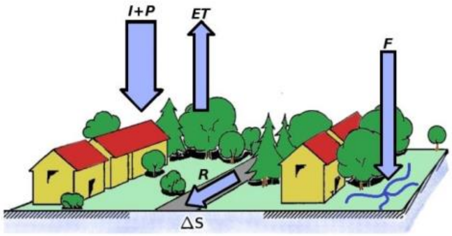
— **the role of the ET on local cooling issues**

— **the sustainability of the vegetation**

(1) Background: ET is a component of water and energy balances

- **Water balance (hydrological model)**

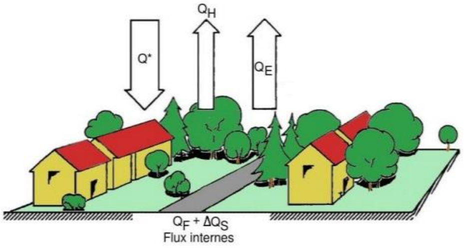
$$P + I + F = ET + R + \Delta S$$



Water balance of an urban area, **ΔS** represents the variations of the soil water stock, **P** the precipitation, **I** the water adductions, **F** the water emissions due to anthropological flow, **ET** the evapotranspiration and **R** the runoff. Source: Grimmond et al,(1991), Combas et al,(2013).

- **Energy balance (energy balance model)**

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S$$



Energy balance in urban areas, Q_F (anthropogenic flux) and ΔQ_S (stored heat flux), Q^* the net radiative flux, Q_E and Q_H the heat fluxes. Source : Grimmond (1991) , Combas et al,(2013)

- **hydro-microclimatic modelling approaches**

(1) Background: ET is a component of water and energy balances

- **Examples of models**

TV : Green roof, JP : rain garden, A : tree et F : urban forest

	hydro-microclimatic models				hydrological model				
	TEB –hydro (Stavropulos-Laffaille et al. 2018, 2021)	SUEWS (Jarvy et al.2011)	SiSPAT (Braud et al., 1999)	SEtHyS (Coudert et al., 2006)	Hydrus (Šimůnek et al., 2018)	MARIE Robineau et al. (2021)	FAVEUR (Ramier et al., 2018)	SWMM-Eva (Hörnschemeyer et al., 2021)	OASIS (Sage et al., 2020)
Previous applications in urban areas	TV	■	■	■	TV, JP, A	F	TV	TV, A	JP
Application options	**TV, JP, A**	**JP, TV, A**	**JP, TV, A**	**JP, TV, A**	**TV, JP, A**	**TV, JP, A**	**TV**	**JP, A, TV**	**TV, JP**
Vegetation	Interaction between urban environment and vegetation, an interface schema (ISBA) Water balance and dual source for energy balance	Interaction between urban environment and vegetation. Water balance and energy balance at one source	Interface schemes, root system description and dual source energy balance.	An interface scheme, Water balance and dual source energy balancee	Description of the root system and energy balance (PM).	Water balance	■	■	■
Soil	The force restore model or Richards' equation	Conceptual (Green and Ampt)	Milly's theory (1982)	The force restore model	Richards' equation	A lumped approach , a mean of the soil water content	■	A lumped approach , a mean of the soil water content	Conceptual (Green and Ampt)
ET scheme	Mass transfers	PM	Mass transfers	Mass transfers	Hargreaves, PM-Fao	PM, PM-Fao	PM-Fao	PM-Fao	PM-Fao

(1) Background: A summary of the issues associated with the representation of ET in urban areas

- **Few studies** in stormwater management facilities have been conducted regarding the above-mentioned issues

- Representation of the **diversity** of vegetation (grasses, trees, etc.)

- Representation of the vegetation **growth** (seasonal, annual, ...)

- the importance to address the **features of the urban environment** such as micro-meteorological conditions (radiation, wind, shading,), heterogeneity (subsoil, surface and canopy);

- the **calibration** of the parameters involved in the **ET schemes** of the models is rarely performed with observed data that reflect **the dynamics of the ET process** or the vegetation itself (LAI, soil water content, measured ET, etc.);

(2) Objective of the thesis:

To understand, estimate and better reproduce the EvapoTranspiration (ET) process on urban green stormwater infrastructure systems

Issues: the identification of scientific questions

- **Assessment of ET on a variety of GIS through observations (daily dynamics - year)**

  - *A comparison of different methods (water balance, energy balance, etc. ....)*
  - *Determinants of ET on **GIS** at different time scales*
  - *(Related measurement uncertainties)*

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  - *Determinants of ET on **GIS** at different time scales*
  - *(Related measurement uncertainties)*

- **Modeling of ET on a variety of GIS**
  - *Over-parameterization of the models (compared to available observations) leads to equifinality problems. The question is how to obtain realistic conclusions on the simulated fluxes and robust conclusions for the models (ability, recommendation).*
  - *Which level of detail is needed in the description of the vegetation and its evolution (growth, season ....)?*
  - *Sensitivity of simulation results to microclimatic input data? Variability of PET and AET if measurements are on site or at a +/- distant station; corrections of the remote data (shading, UHI, ...);*

(3) Context of the work : Scaling, model and case study

Spatial and temporal scales

- *Scale of the vegetated system*
- *At a fine time step (min to 1h) and over long periods of time (years)*
- *Large number of parameters to be studied*

A variety of stormwater management techniques

- *Green roof (lower stratum, thin substrate): Trappes ;*
- *Rain garden (multi-strata on natural soil): MNHN + Ecole du Breuil.*
- *Rain trees (high stratum in artificial pit): Sense-City;*

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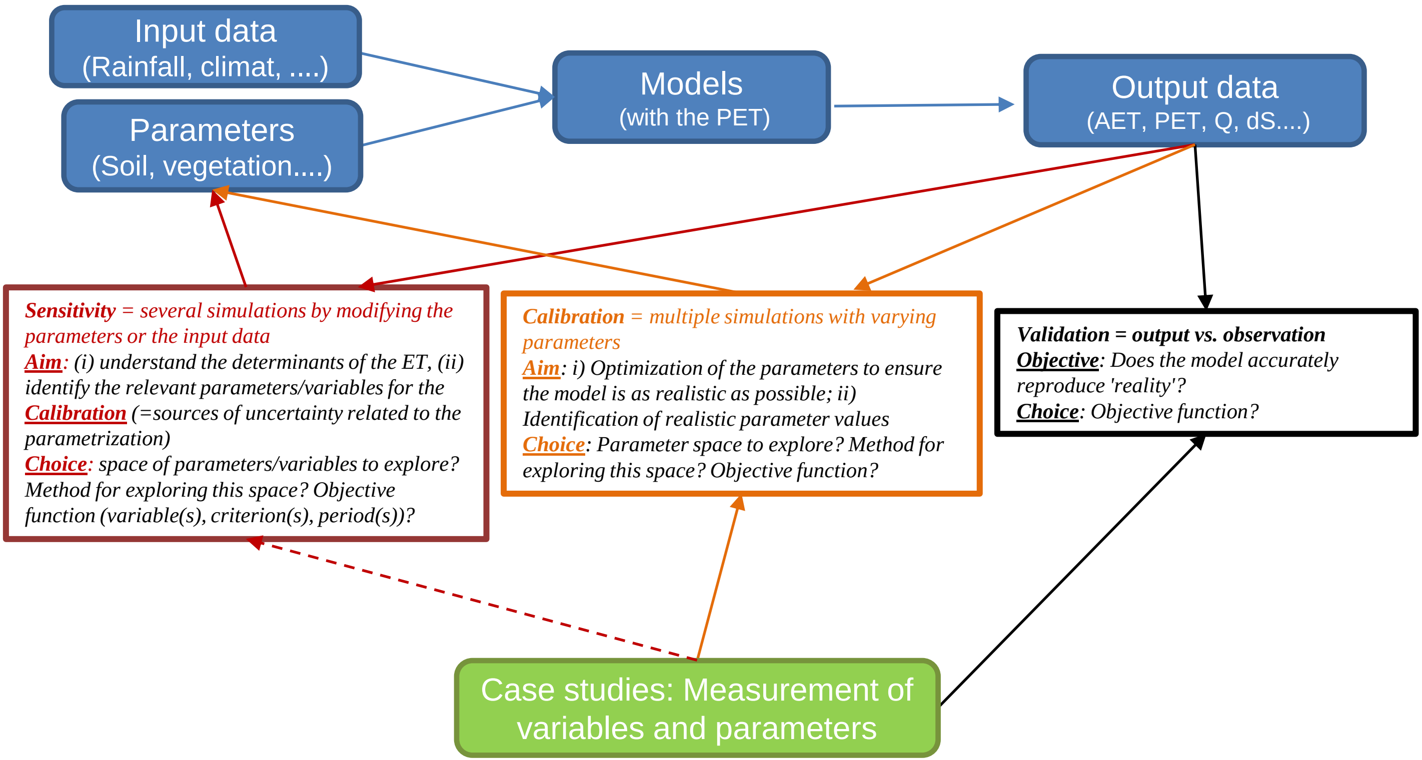
- **Data**
  - *water balance (Rainfall, Discharges et Evapotranspiration, water content)*
  - *Atmospheric data (wind speed, global radiation, humidity, air temperature, etc.)*
  - *Characteristic of the site (dimensions, substrate, végétation, etc.)*
  - *Energy balance (soil temperature, net radiation, energy fluxes, etc.)*

- **Assessment and improvement of different schemes/models**
  - *Assessment of existing models, and improvement of ET schemes if needed*
  - *Choice of models: i) exclusively hydrological model (use of the PET concept) (MARIE and Hydrus,); ii) hydro-climatic model (SiSPAT and TEB-Hydro)*

(4) Assessment of the models

- **Assessment =** ***Sensitivity; Calibration; Validation***

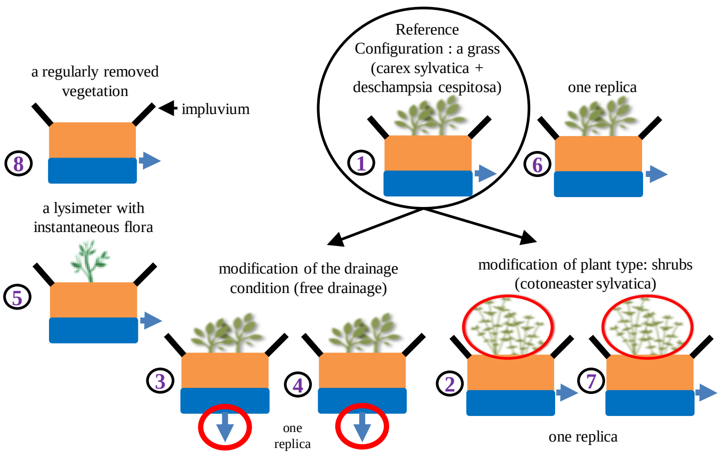


Study area, Experimental Set Up and water balance

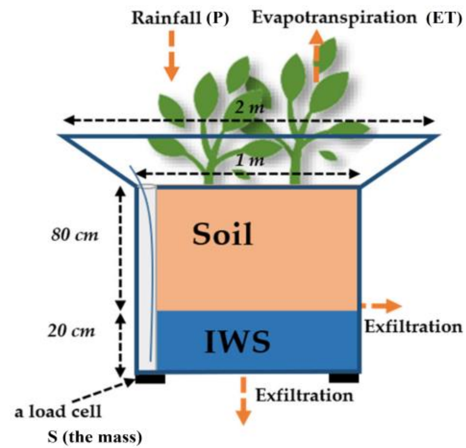
(a) (b)

A top and panoramic views of the site in figures (a) (Source: google earth) and (b), respectively.

- **Site**: Paris, FRANCE (Museum National d'Histoire Naturelle)
- **Data**: 2 minute interval for a period of about 3 years (24/11/2016 – 26/12/2019).
- **Measurement on each lysimeter:** exfiltration (mm), water level (mm) in the Internal water storage (IWS) and lysimeter's mass (kg)
- **Meteorological data :** temperature (◦c) , air humidity (%), rain (mm), water level in the evaporimeter (mm), incoming solar radiation (w/m^2), wind speed (m/s) and atmospheric pressure (hPa).

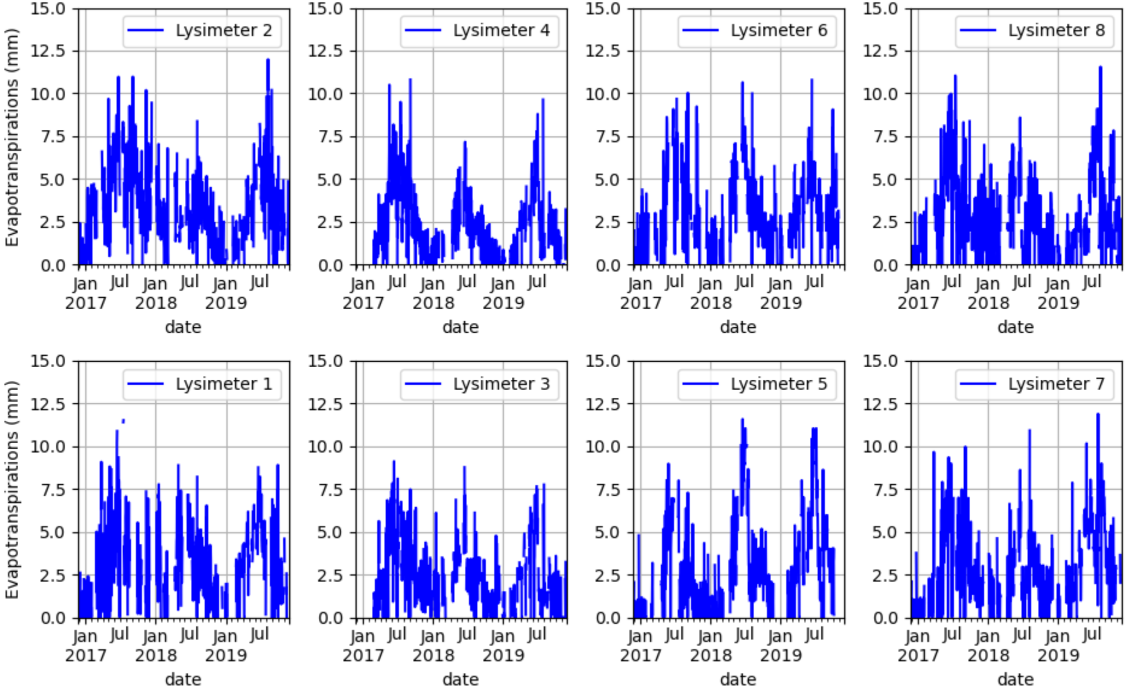


The different configurations compared to the reference. All the settings have the same soil which is silty clay that represents most of the soil in Paris region.



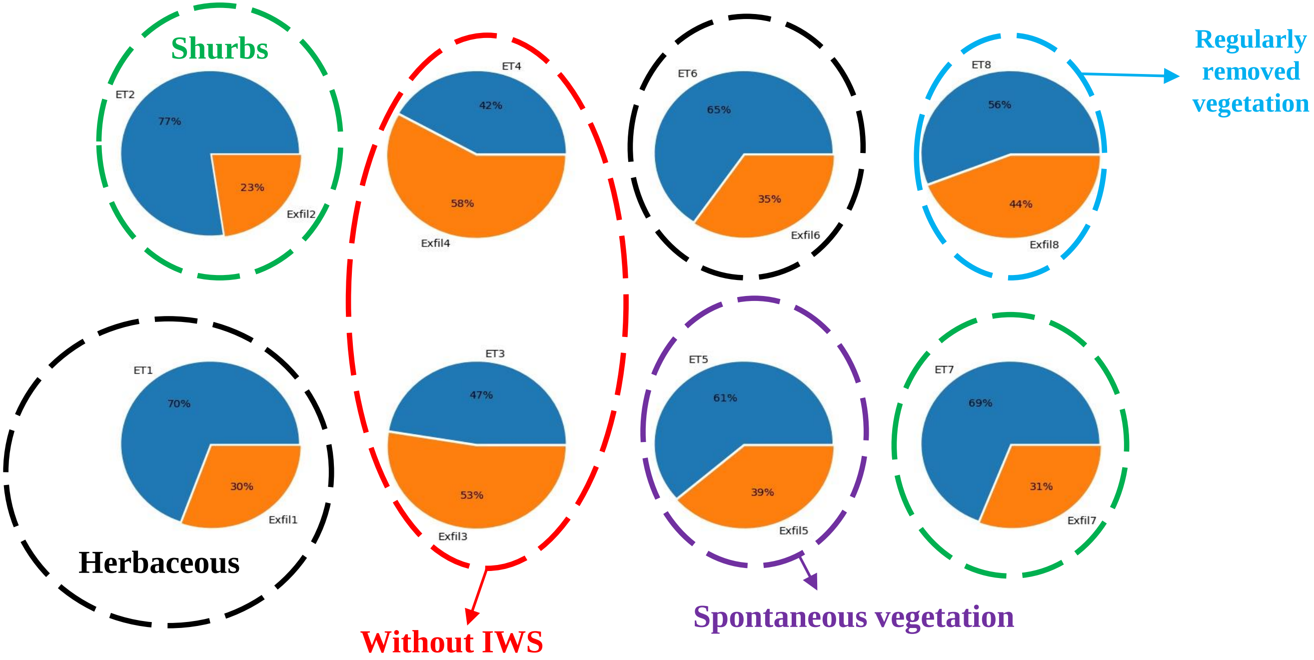
$$ET = 4 * P - Exf - \Delta S$$

Daily evapotranspiration (ET) validated for lysimeters



- ET flux is significant (≥ 8 to 12 mm/d) in summer period and very low values in winter (≤2 mm/d)
- Associated daily ET uncertainties between ±0.42 to ±0.58 mm (*the law of the propagation of uncertainties*)

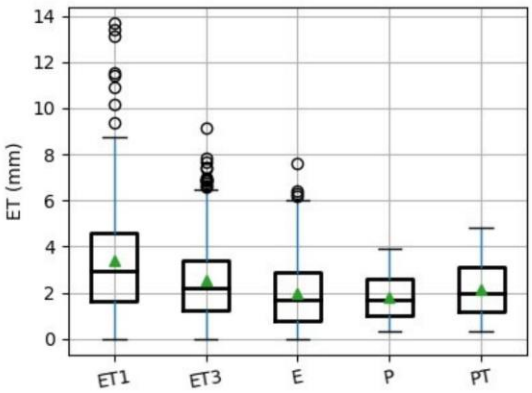
Proportions of ETs (blue) and $Exfil$ (orange) to inputs (P − ΔS) over the 305 common validated days, for the 8 lysimeters. Cumulated rain (4P) is 679 ± 6 mm.



- The Internal Water Storage (IWS) at the base is the most favourable determinant
- The type of the vegetation, here, is a secondary determinant, and less marked
- The positioning of the lysimeters between them: close to (Lysimeter 7) or far from buildings (Lysimeter 2)

A comparison of actuals ETs with reference values (the near evaporimeter (E), the Penman (P) and Priestley–Taylor (PT) potential ETs)

Common validated data = 346 days



(a)

- The ET values for Lysimeter 1 are higher than the reference values (E, P, PT) (in Figure a);

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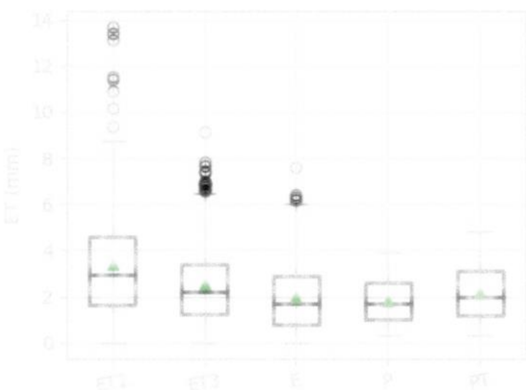
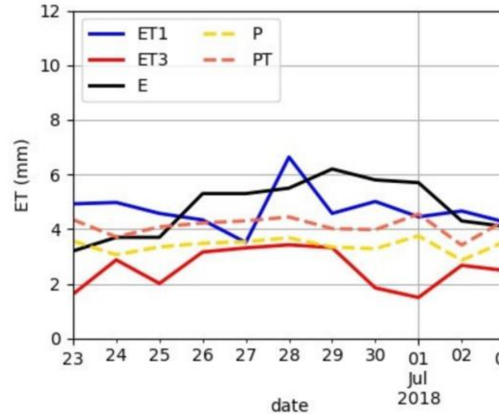
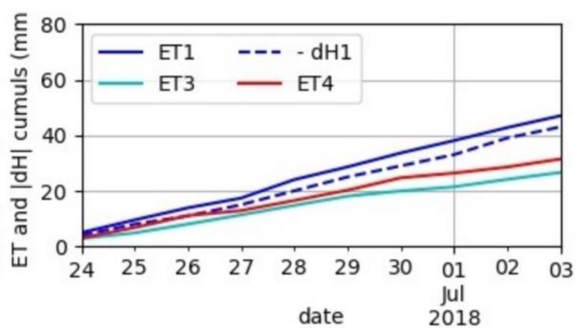


(a)



(b)



(c)

- The ET values for Lysimeter 1 are higher than the reference values (E, P, PT) (in Figure a);

- During a dry period (without rain and exfiltration), the water in the internal storage (dH1) allows lysimeter1 to have a maximum ET rate (Figures b and c).

Evapotranspiration in Urban Rain Gardens

- The ET process should be **included** in the design of SUDS in order to optimise their hydrological functions of stormwater management and their ability to cool the urban area in hot periods

- Experimental set-up used in this work was **pertinent**: Assessment of the multi-annual daily ET with admissible uncertainties (±0.42 to ±0.58 mm)

- **Future studies** : Greater monitoring systems, Shading effects and Vegetation properties (stomatal resistance, LAI, roots expansion, etc.)

- *For more details :* *Ouédraogo, A.A.; Berthier, E.; Durand, B.; Gromaire, M.-C. Determinants of Evapotranspiration in Urban Rain Gardens: A Case Study with Lysimeters under Temperate Climate. Hydrology 2022, 9, 42. https://doi.org/10.3390/hydrology9030042*

The vegetation in the eight lysimeters on 21 June 2018 (Source: DPE-STEA, Paris council)

(6) Case study on the green roof (Trappes) : Experimental set-up

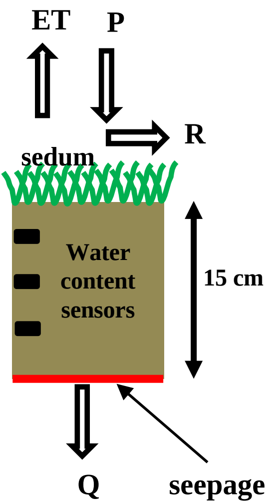
Horizontal view of the green roof (Trappes)

Noms	vegetation	Substrate	Drainage
GI15Y	Grasses + Sedums (G)	Intensive (I), 15 cm	Expanded polystyrene(Y), 4 cm
GE15Y	Grasses + Sedums (G)	Extensive (E), 15 cm	Expanded polystyrene(Y), 4 cm
SE3Y	Sedum (S)	Extensive (E), 3 cm	Expanded polystyrene (Y), 4 cm
SE3Z	Sedum (S)	Extensive (E), 3 cm	Pozzolana (Z), 4 cm
SE15Z	Sedum (S)	Extensive (E), 15 cm	Expanded polystyrene(Y), 4 cm
NE3Y	without végétation (N)	Extensive (E), 3 cm	Expanded polystyrene (Y), 4 cm

- **Rain gauge** (rainfall) and tipping buckets (discharge from each compartment)
- **Weather station** (air temperature and relative humidity at 2 m above the vegetation, wind speed at 3 m above the vegetation, and net radiation at 1 m above the vegetation)
- **Water content sensors**: water content / temperature at different depths in the substrate

data: Juin 2011 - 2018

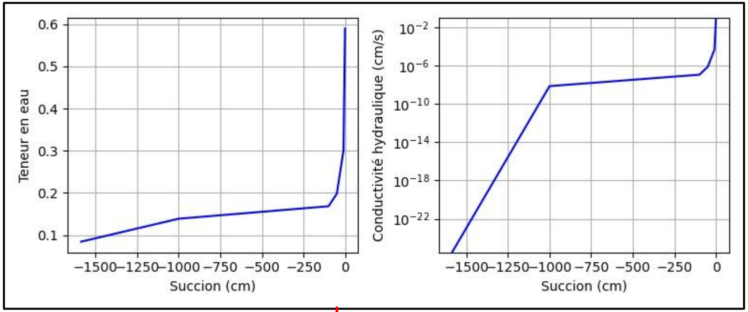
(6) Case study on the green roof (Trappes) : methods and parameters



- **Hydrus 1D: Unsaturated media**

$$\frac{\partial}{\partial z}\left(K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right)=\frac{\partial \theta(\psi)}{\partial t}-S(z,t)$$

- **Hydraulic parameters :**

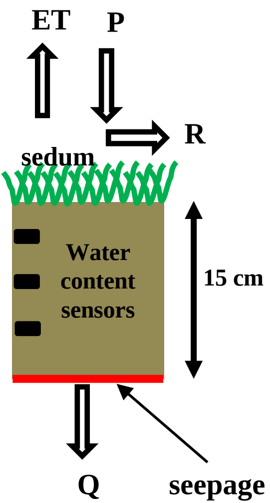


(Ramier et al. 2017) -> expérimental

Inversion with the RETC code
Van Genuchten (1980)

$\theta_r\ (m^3 m^{-3})$	0.084
$\theta_s\ (m^3 m^{-3})$	0.59
$\alpha\ (m^{-1})$	38
$n\ (-)$	1.52
$K_s\ (m/s)$	0.00085

(6) Case study on the green roof (Trappes) : methods and parameters



- **Hydrus 1D: Unsaturated media**

$$\frac{\partial}{\partial z}\left(K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right)=\frac{\partial \theta(\psi)}{\partial t}-S(z,t)$$

- **The tested ET schema :**

(a) Penman-Monteith →

$$ET_P(mm)=\frac{1}{L_e}\frac{\Delta(Q^*-Q_G)+\frac{\rho_a C_p}{r_a}\gamma(e_s^*-e_d)}{\Delta+\gamma\left(1+\frac{r_s}{r_a}\right)}$$

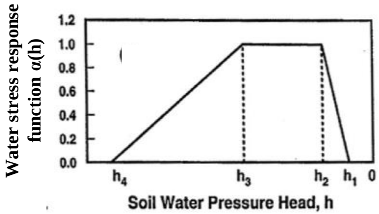
$$r_s(s/m)= r_{sf}/(0.5\times LAI)$$

$$r_a=f(u,h_{veg})$$

(b) Partition of ET_P →

$$T_p=ET_p\left(1-e^{-k*LAI}\right)$$

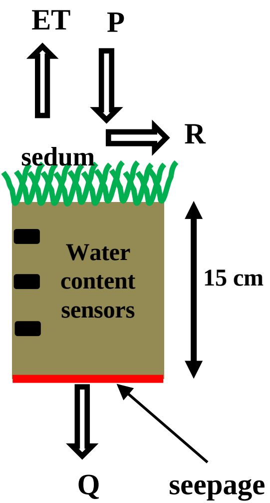
$$E_p=ET_p e^{-k*LAI}$$



(c) water absorption function ***S(z,t)*** →

$$S(z,t)=\beta(z)\alpha(h)T_p$$

β(z)*: a function of the root density normalized to* m^{-1}



- **Hydrus 1D: Unsaturated media**

$$\frac{\partial}{\partial z}\left(K(\psi)\left(\frac{\partial \psi}{\partial z}+1\right)\right) = \frac{\partial \theta(\psi)}{\partial t} - S(z,t)$$

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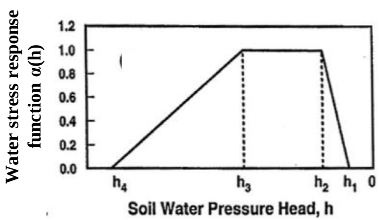


*(c) water absorption function **S(z,t)*** → $S(z,t) = \beta(z)\alpha(h)T_p$

- **Vegetation parameters**

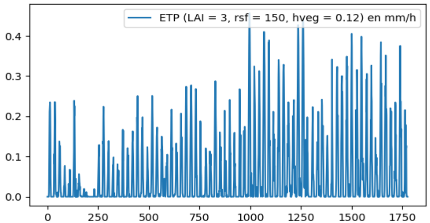
LAI	**3**
$r_{sf}(s/m)$	**150**
h_{veg} (m)	**0.12**
h_r (m)	**0.05**
Extinct (k)	**0.39**

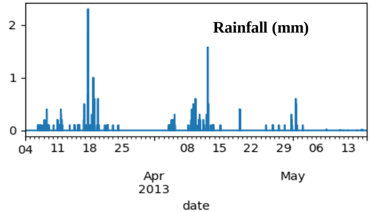
$\beta(z)$: *a function of the root density normalized to m^{-1}*

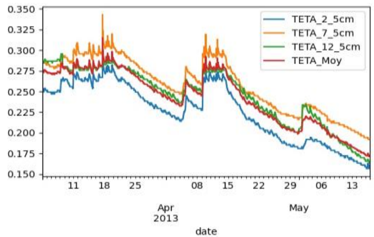
(6) Case study on the green roof (Trappes)

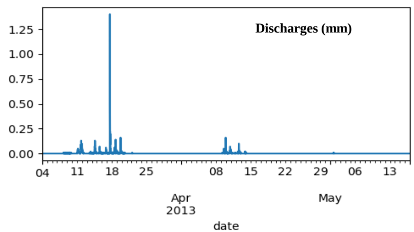
❑ Study period:

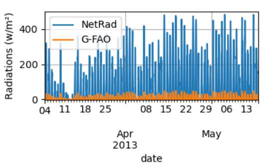
data: March 4 to April 17, 2013, 5 min intervals

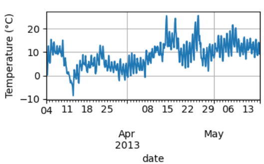


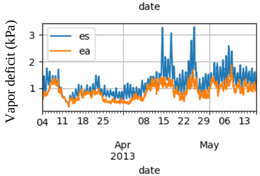


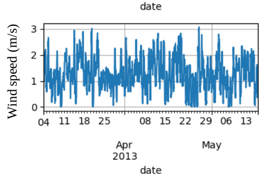












❑ Definition of parameters space

- *Random with 1000 simulations*

(Bouzouidja et al. 2018), (Charpentier 2015), (Wen-Yu et al.2014), (Mesgouez et al., 2013), (Ramier et al. 2017)

θ_r (mm^3mm^{-3})	**0,0 – 0,09**
θ_s $(\mathrm{mm^3mm^{-3}})$	**0,29 – 0,79**
α $(\mathrm{mm^{-1}})$	**0,001 – 0,074**
n $(-)$	**1,3 – 2**
K_s $(\mathrm{mm/h})$	**38 – 6120**
LAI $(-)$ $r_{s,f}(s/mm)$	**2-5** **0,1 – 0,2**
h_{veg} (mm)	**50 – 120**
$\mathrm{h_r}$ (mm)	**10 - 50**
Extinct (k)	**0.3 – 0,7**
h_ini (mm)	**0.19 – 0.275**

(6) Case study on the green roof (Trappes)

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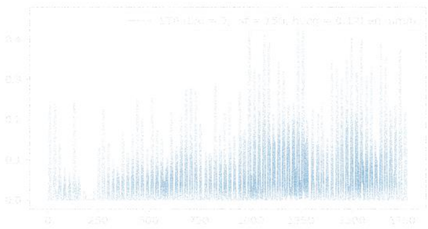
<u>data</u>: *March 4 to April 17, 2013, 5 min intervals*



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α ($\mathrm{mm^{-1}}$)	**0,001 – 0,074**
n (–)	**1,3 – 2**
K_s (mm/h)	**38 – 6120**
LAI (–)	**2-5**
$r_{s,f}$(s/mm)	**0,1 – 0,2**
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Extinct (*k*)	**0.3 – 0,7**
h_ini (*mm*)	**0.19 – 0.275**

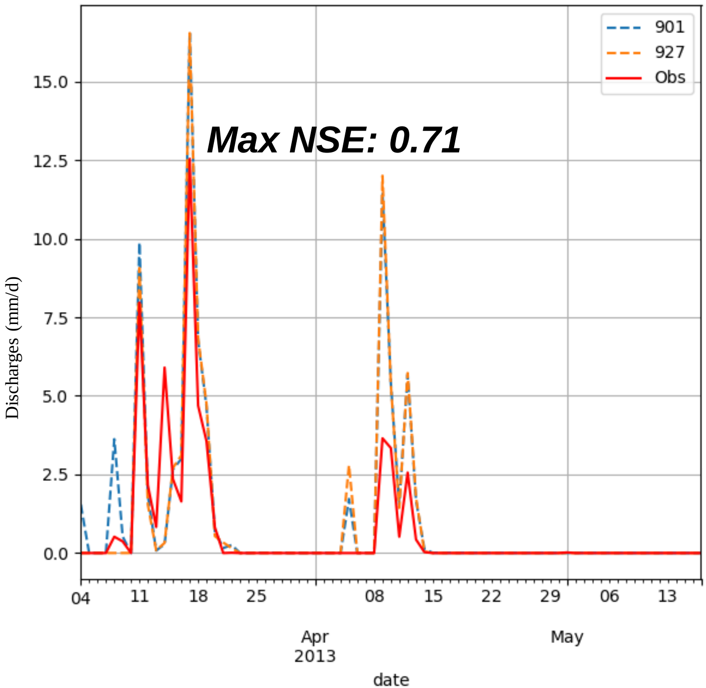
❑ Statistical criteria

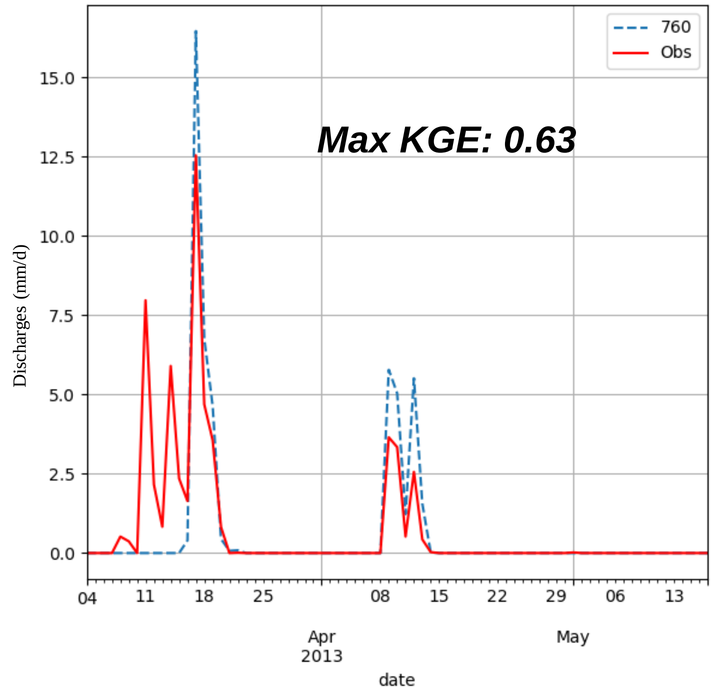
- $NSE = 1 - \frac{\sum_1^n (X_{obs} - X_{sim})^2}{\sum_1^n (X_{obs} - \overline{X_{obs}})^2}$
- $\mathrm{KGE} = 1 - \sqrt{(r-1)^2 + (\alpha_v - 1)^2 + (\beta_m - 1)^2}$

r is the Pearson correlation between the observed and observed values, α_v et β_m are the ratios of the standard deviations and means of the simulated and observed values respectively.

(6) Case study on the green roof (Trappes)

Objective functions using discharges data





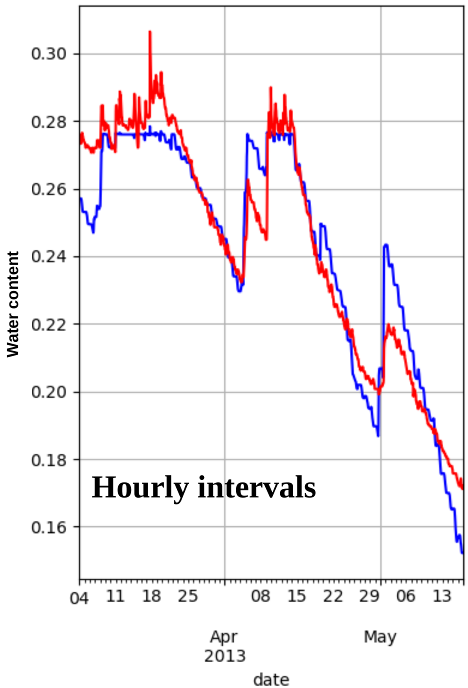
Optimum parameters

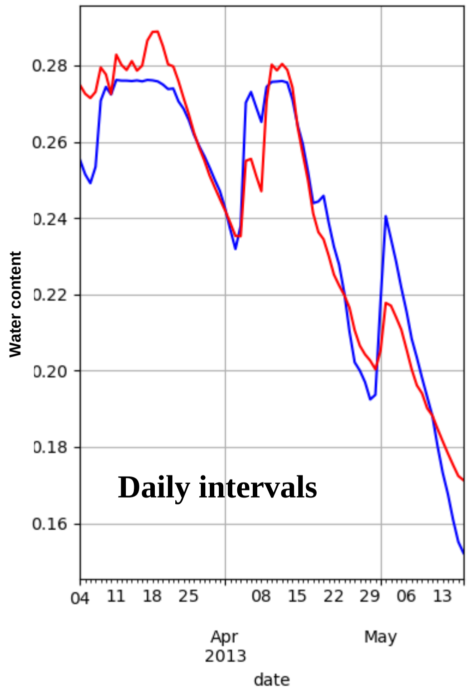
Ks	ths	thr	Alfa	n	r_{sf}	h_{veg}	Ext
471.6	0.77	0.01	0.066	2.24	193.4	0.11	0.5
146.8	0.71	0.07	0.047	2.2	195.9	0.11	0.59

Ks	ths	thr	Alfa	n	r_{sf}	h_{veg}	Ext
74.08	0.41	0.003	0.069	1.19	116.63	0.07	0.32

(6) Case study on the green roof (Trappes)

Objective function based on the mean water content in the 15 cm substrate.





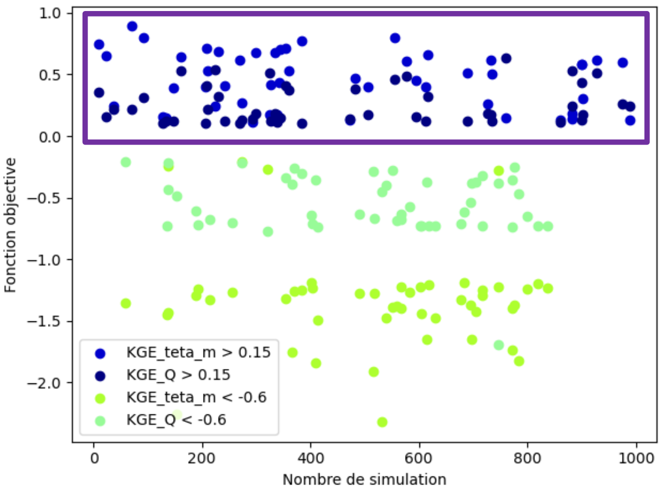
Optimum parameters

Ks	ths	thr	Alfa	n	R_{sf}	h_{veg}	Ext
3505.3	0.63	0.06	0.06	2.03	185	0.09	0.4

Max NSE: 0.95

(6) Case study on the green roof (Trappes) : Parameters distributions

Considering the objective function KGE of average water content and discharge

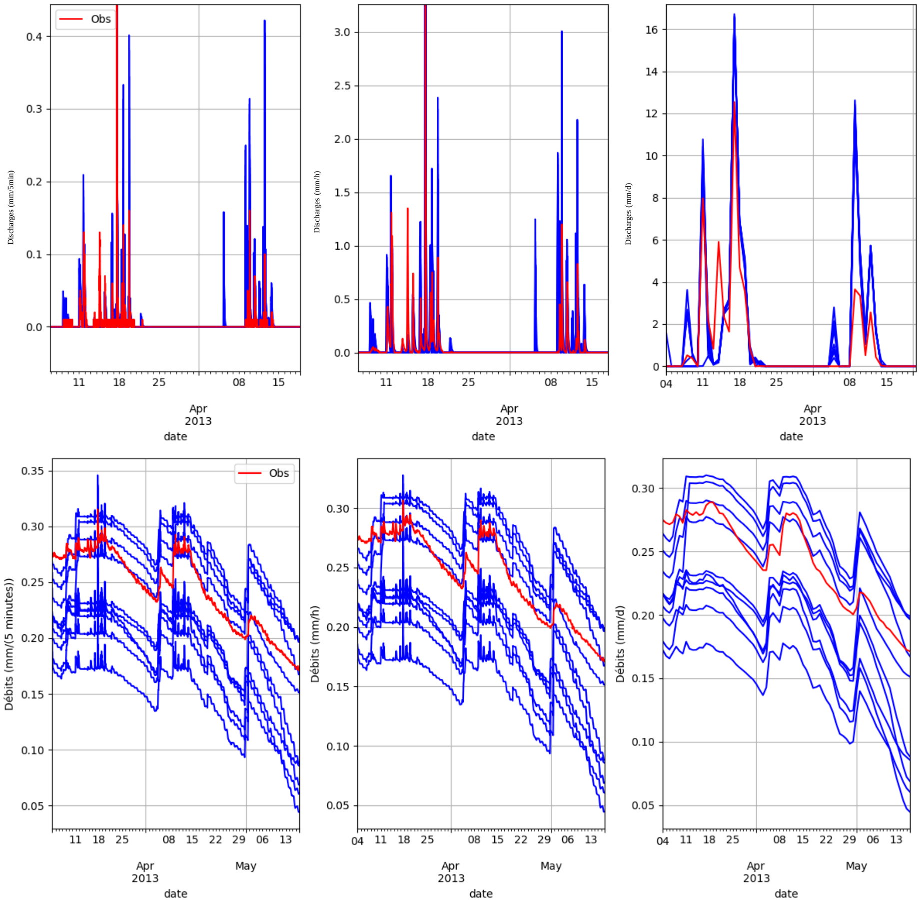


Comparison of the distribution of the parameters with the Wilcoxon test

Parameters	Sim_acpt		Sim_non_acpt		P_Values
	u	σ	u	σ	
$\theta_r\ (mm^3mm^{-3})$	0.045	0.025	**0.046**	**0.026**	0.831
$\theta_s\ (mm^3mm^{-3})$	**0.63**	0,1	**0.68**	**0.11**	0.01
$\alpha\ (mm^{-1})$	0.054	0.01	**0.015**	**0.017**	9.10^{-9}
$n\ (-)$	2.03	0.5	**1.95**	**0.78**	0.4
$K_s\ (mm/h)$	1138.6	**1159.16**	**3463.03**	**1866.9**	2.10^{-7}
$r_{s,f}(s/mm)$	141.8	28.23	**150.85**	**29.05**	0.13
$h_{veg}\ (mm)$	0.09	0.017	**0.084**	**0.023**	0.54
Extinct	0.47	0.11	**0.5**	**0.114**	0.07

θ_s, n, α and K_S have samples of acceptable and unacceptable parameters that are not similar.

(6) Case study on the green roof (Trappes)

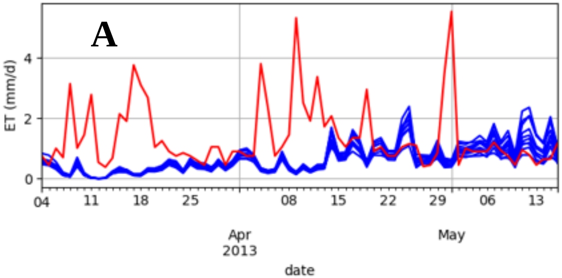


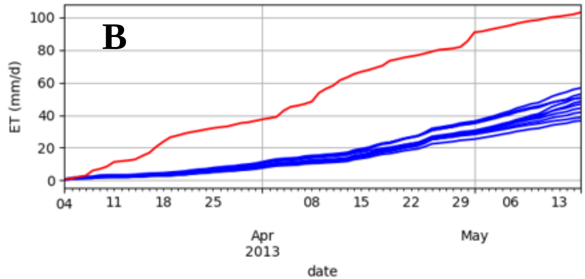
- In blue, the simulated values (10 best KGE_{AG}) from the acceptable parameters
- In red, the observed values on the roof

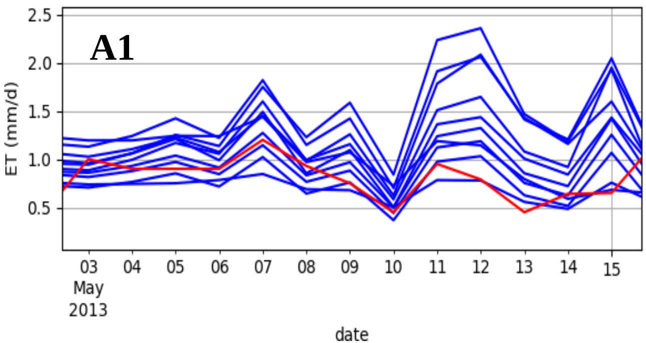
$$KGE_{AG} = KGE(\theta) \times KGE(Q)$$

Simulation	KGE_AG	KGE_teta_m	KGE_Q
556	0.3680	0.80	0.46
161	0.3392	0.64	0.53
927	0.3162	0.62	0.51
577	0.2989	0.61	0.49
354	0.2911	0.71	0.41
209	0.2911	0.71	0.41
9	0.2700	0.75	0.36
901	0.2494	0.58	0.43
92	0.2480	0.80	0.31
229	0.2208	0.69	0.32

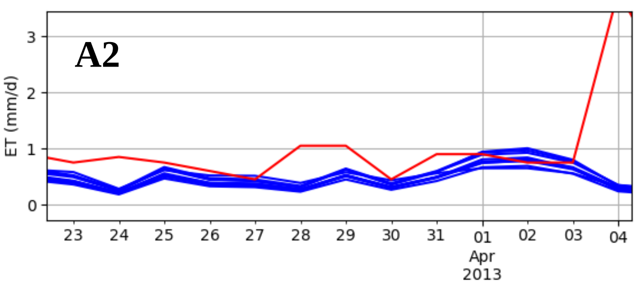
(6) Case study on the green roof (Trappes) : Simulated vs. estimated ETs







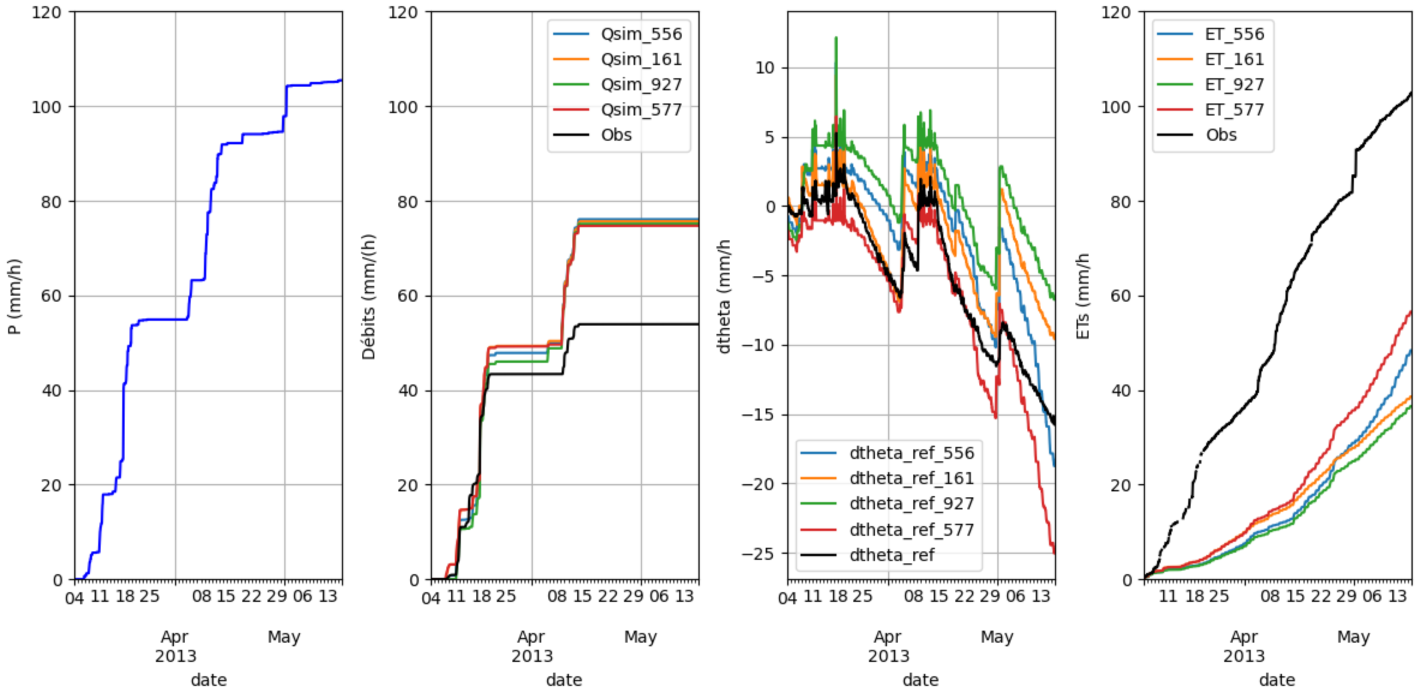
- In red, the ET estimated from the water balance using the average water content;
- In **blue**, the **ETs simulated** from the acceptable parameters



- Underestimation of the measured values
- Different dynamics between the two ETs

(6) Case study on the green roof (Trappes) : Water balance

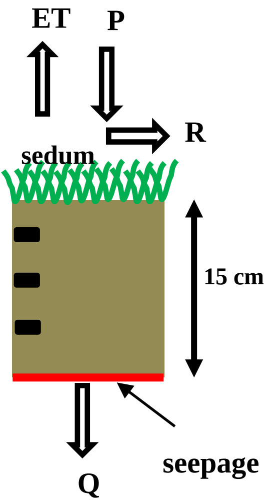
- ***Simulated and observed water balance components***



- Observed discharges are underestimated, especially at the end of the simulation
- ET values are underestimated

Simulation	KGE_AG	KGE_teta_m	KGE_Q
556	0.3680	0.80	0.46
161	0.3392	0.64	0.53
927	0.3162	0.62	0.51
577	0.2989	0.61	0.49

(6) Perspectives



- **Improve the method for the parameters calibration**
  - *Estimate ET for the calibration period by water balance*
  - *Use other approaches to explore parameter space*
  - *Combine objective functions for calibration*
  - *Identify the most important parameters*
- **Validate the model**
- **Simulation of the ET of the roof from 2012-2017**
- **Sensitivity of ET to microclimatic data**
- **Sensitivities of the ET to :**
  - *Thickness of the substrate*
  - *Type of vegetation*
- **Compare this ET scheme with other modelling approaches:**
  - *Use 2 formulations of PET: vegetation PET (Penman-Monteith) and soil PET (Priestley-Taylor)*
  - *A Transpiration scheme with compensation*
  - *Impact of the Transpiration scheme in the ET simulation*

Thanks for your attention

(Legend: In Barcelona, Spain, the trees planted along the Ramblas are not just decorative: they are useful.