Uncertainty propagation in the climate hydrological modelling chain

Global Changes and Water Resources:
Past, Present and Future
Workshop
Pisa, May 26-27 2022

M. Vanclooster, UCLouvain – Earth and Life Institute
With contributions of
- **Dr. H. Sellami, CERTE, Tunisie**
- **Ir. G. Ahlem, G. Khouloud, INAT et ESIM, Tunisie**
- **Pr. S. Khlifi, ESIM, Tunisie**
- **Ir I. El Ghoul, ESIM, Tunisie**

Circle U. European University Alliance LOUV4IN Water UCLouvain

Table of contents

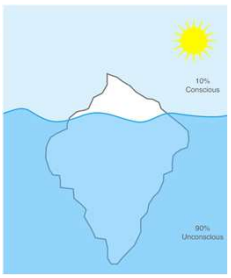
About certain and uncertain uncertainty

"Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tends to be the difficult ones"

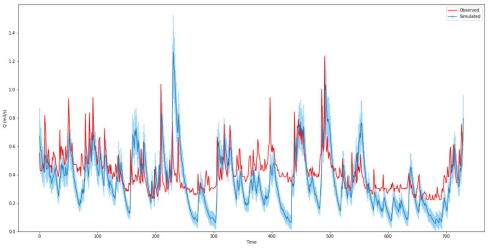
Source: Donald Rumsfeld, 2002

https://www.youtube.com/watch?v=GiPe1OiKQuk

About certain and uncertain uncertainty

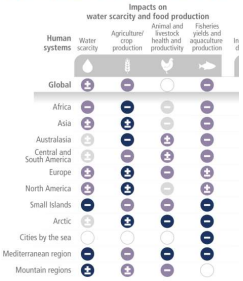


About communicating uncertainty



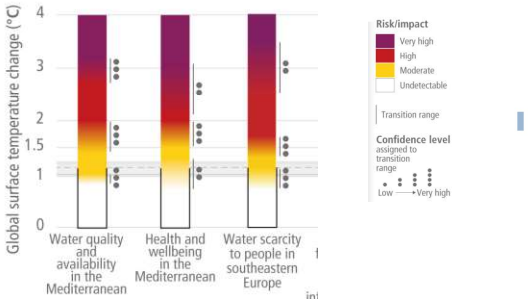
About communicating uncertainty

(b) Observed impacts of climate change on human systems



Source: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

UCLouvain
Earth and Life Institute (ELI)



Source: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

UCLouvain
Earth and Life Institute (ELI)

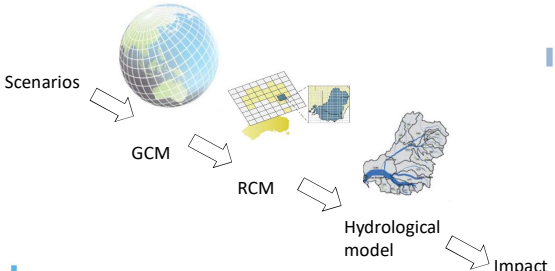
About communicating uncertainty

"Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., medium confidence. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%."

Source: https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf

UCLouvain
Earth and Life Institute (ELI)

The modelling chain for assessing hydrological impacts of climate change



UCLouvain
Earth and Life Institute (ELI)

Modelling uncertainty sources

- Model input uncertainty and model parameter uncertainty
- Observational uncertainty
- Structural model uncertainty

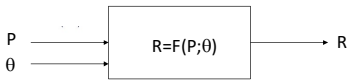
UCLouvain
Earth and Life Institute (ELI)

Modelling uncertainty sources

- Model input uncertainty and parameter uncertainty
- Observational uncertainty
- Structural model uncertainty

UCLouvain
Earth and Life Institute (ELI)

A simple hydrological model, « F »



- Without uncertainty:

$$P_{exact}; \theta_{exact} \rightarrow R_{exact}$$

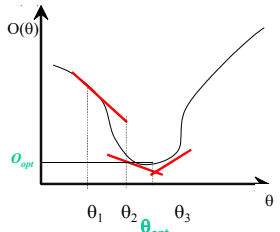
- With uncertainty:

$$P_1; \theta_1 \rightarrow R_1$$
$$P_2; \theta_2 \rightarrow R_2$$
$$\dots$$
$$P_n; \theta_n \rightarrow R_n$$

UCLouvain
Earth and Life Institute (ELI)

Assessing parameter uncertainties

$$O(\theta) = \sum (R_{simulated}(P;\theta) - R_{observed})^2$$



$$Uncertainty(\theta) \sim O_{opt}(\mathbf{J}^T\mathbf{J})^{-1}$$

UCLouvain
Earth and Life Institute (ELI)

Assessing parameter uncertainties

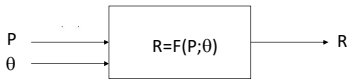
- Given observations, Ri
- Given a prior distribution of θ
- A posterior distribution can be retrieved using e.g. Bayesian rule:

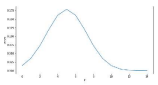
$$f_\theta(\theta|R_1, R_2..R_n) \propto f(R_1, R_2..R_n|\theta).\xi(\theta)$$

Posterior distribution — Likelihood function — Prior distribution

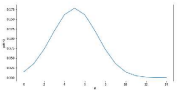
UCLouvain
Earth and Life Institute (ELI)

Propagating parameter uncertainties





Probability density of P or θ



Probability density of R

UCLouvain
Earth and Life Institute (ELI)

First order analysis

$$E(R) = F(E(P)) + \frac{1}{2}\left\{\sum_i \sum_j \left(\frac{\partial F^2}{\partial P_i \partial P_j}\right)\mathrm{cov}(P_i, P_j)\right\} + O(3)$$

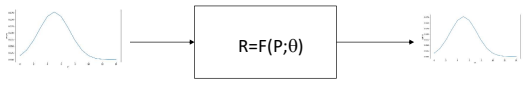
$$\mathrm{var}(R) = \sum_i \sum_j \left(\frac{\partial F}{\partial P_i}\right)\left(\frac{\partial F}{\partial P_j}\right)\mathrm{cov}(P_i, P_j)$$

UCLouvain
Earth and Life Institute (ELI)

First order analysis

$$E(R) = F(E(P))$$

$$\mathrm{var}(R) = \sum_i \left(\frac{\partial F}{\partial P_i}\right)^2 \mathrm{var}(P_i)$$

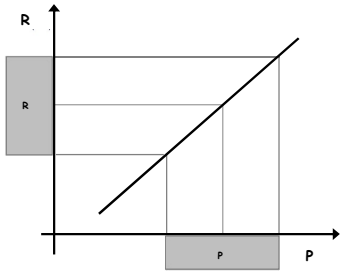


UCLouvain
Earth and Life Institute (ELI)

Propagating uncertainty

$$E(R) = F(E(P))$$

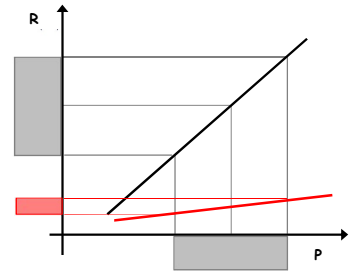
$$\mathrm{var}(R) = \sum_i \left(\frac{\partial F}{\partial P_i}\right)^2 \mathrm{var}(P_i)$$



UCLouvain
Earth and Life Institute (ELI)

Propagating uncertainty: Effect of sensitivity

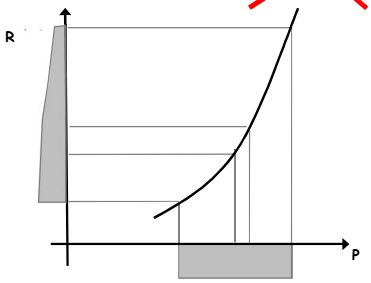
$$E(R) = F(E(P))$$
$$\mathrm{var}(R) = \sum_i \left(\frac{\partial F}{\partial P_i}\right)^2 \mathrm{var}(P_i)$$



UCLouvain
Earth and Life Institute (ELI)

Propagating uncertainty: Effect of non linearity

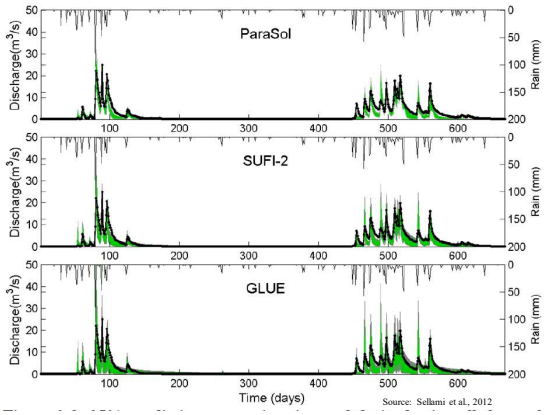
~~$E(R) = F(E(P))$~~
~~$\mathrm{var}(R) = \sum_i \left(\frac{\partial F}{\partial P_i}\right)^2 \mathrm{var}(P_i)$~~



UCLouvain
Earth and Life Institute (ELI)

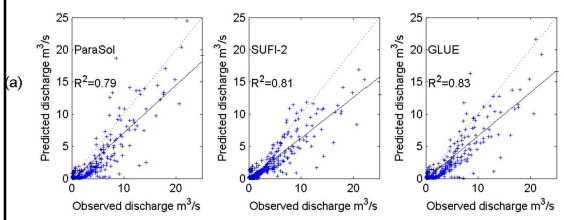
Example: Behavioural parameter sets for simulating discharge in the Vène catchment (Southern France) with the SWAT model: Impact of model inversion scheme

Source: Sellami et al., 2012



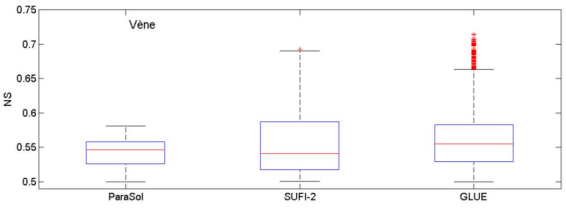
Source: Sellami et al., 2012

UCLouvain
Earth and Life Institute (ELI)



Source: Sellami et al., 2012

UCLouvain
Earth and Life Institute (ELI)



Source: Sellami et al., 2012

UCLouvain
Earth and Life Institute (ELI)

Example: Simulating discharge in the Siliana catchment (Tunisie) with the SWAT model. Impact of land use change

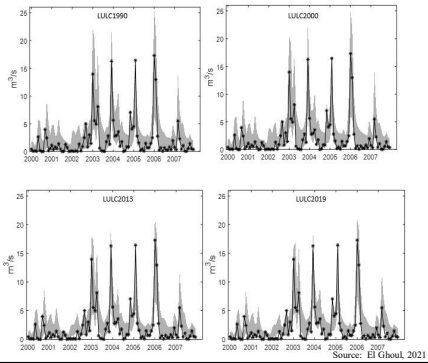
Rate of change (ha/yr) as reference to 1990

Landuse class	Area 1990 (ha)	2000	2013	2019
Field crop	73678	-29.1	+64.45	+67.21
Olive plantation	357	+45	+64.5	+47.97
Pasture	7302	-97.1	-150.2	-159
Clear forest	4481	-23	-64.9	-36.48
Dense forest	14617	+1.6	-44.65	-56.90
Urban land	271	+17	+20.75	+19.21
Irrigated land	967	+49.5	+94.15	+103.21
Water	1104	+32	+15	+14

Source: El Ghoul, 2021

25

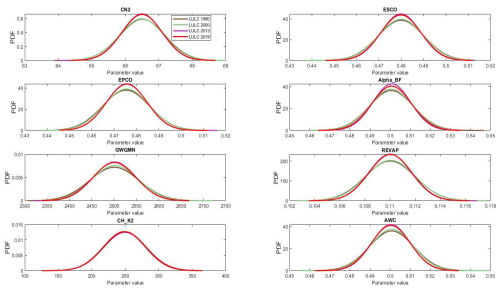
UCLouvain
Earth and Life Institute (ELI)



Source: El Ghoul, 2021

26

UCLouvain
Earth and Life Institute (ELI)

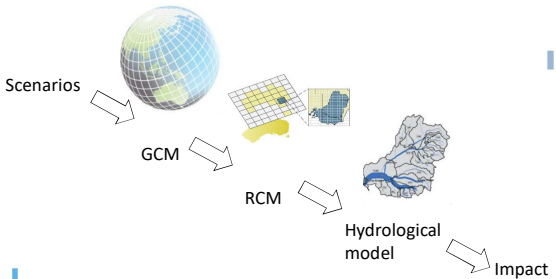


Source: El Ghoul, 2021

27

UCLouvain
Earth and Life Institute (ELI)

The modelling chain for assessing hydrological impacts of climate change



28

UCLouvain
Earth and Life Institute (ELI)

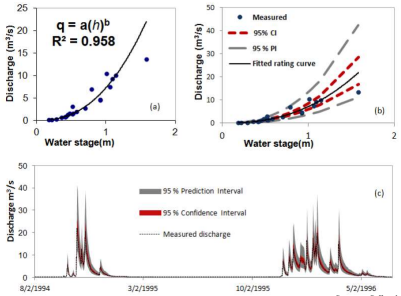
Modelling uncertainty sources

- Model input uncertainty
- Model parameter uncertainty
- Observational uncertainty
- Structural model uncertainty

29

UCLouvain
Earth and Life Institute (ELI)

Observational uncertainty



Source: Sellami et al., 2012

30

UCLouvain
Earth and Life Institute (ELI)

Statistical criteria		Deterministic rating curve		Uncertain rating curve	
	Method	Catchment			
		Vène	Pallas	Vène	Pallas
NS*	SUFI-2	0.69	0.73	---	---
	GLUE	0.71	0.76	---	---
	ParaSol	0.58	0.67	---	---
R^{2*}	SUFI-2	0.81	0.78	---	---
	GLUE	0.83	0.81	---	---
	ParaSol	0.79	0.69	---	---
p-factor (%)	SUFI-2	38	48	47	54
	GLUE	50	61	67	75
	ParaSol	19	28	21	29
R-factor	SUFI-2	0.38	0.36	0.44	0.41
	GLUE	0.46	0.44	0.67	0.59
	ParaSol	0.13	0.10	0.20	0.18

Source: Sellami et al., 2012

31

UCLouvain
Earth and Life Institute (ELI)

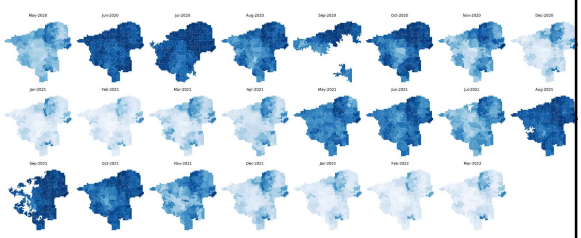
Reducing observational uncertainty

- Increasing space-time resolution of observational data

- SMART monitoring (Internet of Things)


32

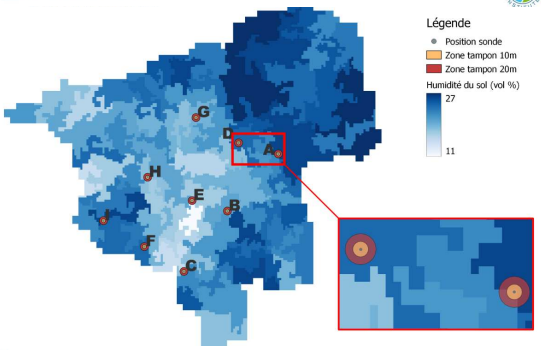
UCLouvain
Earth and Life Institute (ELI)



Source: Kahn 2022

33

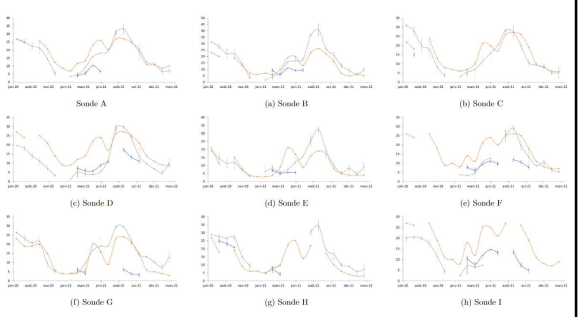
UCLouvain



Source: Kahn 2022

34

UCLouvain
Earth and Life Institute (ELI)



Source: Kahn 2022

35

UCLouvain
Earth and Life Institute (ELI)

Modelling uncertainty sources

- Model input uncertainties
- Model parameter uncertainty
- Observation uncertainty
- Structural model uncertainty

36

UCLouvain
Earth and Life Institute (ELI)

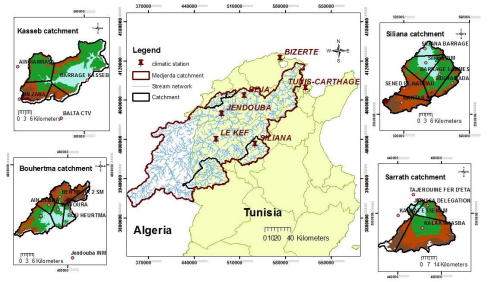
Reducing model structural uncertainty

- Model validation
- Modelling validation
- Scenario validation

37

UCLouvain
Earth and Life Institute (ELI)

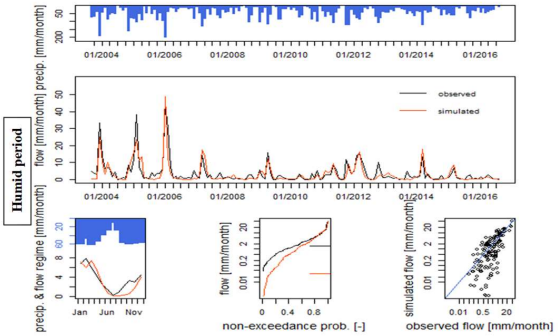
Model validation



Source: Khouloud, 2022

38

UCLouvain
Earth and Life Institute (ELI)



Source: Khouloud, 2022

UCLouvain
Earth and Life Institute (ELI)

Catchment	Period	NSE	KGE	RMSE	Pbias	RSR
Kasseb	calibration	85	80	24,5	7,2	40
	validation dry period	85	80	17,7	9,4	40
	validation humid period	84	80	29,6	5,0	40
Sarrath	calibration	75	80	1,0	-4,0	50
	validation dry period	67	70	1,1	-8,0	60
	validation humid period	78	90	1,0	-3,7	50
Siliana	calibration	75	80	2,7	-18,1	50
	validation dry period	76	70	3,2	11,3	40
	validation humid period	58	80	1,3	-5,8	60
Bou Heurtma	calibration	78	80	19,7	2,1	50
	validation dry period	64	70	16,1	19,4	60
	validation humid period	80	80	22,0	-3,8	40

Source: Khouloud, 2022

40

UCLouvain
Earth and Life Institute (ELI)

Model validation vs. modelling validation

41

UCLouvain
Earth and Life Institute (ELI)

Scenario validation

The quality of a scenario is defined as the adequacy for a given use.

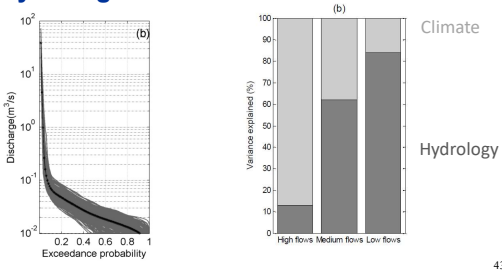
Components of scenario validation:

- Representativeness
- Theoretical and logical consistency
- Juridical conformity
- Political conformity

42

UCLouvain
Earth and Life Institute (ELI)

What dominates? Climate model uncertainty or hydrological model uncertainty



Source: Sellami et al., 2021

UCLouvain
Earth and Life Institute (ELI)

Take ahome messages

- Sure, there is much uncertainty in the climate change hydrological impact modelling chain.
- The science community very often propagate the certain uncertainties, much less effort is devoted to deep uncertain uncertainty.
- Take care of good uncertainty communication.
- Uncertainty on predicted impacts is very often determined by case study specific conditions.
- Impact of certain uncertainty can be reduced by increasing observational quality, improving model and modelling validation.
- Save a seat for the deep uncertain uncertainty.

UCLouvain
Earth and Life Institute (ELI)

References

- El Ghoul, Imen ; Sellami, Haykel ; Vanclooster, Marnik ; Khlifi, Slaheddine. Combined effects of climate and land use change on hydrological alteration of a Mediterranean catchment: case study of the Silia. International virtual conference Interdisciplinary approaches for adressing the 21 century water challenges (Louvain-la-Neuve, Belgium, 26/04/2021).
- Sellami, Haykel ; Benabdallah, Sihem ; La Jeunesse, Isabelle ; Vanclooster, Marnik. *Climate models and hydrologic parameter uncertainties in climate change impacts on monthly runoff and daily flow duration curve of a Mediterranean catchment.* In: *Hydrological Sciences Journal*, Vol. 61, no. 5-8, p. 1415-1429 (2016). doi:10.1080/02626667.2015.1040801.
- Sellami, Haykel ; La Jeunesse, Isabelle ; Benabdallah, Sihem ; Baghdadi, Nicolas ; Vanclooster, Marnik. Uncertainty analysis in model parameters regionalization: a case study involving the SWAT model in Mediterranean catchments (Southern France). In: Hydrology and Earth System Sciences, Vol. 18, p. 1-21 (22.05.2014). doi:10.5194/hess-18-2393-2014.
- Sellami, Haykel ; La Jeunesse, Isabelle ; Benabdallah, Sihem ; Vanclooster, Marnik. *Parameter and rating curve uncertainty propagation analysis of the SWAT model for two small Mediterranean catchments.* In: *Hydrological Sciences Journal*, Vol. 58, no. 8, p. 1-23. doi:10.1080/02626667.2013.837222.
- Gara, Ahlem ; Gader, Khoulloud ; Khlifi, Slaheddine ; Vanclooster, Marnik ; Jendoubi, Donia ; Bouvier, Christophe. The added value of spatially distributed meteorological data for simulating hydrological processes in a small Mediterranean catchment. In: Acta Geophysica, p. 1-21 (2019). doi:10.1007/s11600-019-00379-y.
- Gader, Khoulloud ; Gara, Ahlem ; Vanclooster, Marnik ; Khlifi, Slaheddine ; Slimani, Mohamed. Drought assessment in a south Mediterranean transboundary catchment. In: Hydrological Sciences Journal, , p. 1-16 (2020). doi:10.1080/02626667.2020.1747621.
- Kahan, R. 2022. Caractérisation de l'humidité du sol dans le bas-fond Itchedjero, Benin. Master thesis, AGRO-Louvain. In progress.