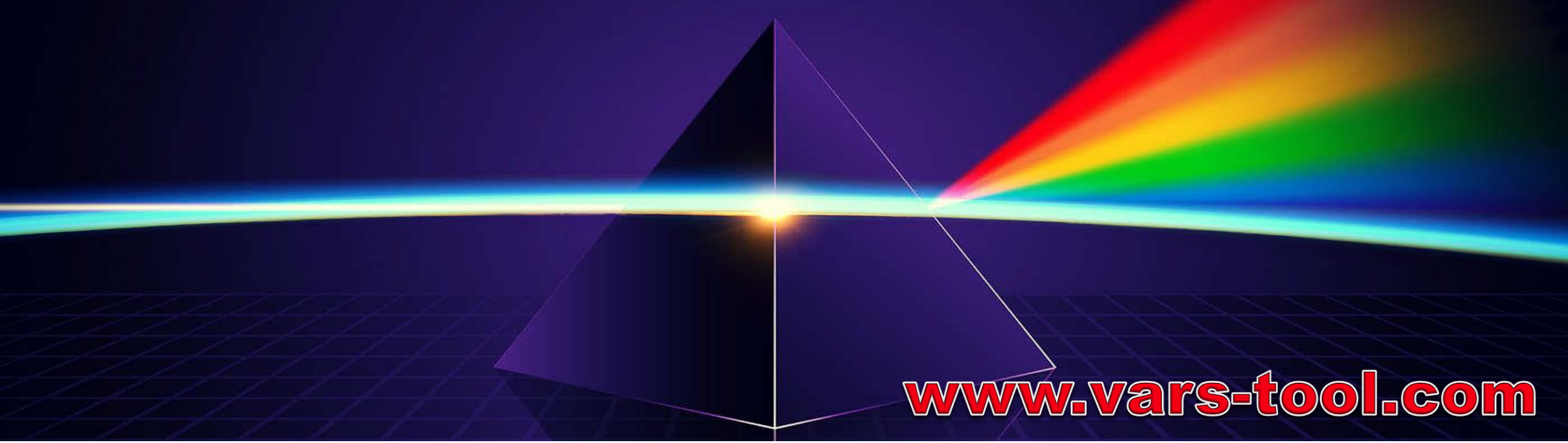


A Toolbox for Comprehensive, Efficient, and Robust Sensitivity and Uncertainty Analysis – Version 2

Saman Razavi

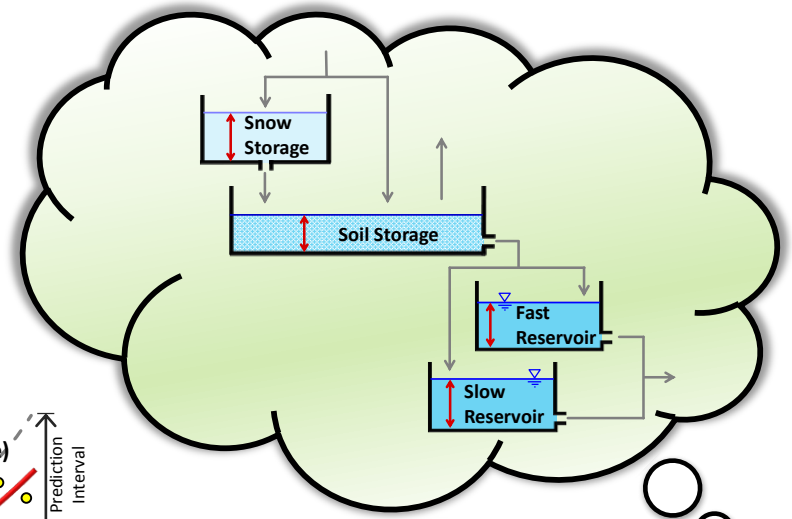
Second IMPC Annual General Meeting, June 12-19, 2019

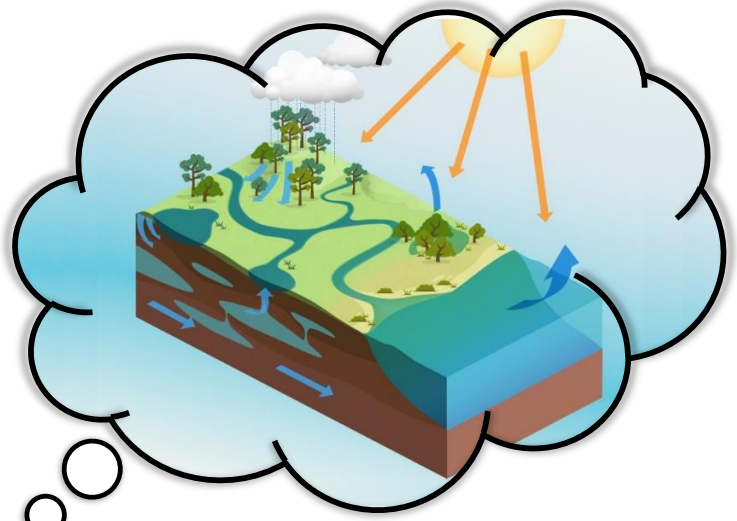
UNIVERSITY OF SASKATCHEWAN
Global Institute for Water Security
USASK.CA/WATER

GLOBAL WATER FUTURES
SOLUTIONS TO WATER THREATS IN AN ERA OF GLOBAL CHANGE

Integrated Modelling Program for Canada
Global Water Futures

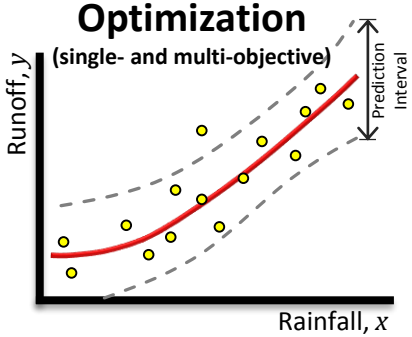
How Well Does a Hydrologic Model Represent the Real System?





Optimization

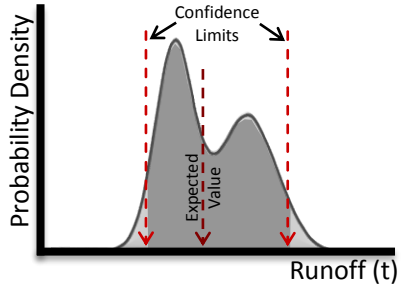
(single- and multi-objective)



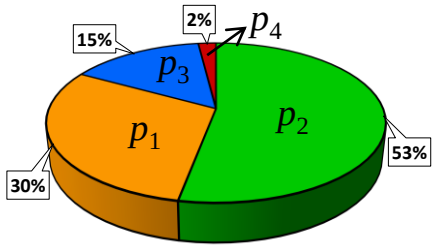
E.g.,

Razavi & Tolson (2013 WRR)
Razavi et. (2012 WRR)
Razavi et. (2012 EMS)
Razavi et al. (2010 WRR)

Uncertainty Propagation



Sensitivity Analysis



E.g.,

Haghnegahdar, Razavi et al. (2017 HP)
Sheikholeslami & Razavi (2017 EMS)
Haghnegahdar & Razavi (2017 EMS)
Yassin, Razavi et al. (2017 HP)
Gupta & Razavi (2018 WRR)
Razavi & Gupta (2016b WRR)
Razavi & Gupta (2016a WRR)
Razavi & Gupta (2015 WRR)
⋮

How Well Does a Hydrologic Model Represent the Real System?

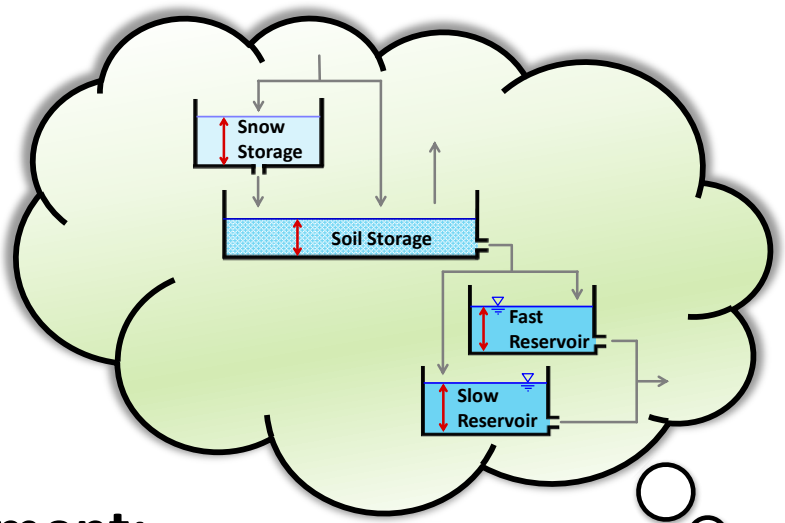
… and how can Sensitivity Analysis (SA) be useful?

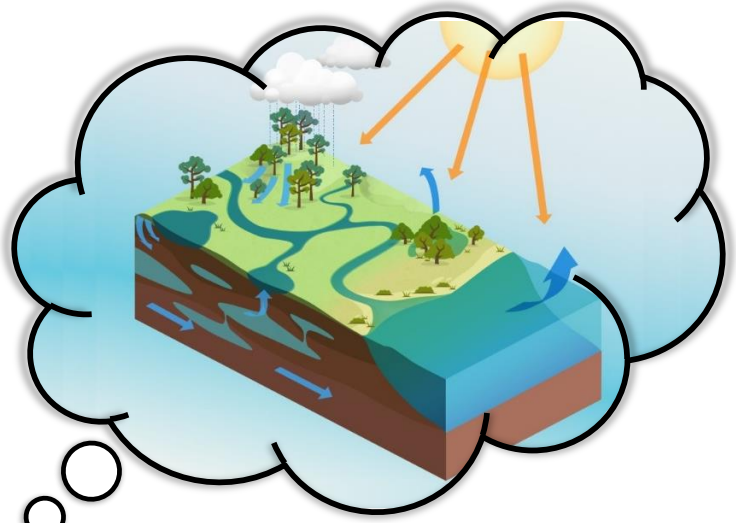
Diagnostic Testing:
How is the *fidelity* of the model structure, conceptualization, and parameterization?

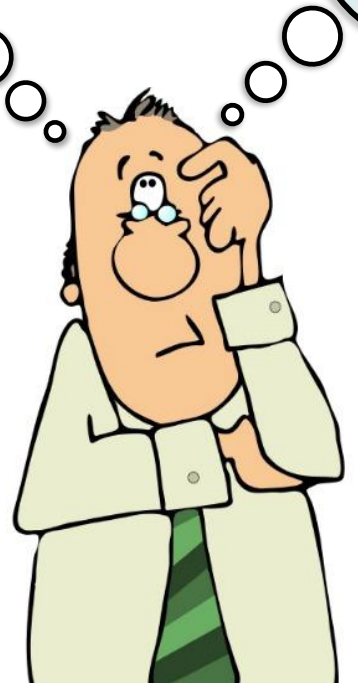
Uncertainty Apportionment:
When and how does *uncertainty* matter?

Factor and Model Reduction:
What model component or parameter might be *uninfluential* or redundant?

⋮







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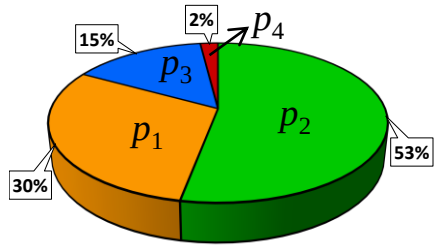


For more see: Razavi and Gupta (2015), *What do we mean by sensitivity analysis? The need for comprehensive characterization of "global" sensitivity in Earth and Environmental systems models*, Water Resources Research.

Major Challenges with SA

1. Ambiguous Definition of Sensitivity?!

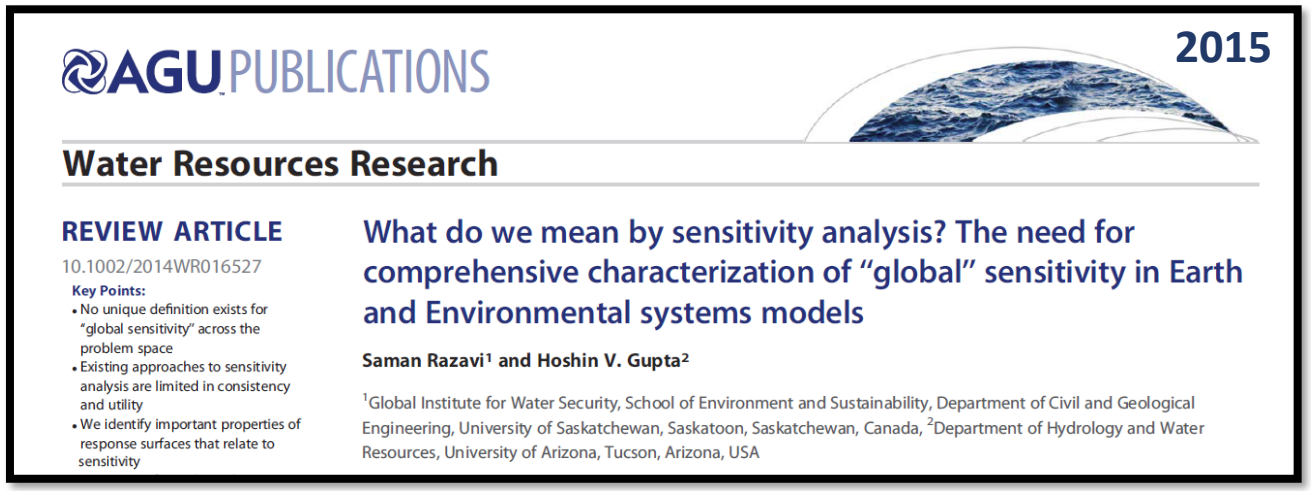
Non-unique, conflicting, incomprehensive.

2. Ignorance of "Structure" of Response Surfaces

Surface shape, covariance, multi-modality.

3. Computational Inefficiency

Large numbers of samples required.



AGU PUBLICATIONS 2015

Water Resources Research

REVIEW ARTICLE

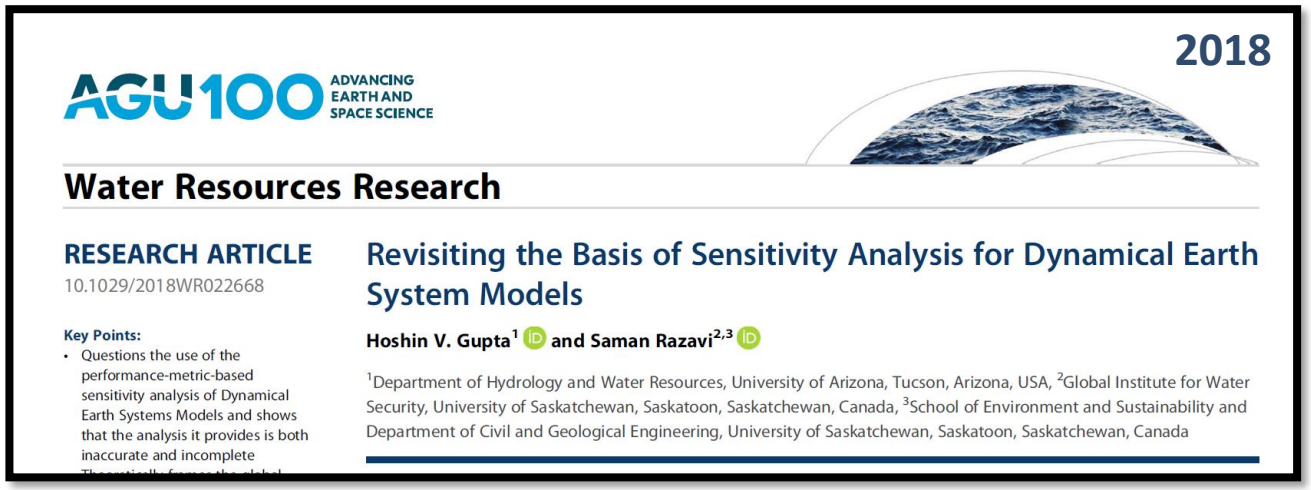
10.1002/2014WR016527

Key Points:
- No unique definition exists for "global sensitivity" across the problem space
- Existing approaches to sensitivity analysis are limited in consistency and utility
- We identify important properties of response surfaces that relate to sensitivity

What do we mean by sensitivity analysis? The need for comprehensive characterization of "global" sensitivity in Earth and Environmental systems models

Saman Razavi[1] and Hoshin V. Gupta[2]

[1]Global Institute for Water Security, School of Environment and Sustainability, Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [2]Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA



AGU100 ADVANCING EARTH AND SPACE SCIENCE 2018

Water Resources Research

RESEARCH ARTICLE

10.1029/2018WR022668

Key Points:
- Questions the use of the performance-metric-based sensitivity analysis of Dynamical Earth Systems Models and shows that the analysis it provides is both inaccurate and incomplete

Revisiting the Basis of Sensitivity Analysis for Dynamical Earth System Models

Hoshin V. Gupta[1] and Saman Razavi[2,3]

[1]Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA, [2]Global Institute for Water Security, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, [3]School of Environment and Sustainability and Department of Civil and Geological Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

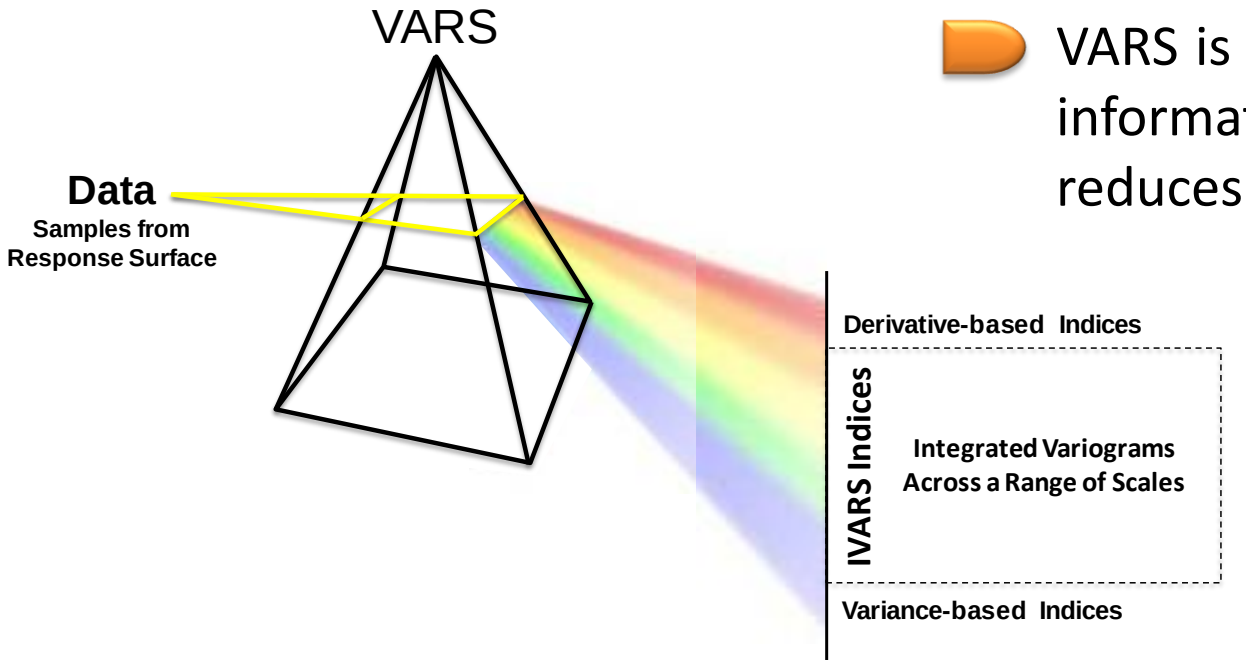
4. Identifiability Analysis or Sensitivity Analysis?!

Mixed understanding and characterization.

5. Misrepresentation of Dynamical Behaviours

Need for proper "time-varying" and "time-aggregate" sensitivity analysis.

VARS Highlights



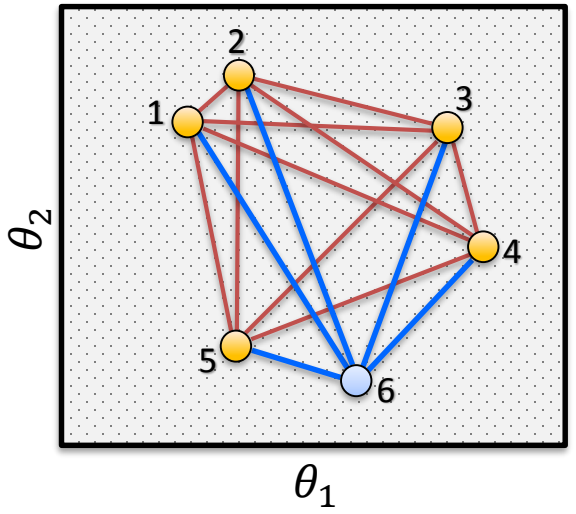
- VARS is a **"unifying theory"**, generating a 'spectrum' of information on sensitivity, while as limiting cases, it reduces to derivative- and variance-based approaches.

(Razavi & Gupta, 2016a)

- VARS is **super-efficient** (1-2 orders of magnitude more efficient than alternatives), because it is based on the information contained in *pairs* of points, rather than in individual points.

  * Number of pairs grows as $\sim n^2$, where n is rate of increase of points.

(Razavi & Gupta, 2016b)



VARS-TOOL

VARS-TOOL , by incorporating a diversity of tools and features within a *single* platform, conveniently provides the user with the ingredients necessary for conducting exploratory research with a view to discovering new directions for advancing the field of sensitivity and uncertainty analysis.

(*Razavi et al.*, 2019 EMS)

VARS-TOOL

Variogram Analysis of Response Surfaces

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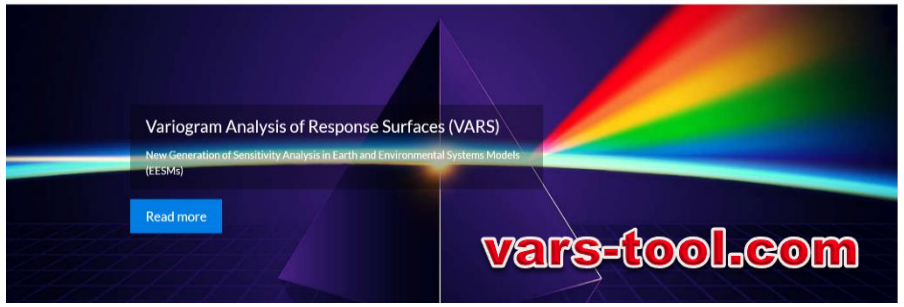

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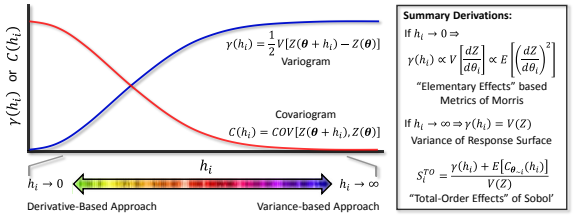


Summary Derivations:

If $h_i \to 0 \Rightarrow$

$\gamma(h_i) \propto V\left[\frac{dZ}{d\theta_i}\right] \propto E\left[\left(\frac{dZ}{d\theta_i}\right)^2\right]$

"Elementary Effects" based Metrics of Morris

If $h_i \to \infty \Rightarrow \gamma(h_i) = V(Z)$

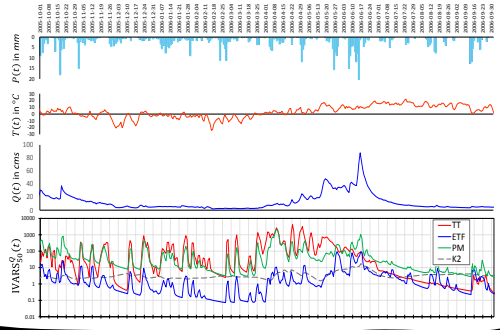
Variance of Response Surface

$S_i^{TO} = \frac{\gamma(h_i) + E[C_{\boldsymbol{\theta}_{-i}}(h_i)]}{V(Z)}$

"Total-Order Effects" of Sobol'

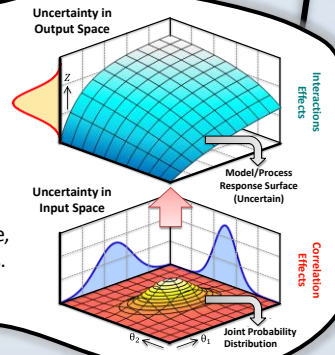
Time-Varying Sensitivity Analysis

Properly accounting for the dynamical nature of Earth and environmental system models, and providing means to compress the full spectrum of sensitivity information across temporal or spatio-temporal domains. (*Gupta and Razavi*, 2018 WRR; *Razavi and Gupta*, 2019 EMS)



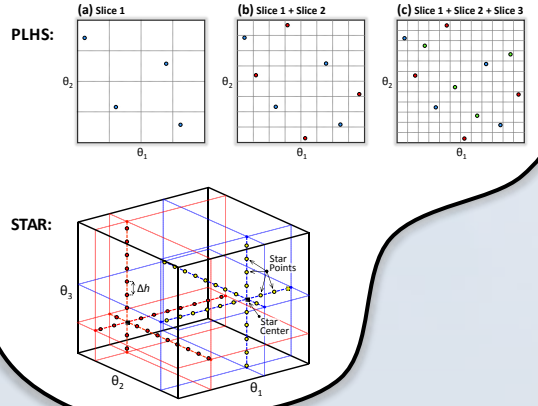
Correlation Effects and Non-Uniformity of Factors

Handling non-uniformly distributed and/or correlated factors efficiently and generating of a range of sensitivity indices, including ones based on derivative, variance, and variogram concepts. (*Do and Razavi*, In Review)



Highly Efficient Sampling Techniques

Including the Progressive Latin Hypercube Sampling (PLHS) and STAR Sampling strategies that maximize robustness and rapid convergence to stable sensitivity estimates (*Sheikholeslami and Razavi*, 2017 EMS).



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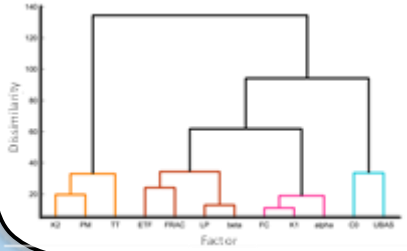
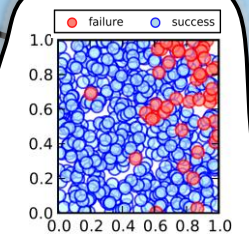
An innovative strategy that employs a clustering mechanism enabled with bootstrap to handle problems involving hundreds of factors and group them based on their sensitivity and function (*Sheikholeslami, Razavi et al.*, 2018 EMS).



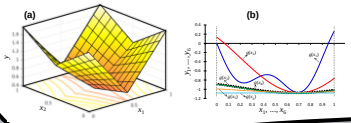


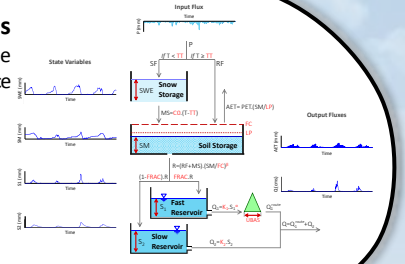
Handling Model Crashes: Model Emulation

Strategies to generate surrogate model responses when a model fails during simulation under particular parameter values, such that the analysis can be completed, while minimizing the impact of those failures on the results. (*Sheikholeslami, Razavi et al.*, 2019 GMDD)

Test Functions and Real-World Case Studies

The ready-to-use collection of many test functions, the HBV-SASK rainfall-runoff model, and MESH land surface model enables the use of VARS-TOOL for a range of learning, teaching, and research purposes. (*Razavi et al.*, 2018 EMS)





HBV-SASK

References:

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VARS-TOOL

Variogram Analysis of Response Surfaces

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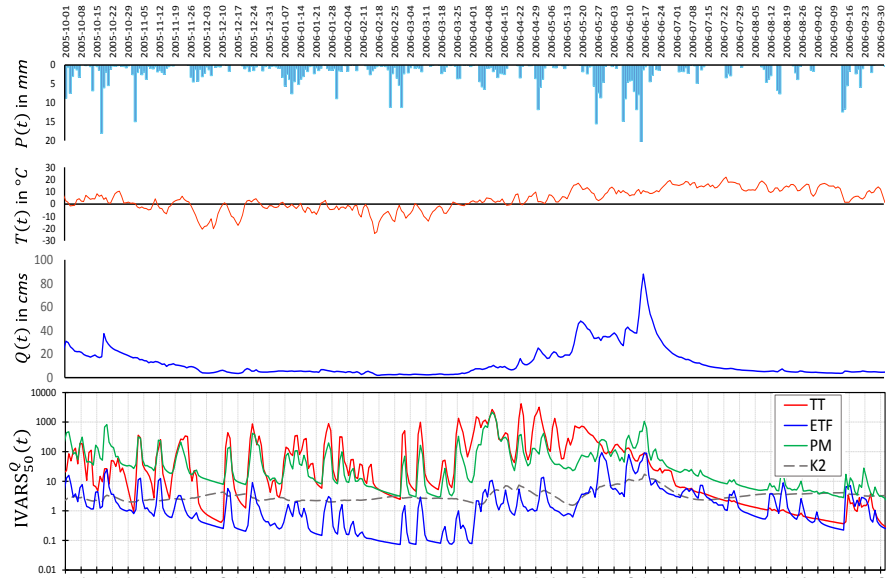

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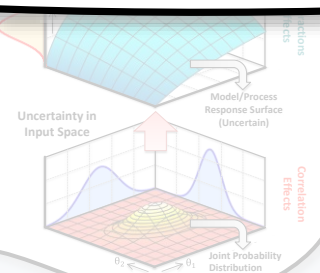

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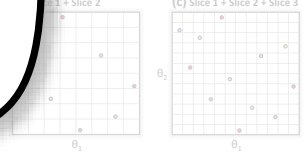

STAR:

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Variogram Analysis of Response Surfaces (VARS)

New Generation of Sensitivity Analysis in Earth and Environmental Systems Models (EESMs)

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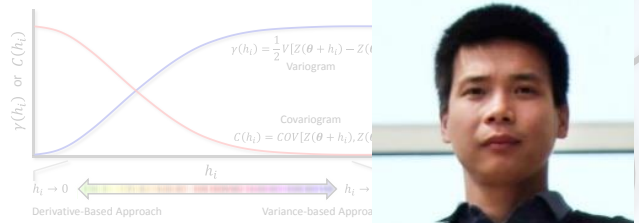

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Properly acc[illegible] system[illegible] s[illegible]

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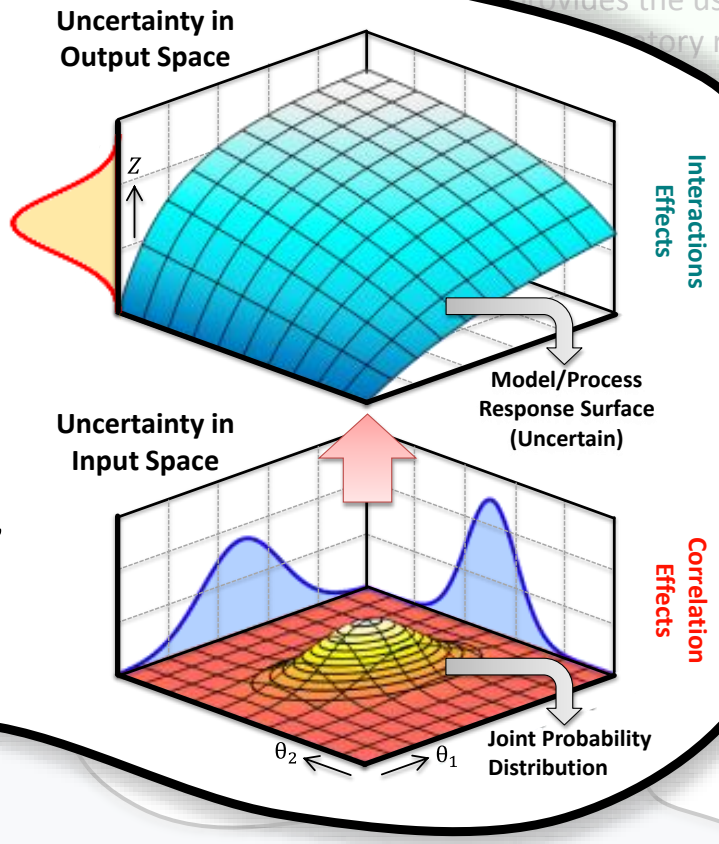

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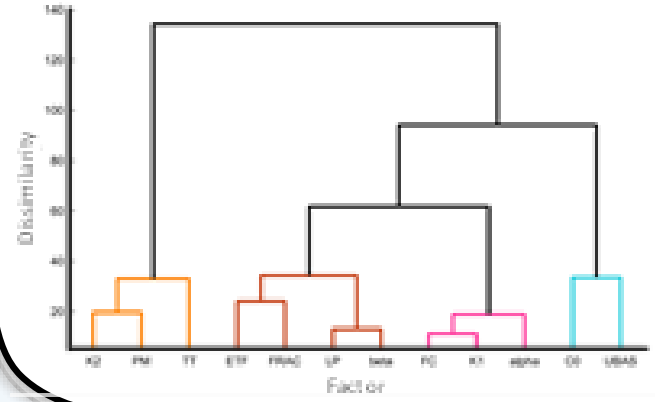

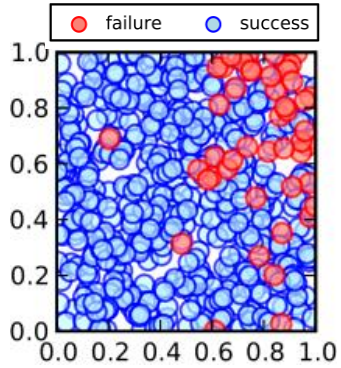

Handling Model Crashes: Model Emulation

Strategies to generate surrogate model responses when a model fails during simulation under particular parameter values, such that the analysis can be completed, while minimizing the impact of those failures on the results. (*Sheikholeslami, Razavi et al.*, 2019 GMDD)

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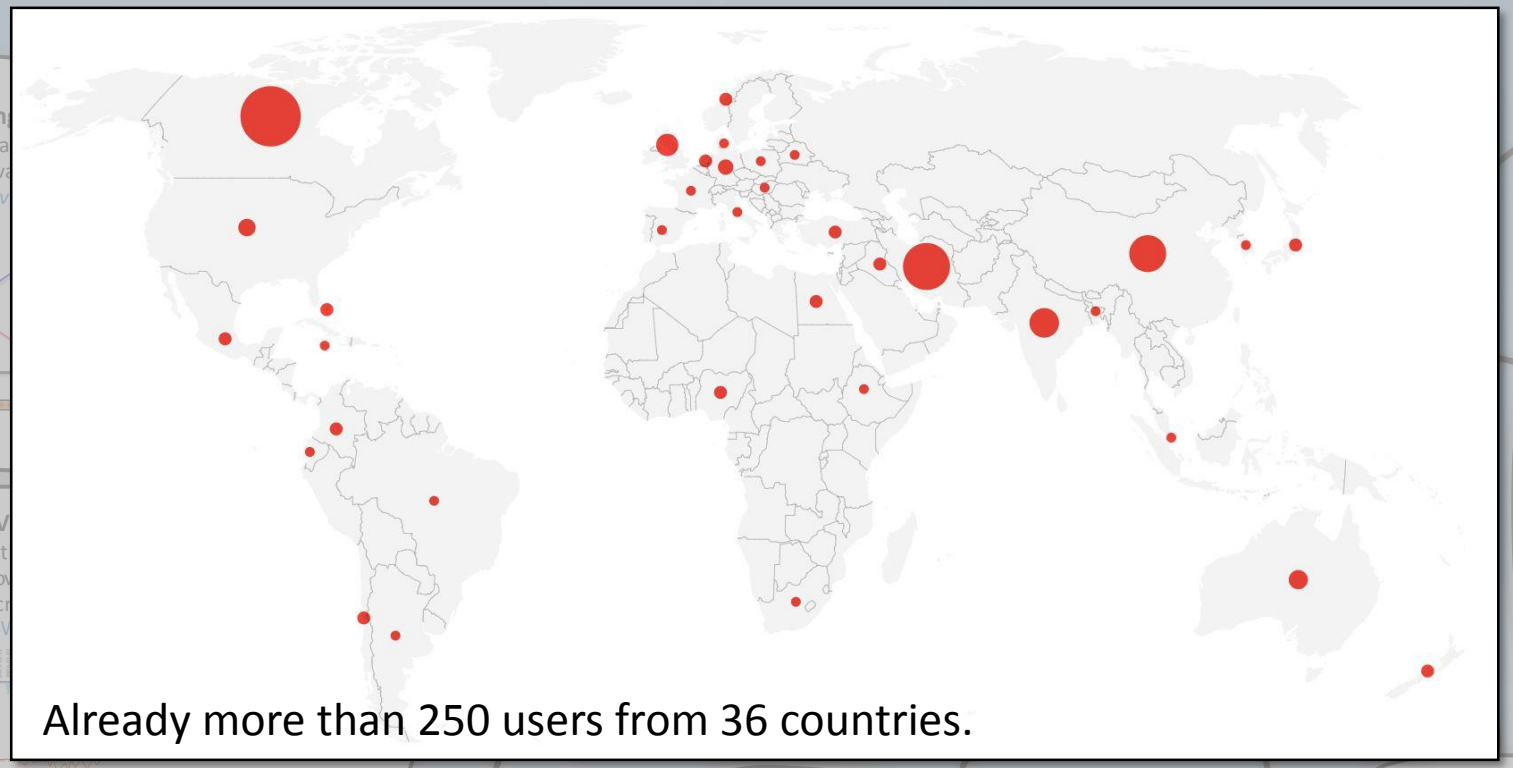

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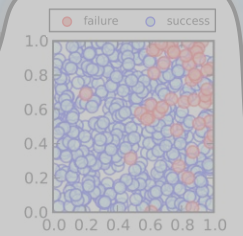
High-Dimensional Problems: Factor Grouping

An innovative strategy that employs a clustering mechanism enabled with bootstrap to handle problems involving hundreds of factors and group them based on their sensitivity and function (*Sheikholeslami, Razavi et al.*, 2018 EMS).



Handling Model Crashes: Model Emulation

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VARS-TOOL: A toolbox for comprehensive, efficient, and robust sensitivity and uncertainty analysis

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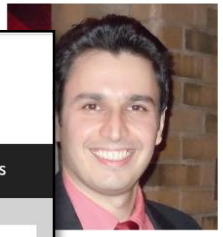
Reframing Sensitivity Analysis in Earth System Models

According to a new study, the performance metric–based methods currently used to evaluate dynamical model sensitivity are based upon faulty reasoning and need to be reenvisioned.

Feature

When Uncertainty Matters

Saman Razavi (University of Saskatchewan;
Deputy Chair of AGU Technical Committee on Hydrologic Uncertainty)



Hydrologic models are widely employed for the simulation of complex physical processes that comprise the Earth's water systems. They have become essential tools for management sion making under uncertainty and non-sta- by providing the capability of prediction and paradigm of "sensitivity analysis" (SA), which seeks to illuminate the controls on model behavior, thereby characterizing the dominant controls on predictive uncertainty.

The "Sparsity of Effects" principle, which originates from the Statistical Design of Experiments, states that the behavior of a system involving several variables is likely to be driven primarily by a small subset of these variables and their low-order interactions (Myers et al., 2011). This principle forms the basis of SA, whereby one aims to attribute the uncertainty in a model prediction to the uncertainties associated with different parameters, and answer a critical question: *when does uncertainty matter?* Imagine that SA could tell you the following about two example parameters in the analysis of a model: parameter A that is highly un-

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