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THE MODELING TRILEMMA:

UNCERTAINTY, COMPLEXITY AND RELEVANCE

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- Prof. A. Saltelli and team, UE JRC, ISPRA (Italy).

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OUTLINE

- Models and Uncertainty
- Uncertainty, Complexity and Relevance
- A New Hope? Global Sensitivity/Uncertainty Analysis
- Case study 1: Complex modeling in Everglades
- Case study 2: Sea level rise and coastal habitat
- Take Home Message: Opportunities/challenges

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- Models are built in the present of **uncertainty**
  - Input factors (parameters, initial and boundary conditions)
  - calibration data (error, scale, etc.)
  - equations/model structure…
- This is a source of growing **anxiety** among developers and users of dynamic, complex simulation models
- In particular, there is anxiety about the effects of various sources of uncertainty on **model output**

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Have models fallen out of grace?

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'…all models are wrong, some are useful'

W.E. Deming

George Box, the industrial statistician, is credited with the quote, although probably the first to say that was W. Edwards Deming.

G. Box

[from A. Saltelli. 2008. SAMO'08. Venice, Italy]

We just can't predict, concludes N. N. Taleb, and we are victims of the "ludic fallacy", of "delusion of uncertainty", and so on... Modelling is just another attempt to 'Platonify'reality...

Nassim Nichola Taleb, The Black Swan, Penguin, London 2007

[from A. Saltelli. 2008. SAMO'08. Venice, Italy]

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"Groundwater models cannot be validated"

(Konikov and Bredehoeft, 1992)

"Verification, Validation and Confirmation of numerical models in the earth sciences".

(Oreskes et al. 1994, *Science*)

According to Oreskes, natural systems are never closed, and models put forward as description of these are never unique.

Models can never be 'verified' or 'validated', but only 'confirmed' or 'corroborated'.

[from A. Saltelli. 2008. SAMO'08. Venice, Italy]

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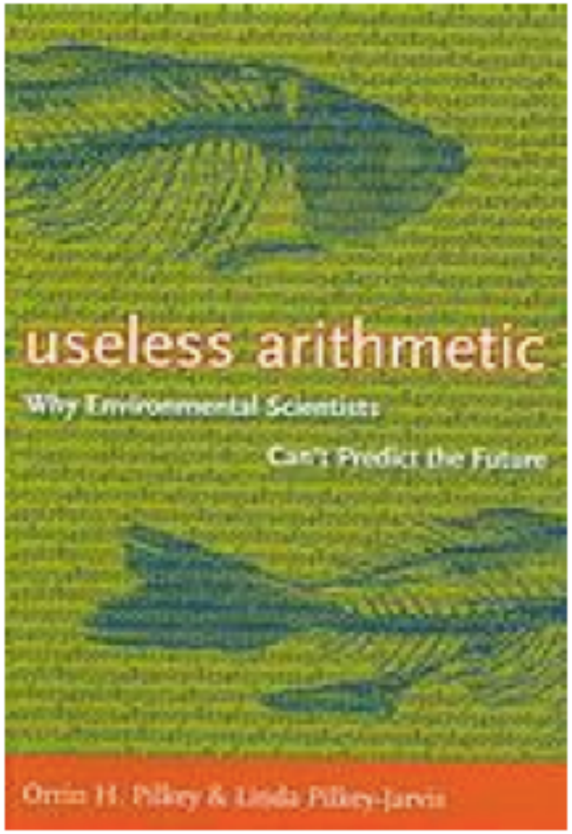

Useless Arithmetic: Why Environmental Scientists Can't Predict the Future

by Orrin H. Pilkey and Linda Pilkey-Jarvis

‘Quantitative mathematical models used by policy makers and government administrators to form environmental policies are seriously flawed’

[from A. Saltelli. 2008. SAMO’08. Venice, Italy]

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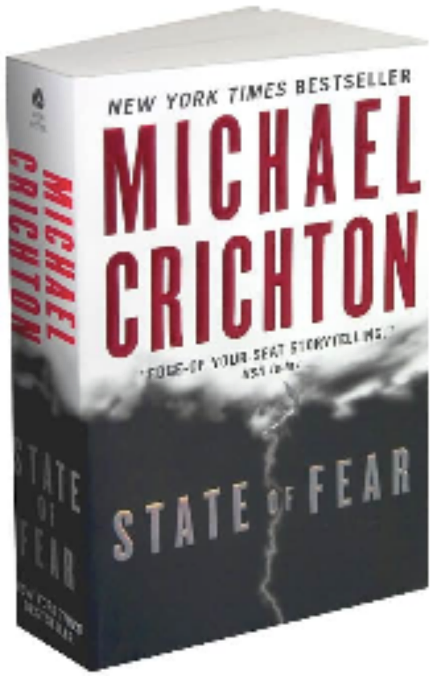

… in the context of climate change….

“They talk as if simulation were real- world data. They ‘re not. That‘s a problem that has to be fixed. I favor a stamp:

WARNING: COMPUTER SIMULATION – MAY BE ERRONEOUS and UNVERIFIABLE

Like on cigarettes [...]”
Op. Cit. p. 556 .

[from A. Saltelli. 2008. SAMO’08. Venice, Italy]

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The Real Issue…

- The real issue, when modeling, is the need to assess uncertainty (**transparency**) and how to develop reliable procedures for this.

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **20**, 0–0 (2006)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.6396

On undermining the science?

Keith Beven*
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E-mail: k.beven@lancaster.ac.uk

At the 2006 European Geophysical Union meeting in Vienna, I was challenged (and not for the first time) about overemphasising the issue of model uncertainty and model rejection, with the consequent danger of undermining the confidence of stakeholders and users of model predictions, in the science on which they are based. It is therefore interesting to consider whether this is a reasonable charge.

We can break the issue down into three parts, which will be considered in turn with a view to starting a debate, in *HPToday*, about the issues raised:

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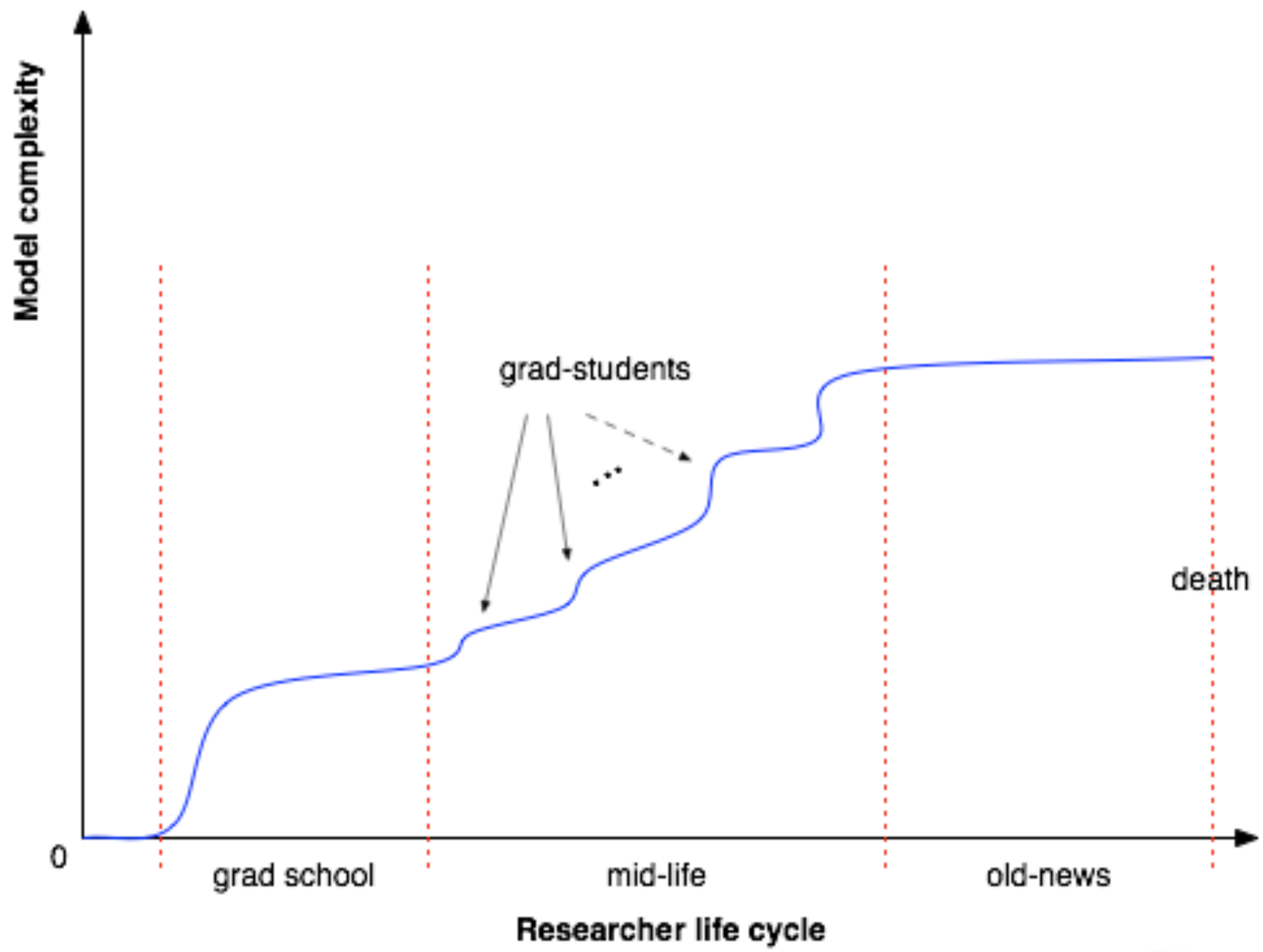
Life-cycle of a model



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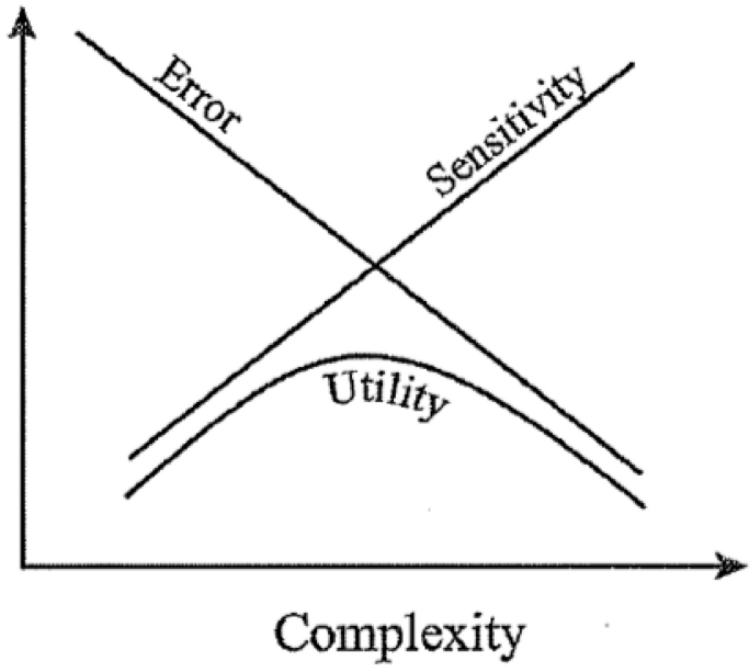
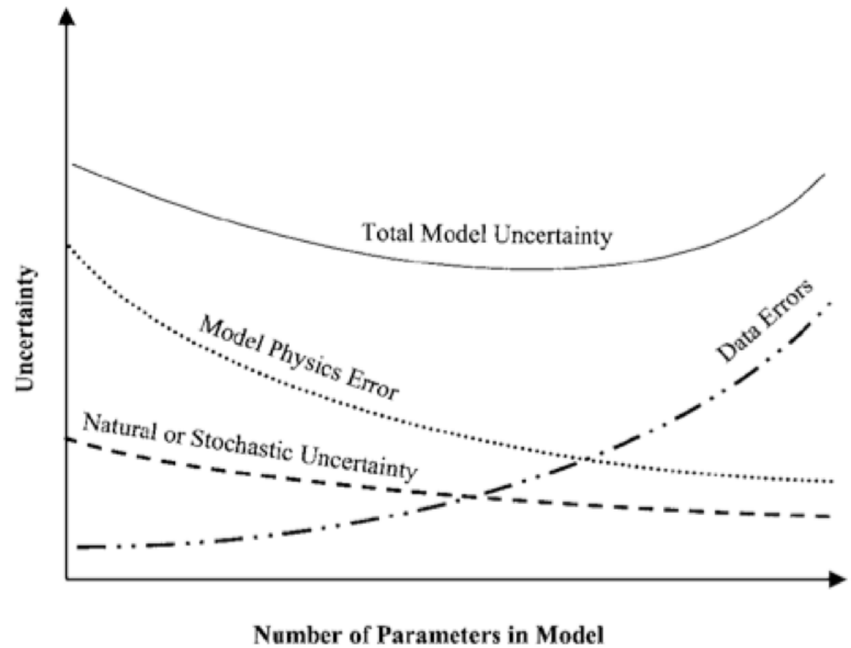
Model Complexity vs. Uncertainty: A Tug of War?



(Snowling and Kramer,1991)



(Hanna, 1993)

Model RELEVANCE: significance with respect to the output(s) of interest (objective functions)

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Complexity vs. Relevance Conundrum

As model complexity increases it leads to:

- Over-parameterization
- Hard/impossible to parameterize
- Equifinality, non-uniqueness
- …
- Loss of **RELEVANCE**

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Complexity vs. Relevance Conundrum

"Principle of Incompatibility" (Zadeh, 1973)

*…as the **COMPLEXITY** of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which **PRECISION** and **RELEVANCE** become almost **mutually exclusive characteristics**…"*

Lofti Zadeh

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When to Stop?

- What processes should be added?
- How does this impact uncertainty?
- Can the real system behavior be modeled?
- Will the model be usable based on available knowledge of the system (input factors)?

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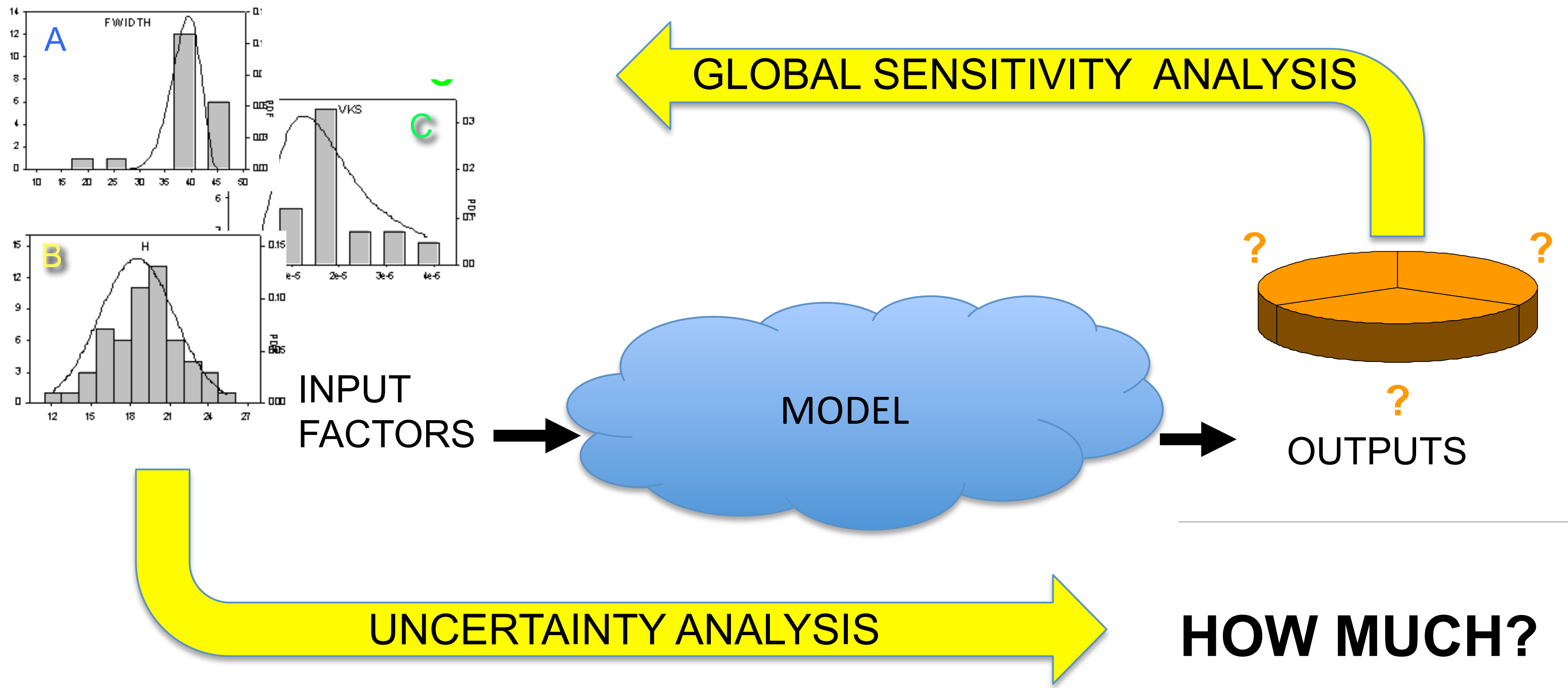
Global Sensitivity/Uncertainty Analysis

WHY? **Apportions** output variance into input factors



Propagates input factor variability into output

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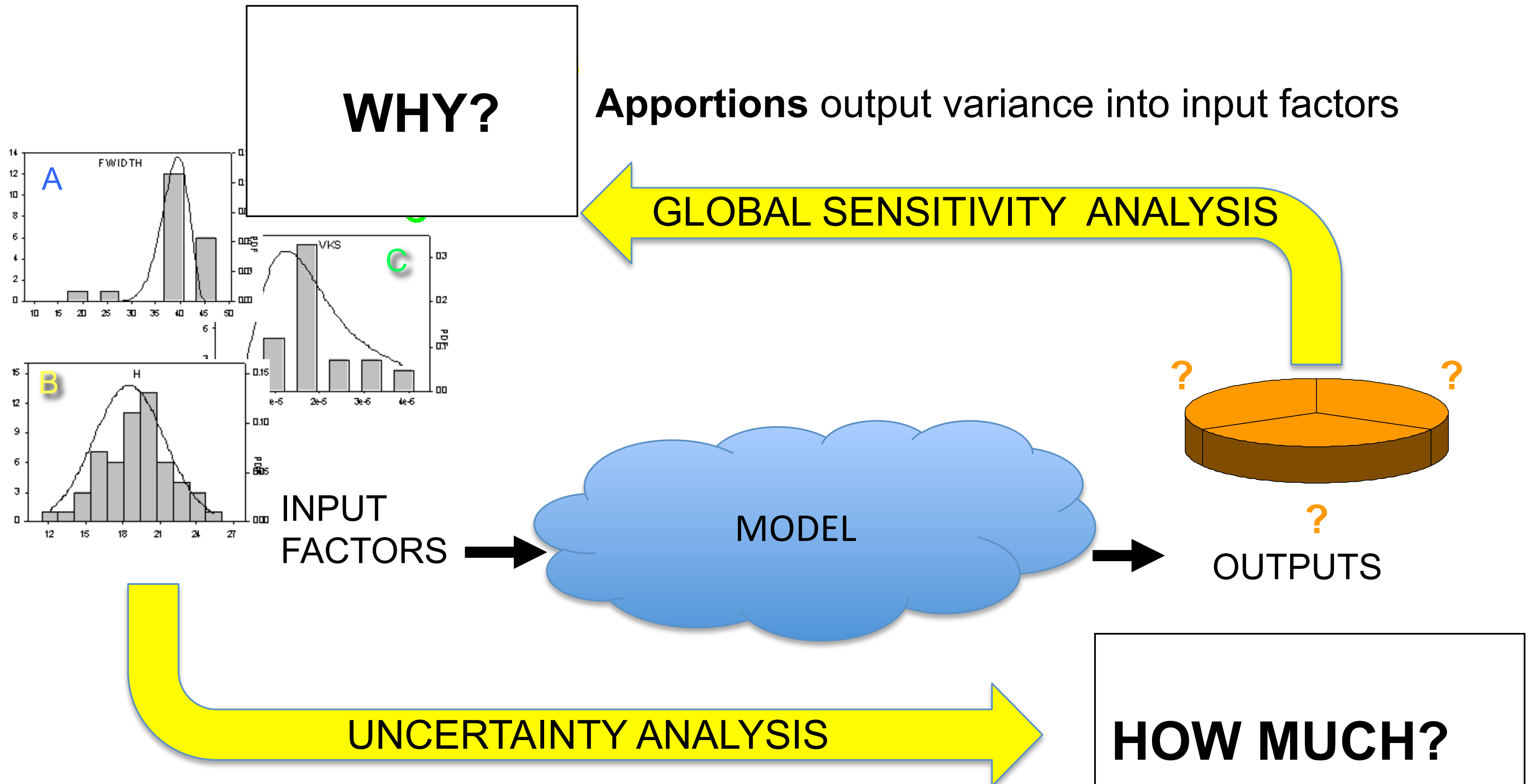
Global Sensitivity/Uncertainty Analysis



Propagates input factor variability into output

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Global Sensitivity Analysis

- Local vs. global sensitivity

	Classic SA	GSA
Model	Linear Monotonic additive	No assumptions
No. of factors	O-A-T	All
Factor range	Local (derivative)	Whole PDF
Interactions	No	Yes

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Global Sensitivity Analysis

HOW MUCH, WHY, WHEN…

- surprise the analyst,
- find technical errors in the model,
- gauge model adequacy and relevance,
- identify critical regions in the space of the inputs (including interactions),
- establish priorities for research,
- simplify models,
- verify if policy options make a difference or can be distinguished.
- anticipate (prepare against) falsifications of the analysis
- …

[Saltelli, 2006, SAMO Venice]

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GSA/UA evaluation framework

For model with large number of factors a two-step global process is recommended:

1. **Qualitative Screening** with limited number of simulation (p.ej. Morris Method)
   Ranking and selection of important factors (μ*); Presence of interactions (σ)

2. **Quantitative Variance-based** method: (p.ej. Extended Fourier Analysis of Sensitivity Test - Extended FAST, Sobol, etc.)
   First order indexes (S_i, direct effects); Total order (S_{Ti}, interactions), Uncertainty analysis

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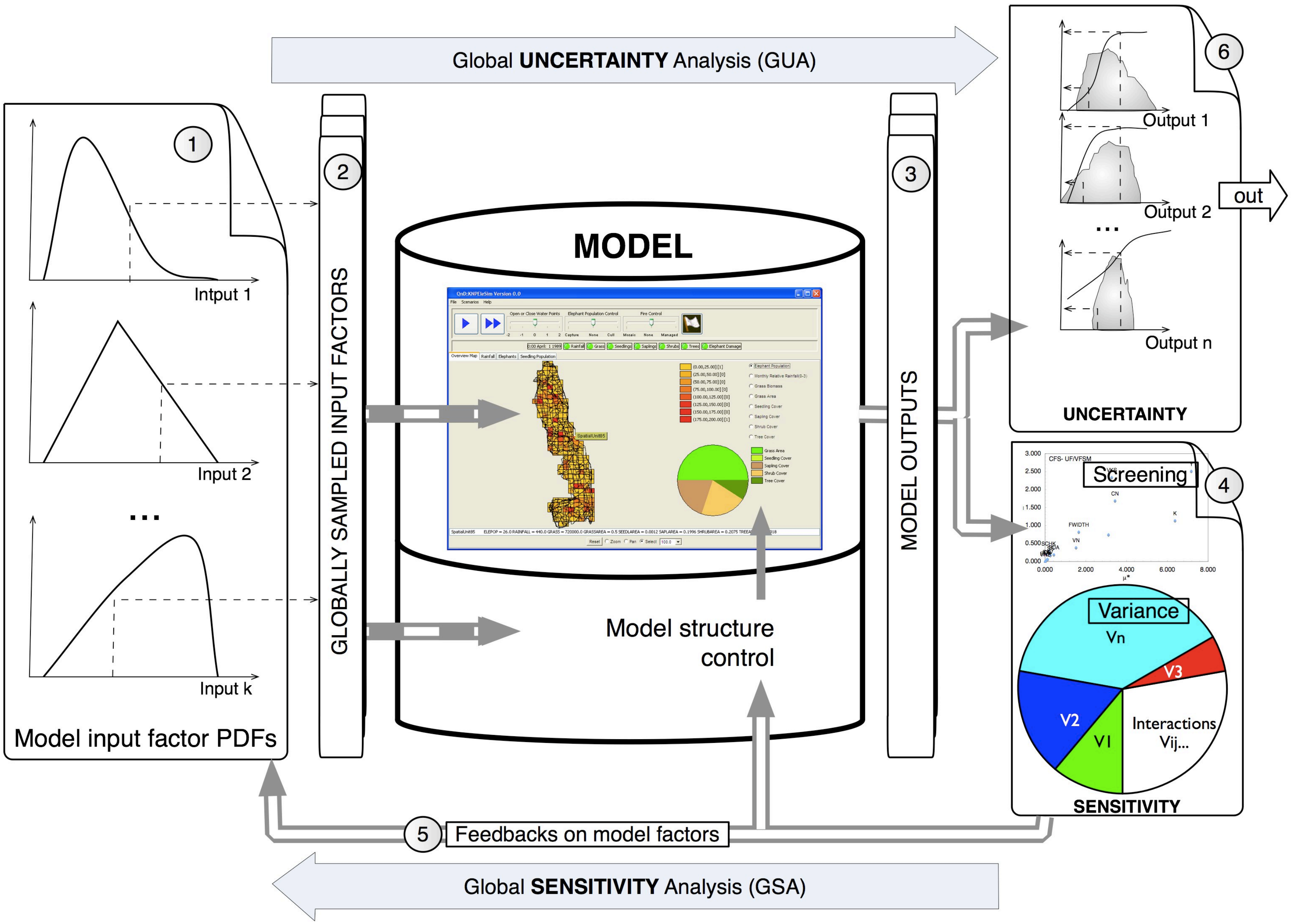
GSA/UA evaluation framework



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A New Hope?

- A step-wise model-building approach integrated with global uncertainty and sensitivity analysis to evaluate sources of uncertainty can be used to guide model development across increasing levels of model complexity,
  - Avoid unintended effects
  - Achieve precision and capacity of the model to reproduce real, and complicated, system responses (alternative states, etc.)

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A Complex Problem, Everglades, USA

- **Currently the Water authority (SFWMD) is deploying a hydrodynamic regional simulation model (RSM) to manage the large and complex south Florida Everglades region.**
- **Because of the current emphasis on water quality in the Restoration process, water quality components specific to the area needed to be developed for this and other models.**
- **A new biogeochemical model to predict solute pollutant (P) reaction and transport model suitable for conditions present in coastal wetlands of Southern Florida was developed and integrated into RSM.**
- No agreement among experts on what components (complexity) are needed to simulate these processes

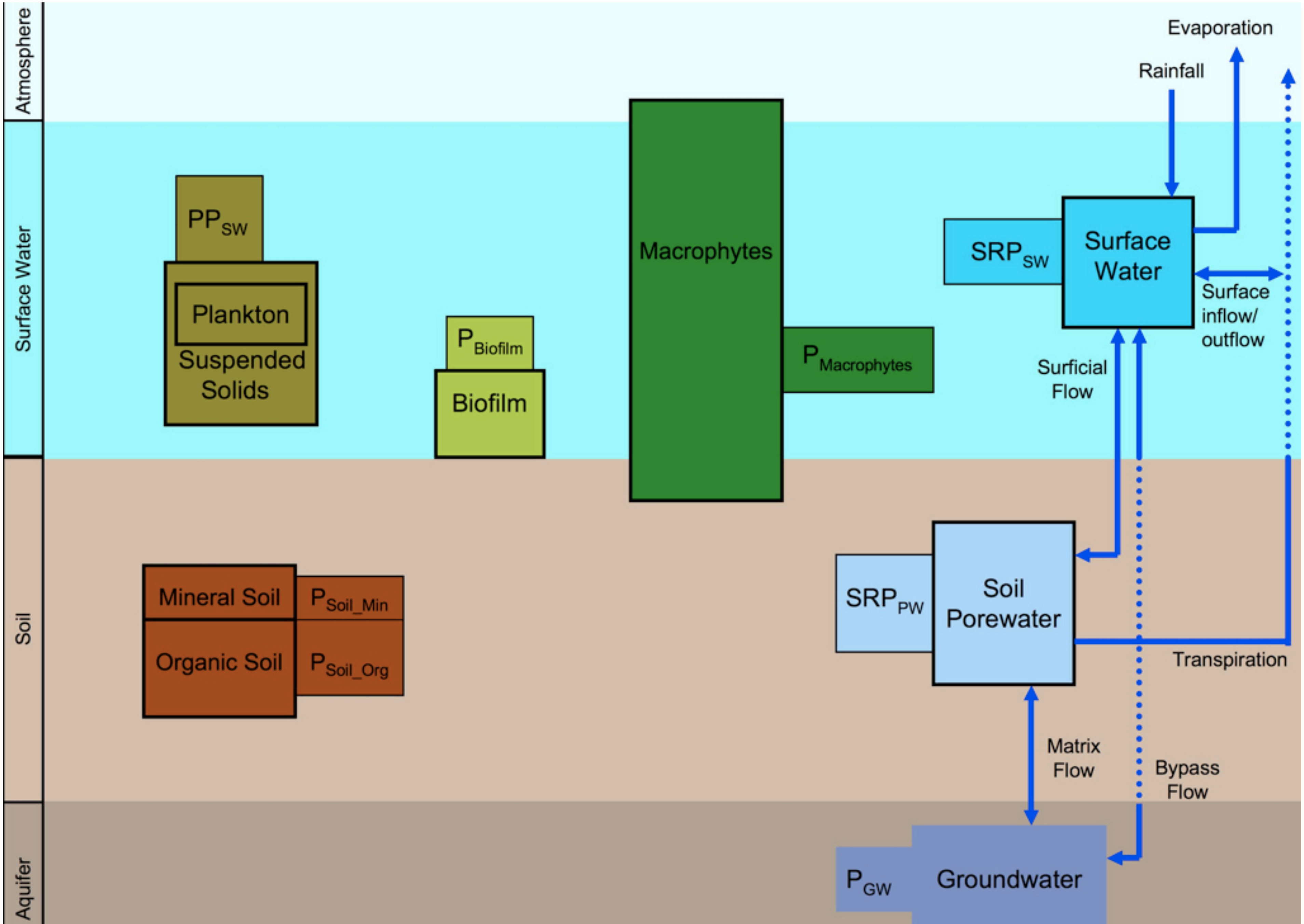

Fig. 1 Water Flows

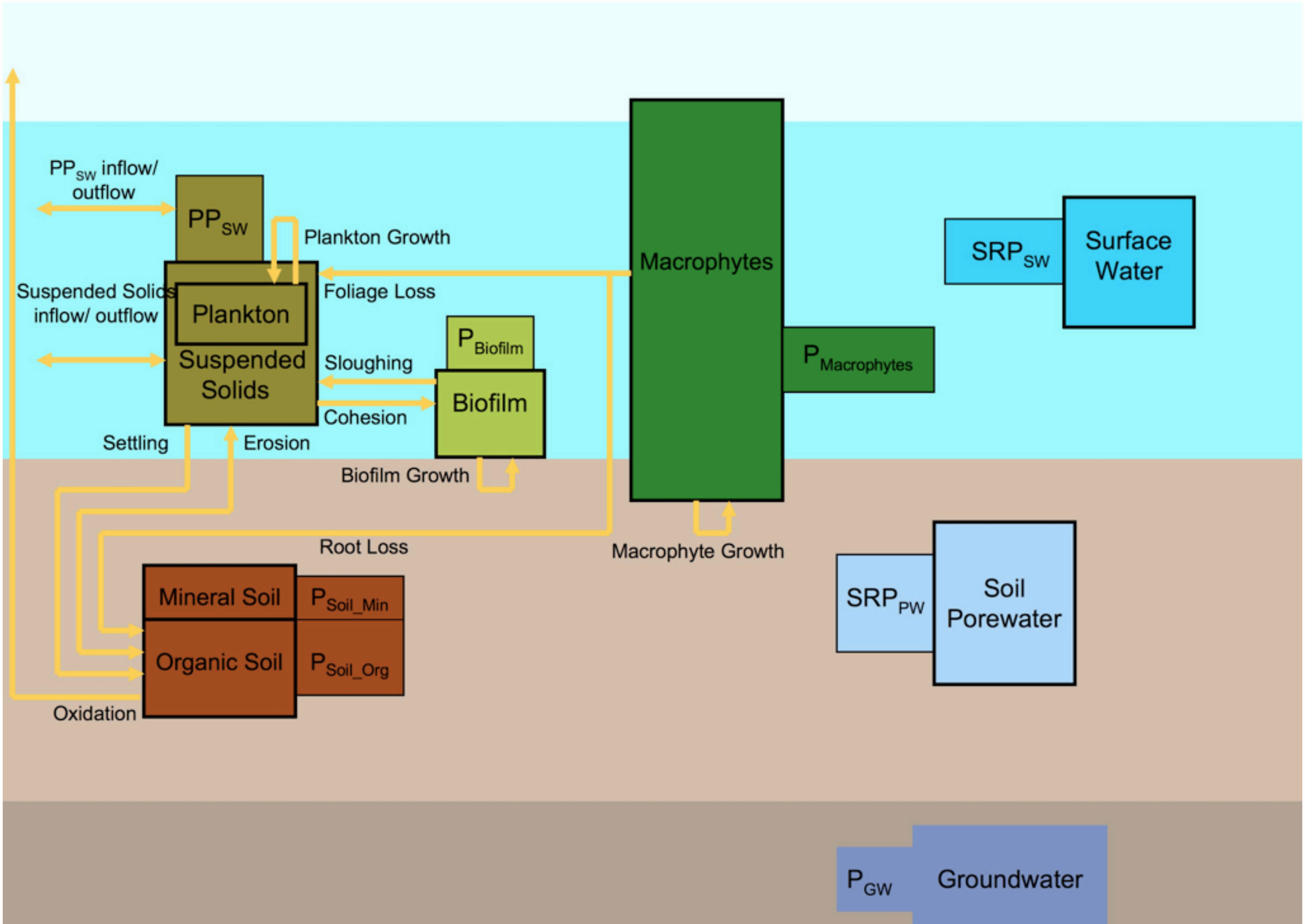

Fig. 2 Material Flows

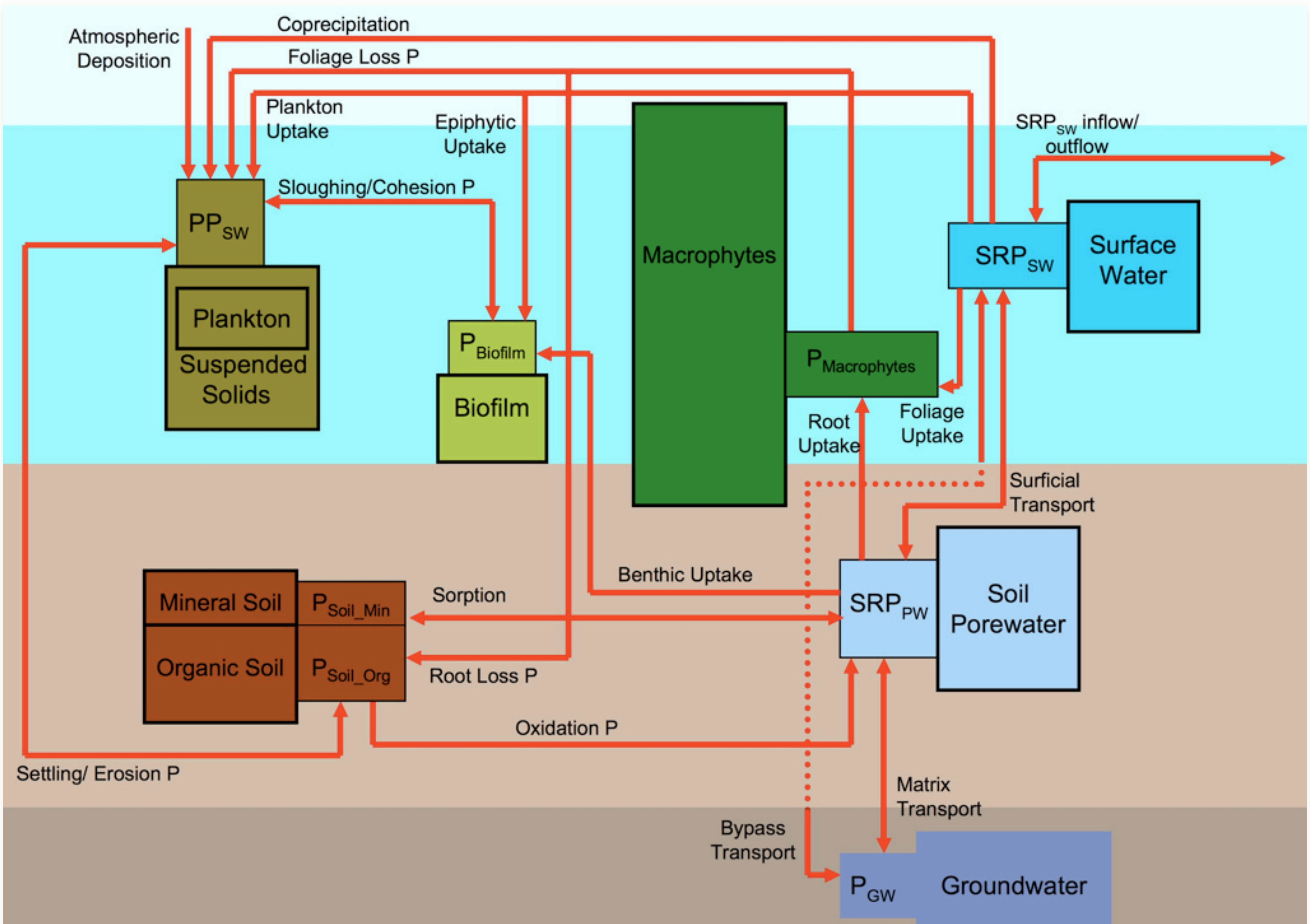

Fig. 3 Phosphorus Flows

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Complex System Behavior - Relevance

- Two stable system states are observed in these wetland systems (Beisner et al., 2003; Scheffer, 1990; Scheffer et al. 1993)
  - algae (phytoplankton)-dominated state
  - macrophyte-dominated (saw-grass/cat-tails)

- In addition to **complexity** vs. **uncertainty/ sensitivity** changes, what is the model complexity needed to simulate alternative equilibrium states (**relevance**)?

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When to Stop?

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Complexity vs. Relevance Analysis

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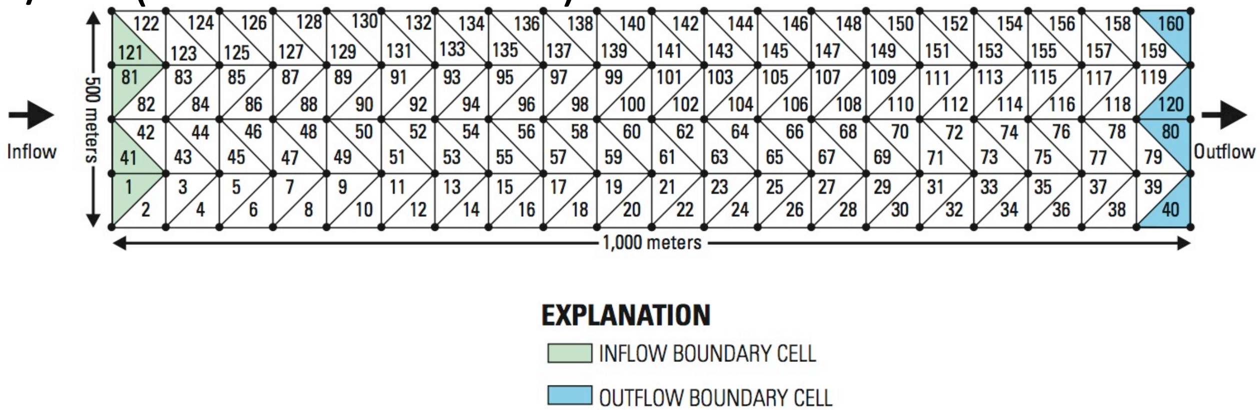
- Run GSA/UA (Morris and eFAST) for a test domain



- Effect of 3 alternative complexity levels
- Effect of 3 Engineering Designs (velocity= 50, 100 & 500 m/d)

Table 5-4. RSM/WQ simulations run in the analysis

Level	No. velocities	No. parameter	No. of simulations		
			Morris	FAST	Total
1	3	8	90x3	5000x3	15270
2	3	12	130x3	5004x3	15402
3	3	16	170x3	5008x3	15534
		Total simulations=	1170	45046	46206

- Studied many outputs – here we present surface water dissolved P (C^{P}_{sw})

Jawitz, Muñoz-Carpena, Muller and James. 2008. U.S. Geological Survey Scientific Investigations Report 2008-5029. http://pubs.usgs.gov/sir/2008/5029

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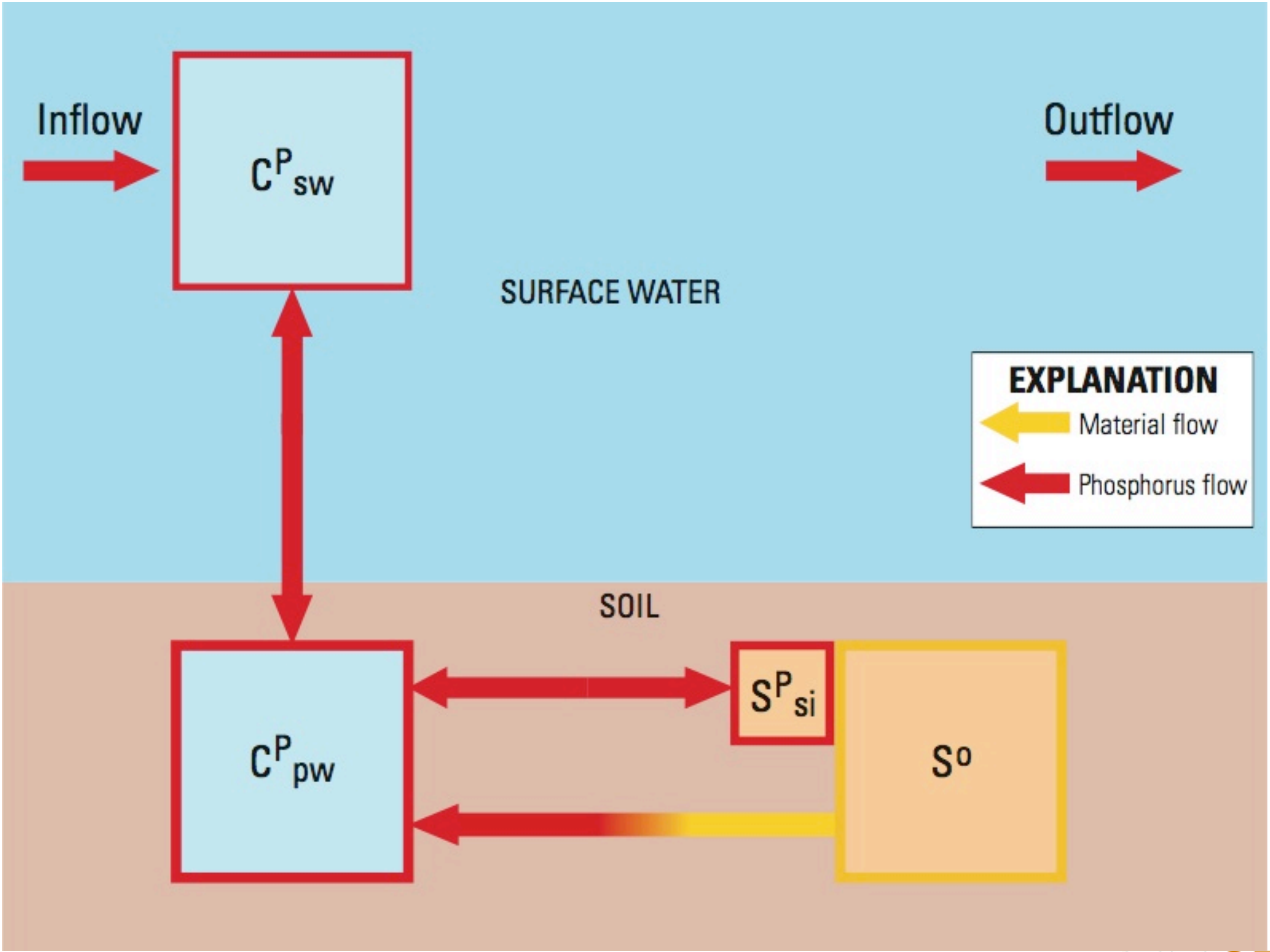
Level 1



Jawitz, Muñoz-Carpena, Muller and James. 2008. U.S. Geological Survey Scientific Investigations Report 2008-5029. http://pubs.usgs.gov/sir/2008/5029

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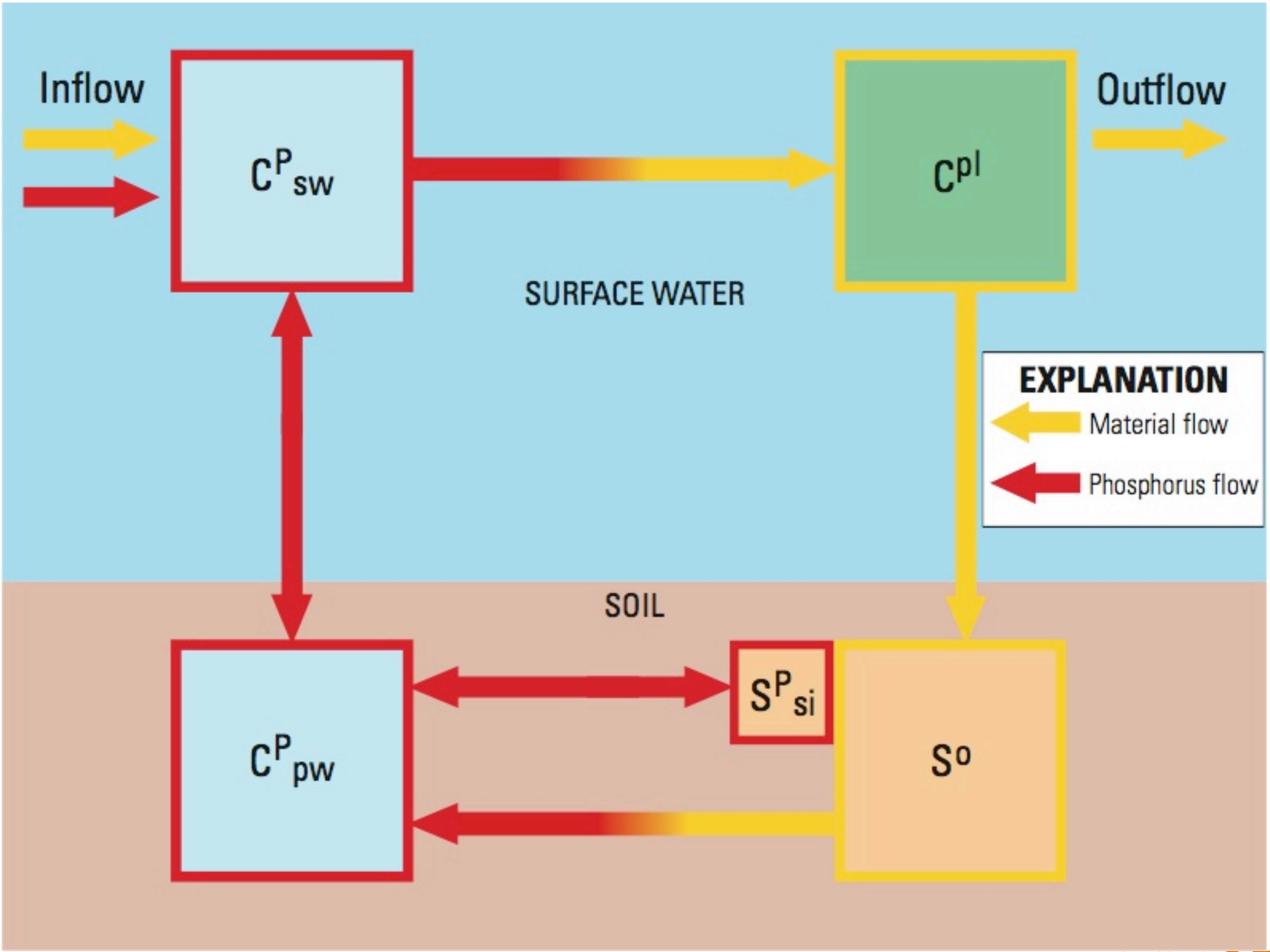
Level 2



Jawitz, Muñoz-Carpena, Muller and James. 2008. U.S. Geological Survey Scientific Investigations Report 2008-5029. http://pubs.usgs.gov/sir/2008/5029

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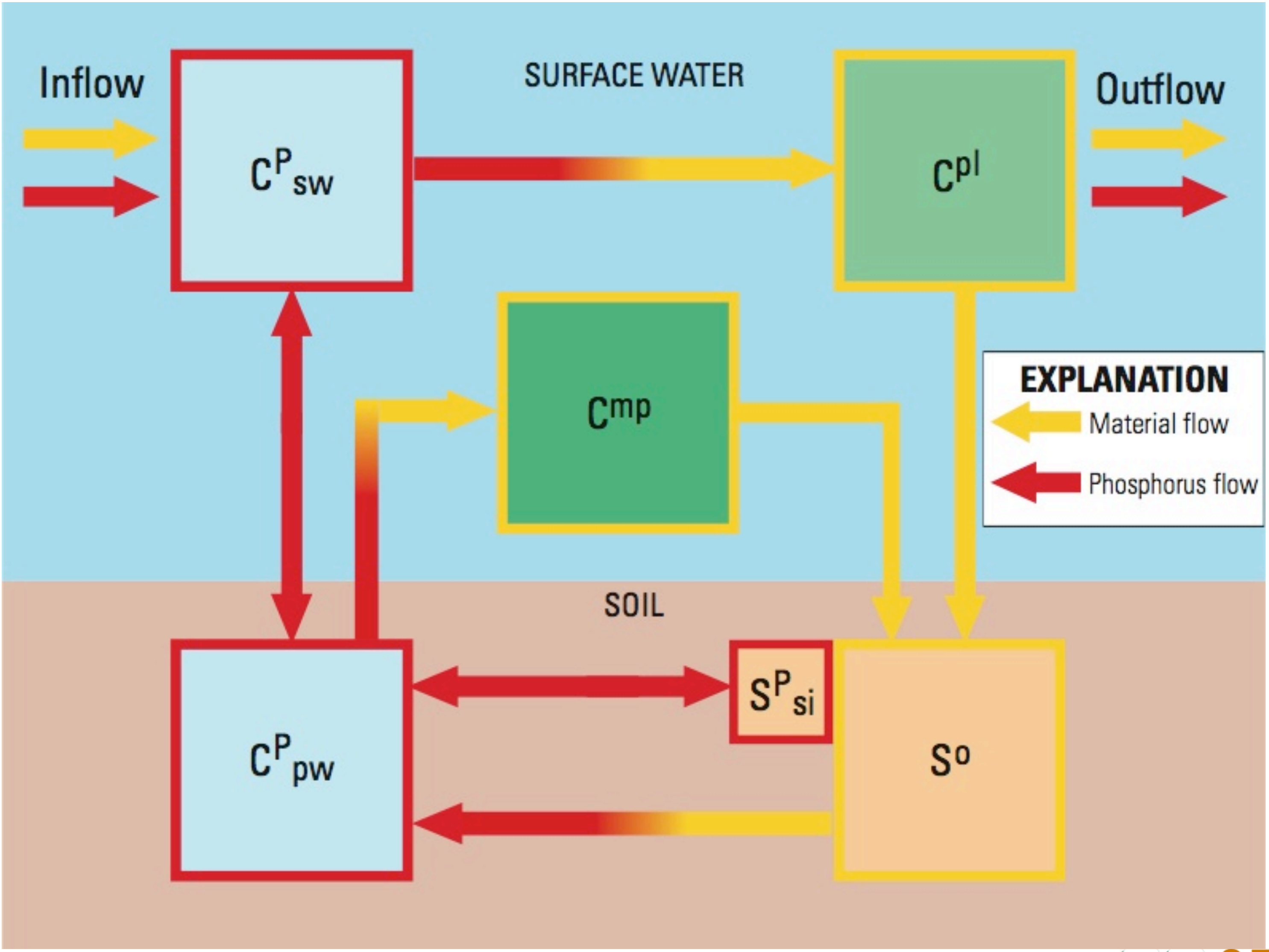
Level 3



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Input factor probability distributions

Parameter definition	Symbol	Distribution	Units	Complexity		
				L1	L2	L3
Coefficient of diffusion	k_{df}	β $(7\times10^{-10}, 4\times10^{-9})$	m^2/s	x	x	x
Coefficient of adsorption	k_d	β $(8\times10^{-6}, 11\times10^{-6})$	m^3/g	x	x	x
Soil porosity	θ	β (.7, 0.98)	Unitless	x	x	x
Soil bulk density	ρ_b	β (.05, 0.5)	Unitless	x	x	x
Soil oxidation rate	k_{ox}	β (.0001, 0.0015)	1/d	x	x	x
P mass fraction in organic soil	C_{so}^P	β (.0006, 0.0025)	Unitless	x	x	x
Longitudinal dispersivity	λ_l	U (70, 270)	m	x	x	x
Transverse dispersivity	λ_t	U (70, 270)	m	x	x	x
Plankton growth rate	k_g^{pl}	β (.2, 2.5)	1/d		x	x
Plankton half saturation constant	$k_{1/2}^{pl}$	β (.005, 0.08)	g/m^3		x	x
Plankton settling rate	k_{st}^{pl}	β $(2.3\times10^{-7}, 5.8\times10^{-6})$	m/s		x	x
P mass fraction in plankton	C_{pl}^P	b (.0008, 0.015)	Unitless		x	x
Macrophyte growth rate	k_g^{mp}	β (.004, 0.17)	1/d			x
Macrophyte half saturation constant	$k_{1/2}^{mp}$	β (.001, 0.01)	g/m^3			x
Macrophyte senescence rate	k_{sn}^{mp}	β (.001, 0.05)	1/d			x
P mass fraction in macrophytes	C_{mp}^P	β (.0002, 0.005)	Unitless			x

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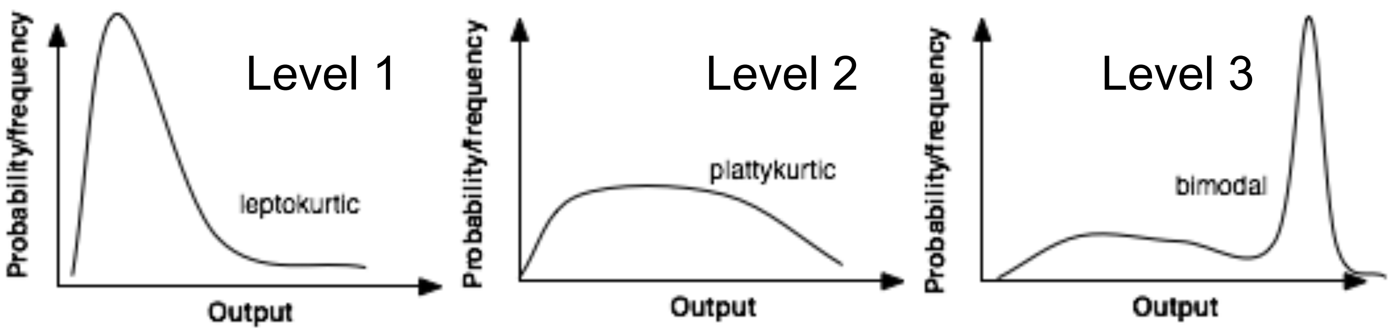
Uncertainty, complexity and relevance

- Changes of the output PDFs w/complexity



- At level 3, the platykurtic area represents conditions of phytoplankton dominance and the second equilibrium dominance of macrophytes → **RELEVANCE**

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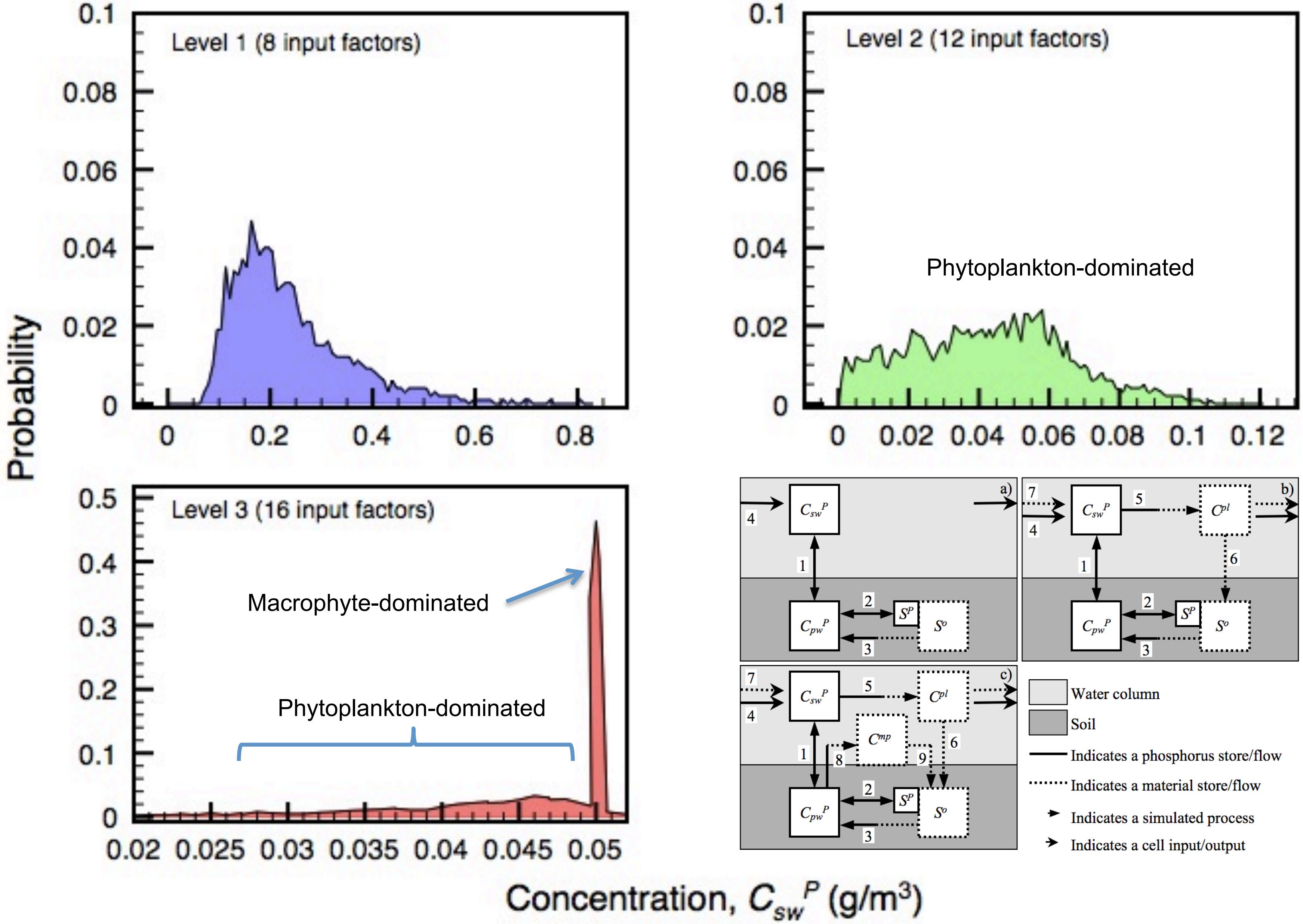
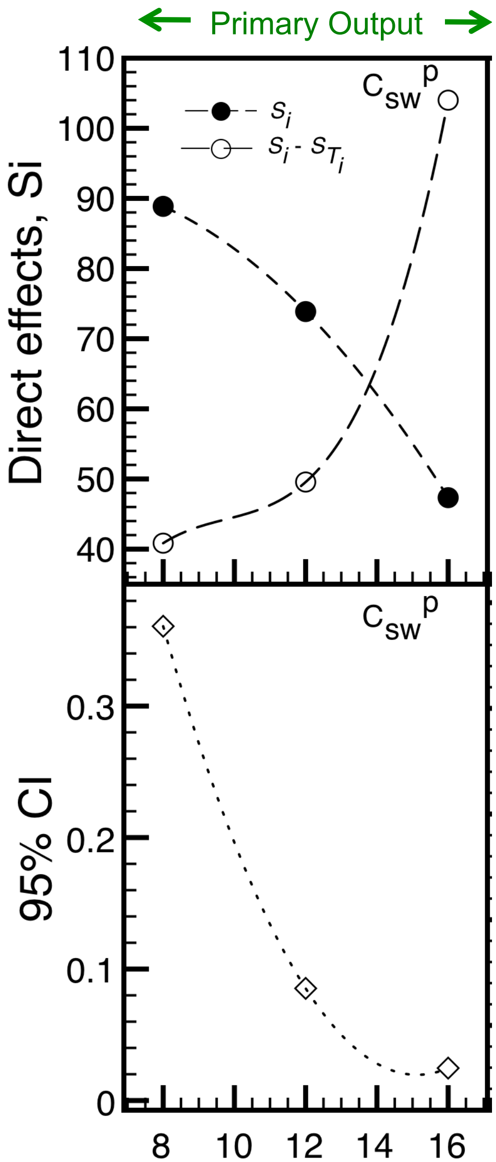
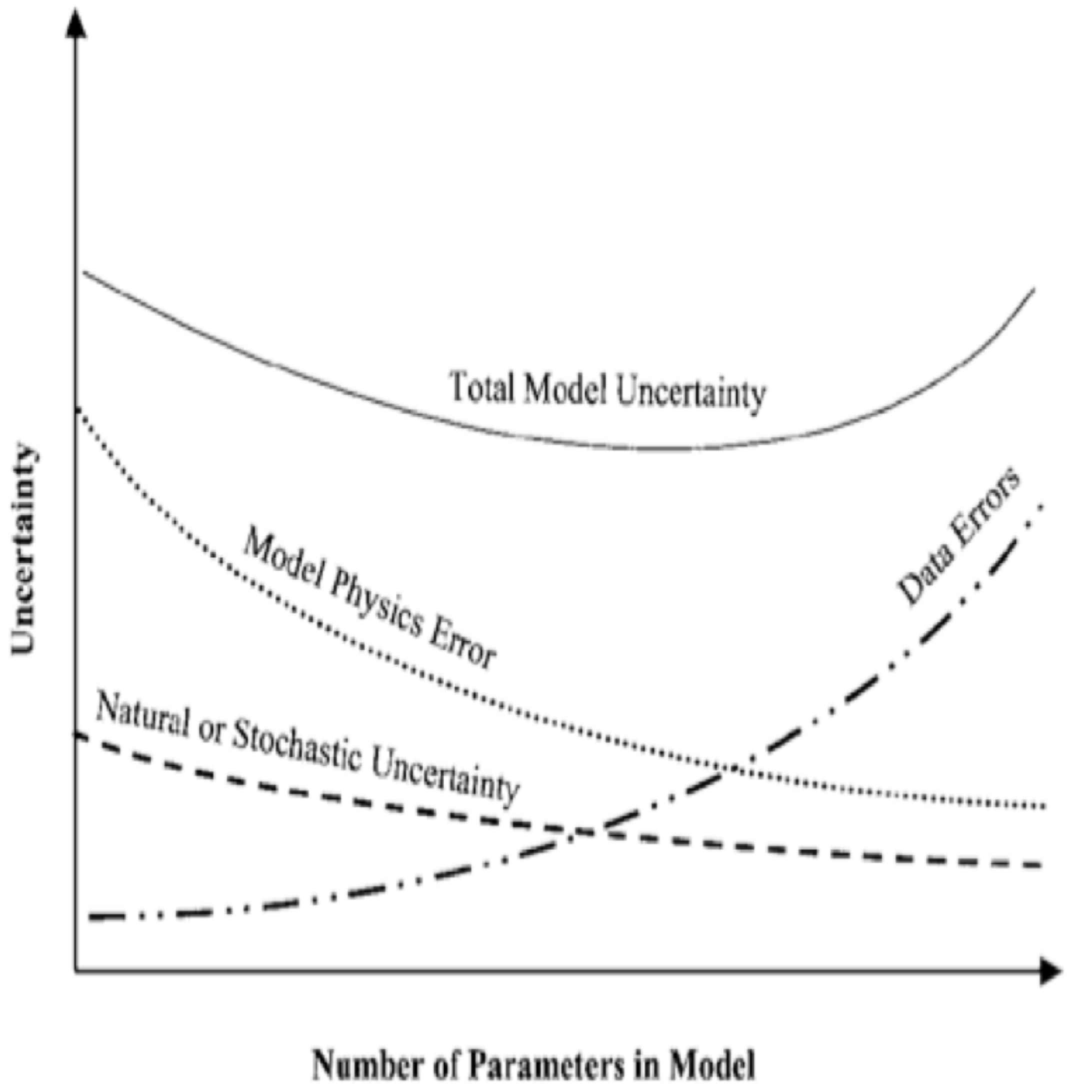
Output PDF



Level 1 (8 input factors)
Level 2 (12 input factors)
Phytoplankton-dominated
Level 3 (16 input factors)
Macrophyte-dominated
Phytoplankton-dominated
Probability
Concentration, C_{sw}^P (g/m^3)
Water column
Soil
Indicates a phosphorus store/flow
Indicates a material store/flow
Indicates a simulated process
Indicates a cell input/output

Sensitivity and uncertainty vs. complexity





Number of input factors

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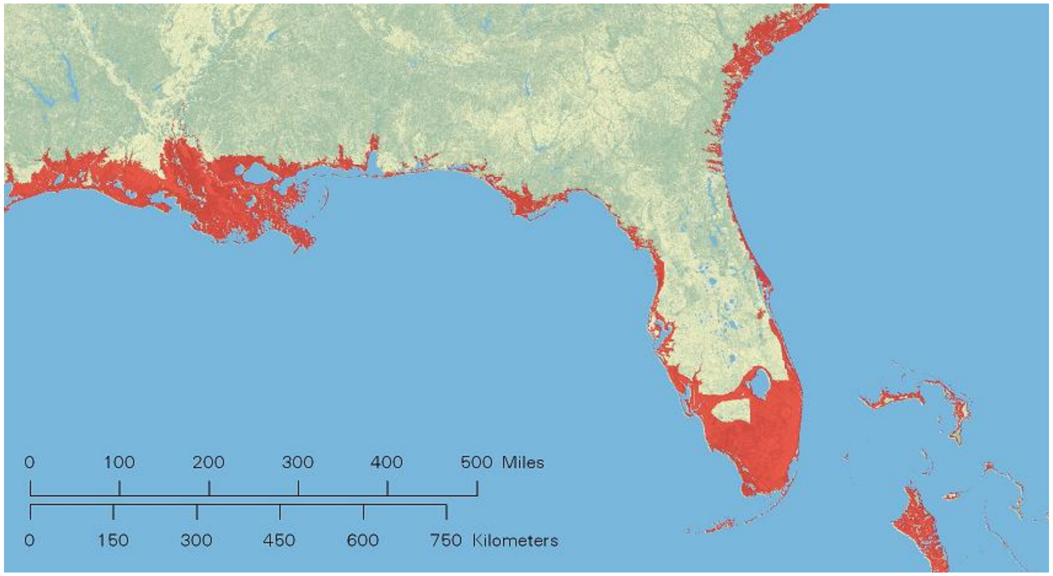
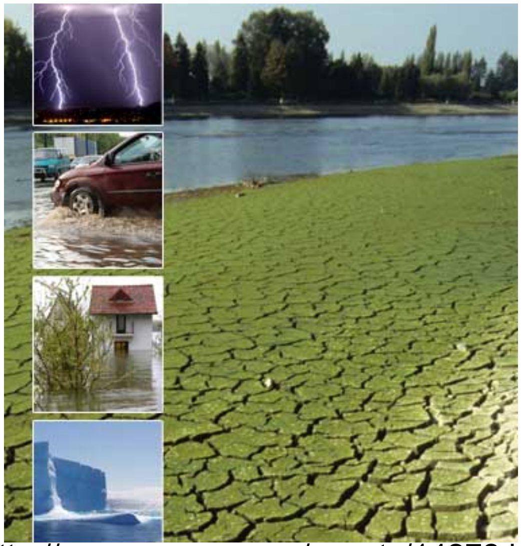
The problem: threatened coastal habitats

- Sea level rise due to climate change
- Land use change (urbanization)
- Hurricane frequency





http://www.cpsu.org.au/events/14272.html

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Military areas are important habitats

- Important forage areas and nesting habitats for endangered shoreline birds

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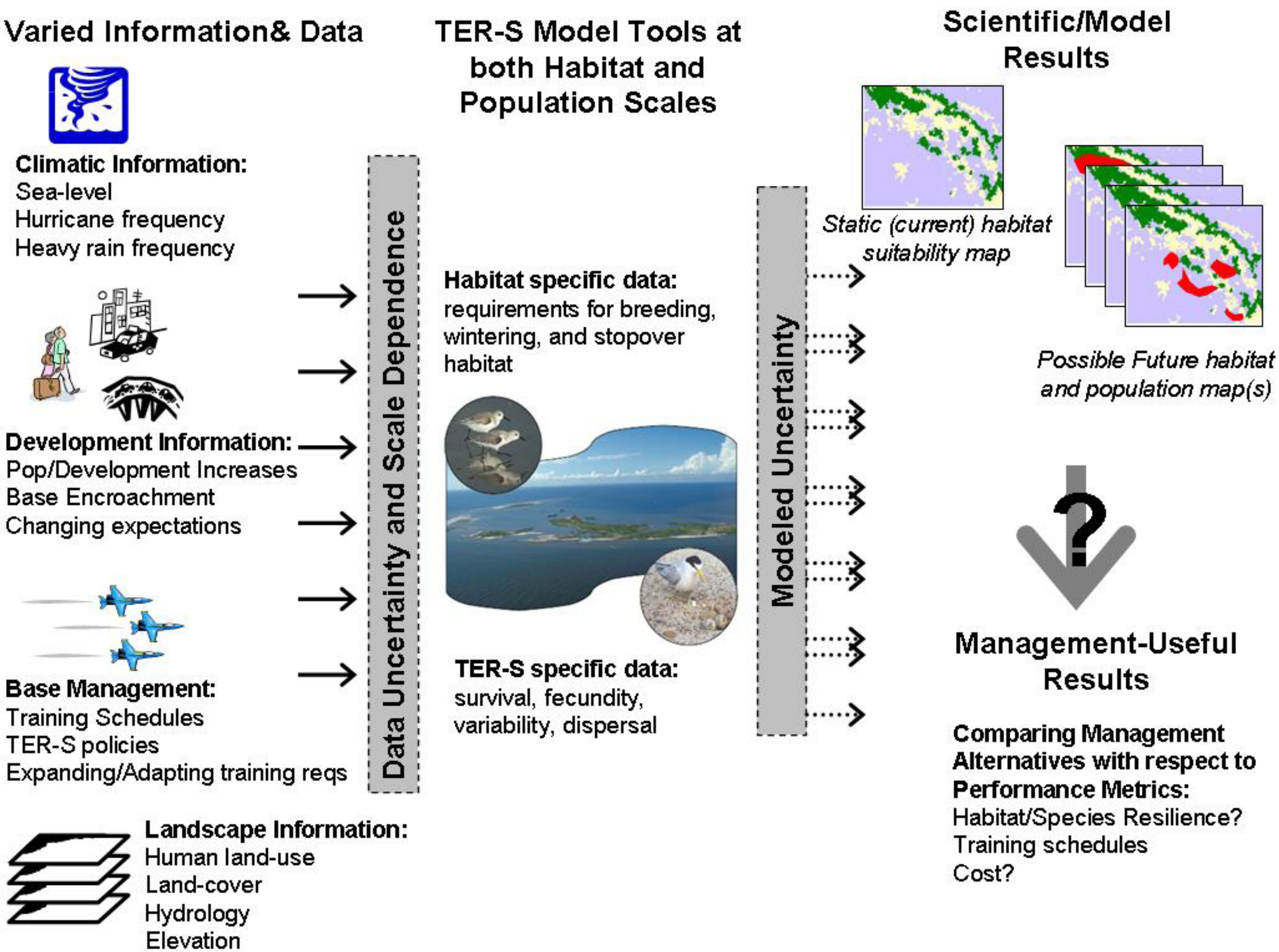
Conceptual model



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Objectives

- Create a systematic modelling tool that integrates climate data, land use and ecosystem information to
- Evaluate the effect of climate alteration on habitats and population dynamics of birds

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Motivating questions:

1. Will beach (bird habitat) disappear due to climate change/sea level rise?
2. If so, what factors will affect the loss of habitat

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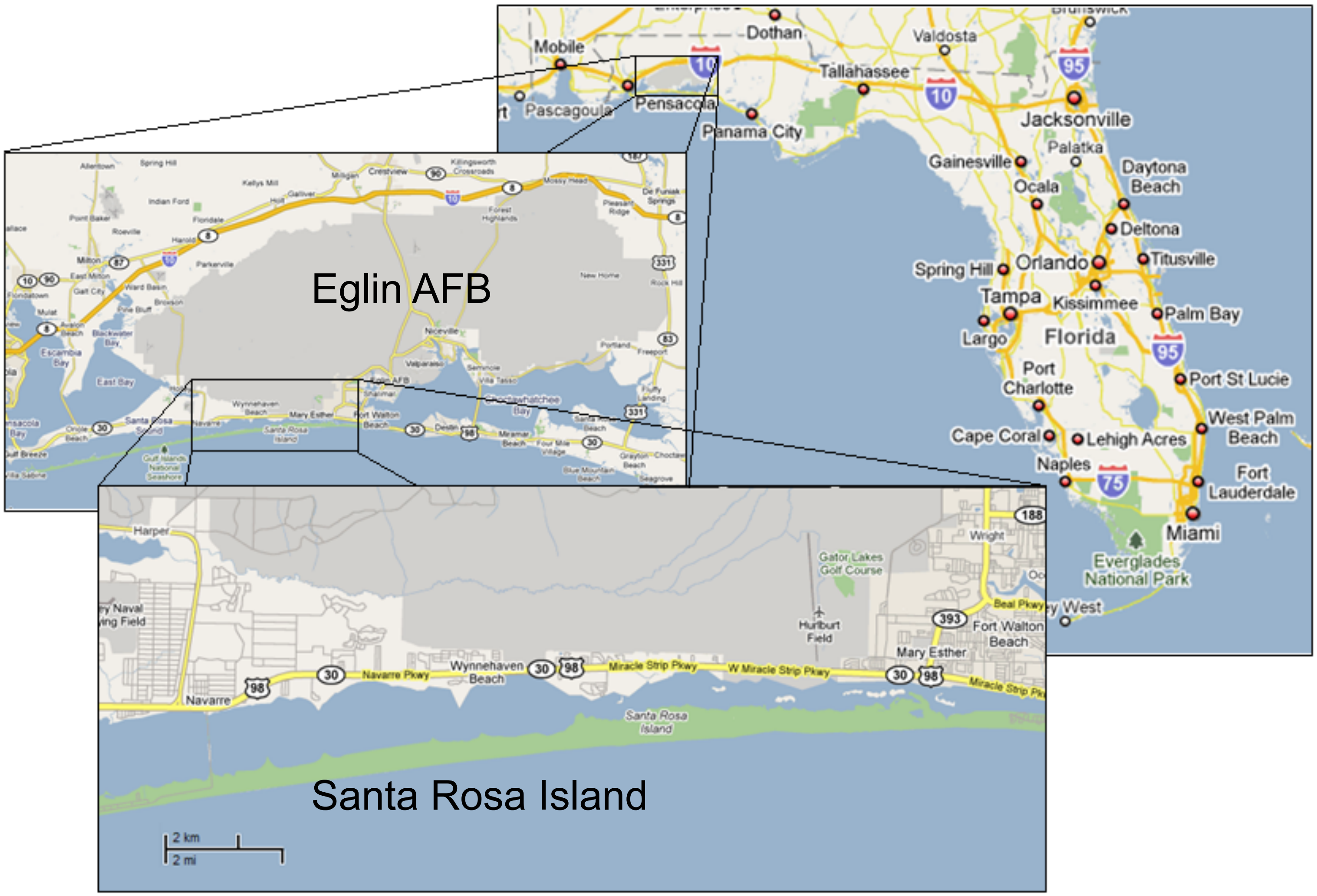
Study Area



SLAMM: Sea Level Affecting Marshes Model

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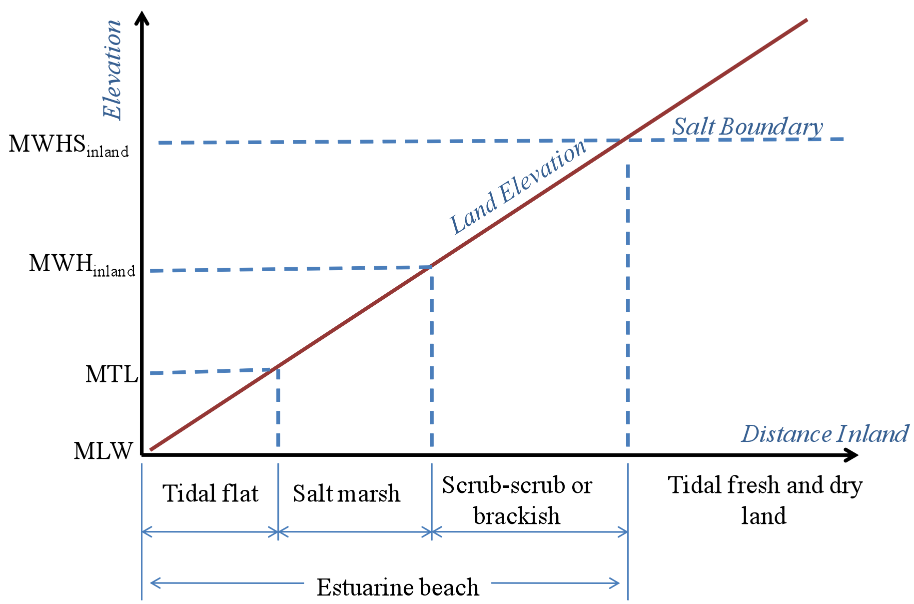
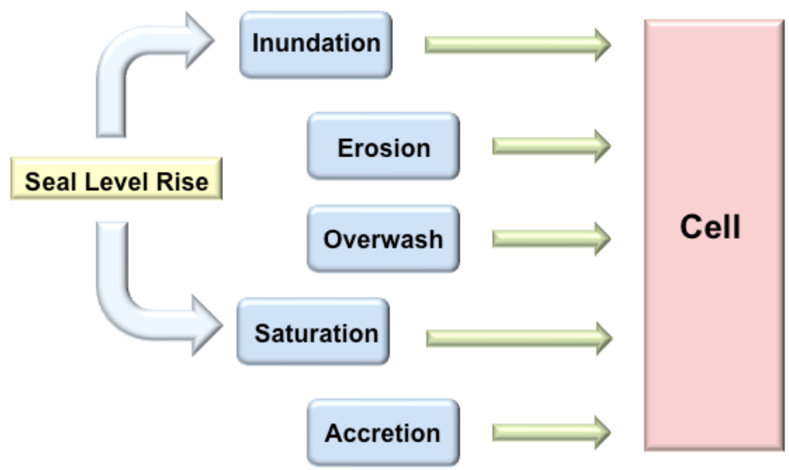
Spatially explicit, land use change as affected by local SLR





Lower-elevation:
- Tidal flat
- Salt marsh
- Beach

Higher-elevation:
- Swamp
- Inland Fresh Marsh

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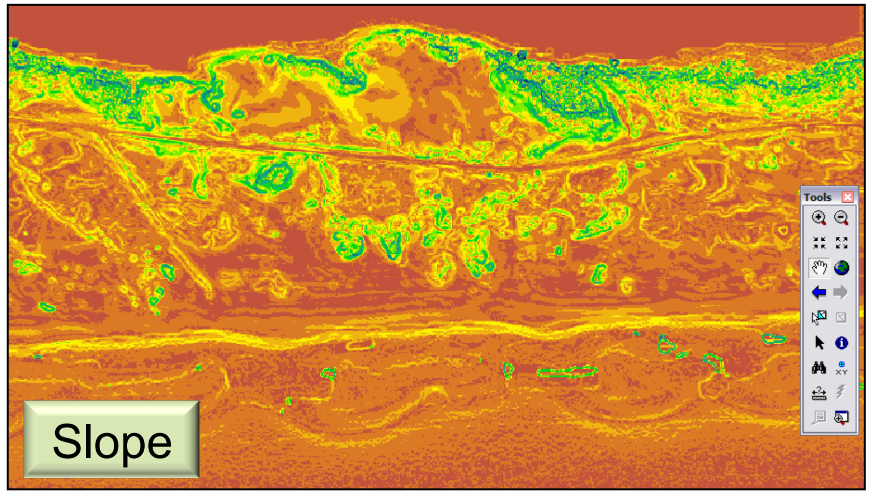
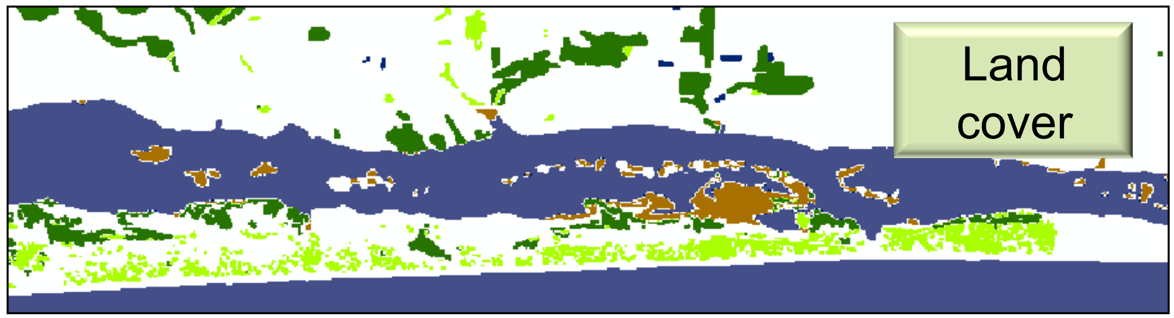
Model Inputs

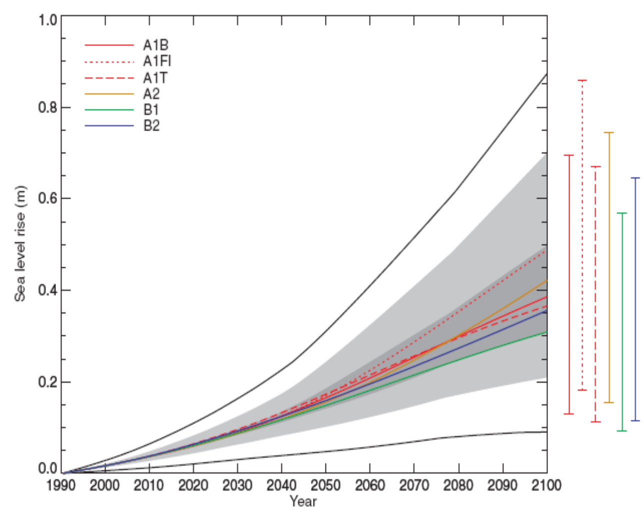


Input data:

- Elevation
- Slope
- Land cover
- Site specific information
- SLR scenarios (IPCC, 2001)

All data is obtained from open source databases





IPCC scenarios

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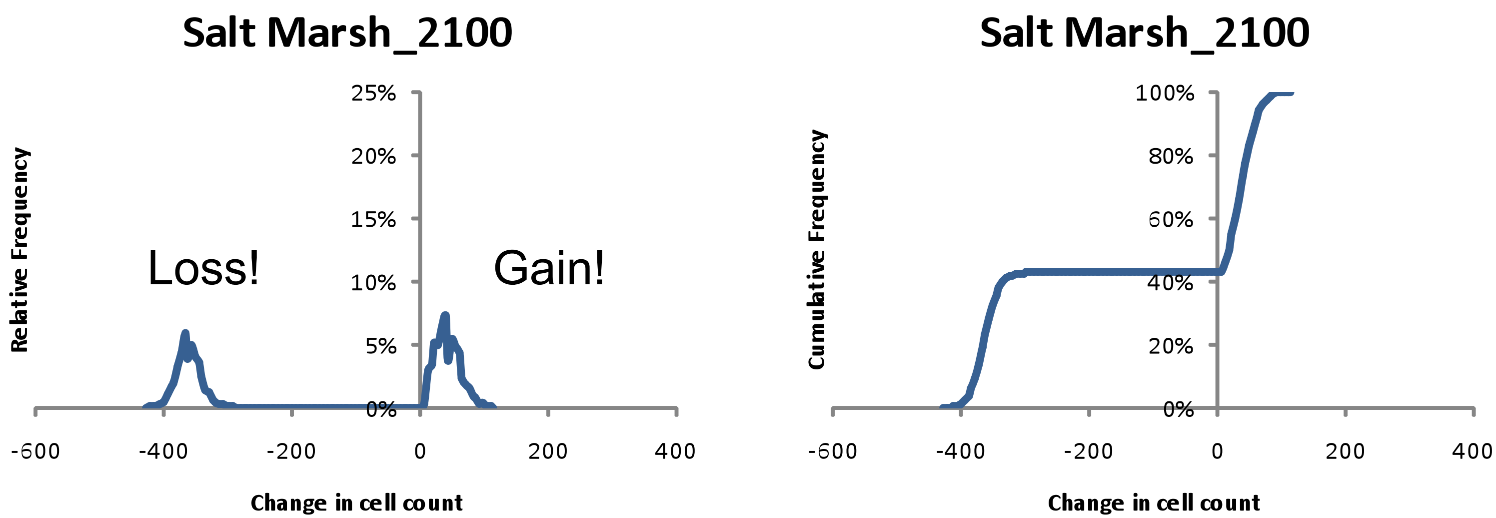
Uncertainty Analysis

Fate of Salt Marsh: Gain or Loss?



Mean IPCC
(A1B)

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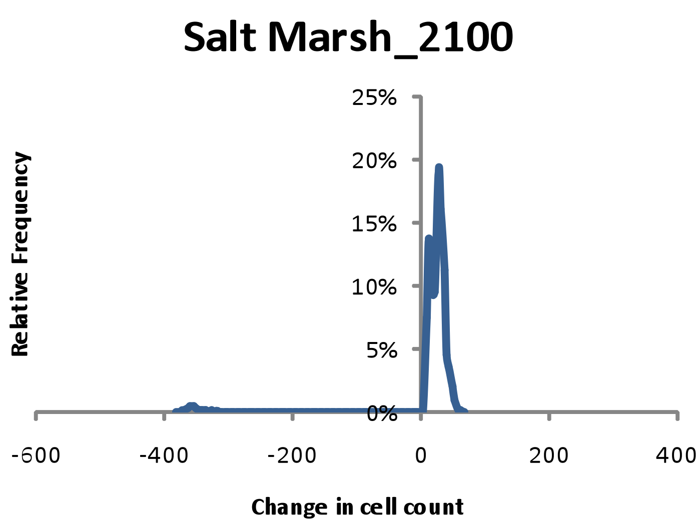
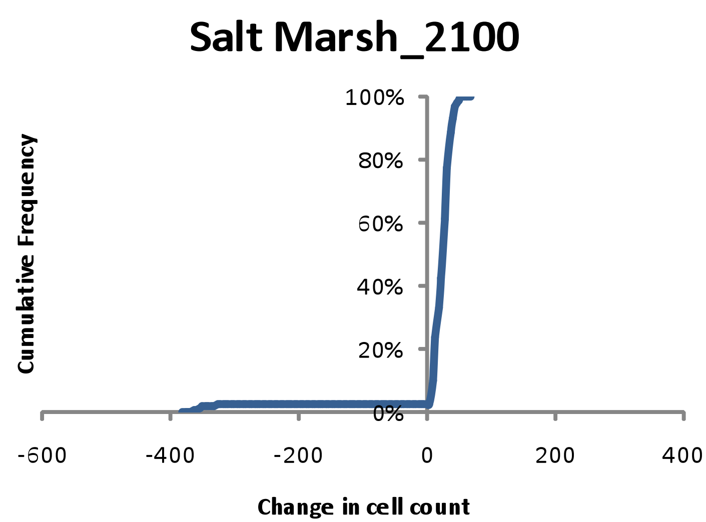
Uncertainty Analysis

Fate of Salt Marsh: Gain or Loss?





Minimum IPCC (A1B)

SERDP

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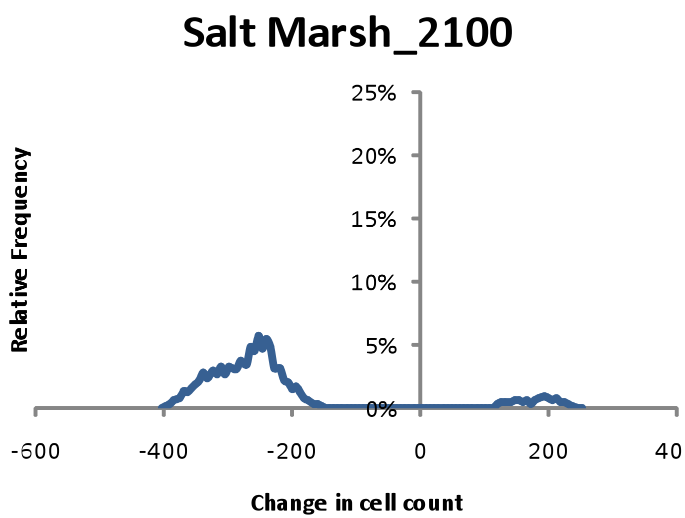

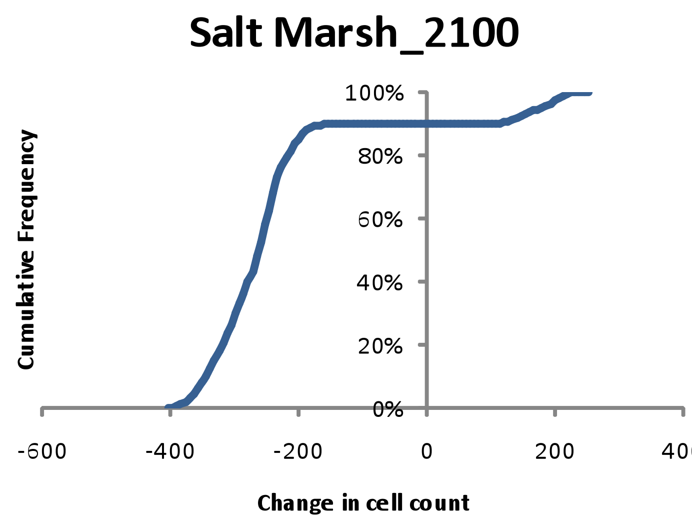

Maximum IPCC
(A1B)

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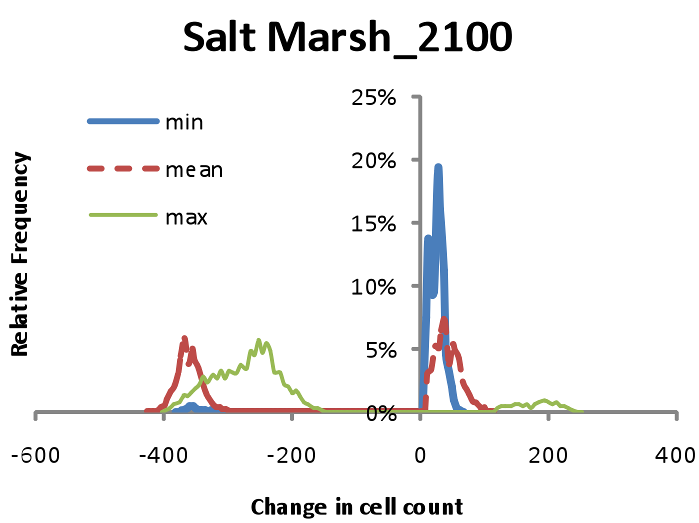

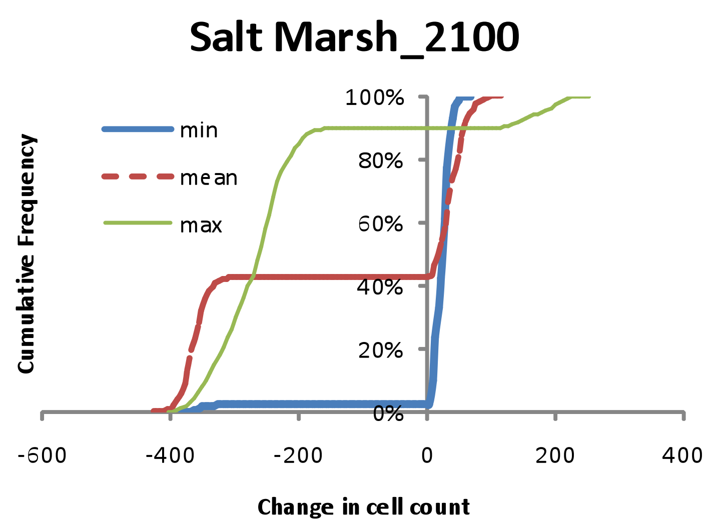

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Global Sensitivity Analysis

- **Important factors**:
  - elevation
  - historic trend of sea level rise
  - accretion/sedimentation rates
- **Interactive factors:**
  - historic trend of sea level rise
  - accretion/sedimentation
- **Dominant processes:**
  - inundation
  - accretion/sedimentation
- **Effects of sea level rise:**
  - accretion/sedimentation outweighed other factors in low-elevation wetlands
  - low elevation areas are more likely to be affected by climate change
  - variance of output is driven by more factors

- *Fate of Plover habitat depends on combinations of input factors?*
  - Larger scale simulations of FL Gulf Coast

Agor-Chu, Muñoz-Carpena, Kiker and Linvov. 2010. *Environmental Modelling & Software* (in review)

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OUTLINE

- Models and Uncertainty
- Uncertainty, Complexity and Relevance
- A New Hope? Global Sensitivity/Uncertainty Analysis
- Case study 1: Complex modeling in Everglades
- Case study 2: Sea level rise and coastal habitat
- Take Home Message: Opportunities/challenges

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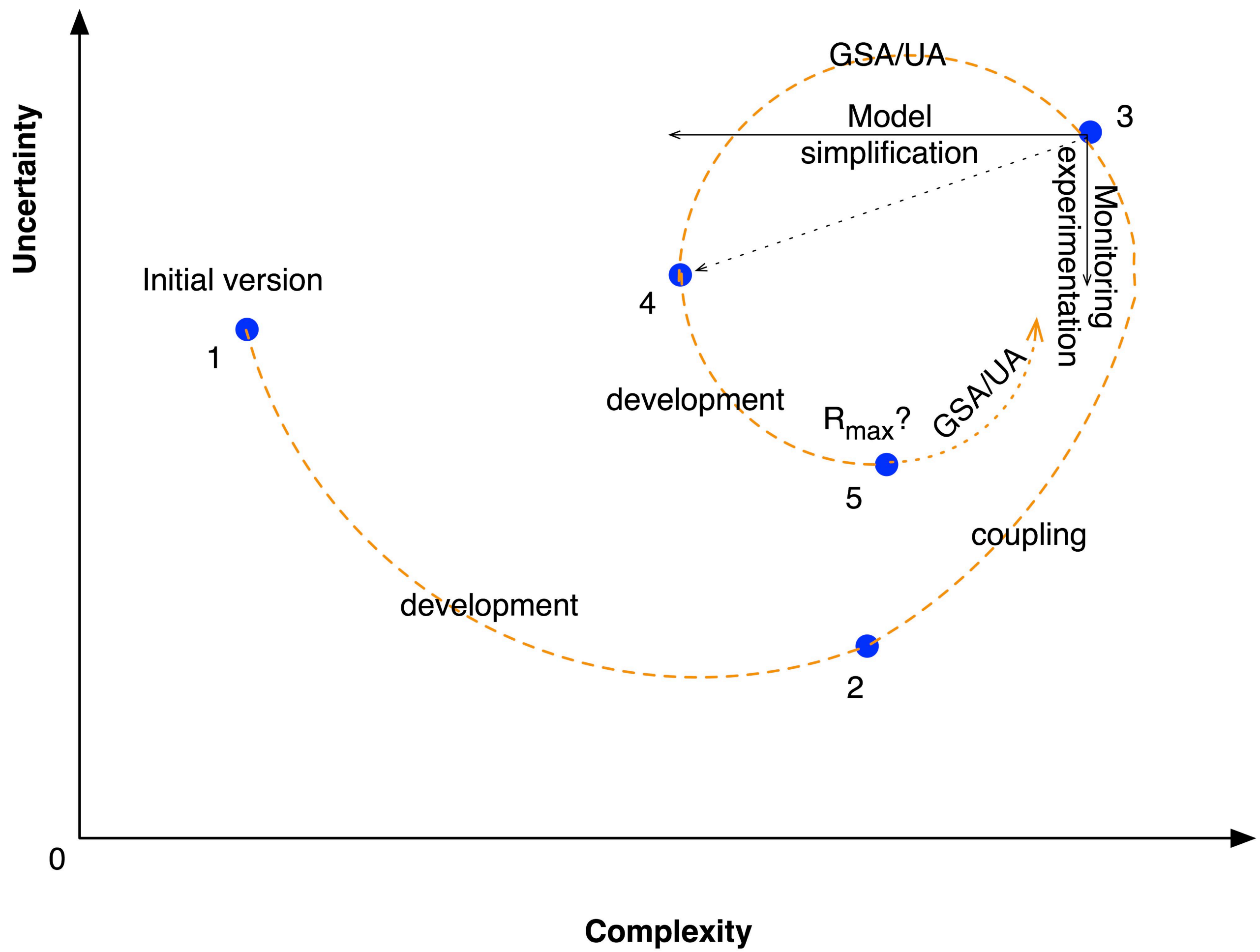
…. in search of the optimal model relevance



R_{max} = optimal relevance? (a.k.a. the "Modeling Holy Grail")

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Thank you for your attention

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