GEUS

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Uncertainty – terminology, concepts, tools and importance in climate change adaptation

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Outline

Part 1 – Terminology and concepts

Part 2 - Tools

Part 3 – Uncertainty in climate change impacts and adaptation

Part 1 – Terminology and concepts

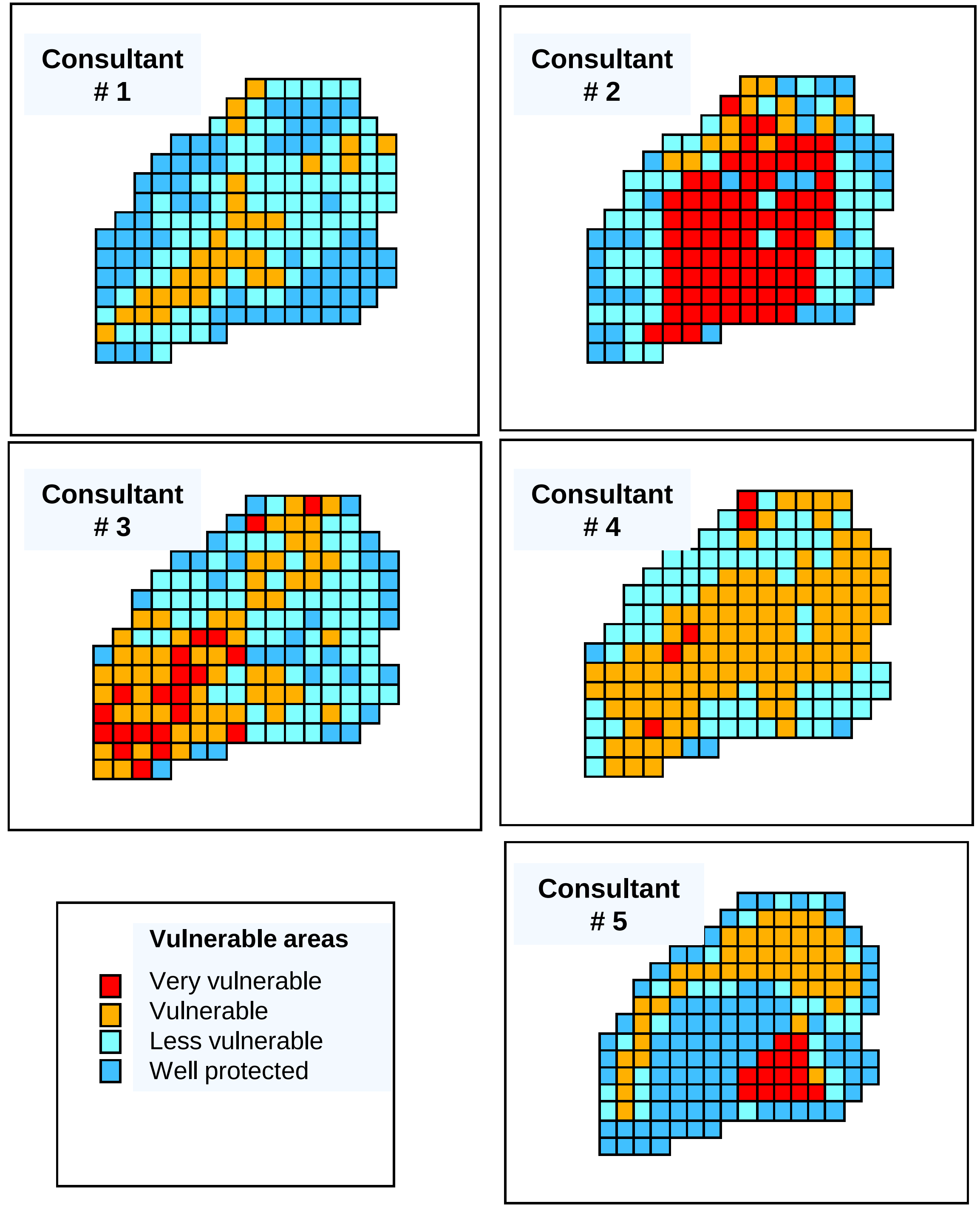
- **Why** is uncertainty assessment important?
- **When** does uncertainty occur in the water management process?
- **What** is uncertainty?
  - Definition
  - Characterisation of uncertainty
    - Level
    - Nature
    - Source
- **What** is risk?
- Conclusions

Prediction uncertainty due to

- data interpretations
- model parameter values
- models (process equations)
- problem framing

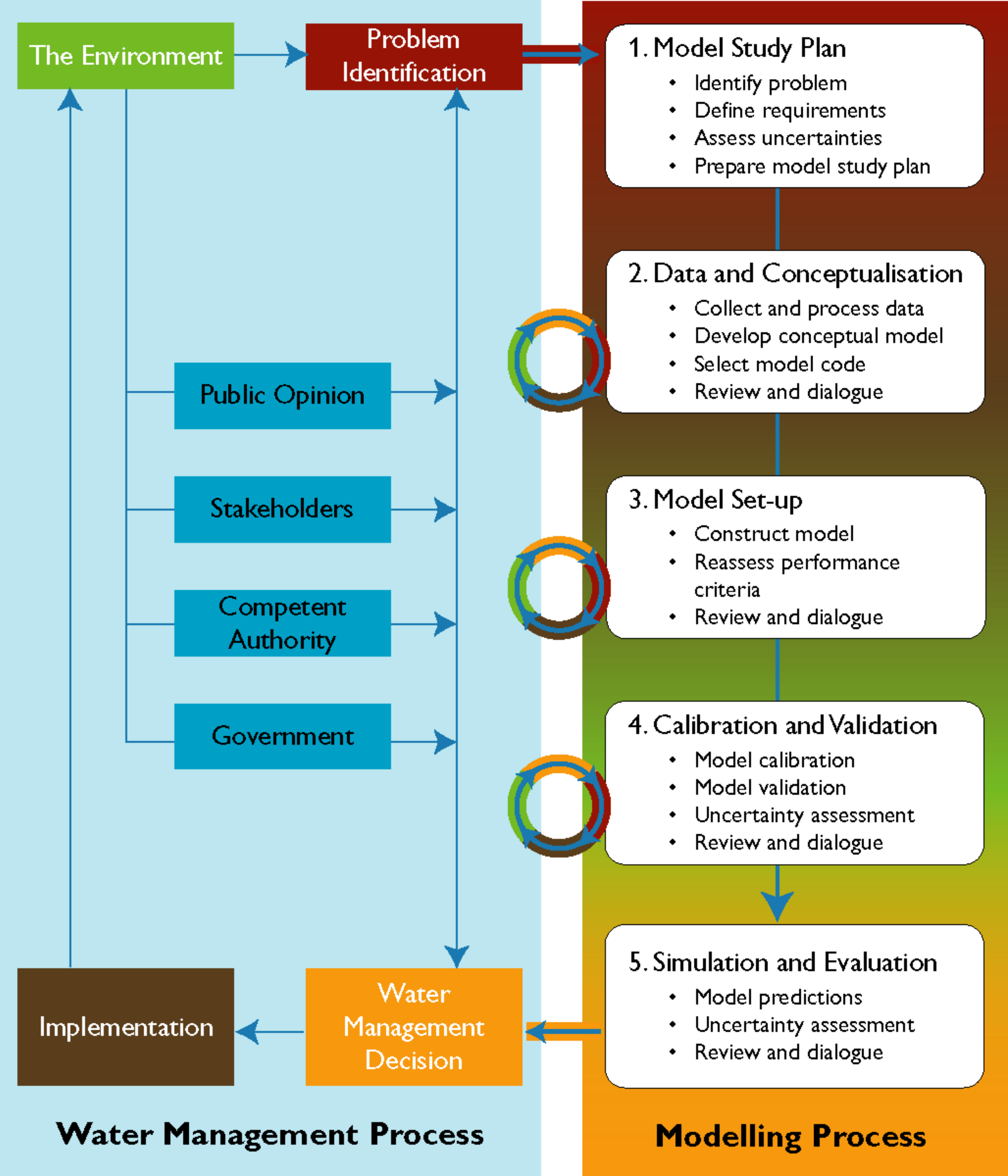
Copenhagen County project on identification of suitable methods for assessing groundwater vulnerability (2000)

Assessments from five consultants on areas vulnerable to nitrate pollution from diffuse sources



The Water Management Process and the Hydrological Modelling Process

➔ **Uncertainty assessments influence throughout – not only in evaluating the final model simulations**



What is uncertainty?

- typical definition in water resources (Klauer and Brown, 2003)

Definition (Uncertainty): *A person is uncertain if s/he lacks confidence about the specific outcomes of an event. Reasons for this lack of confidence might include a judgement of the information as incomplete, blurred, inaccurate or potentially false.*

Uncertainty is a property (state of confidence) of the decision maker rather than a property (state of perfection) of the total body of available knowledge → subjectivity is an important aspect of how we define uncertainty

Example: A person may be uncertain about the exact value of a river discharge value due to uncertainties related to instruments used for measurements, representativeness of measurements, method of transforming measurements (of often secondary variables) to discharge. Two different persons may have different perceptions of the magnitude of this uncertainty.

Uncertainty is not a province of probability theory – it must be seen in a much broader perspective

What is uncertainty – IPCC Glossary

(Bates et al., 2008, Climate change and Water. IPCC Technical Paper VI)

An expression of the degree to which a value (e.g., the future state of the *climate system*) is unknown. Uncertainty can result from lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from quantifiable errors in the data to ambiguously defined concepts or terminology, or uncertain *projections* of human behaviour. Uncertainty can therefore be represented by quantitative measures, for example, a range of values calculated by various models, or by qualitative statements, for example, reflecting the judgement of a team of experts.

What is it?

Where does it come from?

How can it be characterised?

Nature of uncertainty

Epistemic uncertainty

- uncertainty due to imperfect knowledge

➔ *reducible by more data and knowledge*

Ontological uncertainty

(Other names: unpredictability, stochastic, variability uncertainty)

- uncertainty due to inherent variability, e.g. climate variability

➔ *non-reducible*

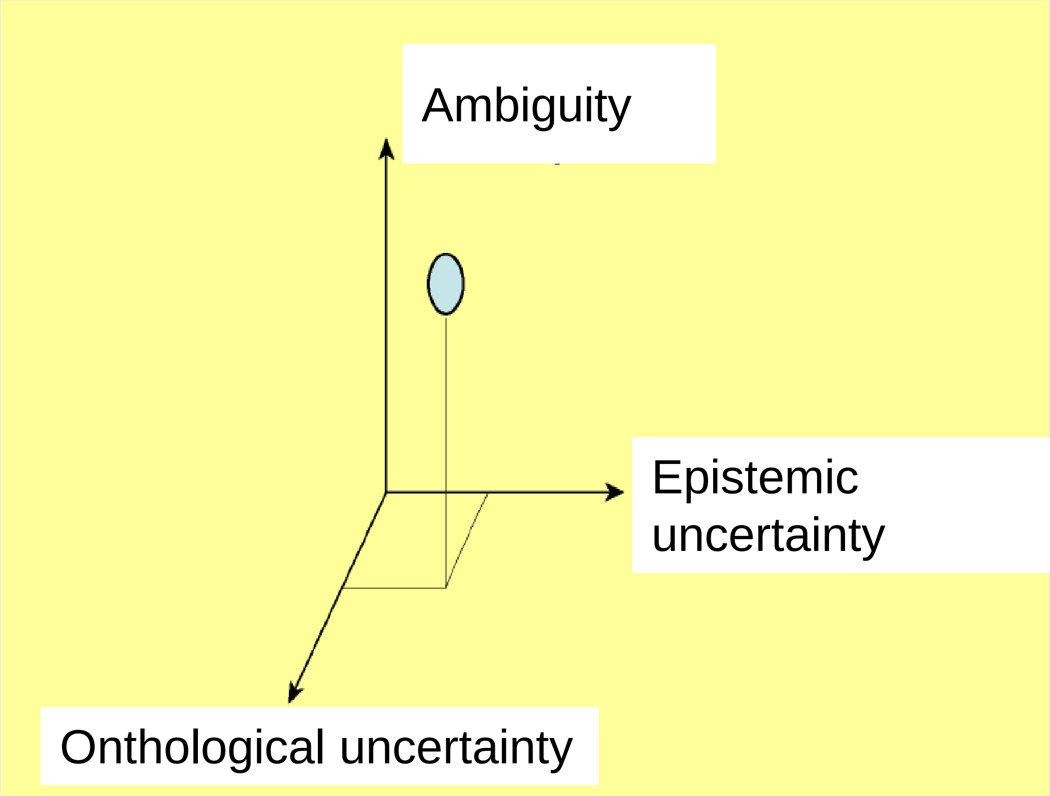
Ambiguity

- uncertainty due to multiple knowledge frames among stakeholders

➔ *reducible by more dialogue and knowledge sharing*

Characterisation of uncertainty according to its nature

(Figure adapted from Brugnach et al., 2009)



Level of uncertainty

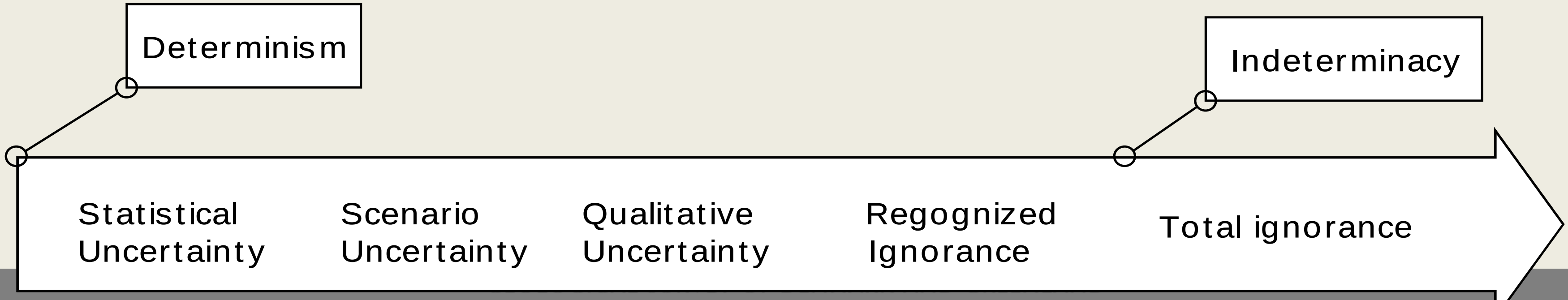
Statistical uncertainty
- All outcomes known
- All probabilities known

Scenario uncertainty
- Range of outcomes of plausible futures (not all known)
- No probabilities known

Qualitative uncertainty
- Not all outcomes necessarily known
- Cannot be described statistically

Ignorance
- We are aware that there is something we do not know

Total ignorance (=epistemic arrogance)
- We do not know that there is something we do not know



Sources of uncertainty in Water Resources Management

Data
- physical, chemical, biological, etc.
- scale problems (temporal and spatial)

Model
- bugs in model code
- numerical solution (approximations)
- parameter values
- model structure (process equations, hydrogeological conceptual model)

Context – boundary conditions
- future climate
- legislation, regulatory conditions, etc.

Framing of problem
- multiple knowledge frames among decision makers and stakeholders

Uncertainty Matrix

- Mapping of uncertainty characteristics

Source of uncertainty		Level (type) of uncertainty				Nature		
		Statistical uncertainty	Scenario uncertainty	Qualitative uncertainty	Ignorance	Epistemic uncertainty	Ontological uncertainty	Ambiguity
Inputs	System data							
	Driving forces							
Model	Model structure							
	Technical							
	Parameters							
Context (boundary conditions)	Future climate							
	Regulatory conditions							
Framing	Multiple knowledge frames							

Adapted from Walker et al. (2003)

What is risk?
- alternative definitions

- Risk is something you can compute (= *statistical uncertainty*) while uncertainty is something you cannot compute (= *the other types of uncertainty*)
- Risk = probability
- Risk = probability of exceedance of a critical threshold

→ A risk is characterised through a probability of an adverse event occurring and a measure of the associated event. Larger consequence and larger probability lead to a larger overall risk (e.g. Risk = Probability x Damage)

Conclusions – Part 1

Terminology

- Be aware of ambiguities in terminology used by others – and be specific defining the terminology you use

Concepts

- Uncertainty assessment should influence the entire management approach right from the beginning – and not only after some modelling studies
  - ➔ Stakeholders should be involved in evaluating uncertainties in connection with problem framing – and throughout a decision process and associated model studies
  - ➔ Model predictions should always include information on prediction uncertainties
- All sources and types of uncertainty should be considered in decision making – not only statistical uncertainty

Part 2 – Tools

- **Tools for different purposes**
  - Statistical uncertainty
  - Scenario uncertainty
  - Qualitative uncertainty

Tools for uncertainty assessment

- Numerous methods/tools and some guidances to identify appropriate tools

- Harmoni-CA Guidance 1 Uncertainty Analyses / Refsgaard et al. (2007) *Environmental Modelling and Software*
  - 14 groups of tools for quantitative, scenario and qualitative analyses.
- Matott et al. (2009) *Water Resources Research*
  - 65 tools for quantitative analyses
- Van der Keur et al. (2010) *Water Resources Management*
  - Overview over 22 different guidance documents providing guidance to select appropriate uncertainty assessment tools.

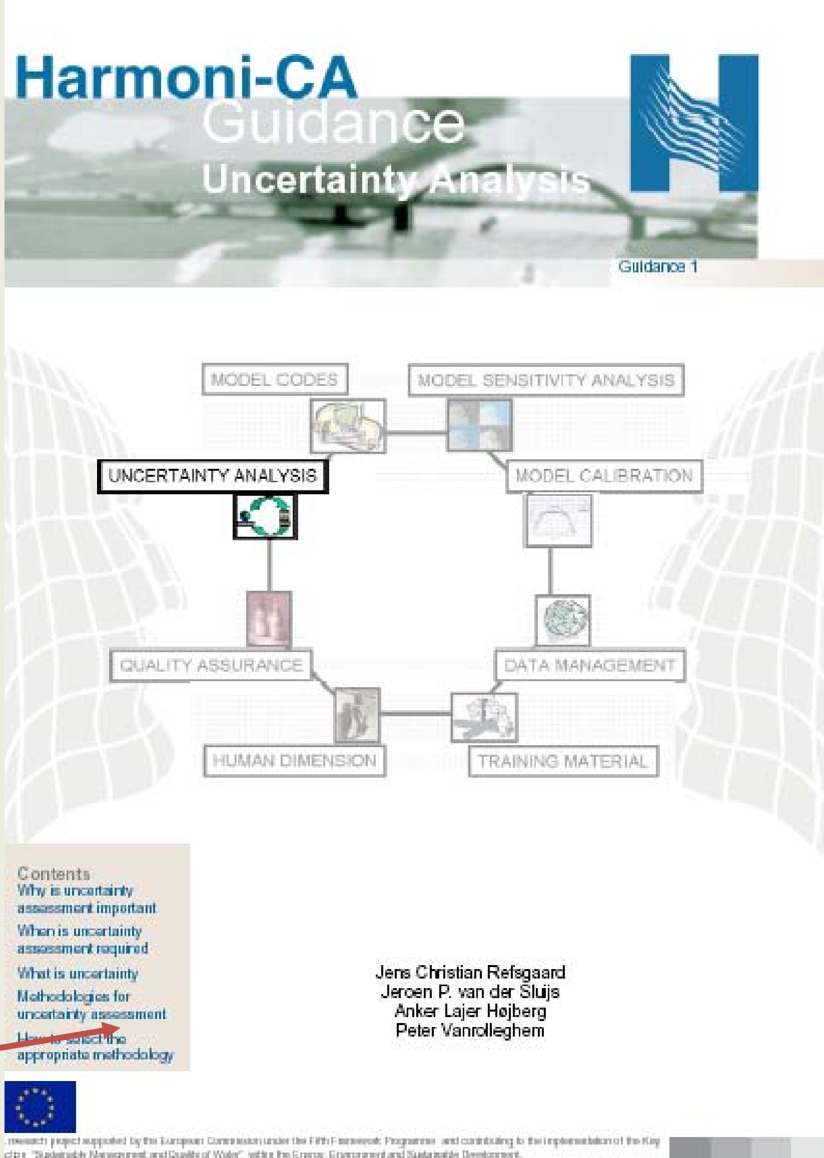
Methodologies for uncertainty assessment

- Selected methods described in Harmoni-CA Uncertainty Guidance Document

- Data Uncertainty
- Error Propagation Equations
- Expert Elicitation
- Extended Peer Review (review by stakeholders)
- Inverse modelling (parameter uncertainty)
- Inverse modelling (predictive uncertainty)
- Monte Carlo Analysis
- Multiple Model Simulation
- NUSAP
- Quality Assurance
- Scenario Analysis
- Sensitivity Analysis
- Stakeholder Involvement
- Uncertainty Matrix

More details in

- **Harmoni-CA Guidance**
- **Refsgaard et al. (2007)**



Suitable methods to deal with various types of uncertainty

Source of uncertainty		Taxonomy (types of uncertainty)			
		Statistical uncertainty	Scenario uncertainty	Qualitative uncertainty	Recognised ignorance
Context	Natural, technological, economic, social, political	EE	EE, SC, SI	EE, EPR, NUSAP, SI, UM	EE, EPR, NUSAP, SI, UM
Inputs	System data	DA, EPE, EE, QA	DA, EE, SC, QA	DA, EE	DA, EE
	Driving forces	DA, EPE, EE, QA	DA, EE, SC, QA	DA, EE, EPR	DA, EE, EPR
Model	Model structure	EE, MMS, QA	EE, MMS, SC, QA	EE, NUSAP, QA	EA, NUSAP, QA
	Technical				QA
	Parameters	IN-PA, QA	IN-PA, QA	QA	QA
Model outputs		EPE, EE, IN-UN, MCA, MMS, SA	EE, IN-UN, MMS, SA	EE, NUSAP	EE, NUSAP

Abbreviations of methodologies:

DA	Data Uncertainty	MMS	Multiple Model Simulation
EPE	Error Propagation Equations	NUSAP	NUSAP
EE	Expert Elicitation	QA	Quality Assurance
EPR	Extended Peer Review (review by stakeholders)	SC	Scenario Analysis
IN-PA	Inverse Modelling (parameter estimation)	SA	Sensitivity Analysis
IN-UN	Inverse Modelling (predictive uncertainty)	SI	Stakeholder Involvement
MCA	Monte Carlo Analysis	UM	Uncertainty Matrix

Uncertainty Matrix

- A dialogue platform for modeller, water manager and stakeholders to identify and characterise uncertainty as a basis for framing of the modelling study

Source of uncertainty	Type of uncertainty				Importance	
	Statistical uncertainty	Scenario uncertainty	Qualitative uncertainty	Recognised ignorance	Weight	(uncertainty x weight)
Problem context						
- future agritultural practise		medium	medium	medium	large	medium
- future climate		medium	medium	large	medium	medium
Input data						
- catchment data	medium			small	large	medium
- nitrate load from agriculture	small			small	large	small
Parameter uncertainty						
- water quantity	small			small	medium	small
- water quality	medium			medium	medium	small
Model structure (conceptual)						
- geology		large	large	medium	large	large
- nitrate reduction in underground		medium	medium	large	large	large
Model technical uncertainty						
- numerical approximation	small			small	medium	small
- bugs in software				medium	medium	small
					SUM:	

Error propagation

Box 1 Error propagation rules using standard deviation (σ)

Addition and Subtraction: z = x + y + .. or z = x - y - ..

$$\sigma_z = \sqrt{(\sigma_x{}^2) + (\sigma_y{}^2) + ..}$$

Multiplication by an exact number: z = c x

$$\sigma_z = c\sigma_x$$

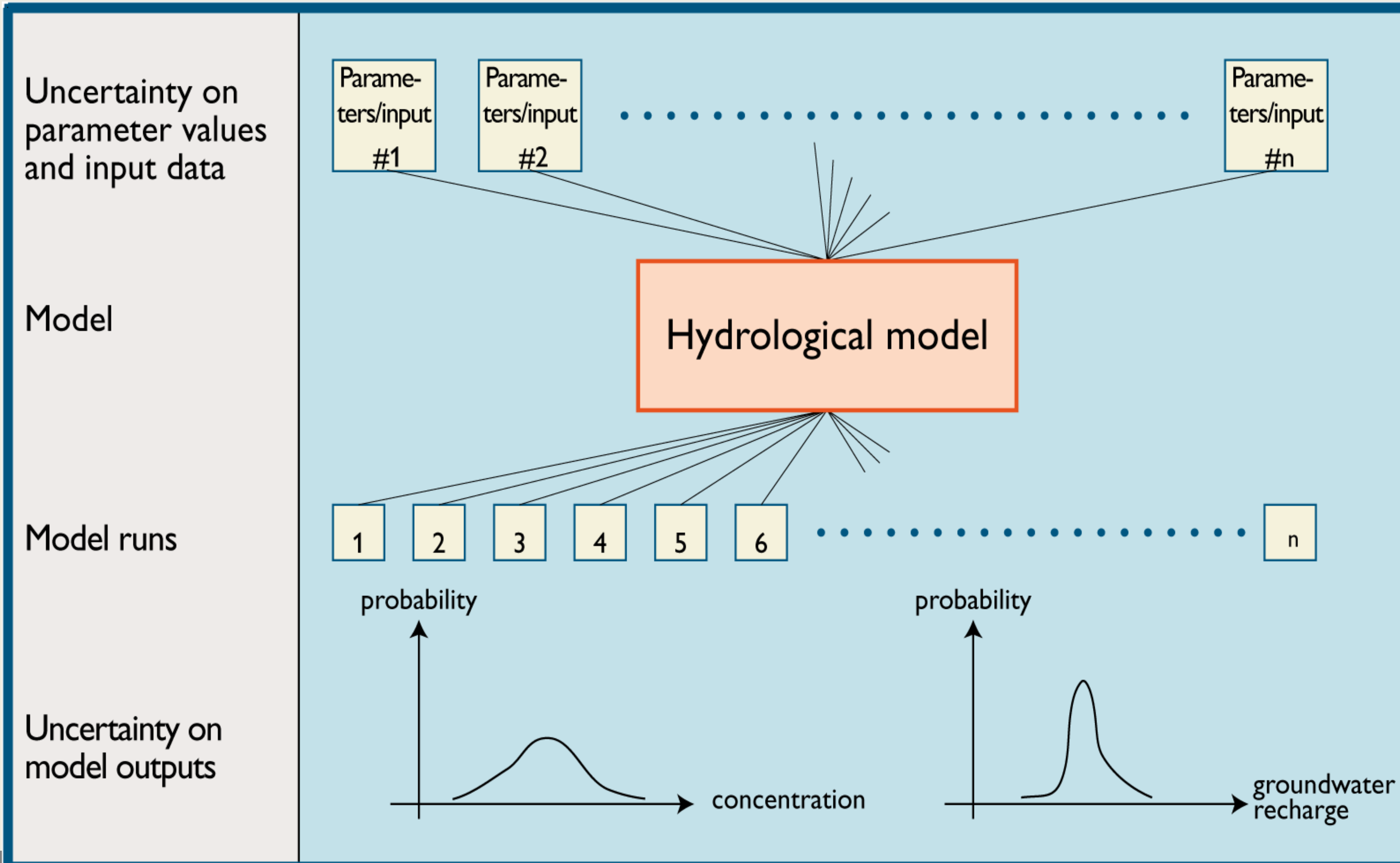
Multiplication and Division: z = x y or z = x/y

$$\frac{\sigma_z}{z} = \sqrt{\left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 + ..}$$

Products of powers: $z=x^m y^n$

$$\frac{\sigma_z}{z} = \sqrt{\left(\frac{m\sigma_x}{x}\right)^2 + \left(\frac{n\sigma_y}{y}\right)^2}$$

Monte Carlo Analysis



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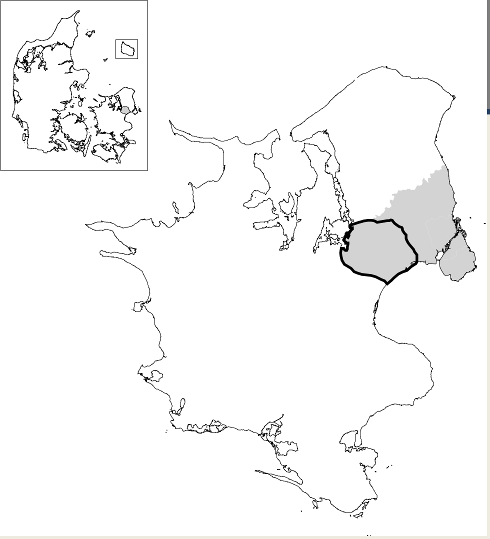
Multiple modelling approach

- Example with focus on alternative geological interpretations



Formulate 3 alternative conceptual models (different geologies)

↓

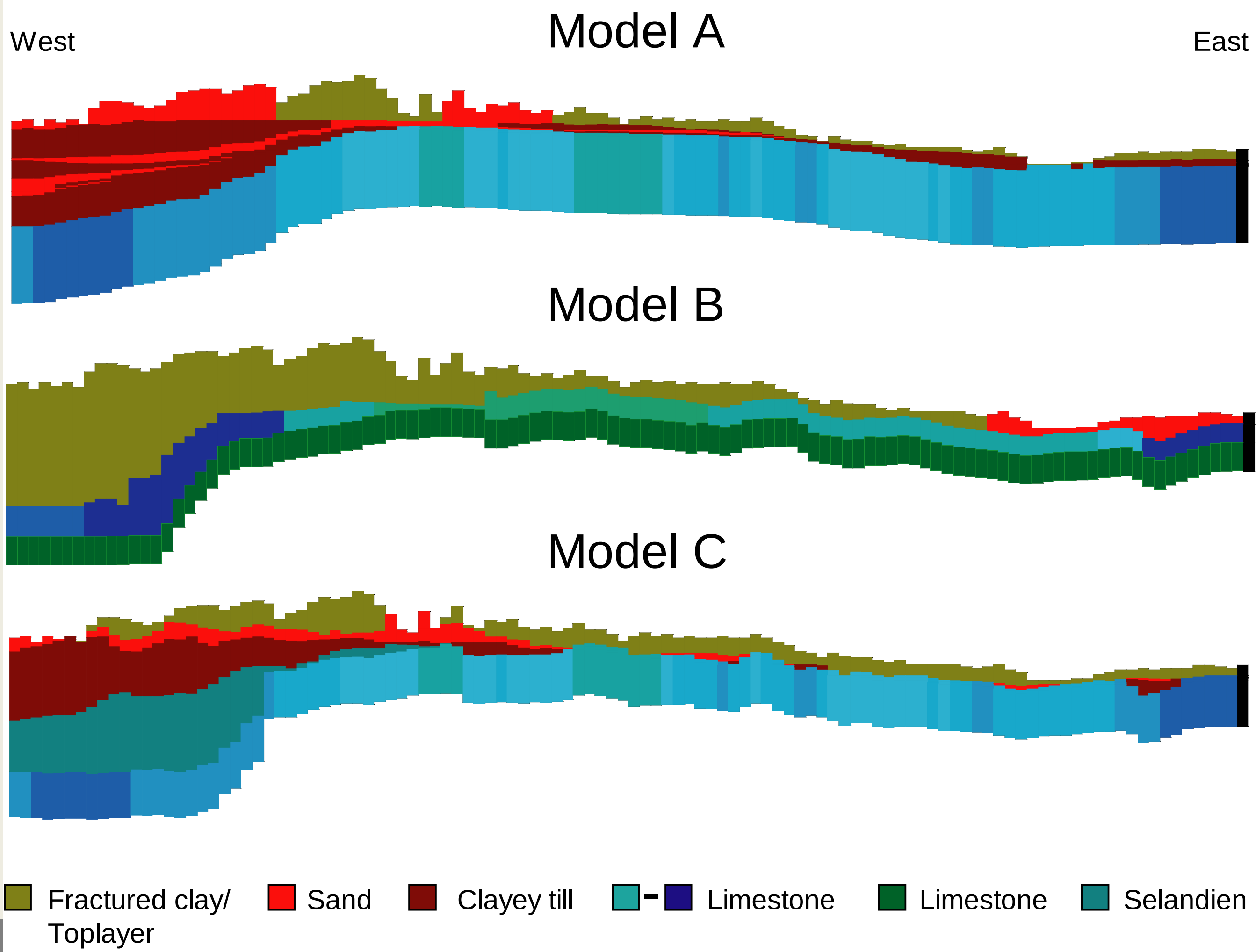
Construct 3 alternative numerical models

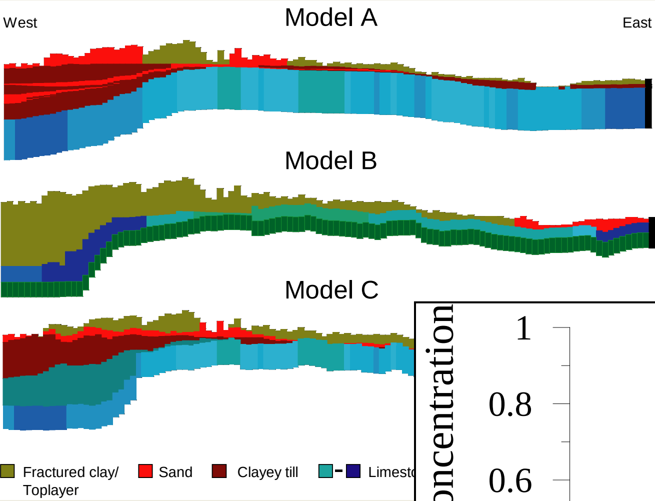
↓

Calibrate models against groundwater head and discharge data

↓

Predict breakthrough curves of groundwater contamination

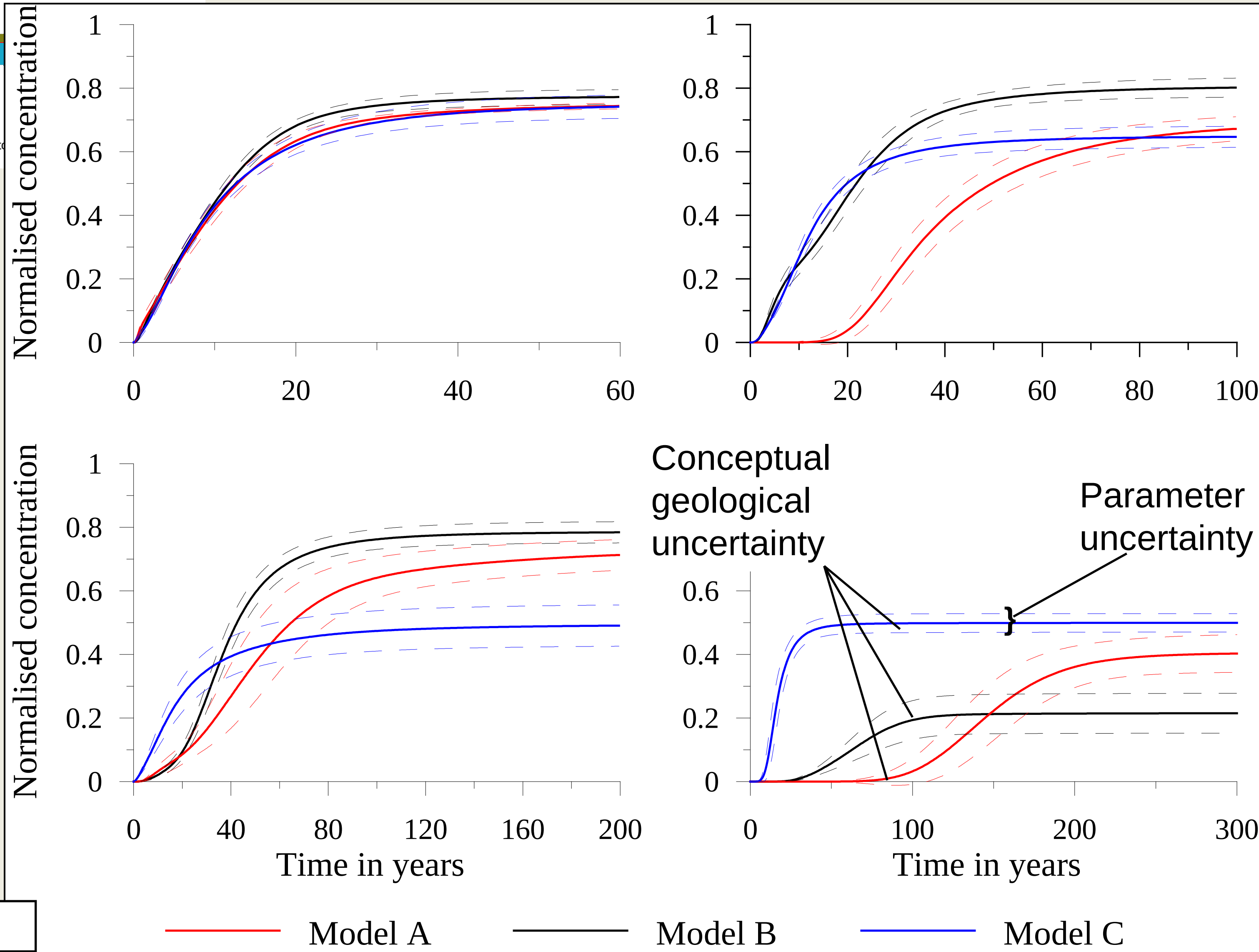




Uncertainty on parameters versus conceptual geological model

- Effects on flow paths/breakthrough curves

Simulated breakthrough in 4 abstraction wells



Højberg and Refsgaard (2005)

NUSAP - Numerical, Unit, Spread, Assessment, Pedigree

- *Example for evaluating goodness of a conceptual model*

Score	Supporting empirical evidence		Theoretical understanding	Representation of understood underlying mechanisms	Plausibility	Colleague consensus
	Proxy	**Quality and quantity**				
4	Exact measures of the modelled quantities	Controlled experiments and large sample direct measurements	Well established theory	Model equations reflect high mechanistic process detail	Highly plausible	All but cranks
3	Good fits or measures of the modelled quantities	Historical/field data uncontrolled experiments small sample direct measurements	Accepted theory with partial nature (in view of the phenomenon it describes)	Model equations reflect acceptable mechanistic process detail	Reasonably plausible	All but rebels
2	Well correlated but not measuring the same thing	Modelled/derived data Indirect measurements	Accepted theory with partial nature and limited consensus on reliability	Aggregated parameterised meta model	Somewhat plausible	Competing schools
1	Weak correlation but commonalties in measure	Educated guesses indirect approx. rule of thumb estimate	Preliminary theory	Grey box model	Not very plausible	Embryonic field
0	Not correlated and not clearly related	Crude speculation	Crude speculation	Black box model	Not at all plausible	No opinion

Example from Refsgaard et al (2006)

Conclusions – Part 2

Tools

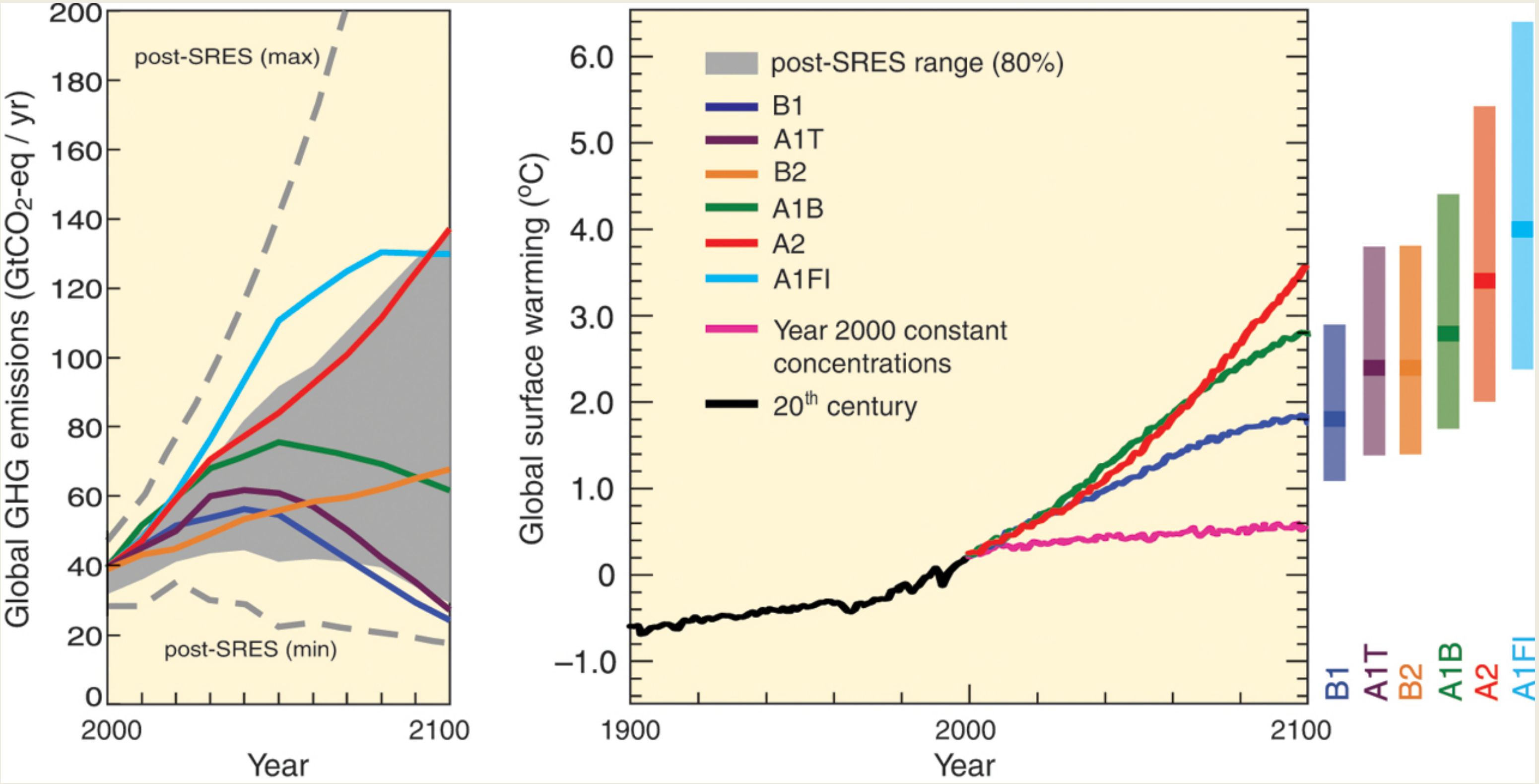
- A large range of suitable methodologies and tools exists
- Different types of tools are suitable for different types/levels of uncertainty
  - Statistical uncertainty
  - Scenario uncertainty
  - Qualitative uncertainty

"Uncertainty is not a province of probability theory"

Part 3 – Uncertainty in climate change impacts and adaptation

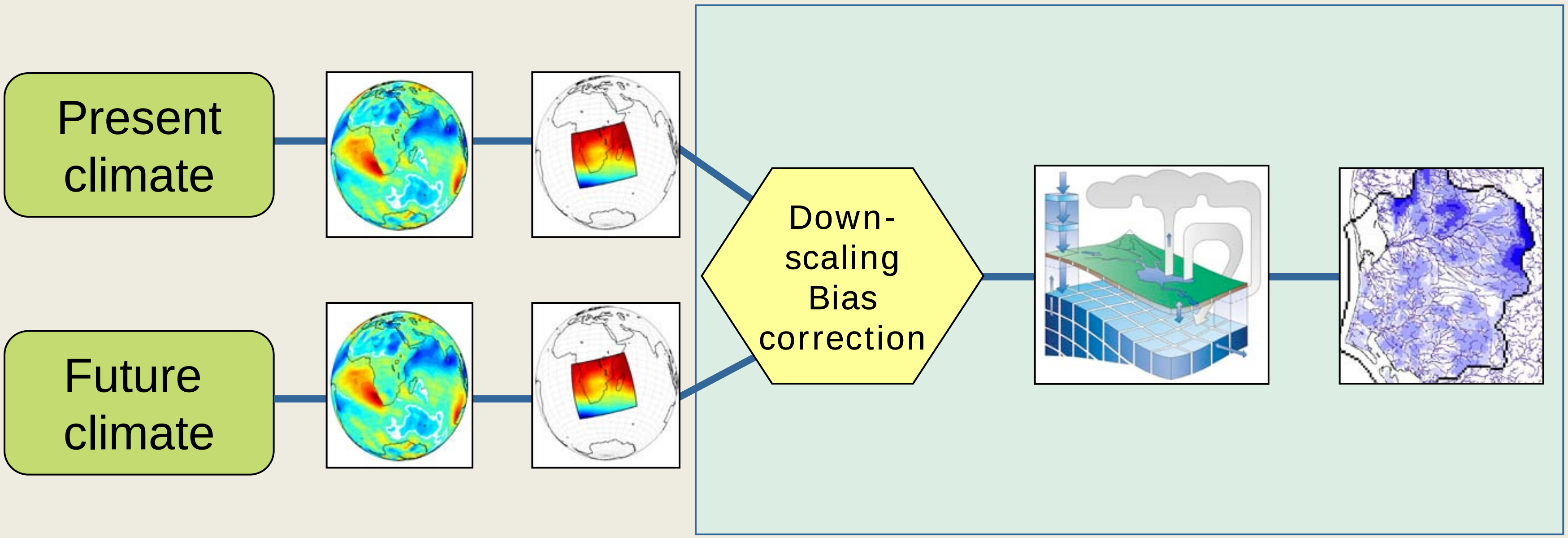
- Why is uncertainty particularly important in climate change studies and management?
- Climate change impact predictions – methodology illustrated by example
- Cascade of uncertainties

Why is uncertainty particularly important in relation to climate change?



- Hydrological models used for climate impact predictions can not be calibrated against data from future climate conditions ➔larger prediction uncertainties

Calculations of climate change effects on hydrology



Global Regional Hydrological **Models**

100-250 km 10-25 km 50-500 m **Scale**

Example of calculation of climate change impacts on hydrology

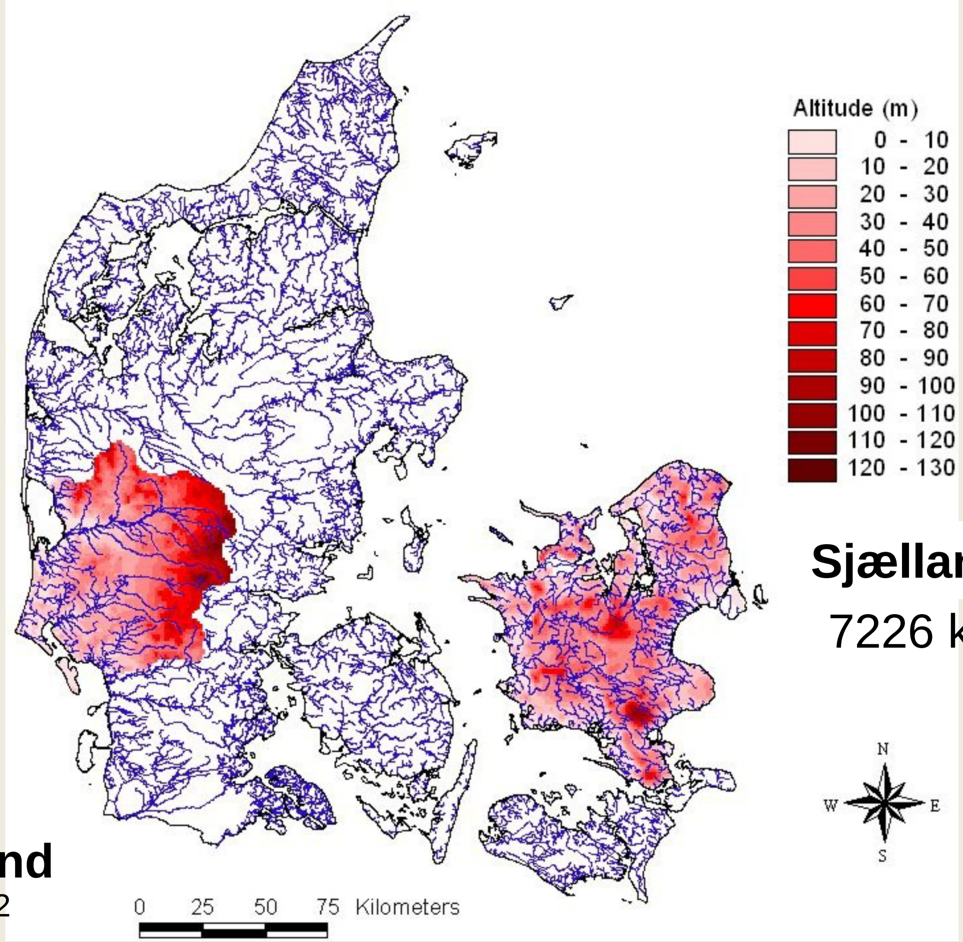
(van Roosmalen et al., 2007, 2010)

Climate model results from PRUDENCE

- A2 og B2 scenarios
- HIRHAM
- 2071-2100

Hydrological model (DK-model version 2003)

Impacts on groundwater heads and river discharges

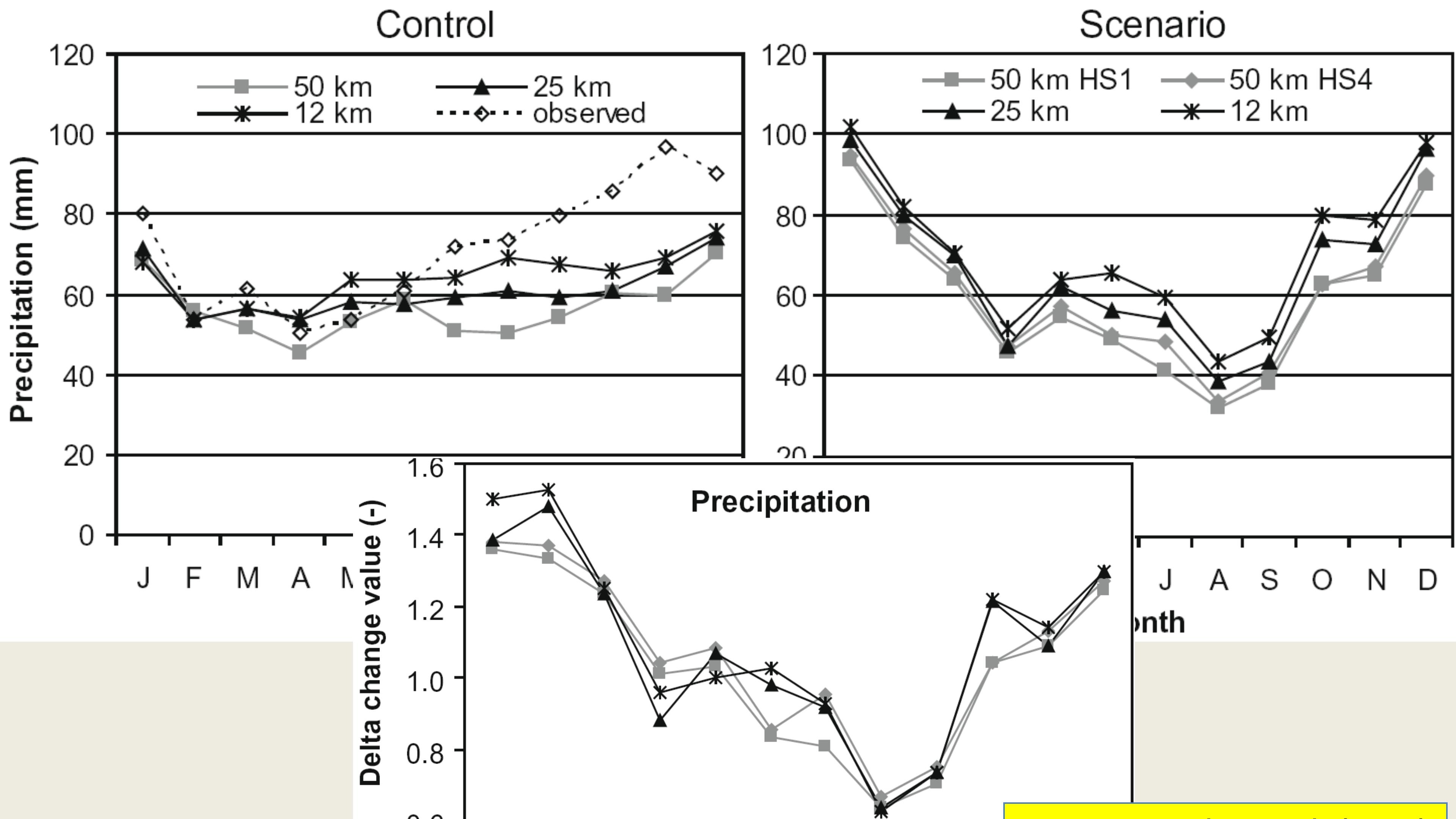


Sjælland
7226 km²

Vestjylland
5459 km²

HIRHAM model results

- A2 scenario, different sea surface temperature forcings over Baltic Sea (HS1, HS4)



Van Roosmalen et al. (2010)

Bias correction (statistical downscaling) of precipitation

Delta Change Method
(correction of observed precipitation)

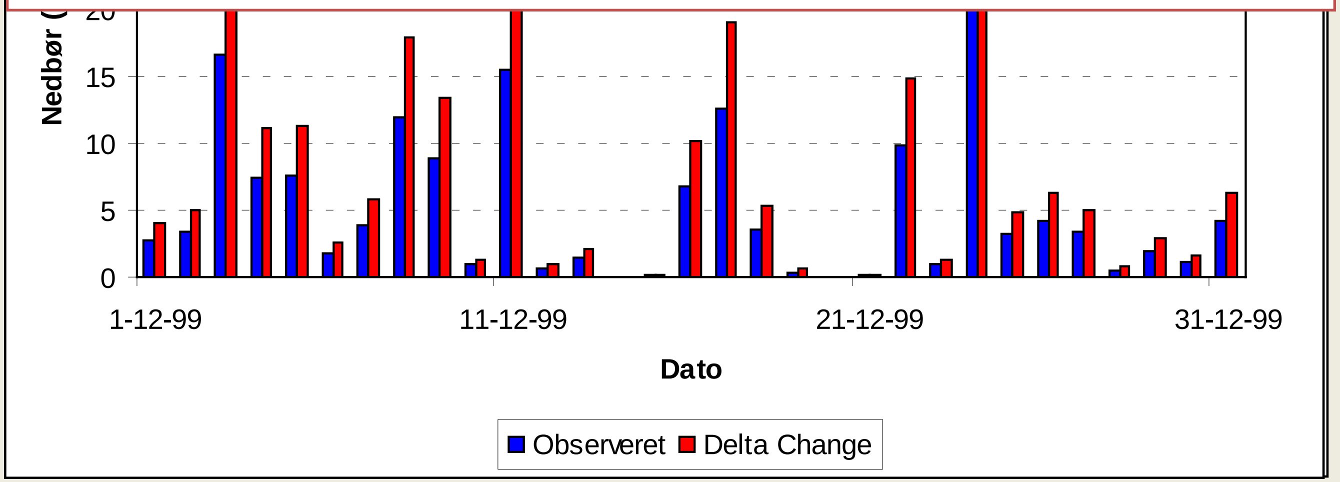
Critical assumption:

Future dynamics = present dynamics

➔No change in number of rainfall days

➔No change in distribution of rainfall intensity

➔Etc.



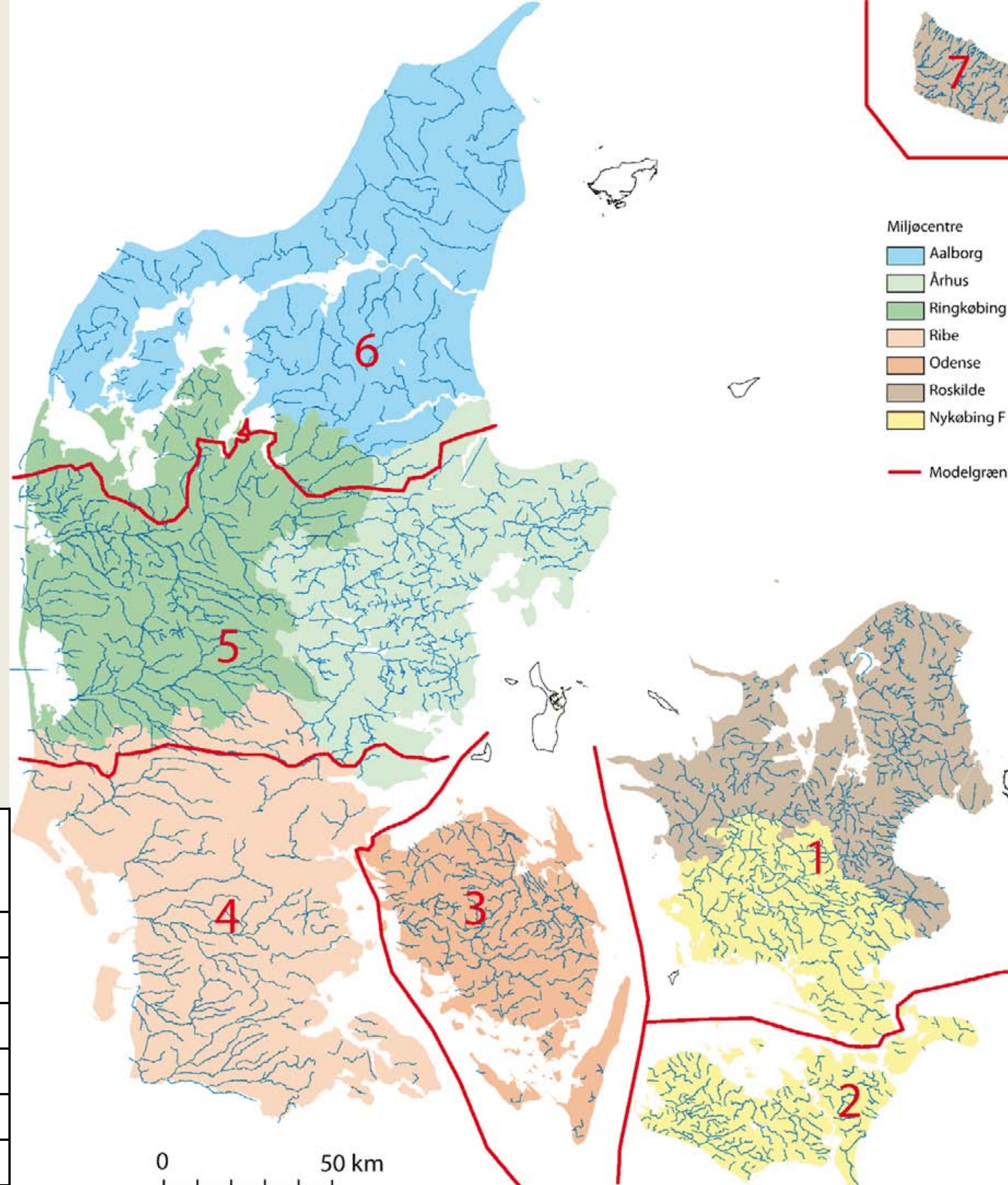
DK-model

- The hydrological model

Seven sub-models

- Horisontal discretization: 500 m
- Vertical discretization – layers, varying numbers and geometry

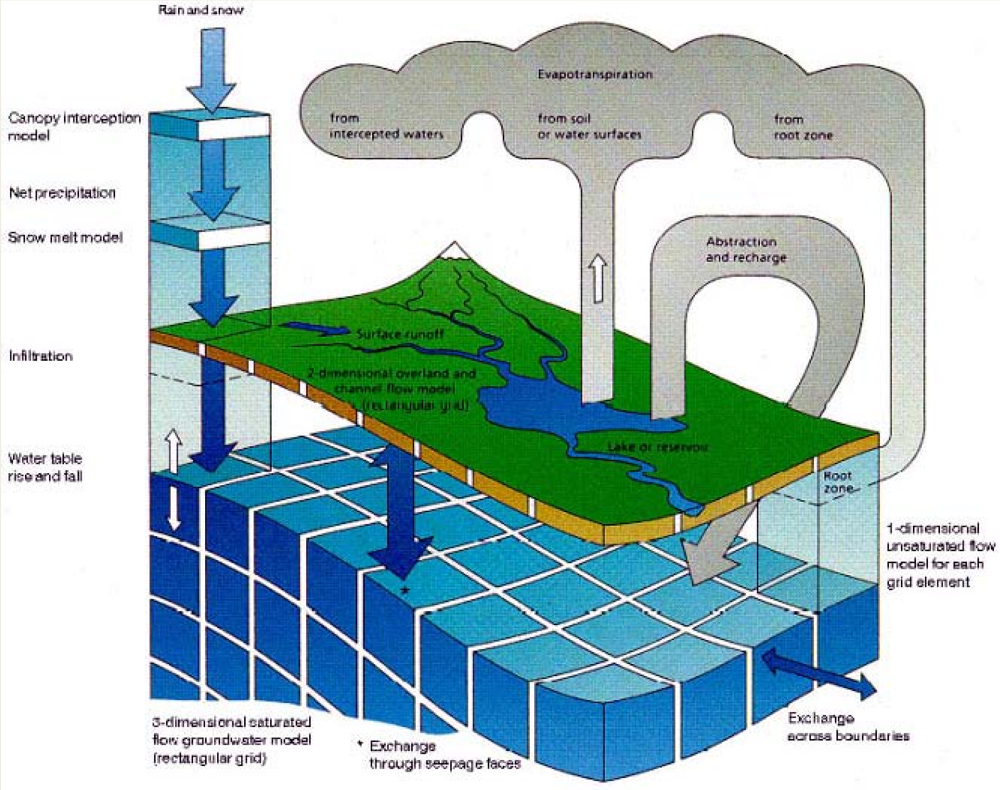
Delmodel	Samlede landareal (km^2)	Aktive grids pr. lag
Omr. 1 – Sjælland	7163	37569
Omr. 2 – Sydhavsøerne	2042	13885
Omr. 3 – Fyn	3473	24009
Omr. 4 – Sønderjylland	7897	35869
Omr. 5 – Midtjylland	11578	49993
Omr. 6 – Nordjylland	9934	47649
Omr. 7 – Bornholm	2358	10106



Model code

MIKE SHE / MIKE11

- 3D groundwater flow
- 2D overland flow
- Drain flow (pipes, ditches)
- 1D river routing
- 1D unsaturated zone, Two-layer module (evapotranspiration)
- Degree-day snow melt/accumulation



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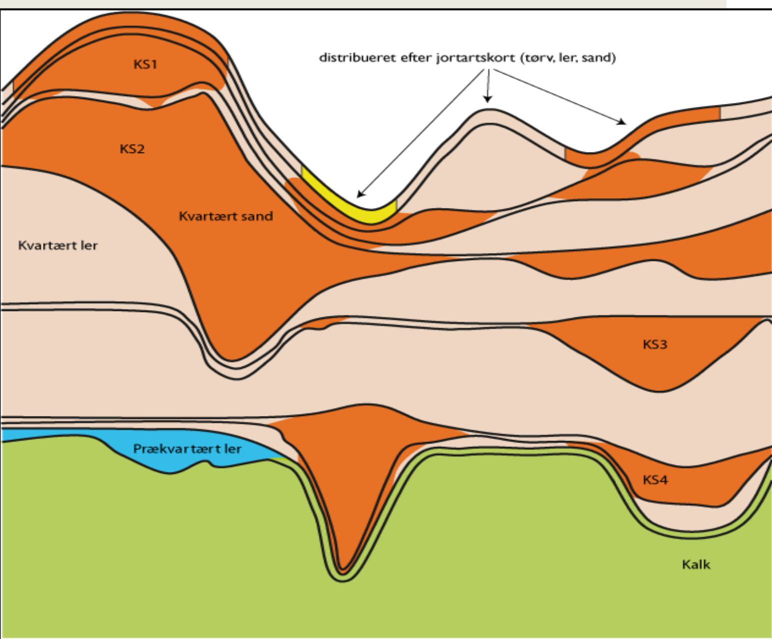
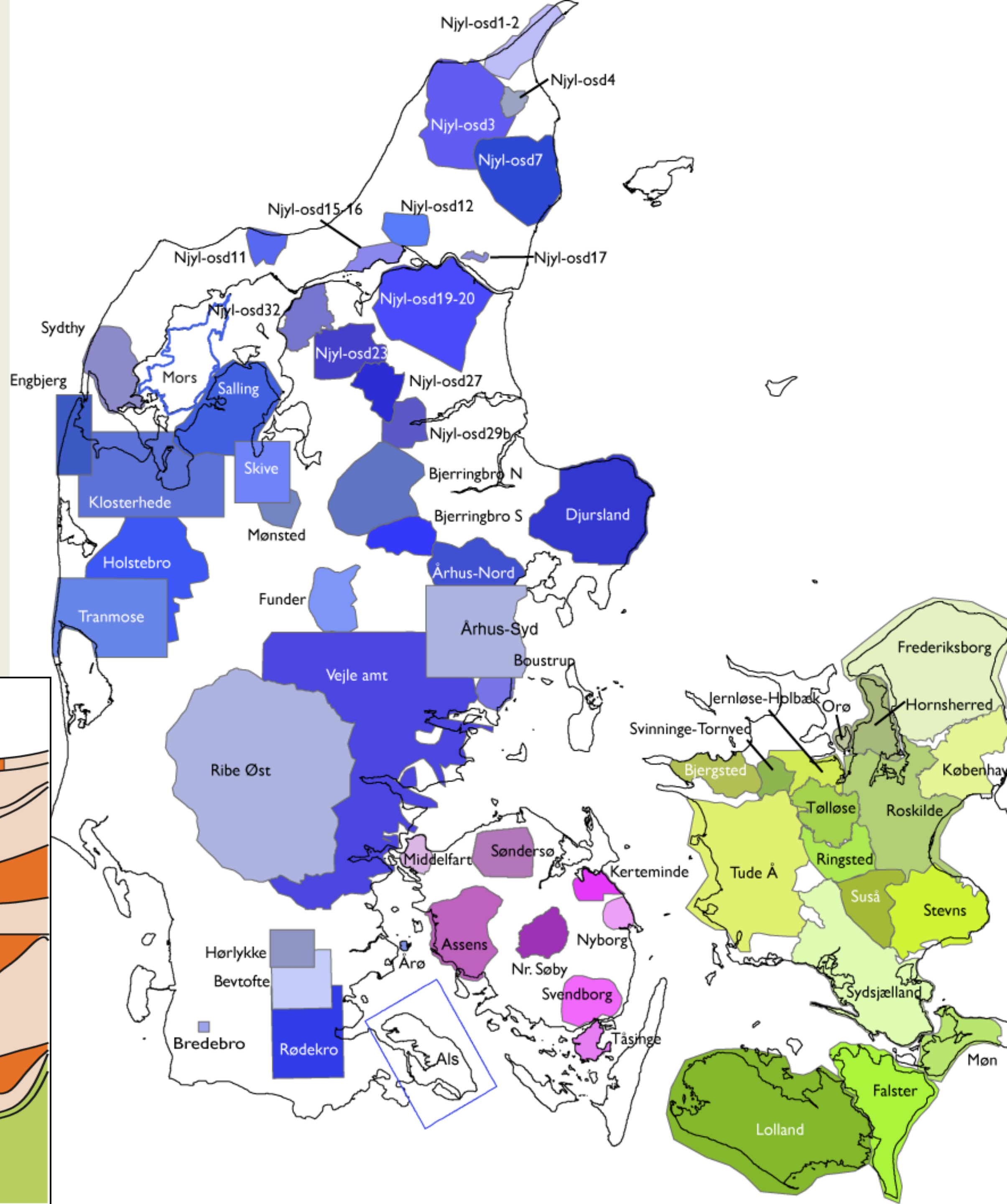
Geology / hydrostratigraphy

•Borehole data

•Geological interpretation

•Incorporation of knowledge from more than 50 local geological models established by regional authorities (incl. geophysical data)





DK-model data basis beyond geology

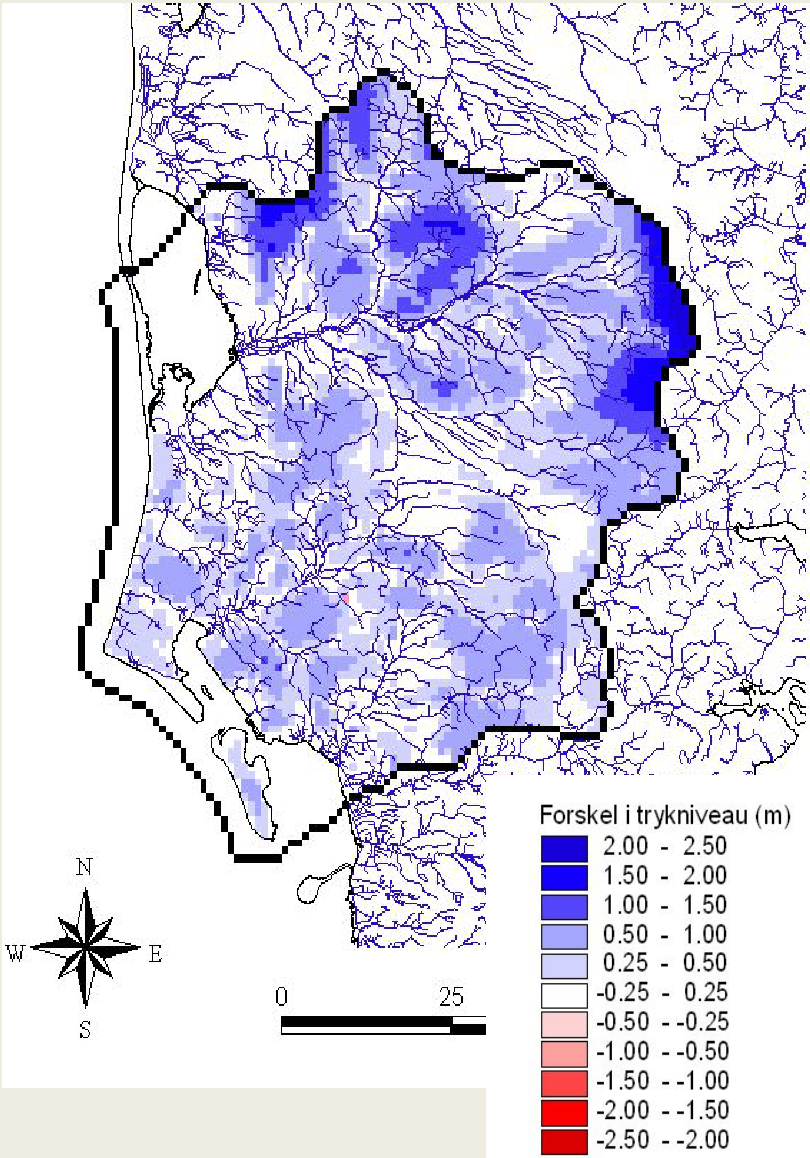
Model setup

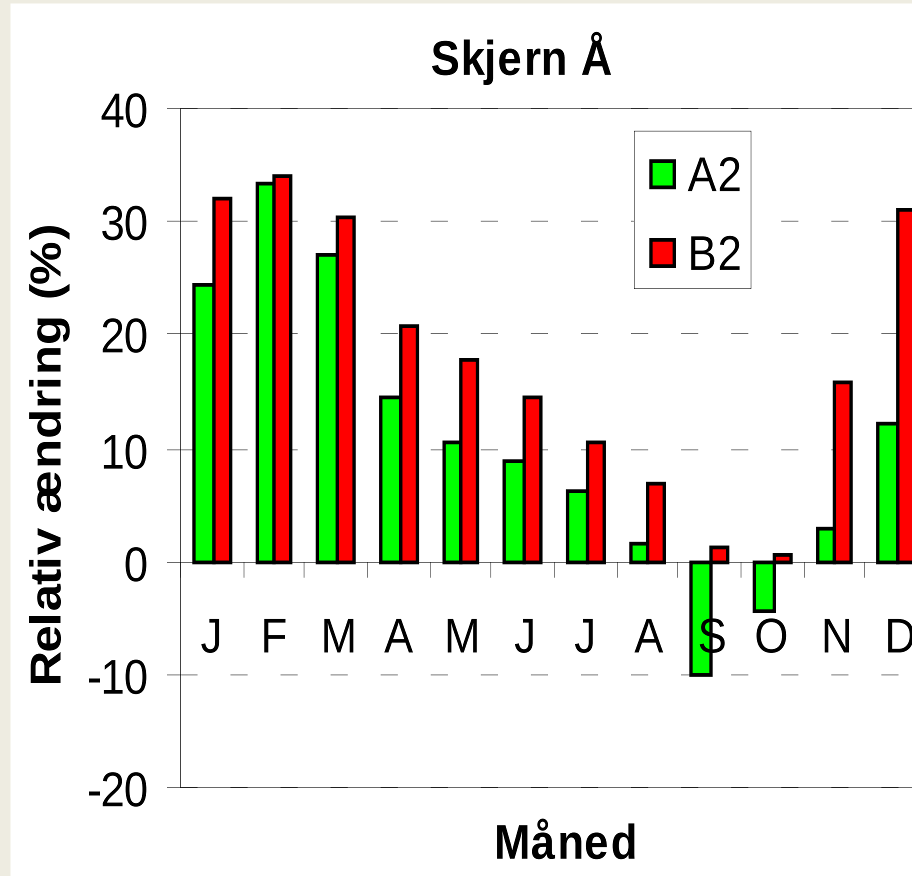
- Rivers
  - River cross-sections (MIKE11) for all major streams
  - Discharge from urban sewage treatment plants
- Water supply – all as groundwater abstraction
  - 23,500 plants (40,000 intakes) for water supply, including irrigation
- Soil types: National database (DJF)
- Precipitation: DMI’s 10 km grid daily values
- Temperature, potential evapotranspiration: DMI’s 20 km grid

Model calibration/validation (1990-2006)

- 183 discharge stations, daily values
- > 10,000 wells with groundwater head observations

Change in groundwater head and discharge

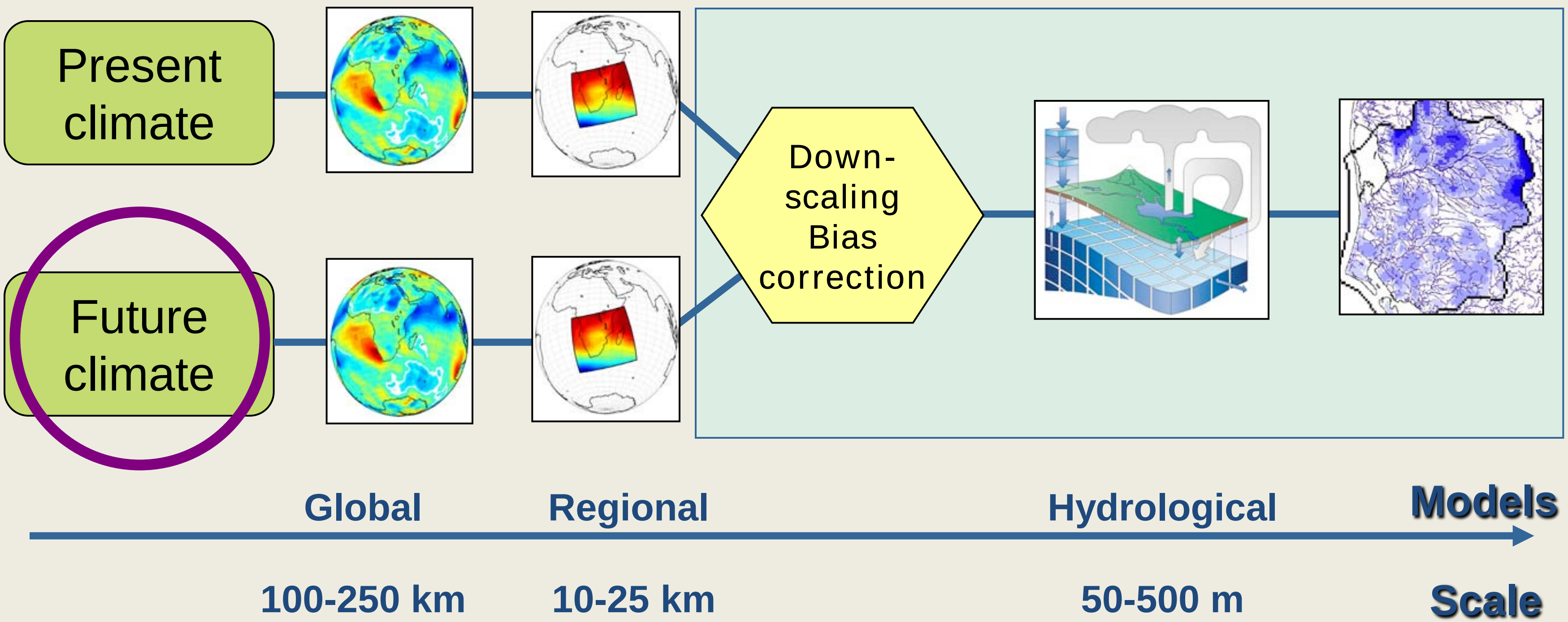




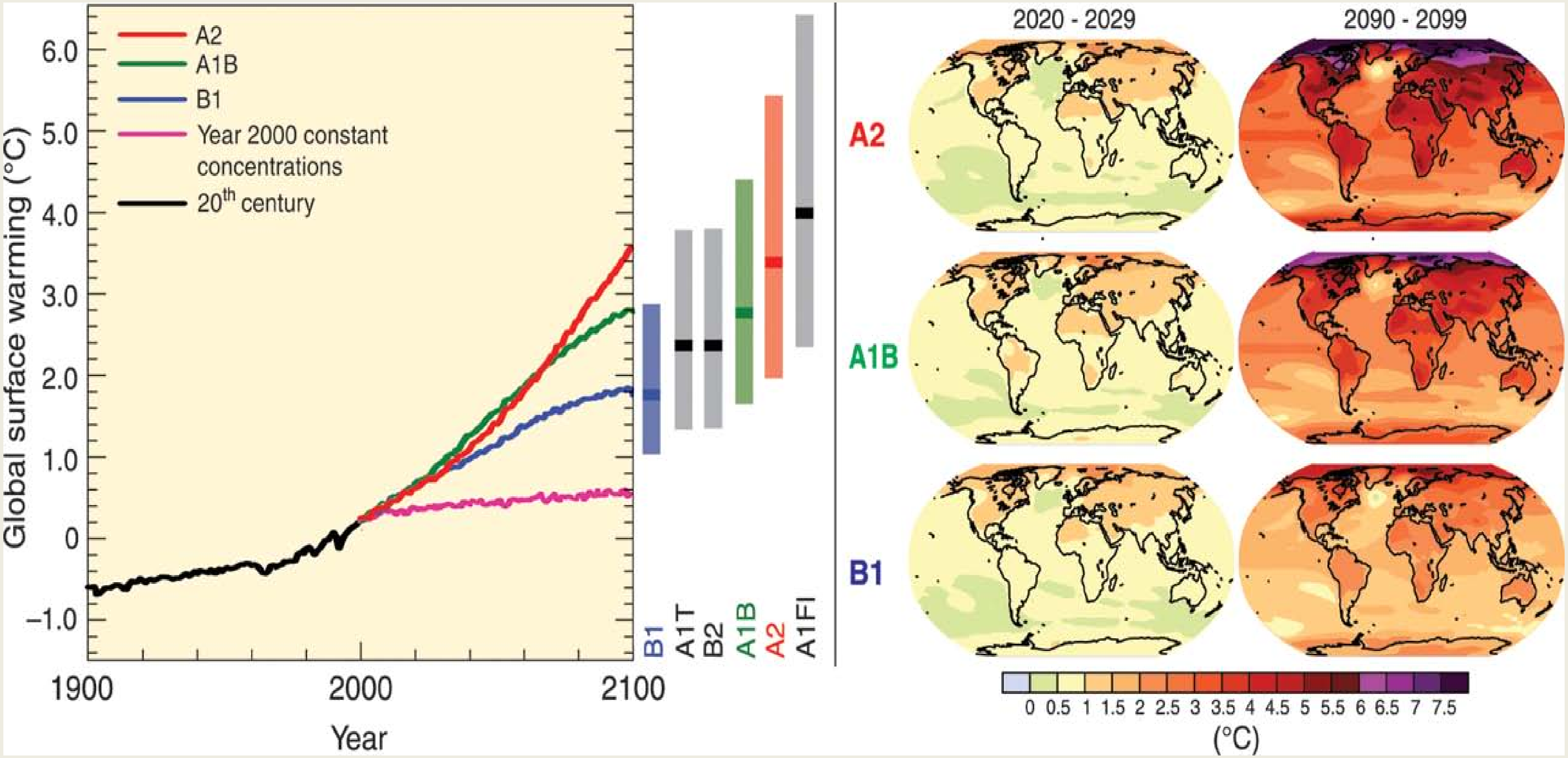
Climate change impacts on hydrology

The cascade of uncertainties

- Emission scenarios



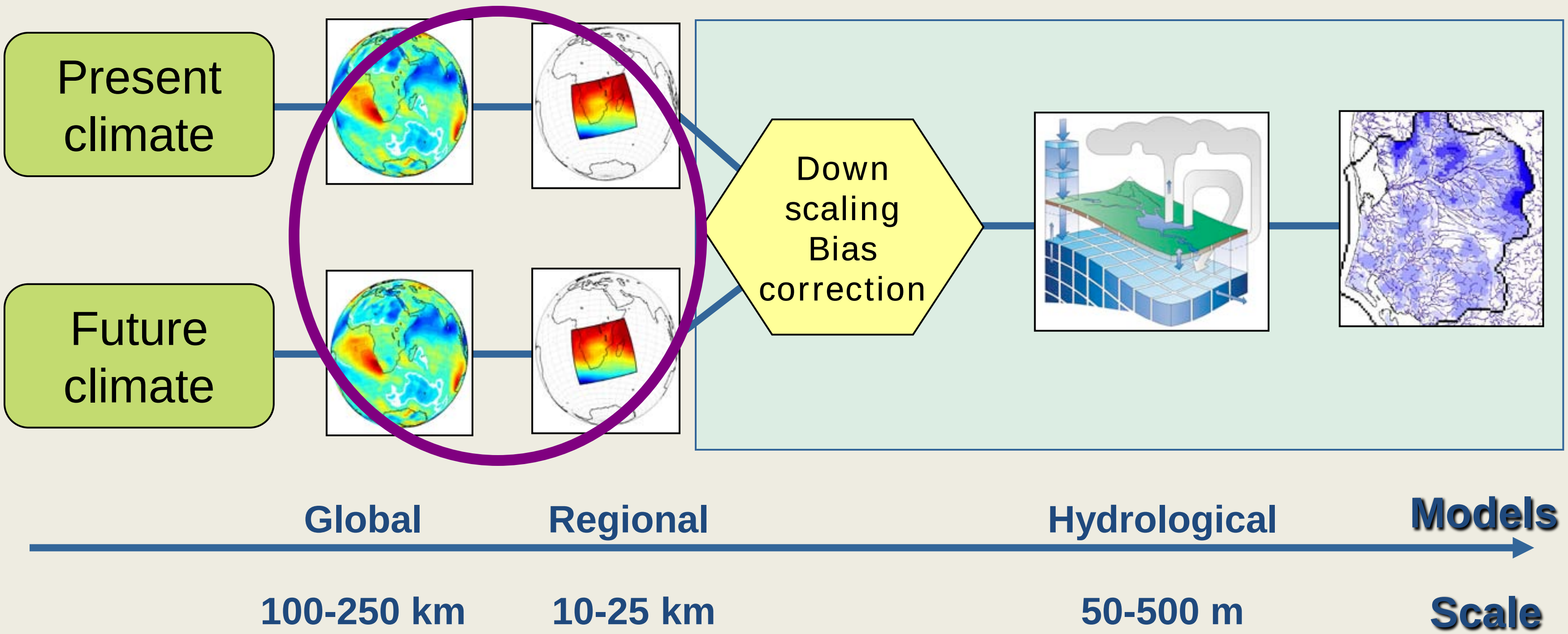
IPCC Greenhouse Gas Emission Scenarios



Climate change impacts on hydrology

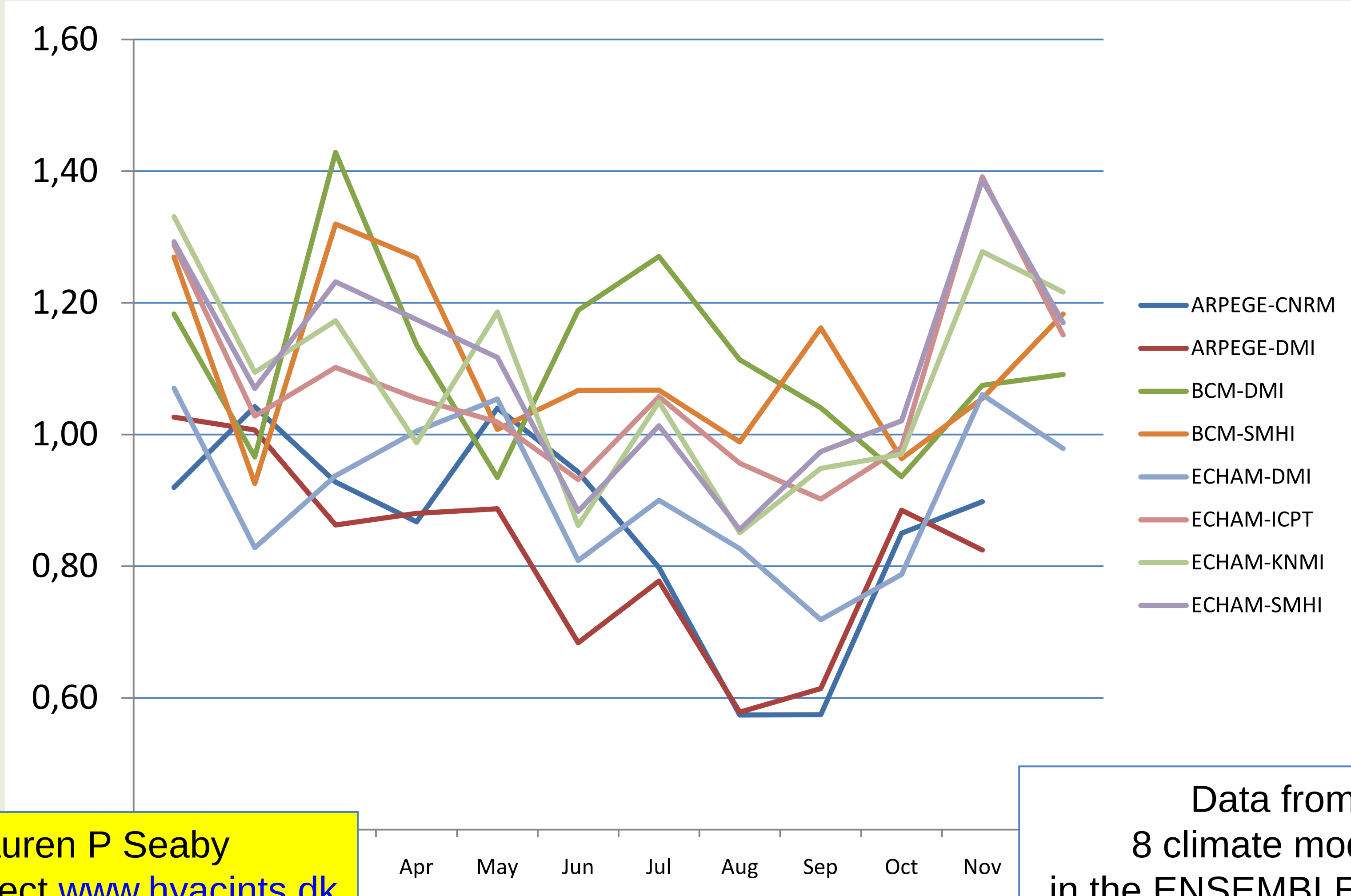
The chain of uncertainties

- Emission scenarios
- Climate models (GCM + RCM)



Uncertainties on climate models' projections

- Delta change factors on precipitation 2071-2100



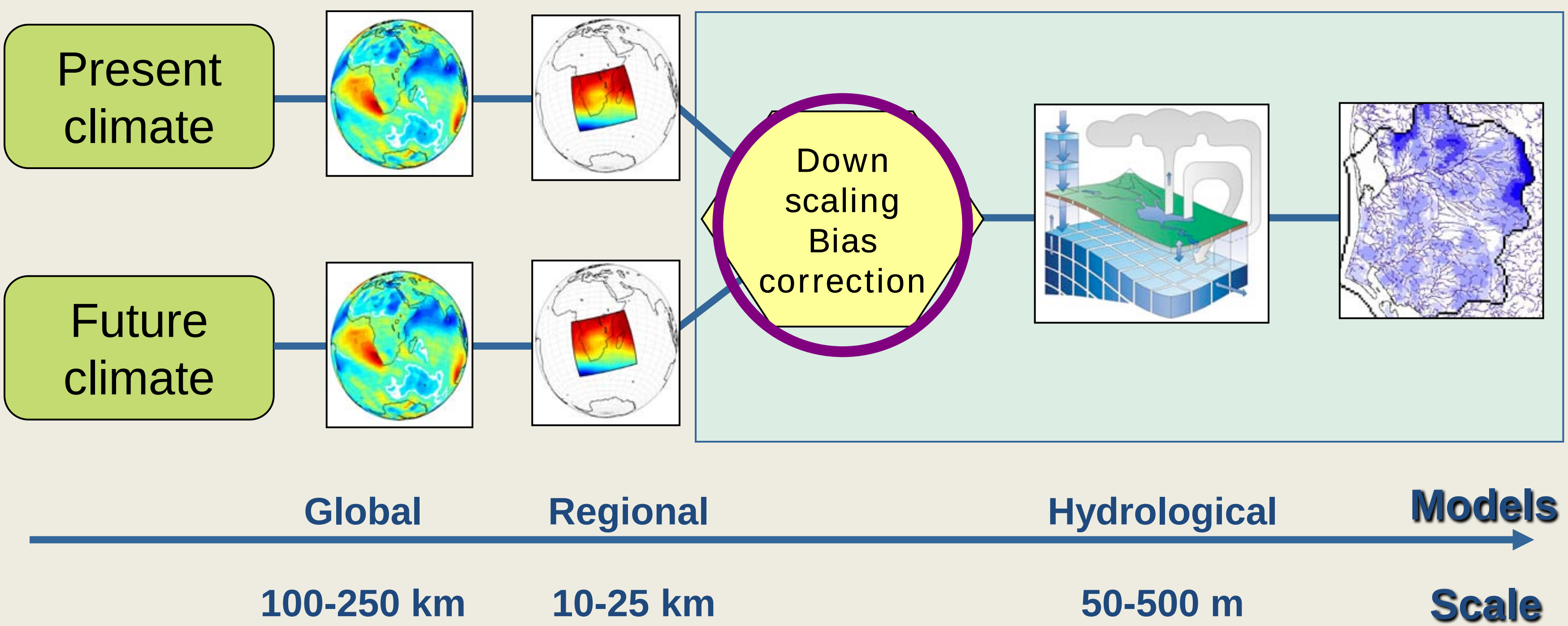
Lauren P Seaby
PhD project www.hyacints.dk
Preliminary results

Data from
8 climate models
in the ENSEMBLES project
(A1B)

Climate change impacts on hydrology

The chain of uncertainties

- Emission scenarios
- Climate models (GCM + RCM)
- Downscaling / bias correction

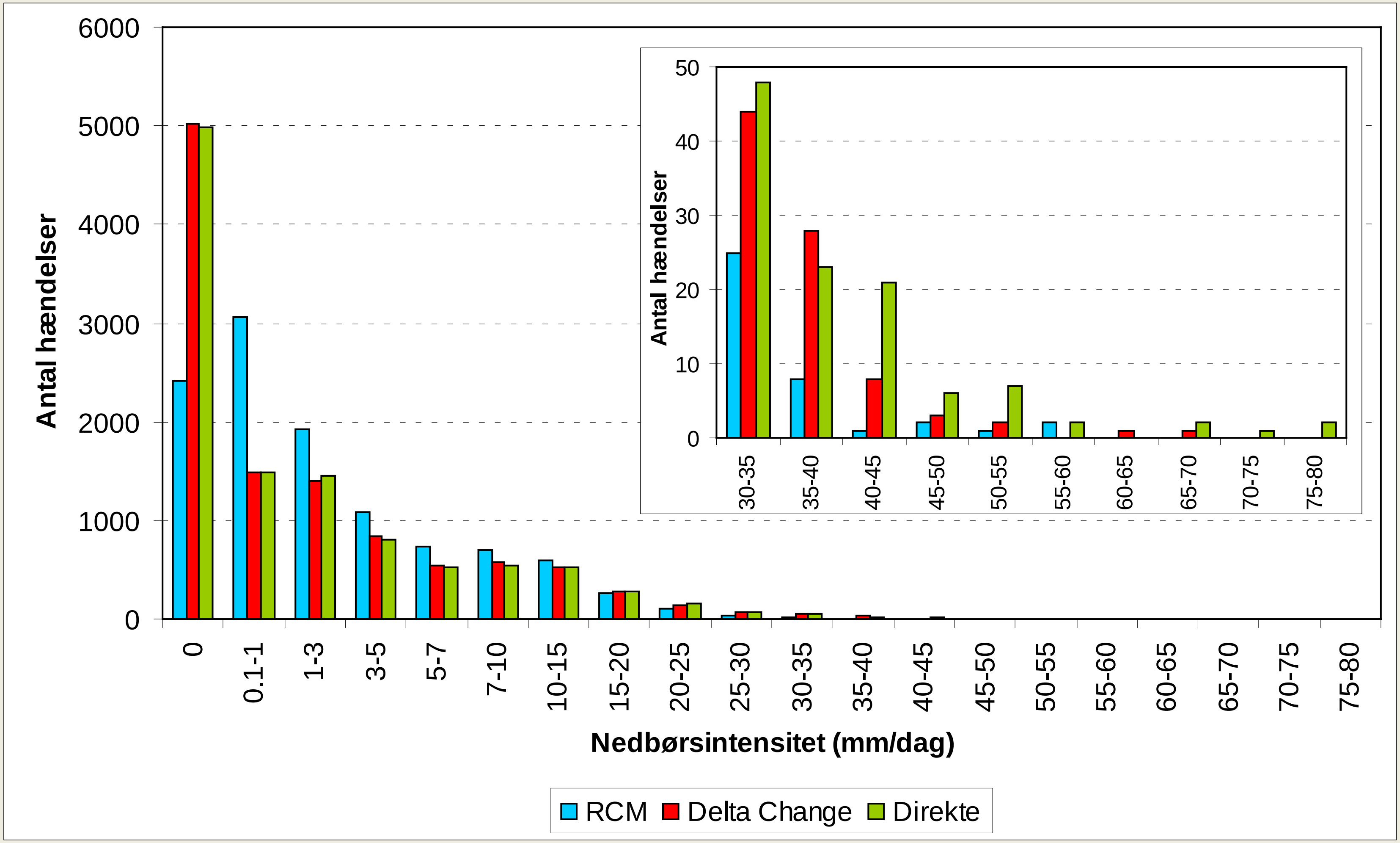


Statistical downscaling / bias correction

- Many different methods for making statistical downscaling ➔ different results
- We cannot know beforehand which downscaling method will turn out to be the best one

- Example – comparison of two methods for future precipitation
  - Delta change (monthly correction factors to observed precipitation)
  - Direct method – Histogram Equalisation Method (Gamma function correction of RCM simulated precipitation)

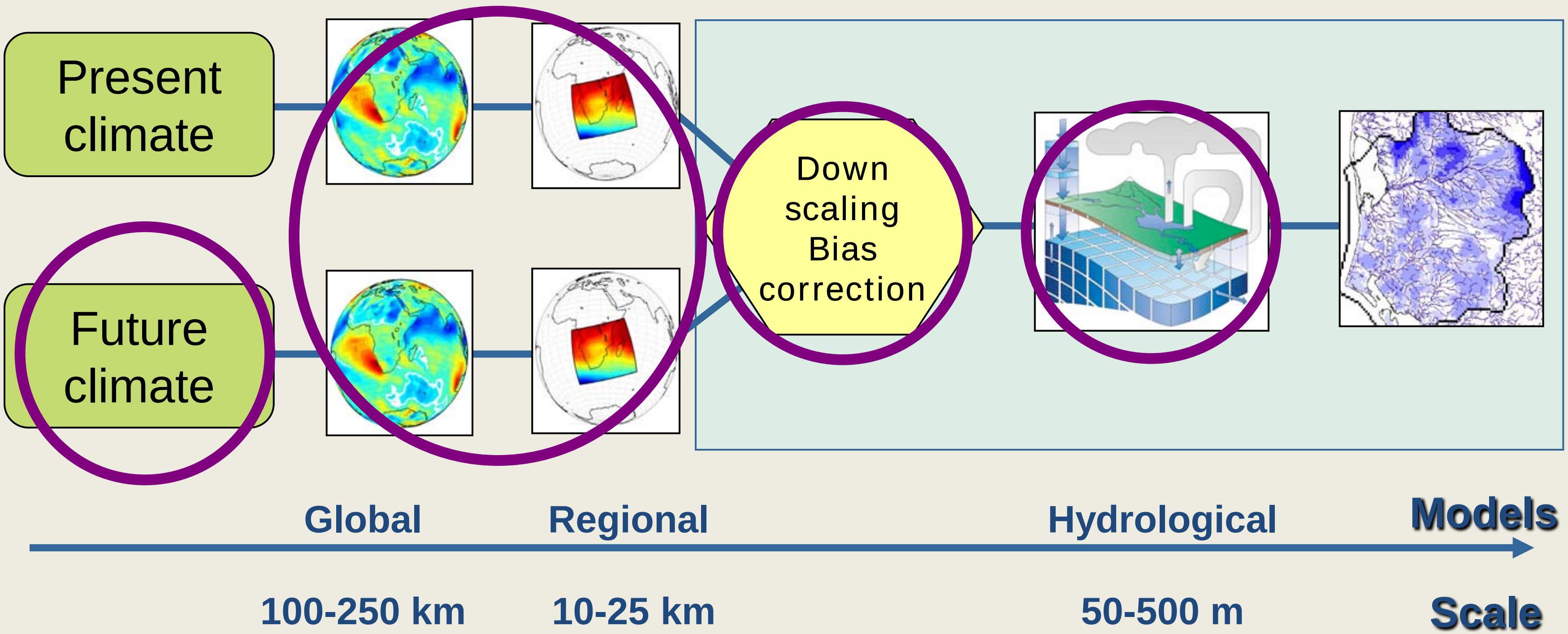
Statistical downscaling of precipitation
- Delta change versus Direct method



Climate change impacts on hydrology

The chain of uncertainties

- Emission scenarios
- Climate models (GCM + RCM)
- Downscaling / bias correction
- Hydrological model (geology, process equations, parameter values, input data)
- Natural variability of climate system

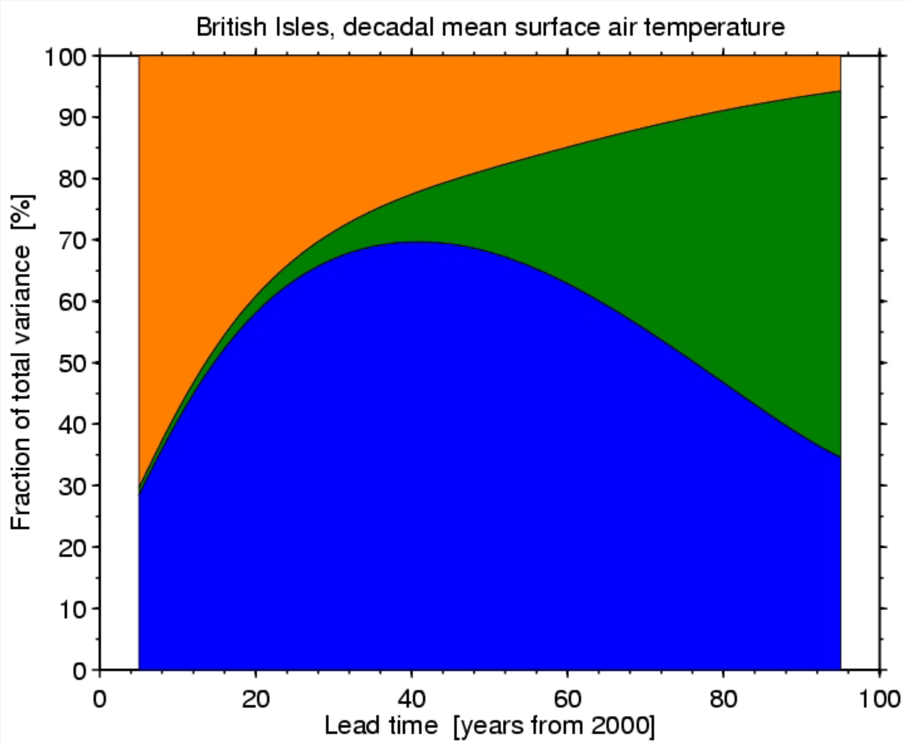


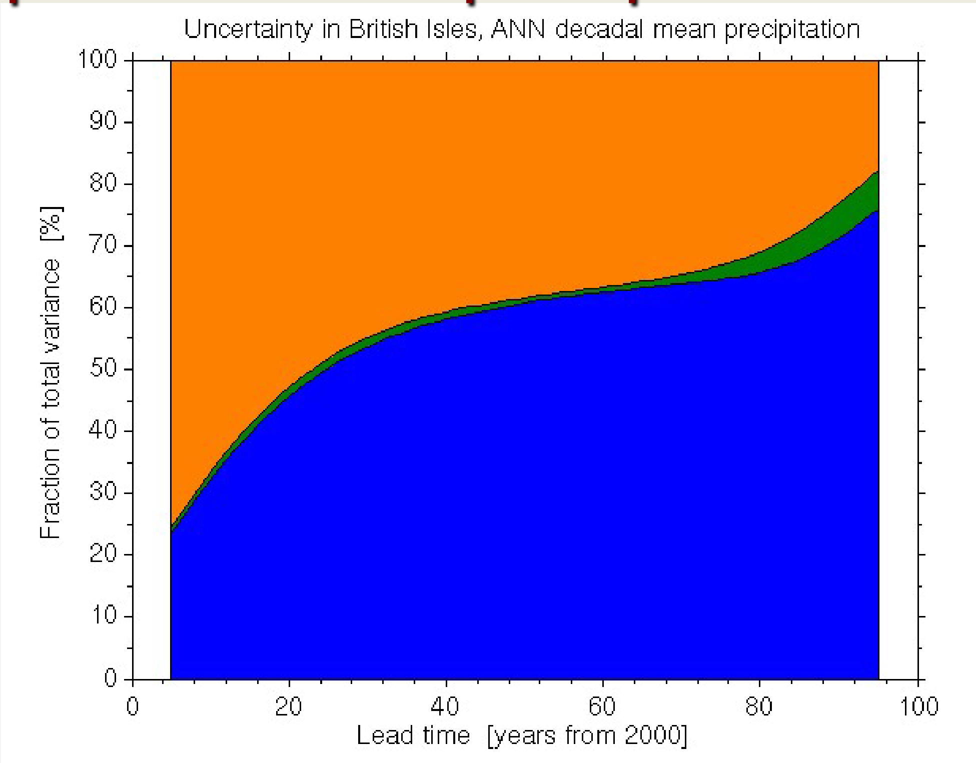
Natural climate variability

Relative importance of different sources of uncertainty

(*Hawkins and Sutton, 2009 & 2010)*

UK - 10 years mean temperature and precipitation





Blue: Uncertainty due to climate models (GCMs)

Green: Uncertainty due to GHG emission scenarios

Orange : Uncertainty due to internal (natural) variability

Uncertainty in climate change adaptation
- *General mapping*

Steps in climate change adaptation analyses (chain in uncertainty cascade)		Sources of uncertainty						Nature of uncertainty		
		Input data	Model			Context	Multiple know-ledge frames	Ambi-guity	Epistemic uncer-tainty (reducible)	Ontological uncer-tainty (ir-reducible)
			Parame-ter values	Model techni-cal aspects	Model struc-ture					
Greenhouse gas emissions						XX	XXX	XXX	XX	
Socio-economic scenarios		XX			XX	XX	XXX	XXX	XX	
Future climate (Climate models)	GCMs			XX	XXX				XXX	
	RCMs			XX	XXX				XXX	
	Initial conditions/natural variability	XX								XXX
Downscaling/statistical correction			XXX		XX				XX	XX
Water system impacts (Hydro-ecological models)		X	XXX	X	XXX	XX	X	X	XXX	X
Socio-economic impacts (Socio-economic tools)		XX			XX	XX	XXX	XXX	XX	
Adaptation measures		XX	XXX	X	XXX	XX	XXX	XXX	XXX	XX

Refsgaard et al (in preparation)
CRES www.cres-centre.dk

Uncertainty in climate change adaptation

- water infrastructure in rural areas, Denmark

Climate change impact					Adaptation			
Type of problem	**Consequence**	**Risk level**	**Dominating uncertainty**		**Option**	**Cost level**	**Additional uncertainty**	
			Source	Nature			Source	Nature
Water supply. Changes in groundwater recharge or acceptable influence on streamflow in critical low flow periods	Change in how much groundwater can be abstracted in a sustainable manner due to either problems in aquifer or low flow conditions in stream.	High	Climate models + hydro-ecological model parameters + structure (geology)	Epistemic	Relocation of groundwater abstraction – influencing also the protection zones (item below) *(structural)*	Med	Same as for impacts	
					Changes in objectives and risk willingness *(non-structural)*	Low	Multiple frames	Ambiguity
Water supply. Changes in wellfield capture zones	The selected areas for groundwater proctection will be the wrong area.	Med	CHG emissions + climate models + hydro-ecological model parameters + structure (geology)	Epistemic	Increase protection areas to account for worst case *(structural)*	High	Same as for impacts	
					Changes in strategy, increased risk to protect wrong area *(non-structural)*	Low	Multiple frames	Ambiguity
Inundations of roads	Road traffic interrupted	Med	CHG emissions + climate model structure	Epistemic+ Ontological	New design to avoid inundation *(structural)*	High	Same as for impacts	
					Close roads + warning in critical periods *(non-structural)*	Low	Multiple frames	Ambiguity
Undermining of road foundation due to increased groundwater table	Roads deteriorate	Med	Climate models + hydro-ecological model parameters and structure (geology)	Epistemic	New designs to accept high groundwater table *(structural)*	High	Same as for impacts	
					New designs to avoid high groundwater table *(structural)*	High		
					Drainage or pumping scheme to keep groundwater table low *(structural)*	Low		

Refsgaard et al (in preparation)
CRES www.cres-centre.dk

Strategies to handle uncertainty in climate change adaptation

- Strategy depends on nature of uncertainty
  - Epistemic: reducible by more knowledge
  - Ambiguity: reducible by dialogue and knowledge sharing
  - Ontological: non-reducible ➔ live with it
- Large uncertainties should not postpone actions
  - Some times the uncertainty has no importance for the decision
  - Planning (assess adaptation options) should be made now – as a basis for optimal timing of measures
- Adaptation assessments should include cross-sectoral synergies
- Risk perception differs among individuals and stakeholders
- Risk strategies should not be based on status quo attitudes to risk acceptance

Conclusions – Part 3

Uncertainty in climate change

- Climate change predictions involves large uncertainties
- Uncertainty sources → cascade of uncertainties
- Adaptations to climate change → additional uncertainties, ambiguity important

→ Adaptive management is about making complex decisions that are robust to uncertain future outcomes