The Art of Modelling

Professor Ian Townend, FREng

With acknowledgements to:

My Background

Civil Engineer with 40 years experience

- Graduated from Exeter in 1975
- Joined Sir William Halcrow & Partners (1975-1993)
  - Worked on a variety of infrastructure projects; mainly marine and coastal
  - Set up coastal numerical modelling group
  - Chief Coastal Engineer
- Managing Director ABP Marine Environmental Research (1993-2003)
  - Developed physical and numerical modelling capability
  - Focussed on estuary research
- Research Director at HR Wallingford (2006-2014)
  - Developed research strategy
  - International research
- Professor at University of Southampton, Visitor at SKLEC and NHRI
  - Ocean and Earth Sciences
- Fellow of the Royal Academy of Engineers (FREng)

Where I live

Winchester

- About 120 km from London
- Originally the Capital of England

COASTALSEA.UK

The Art of Modelling - Outline

- What is modelling?
- Problem solving
- The Conceptual Model
- Defining the problem
- Model abstraction
- Types of Model
- Synthesis
- Communication

What do we need to be able to do?

- What are we trying to achieve through modelling?
  - Interpreting and interpolating data
  - Simulate dynamic behaviour of processes and systems
  - Predict and forecast dynamic change
  - Formalise knowledge, test ideas, solve problems
  - Understand and communicate
    - Behaviour, processes, interactions in complex systems
  - Provide evidence to support decision making
      - Robust > credible, transferable, reliable, objective and well founded
    - Uncertainties identified and ideally quantified

How to Solve it

- Understand the problem
  - What is unknown, what are the data, what are the conditions/constraints?
- Devise a plan
  - Is there a related problem, look at the unknown, could you restate the problem?
- Carry out the plan
  - Check each step. Is each step correct? Can you prove it is correct?
- Look back
  - Check the result and argument. Can you derive the result differently as a cross-check?

After George Polya

Scientific Method

- Understand the problem
  - Identify unsatisfactory explanation in existing theory or data
- Devise a plan
  - Define a hypothesis and decide how to test the hypothesis
- Implement the plan
  - Carry out the tests or experiments and critically examine the findings
- Look back
  - Review the findings against other work and revise or update the theory

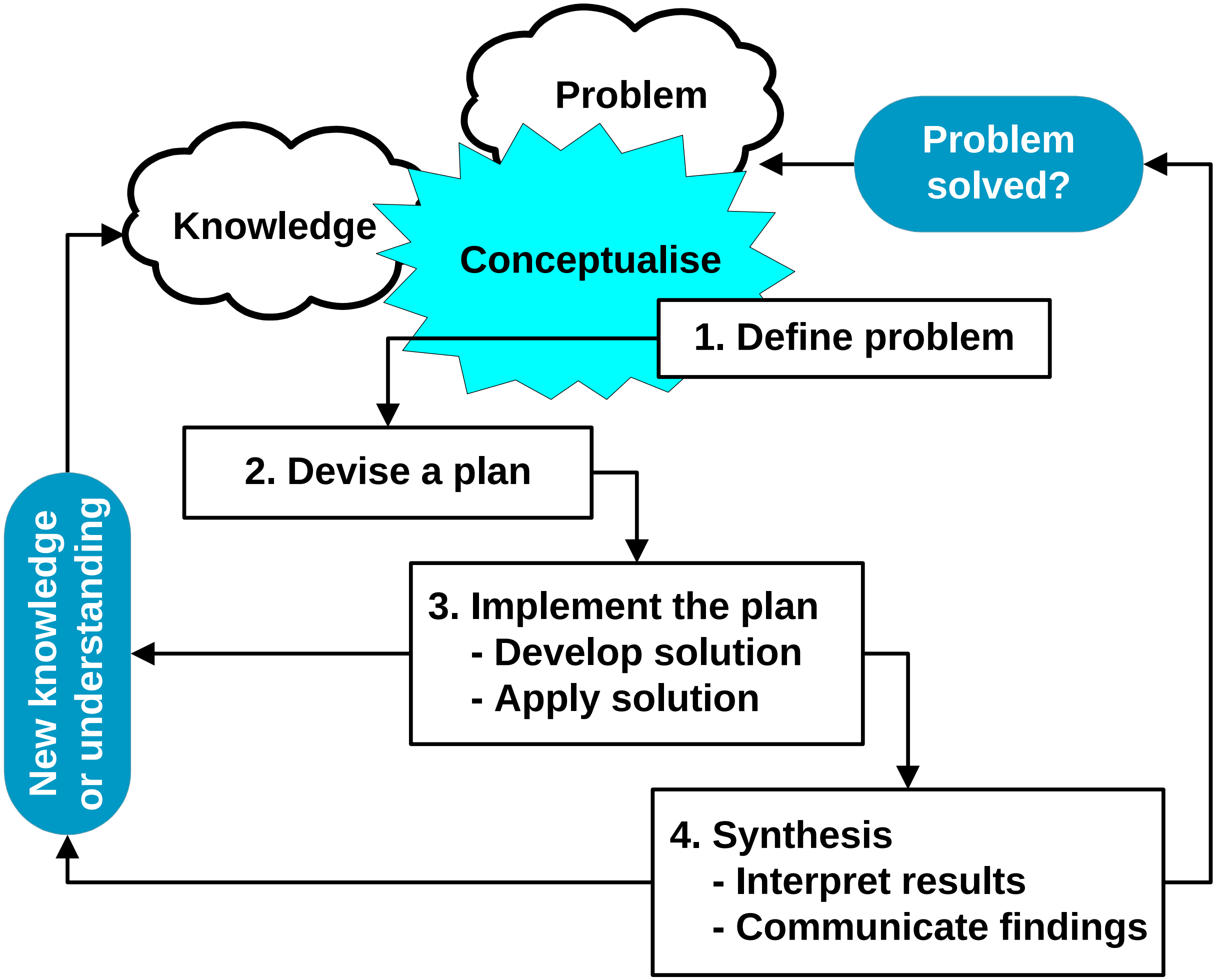
Development Projects

- Understand the problem
  - Identify the aims and objectives of the project
- Devise a plan
  - Scope the approach, using existing information and conceptual models of system
- Implement the plan
  - Carry out the work programme, including data collection, analysis, testing, modelling, sensitivity tests and predictions
- Look back
  - Synthesis of all available evidence, cross-check results and test that proposed solution is robust

Comparison of frameworks

Mathematics	Research	Projects
• Define problem • Devise plan • Implement plan • Look back	• Unsatisfactory explanation • Hypothesis to be tested • Criticism (testing) • Review (update theory)	• Issues to be examined • Scope approach • Work programme • Synthesis
Solution	Accepted theory	Conclusions/Solution

Stages to Solve a Problem



Step 1 – Define Problem

- Develop a good understanding of the problem
- Build on existing knowledge
- Find out about the context (social, political, economic, research)

Output:

- Agreed definition of the problem
  - Hypothesis to be tested; or
  - Project aims and objectives, or performance targets

Step 2 – Devise a Plan

- Plan will draw on:
  - what data already exists;
  - previous research or projects; and the
  - measurements, methods of analysis and modelling techniques available
- Constrained by:
  - Timescale, budget available, existing knowledge and data availability

Output:

- Work programme, milestones and targets

Often useful to develop a "Conceptual Model" at this stage as a framework to guide the development of the work plan and the subsequent synthesis of the results

Step 3 – Implement the Plan

- Develop the Solution
  - Need to decide how to represent, or idealise, the real world – "*abstraction*"
  - Collect supporting field or laboratory data
  - Test the solution is representative and reliable
  - Explore uncertainties

Output: Tested means of solving the problem

- Apply the Solution
  - Replication of known results, or calibration and validation
  - Sensitivity tests and "What if" scenarios

Output: Results for the intended application

- Should be supported with information on assumptions, simplifications, sensitivities and assessment of uncertainties

Step 4 - Synthesis

Simply presenting the output of a data analysis, or series of model runs, is generally not very informative

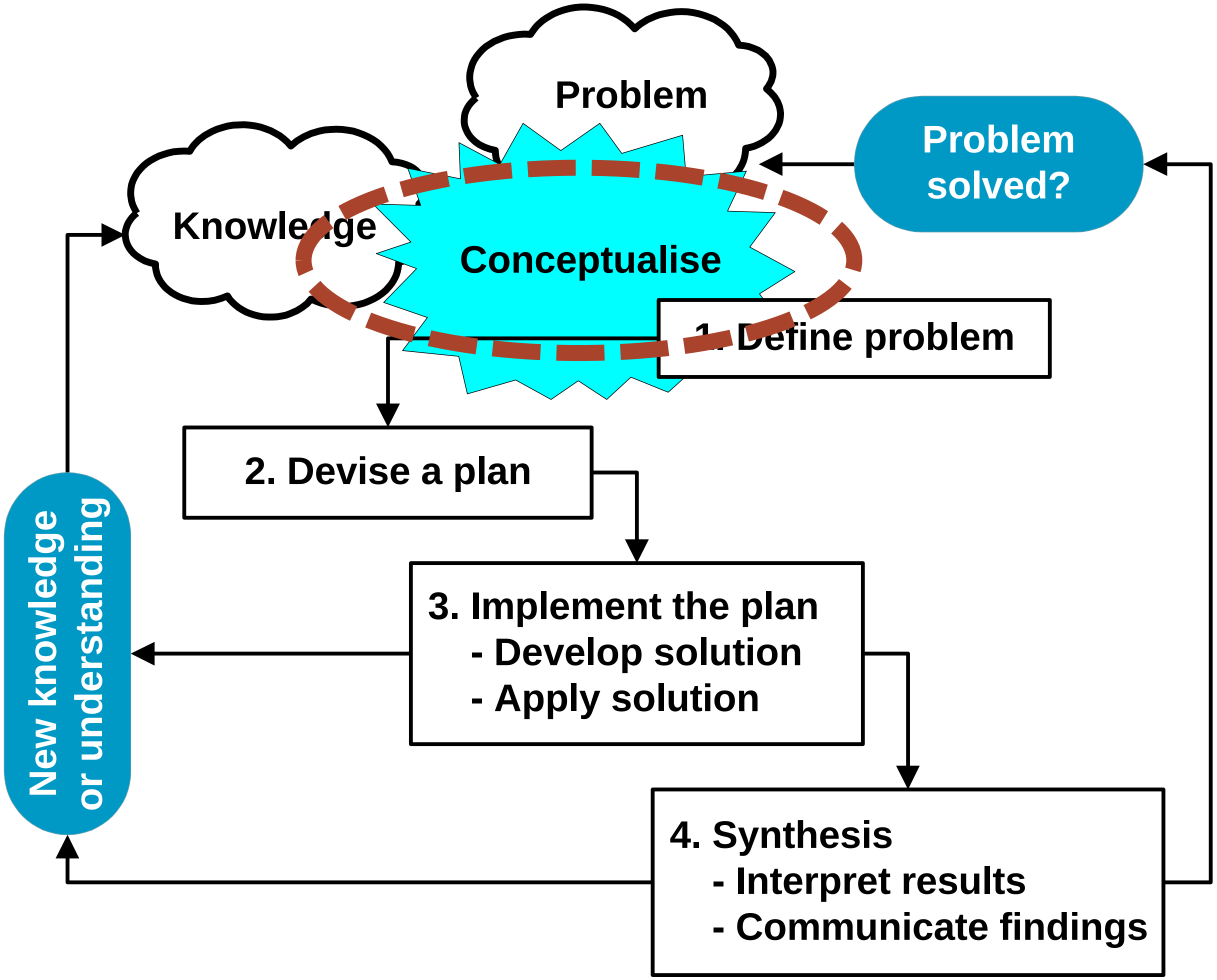
- Interpret the Results
  - check that each step is correct and that the final results make sense;
  - extend understanding by answering specific questions;
  - use conceptual model to refine understanding in the light of the results

Output: answers to the problem posed, with clear lines of evidence

- Communicate the findings:
  - Tell a story to build a clear picture of the evidence and conclusions

Output: clear and concise summary of the findings

Stages to Solve a Problem



Conceptual Model

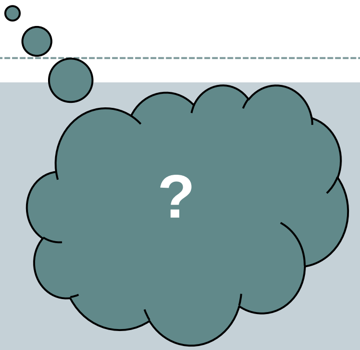
- Variety of Methods and Models can be formulated using many sources of information, such as:
  - Data (observed, synthetic, Big data, Fuzzy, folk-lore)
  - Physical and numerical model results
  - Analysis and interpretation of literature

Each will provide information on the problem

- Conceptual Model could be articulated as:
  - Synthesis of what is known
  - Accepted behavioural model or description

Provides the framework for a research hypothesis or problem definition (aims and objectives)

Conceptual Model



- Descriptive summary of behaviour:
  - Captures complexity of interactions
  - Covers range of space & time scales
  - Identifies state changes:
    - Dynamic equilibrium or steady state; Transitional behaviour; Catastrophic switches
  - Highlights sensitivity to change
    - natural and imposed
- Simple enough to communicate clearly
- Will be limited by current understanding

Conceptual Model

Producing a conceptual model involves…..

Using various sources of data and existing knowledge to develop an understanding of how the system being studied behaves

This needs to be revised (or reformulated) as new data, experimental results, and modelling results become available.

Difficulties in developing a conceptual model

- *Complex interactions:*
  - System will evolve in response to a variety of forces over different time and space scales
  - Resolving all responses is complex, especially when system is non-linear
- *Limits of current understanding:*
  - Methods and models are not available to predict all aspects of coastal processes
  - Uncertainties and errors in data and model results may affect our current understanding

Types of Conceptual Model

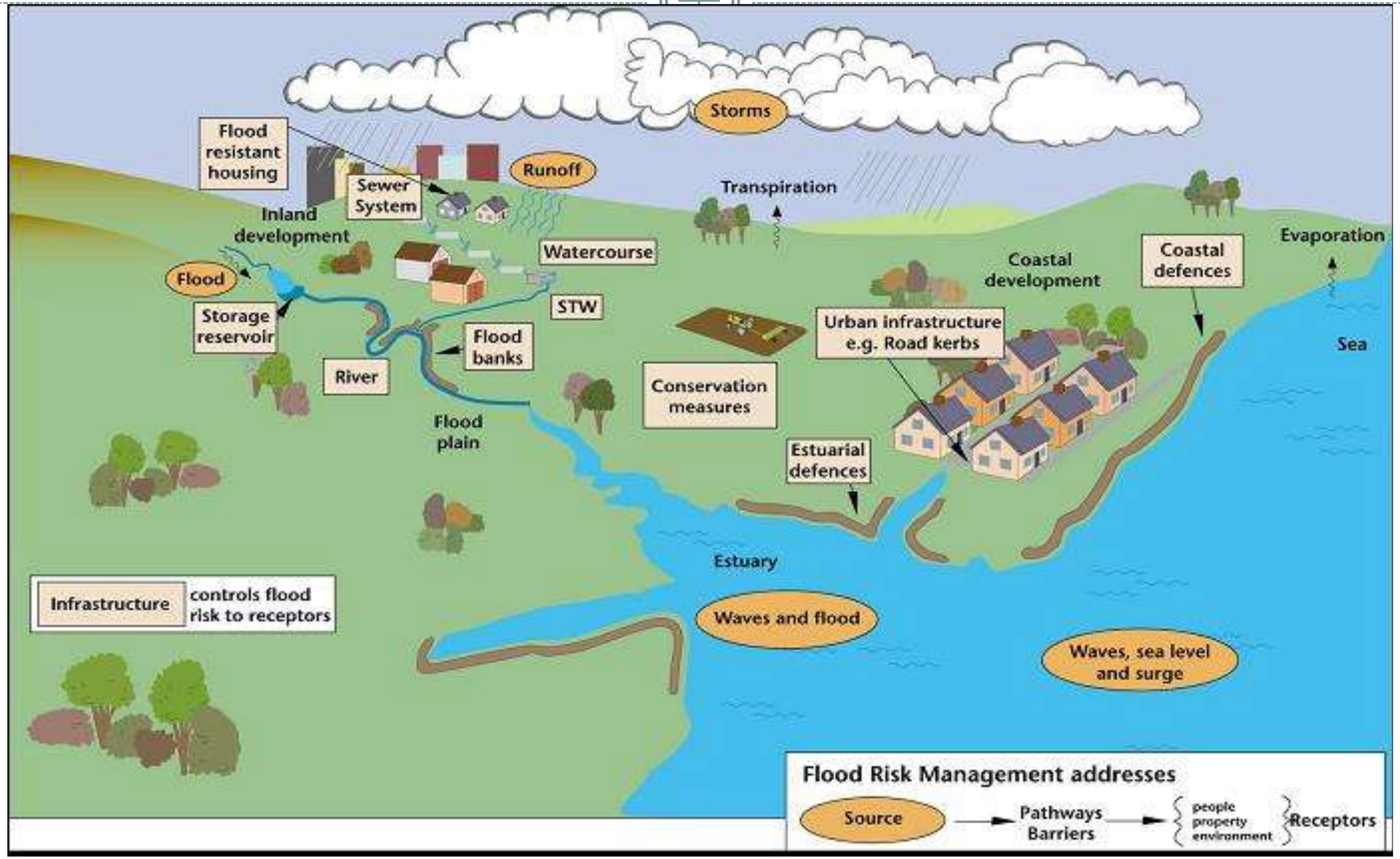
Basic Conceptual Model

- Simple sketch of linkages and feedbacks
- Discussion of likely response to change (usually perturbations to the system)

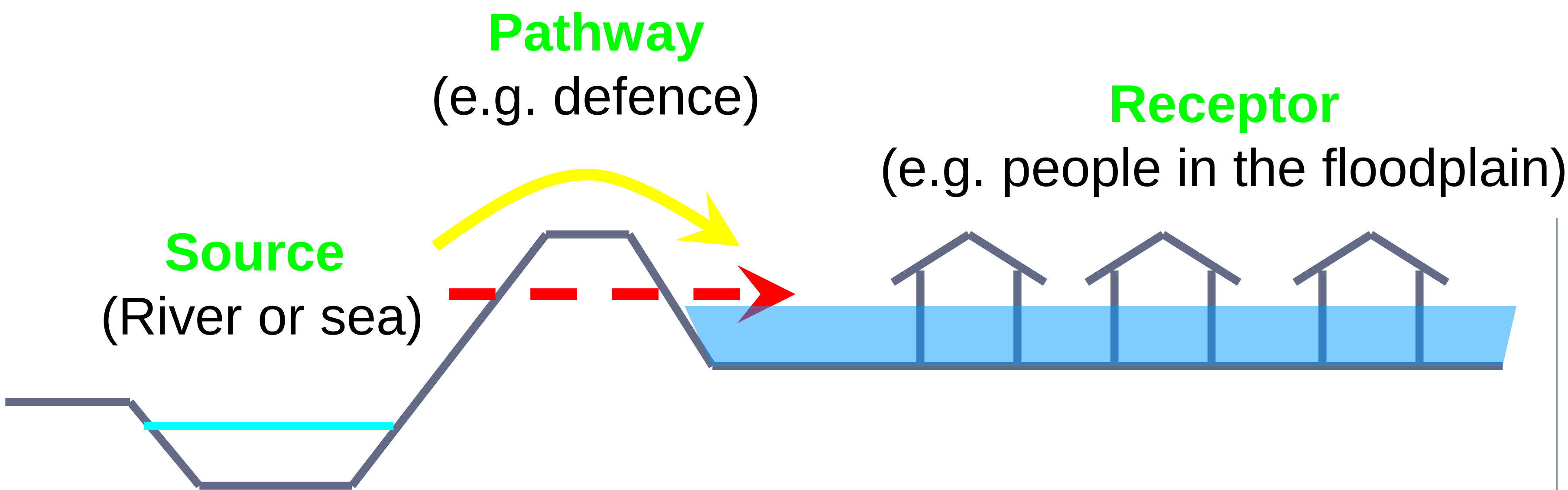
Fully Developed Conceptual Model

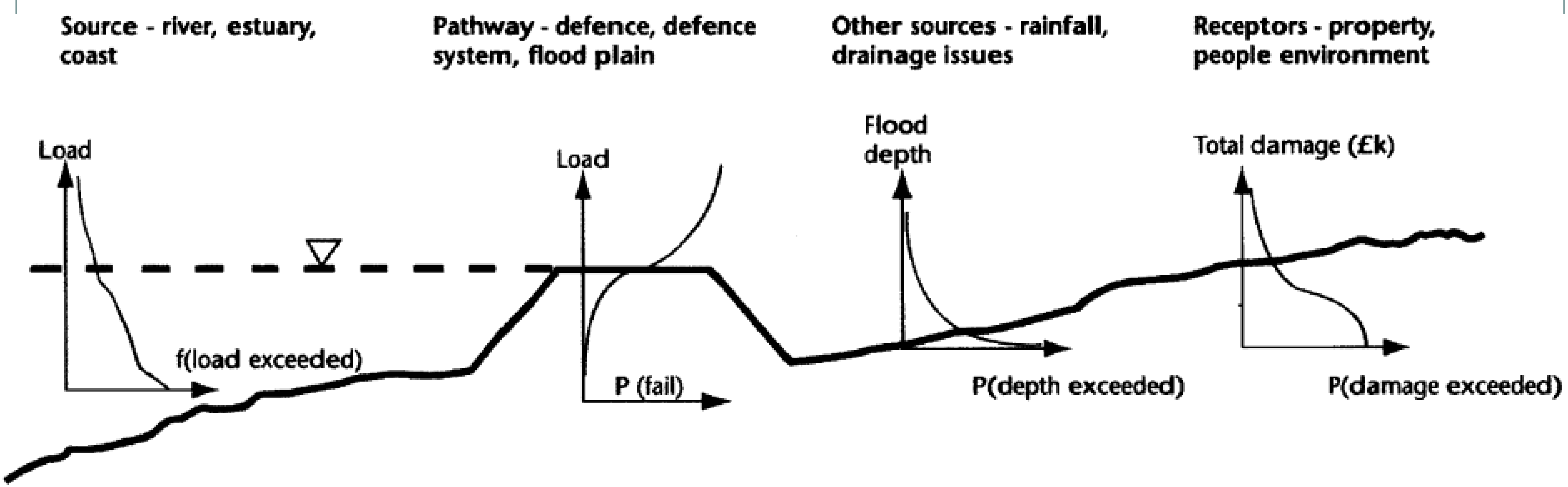
- All components of the system represented
- Key process and feedback controls identified
- Key pathways for mass and energy identified
- Likely system responses understood
- All uncertainties in current understanding highlighted

Flooding Foresight Conceptual Model

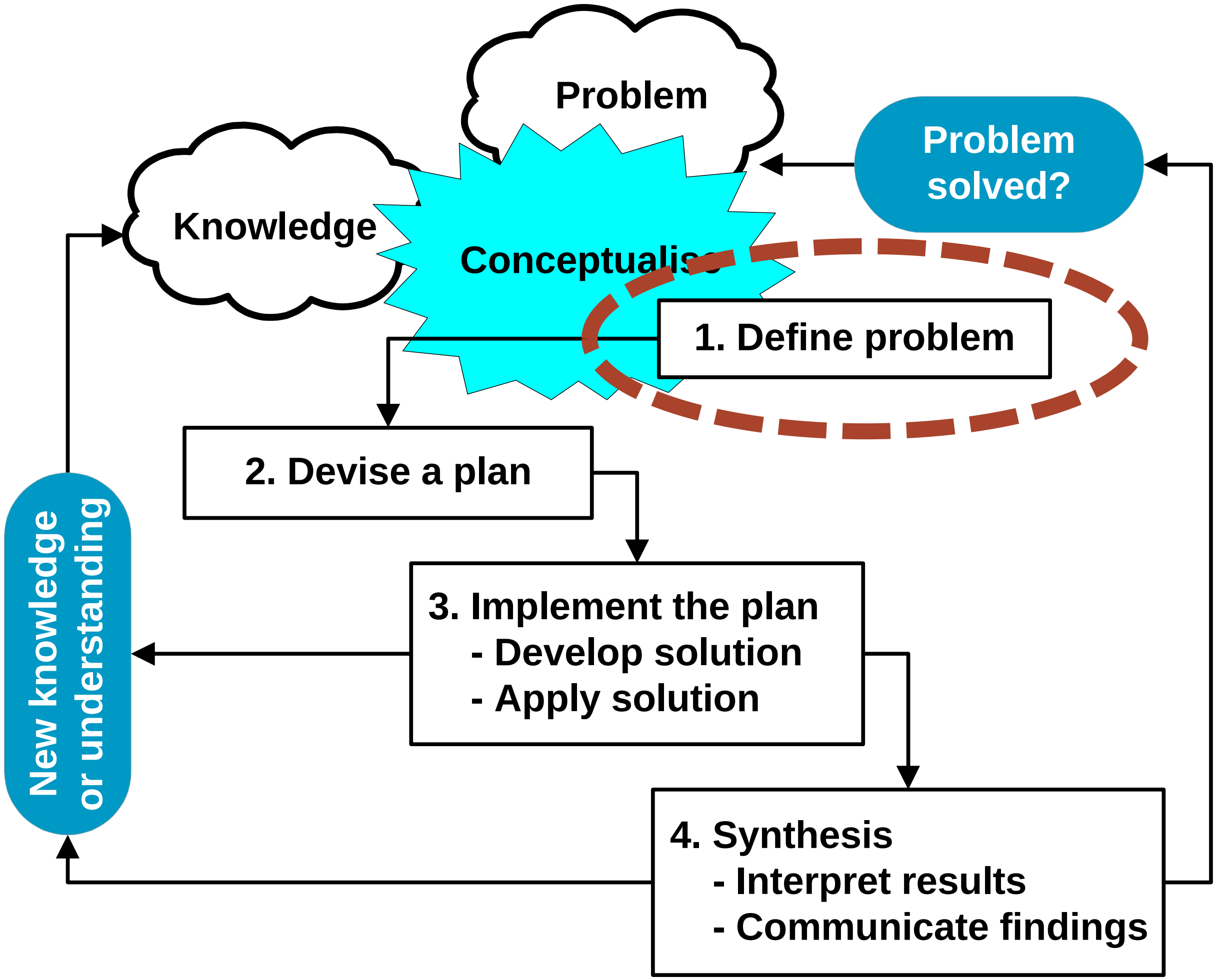


Source - Pathway - Receptor





Stages to Solve a Problem



1. Define Problem

- What is the context or background to the problem?
- What is unknown, what are the data, what are the conditions/constraints?
- Is the problem similar to other problems that have already been solved?

For research:

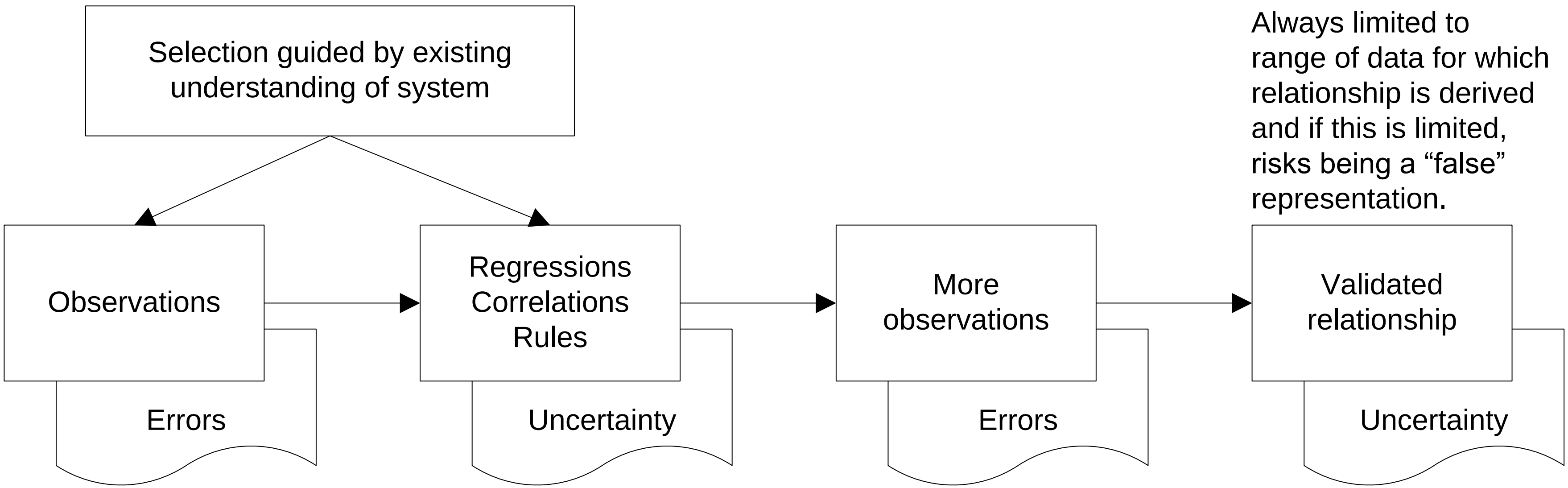
- What are the science questions?
- What is the hypothesis to be tested?

For projects:

- What are the client requirements (aims and objectives)?
- What are the performance targets?
- What are the constraints (budget, timescale, regulations, etc)?

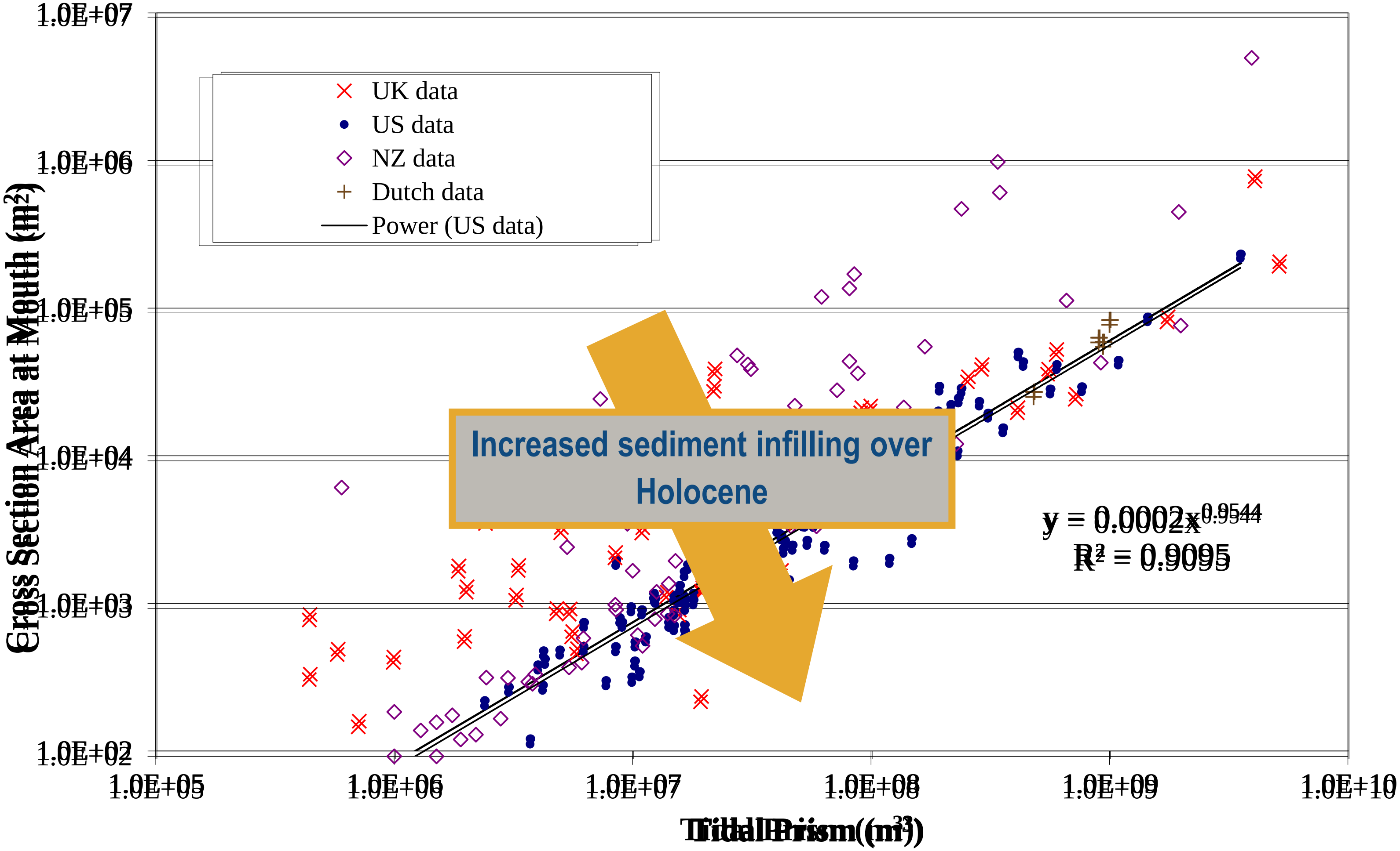
Process of Induction

‘Black-box’ modelling



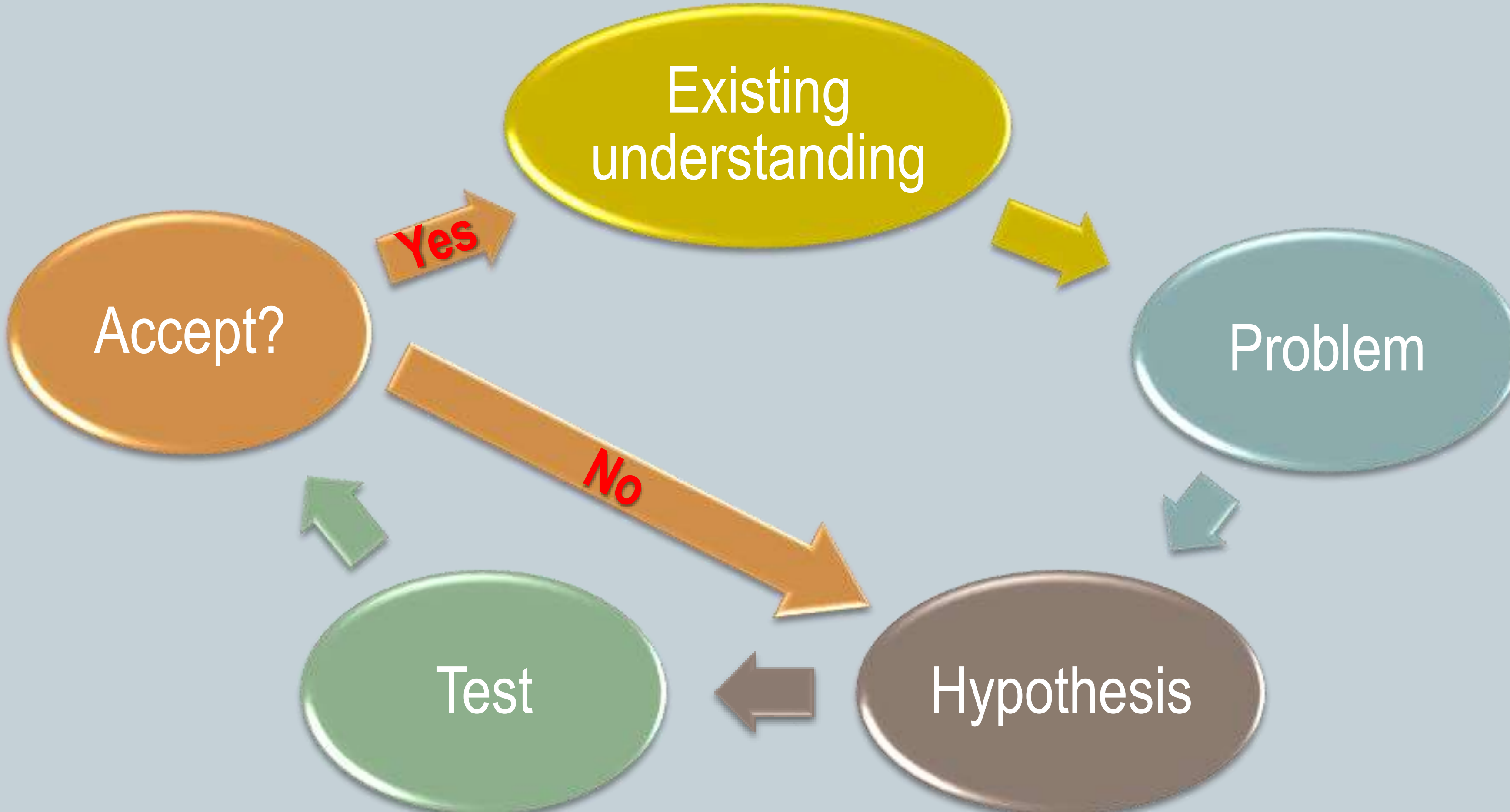
Black swans on a UK beach – May 2016

Black Box or Data Driven Models



Hypothesis led deduction

Reasoning from one or more statements to reach a logically certain conclusion



Generally accepted approach

1. Observation gathering and ordering of data
2. Pattern detection, regularities and generalisation
   - sometimes called induction
3. Development of explanatory theories
4. Deduction of hypotheses to test theories
5. Testing of the hypotheses
6. Support or adjustment of theory

After Coolican, 1996

Example - Research

- Problem
  - Sediment exchange at the mouth of an estuary is complex because of the interaction of tides, river and waves.
  - Understanding the behaviour is important if safe navigation is to be maintained
- Science question
  - What are the key drivers of annual sediment movement in the North Passage of the Yangtze?
- Hypothesis
  - Tidal processes are the dominant mechanism of sediment transport and waves, river flows and density driven currents are all of secondary importance

Example - Research

- Problem

Dominant or main processes (NOT ALL)

e at the mouth of an estuary is complex
raction of tides, river and waves.
behaviour is important if safe navigation is

Time Scale

- Science question
  - What are the key drivers if annual sediment movement in the North Passage of the Yangtze?

Space Scale

- Hypothesis
  - Tidal processes are the … n of sediment transport and waves, river flows and density driven currents are all of secondary importance

Example - Research

- Problem
  - Sediment exchange at the mouth of an estuary is complex because of the interaction of tides, river and waves
  - Unders…
    to be m…
- Science…
  - What a…
    North Passage of the Yangtze?
- Hypothesis
  - Tidal processes are the dominant mechanism of sediment transport and waves, river flows and density driven currents are all of secondary importance

To be able to write this hypothesis one needs an understanding of likely behaviour

Hence the need for a conceptual model

Example - Project

- Problem
  - Major storms cause sever flooding at the coast
  - The flood hazard is increasing as a result of climate change
  - This poses an increasing risk to people and property
- Design question
  - How can we reduce the flood risk to an acceptable level (say the 1 in 100 year probability of damage) for the town of Jinshan over the next 50 years?
- Project aim (what the client wants to know)
  - The level of risk will be acceptable with the proposed new defences (or management plan)
  - Work can be completed within the time and budget available

Example - Project

- Problem
  - Major storms cause sever flooding at the coast
  - The flood hazard … a result of climate change
  - This poses an inc… eople and property

Focus of interest

- Design question
  - How can we reduce the flood risk to an acceptable level (say the 1 in 100 year probability of dan… Jinshan over the next 50 years?

Time Scale

- Project aim (what the client wants to know)
  - … will be acceptable with the proposed new defences (or management plan)
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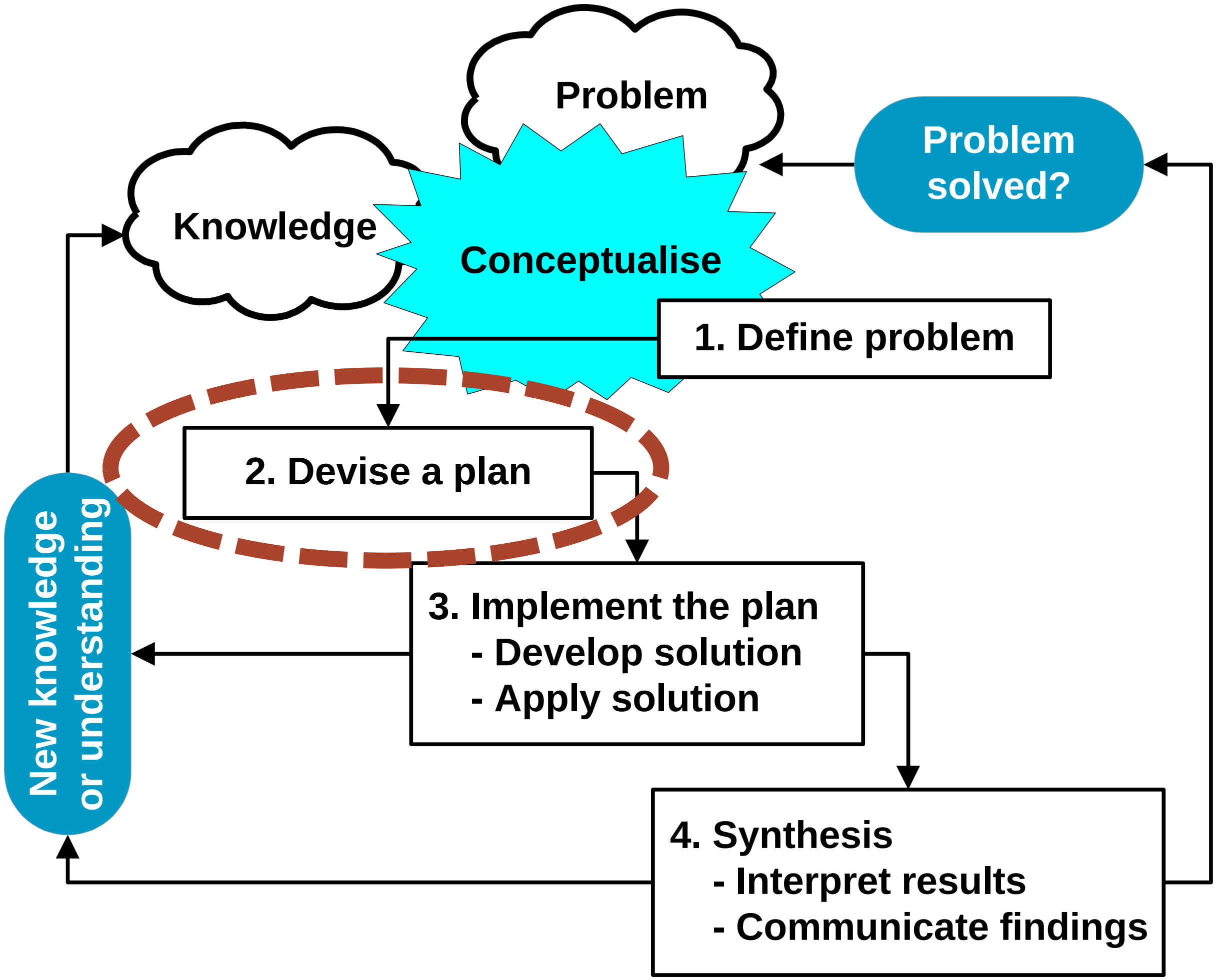
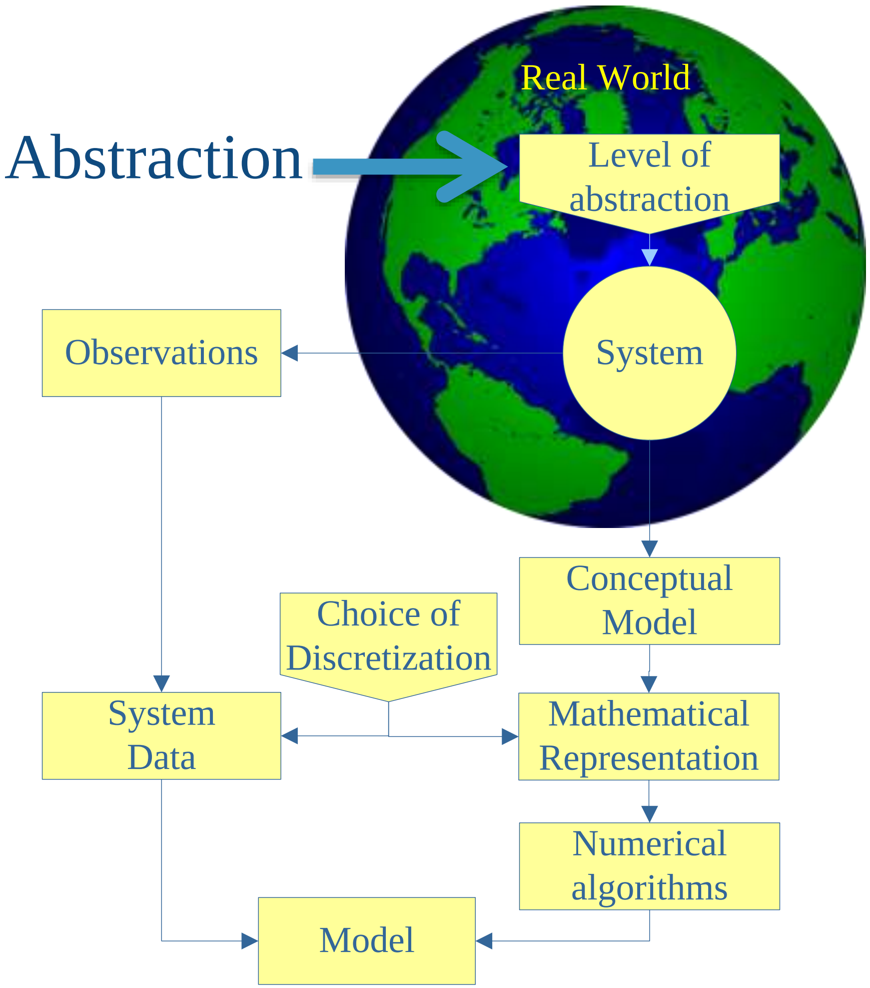
Space Scale

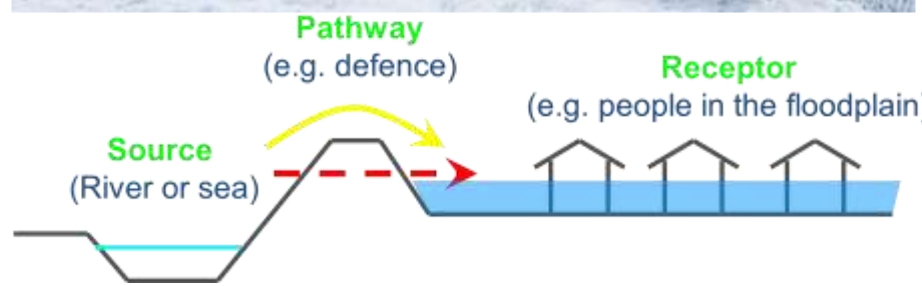
Stages to Solve a Problem



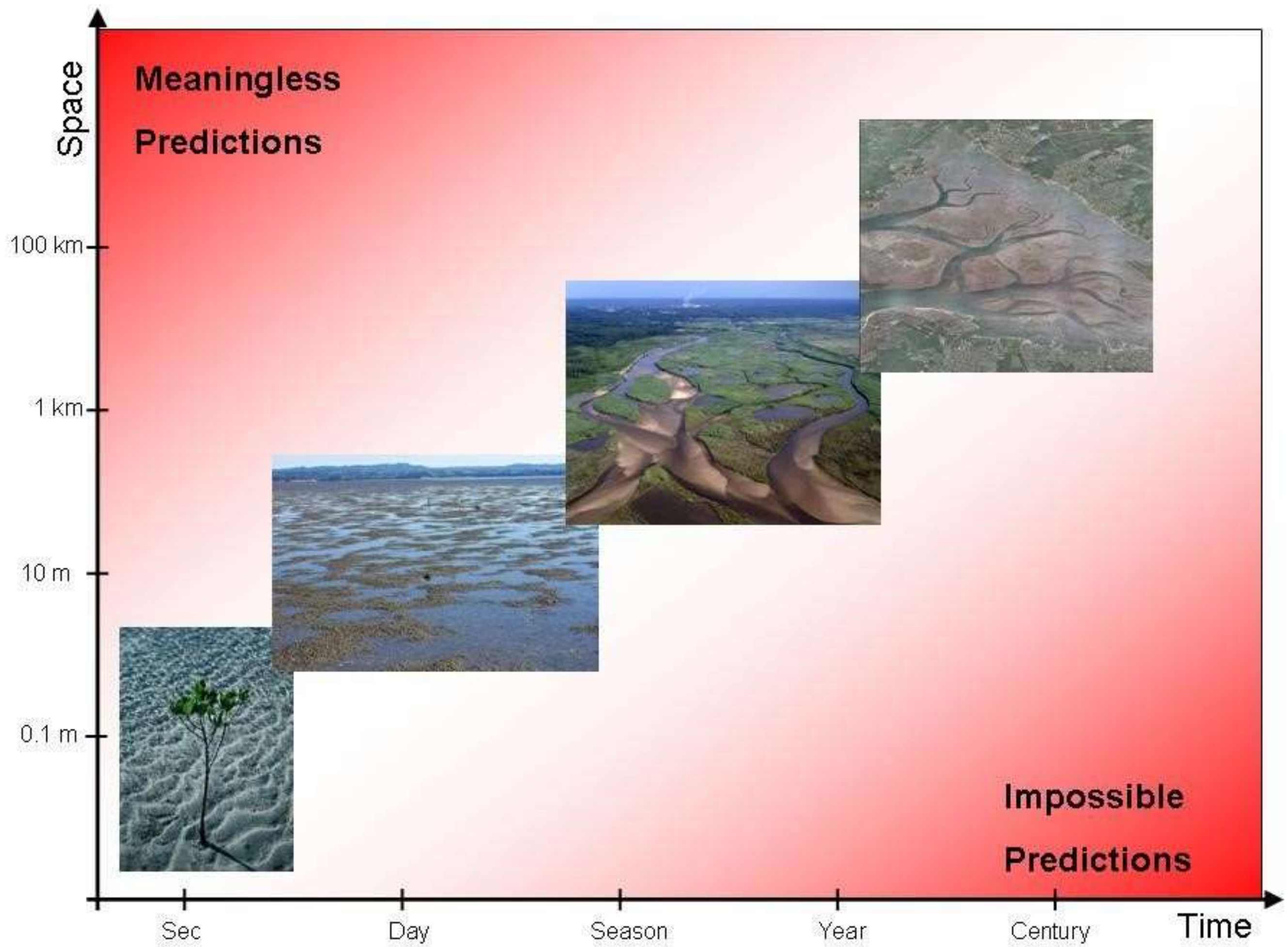
Abstraction – from Real World to Model

From "real world" to model

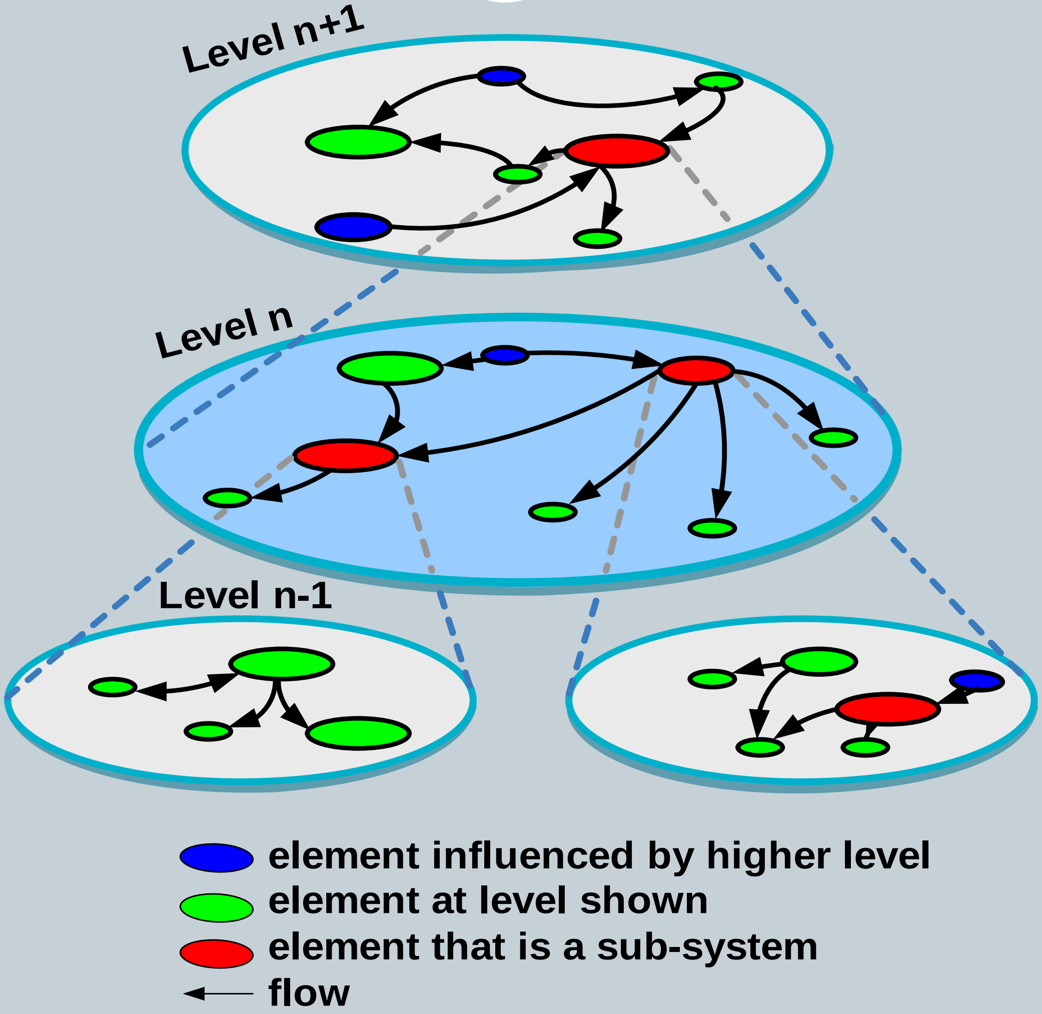




Time & Space Scales



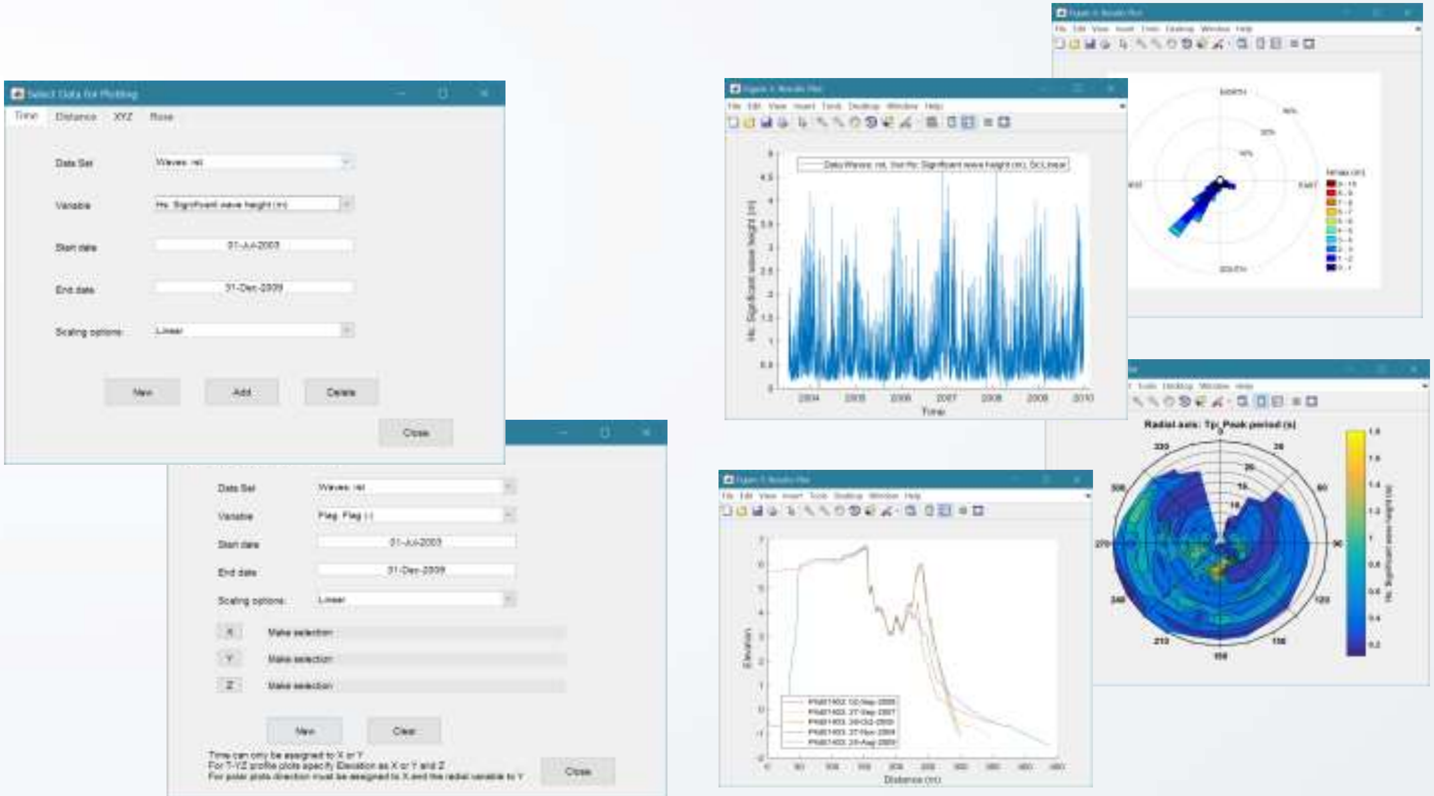
System Levels, Elements & Flows



Example of Abstraction

- Possible levels for the case of an estuary

Higher level:	Global tidal dynamics and meteorological forcing operate at much larger spatial scales and would be typically prescribed as boundary conditions for the model.
Level of interest:	Estuary system to predict water levels, flows and pollutant dispersion
Lower level:	Variations in the character of the bed represented by a "simplification" in the form of a friction factor and turbulence in the flow structure represented by some suitable simplified formulation (turbulence closure).



Types of Model

Some types of model

- Qualitative
  - Conceptual
    - Descriptive
    - Behavioural
  - Frameworks
    - DPSIR:

Driver-Pressure-State-Impact-Response

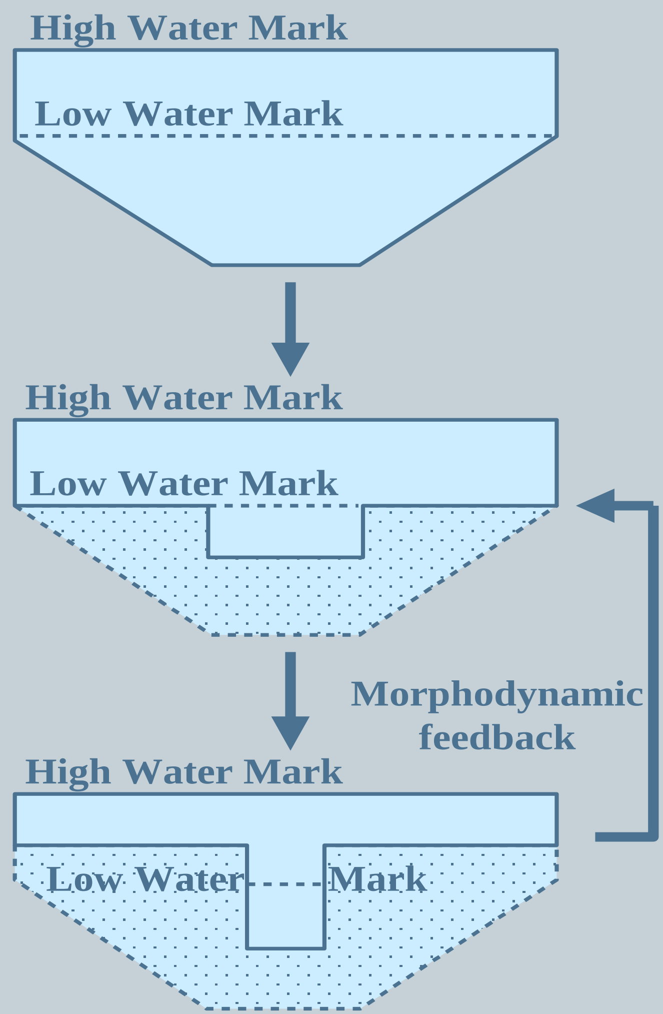
    - S-P-R

Source-Pathway-Receptor

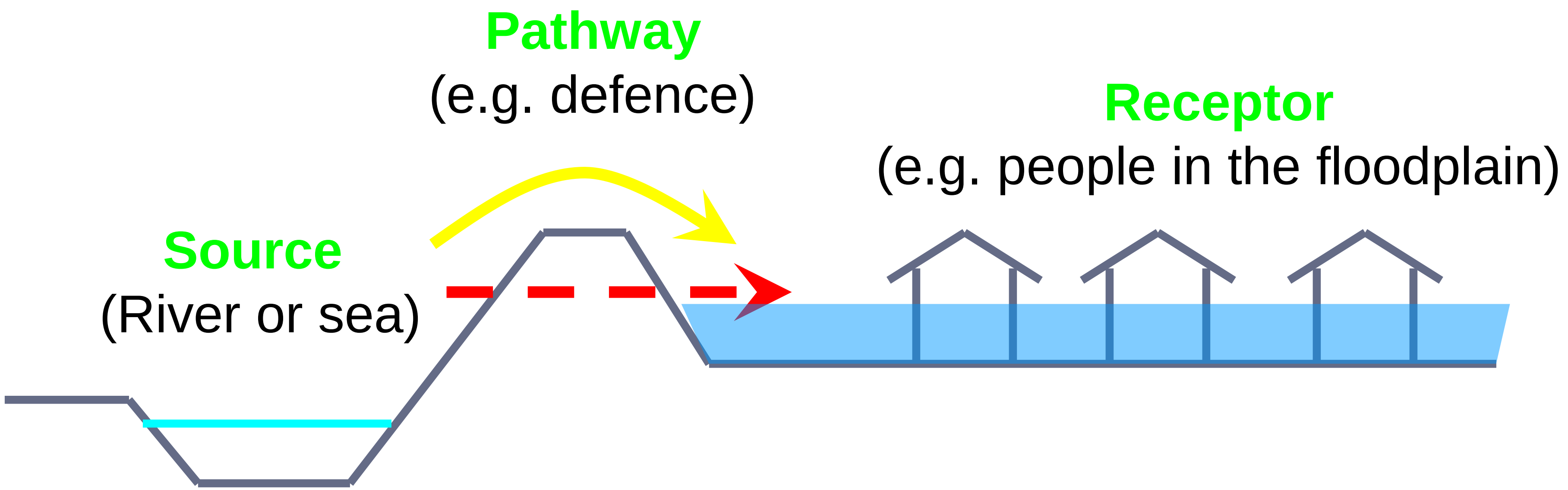
  - Influence & System Diagrams

Behavioural Conceptual Model: Flood/Ebb Dominance in a Tidal Inlet

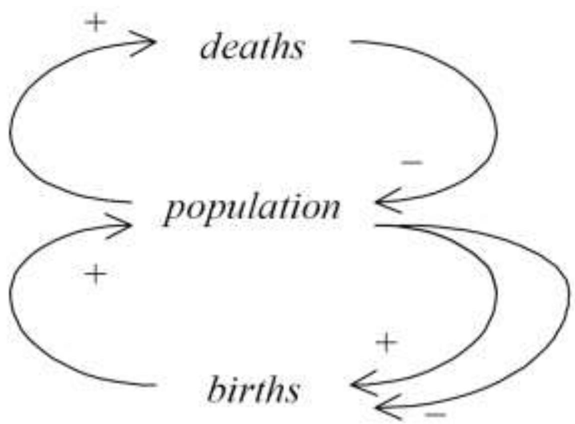
- **Sea level rise**
  - deepen channel
  - increase hydraulic depth
  - increase flood dominance
  - raise intertidal
  - reduce hydraulic depth
  - return to ebb dominance



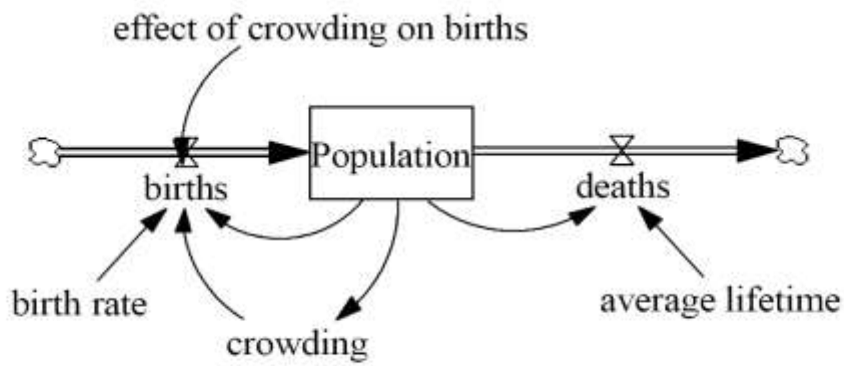
Framework: Source-Pathway-Receptor



Influence & System diagrams



Influence diagram



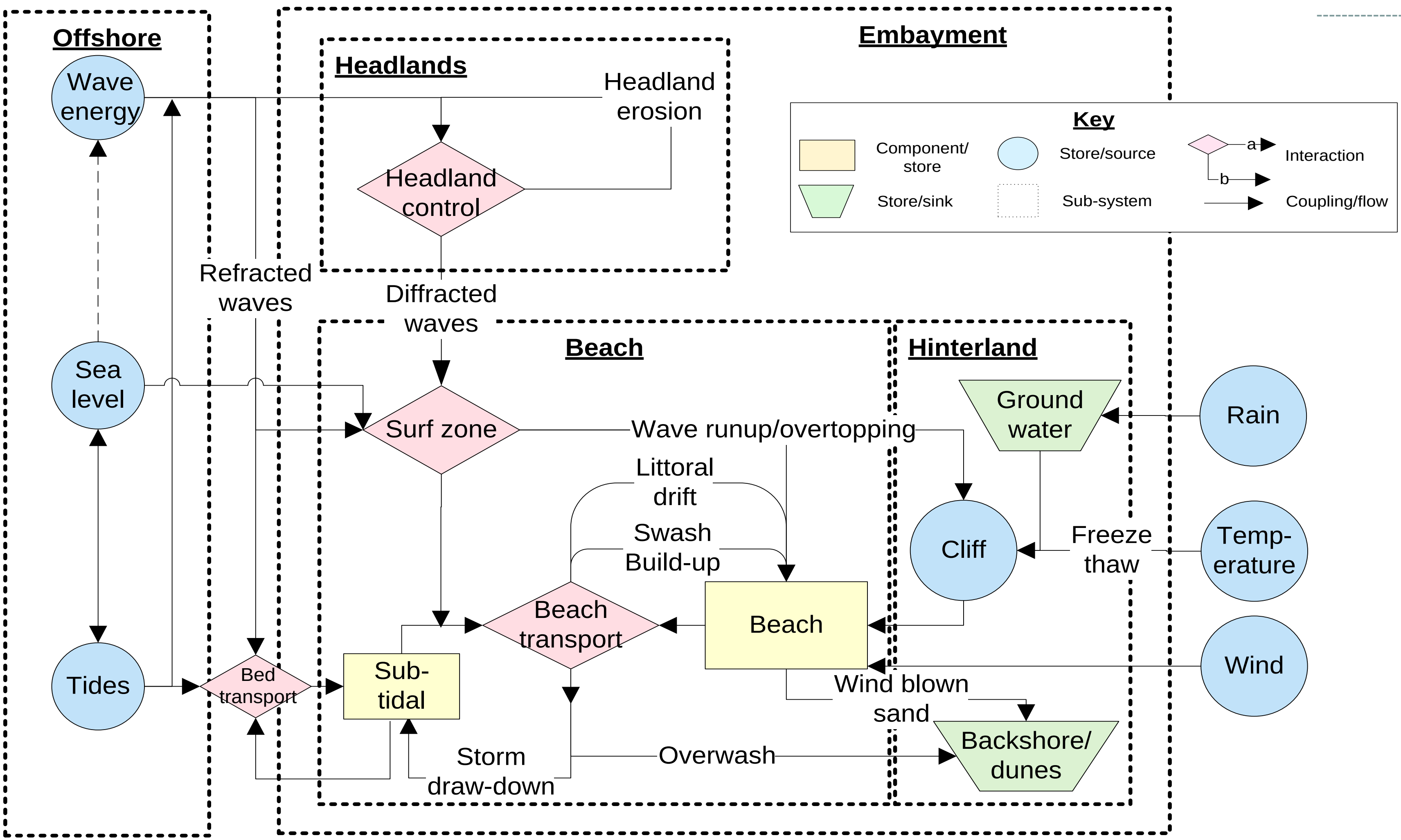
Stock and flow model

Influence diagram, with causal loops, used as a prelude to ‘stock and flow’ simulation for a simple ecosystem model (modified from Smith, 2000).

There is, as yet, no way to fully automate the transition from influence diagram into a set of model equations (Wolstenholme, 1999).

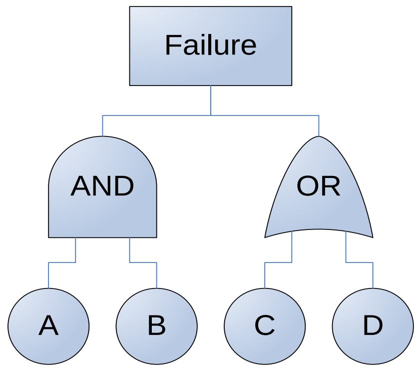
From (French & Burningham, 2007)

System diagram for a coastal embayment

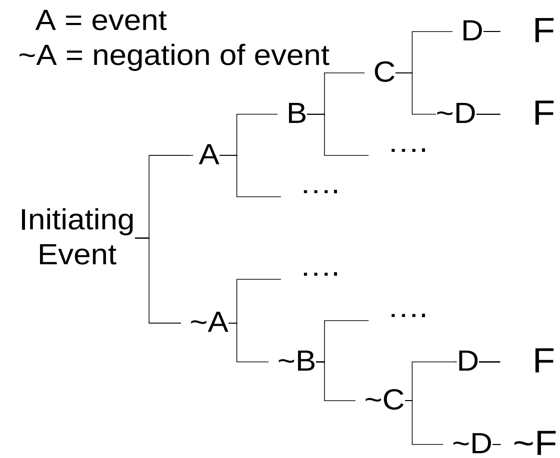


Fault Trees, Event Trees, Cause-Consequence Trees

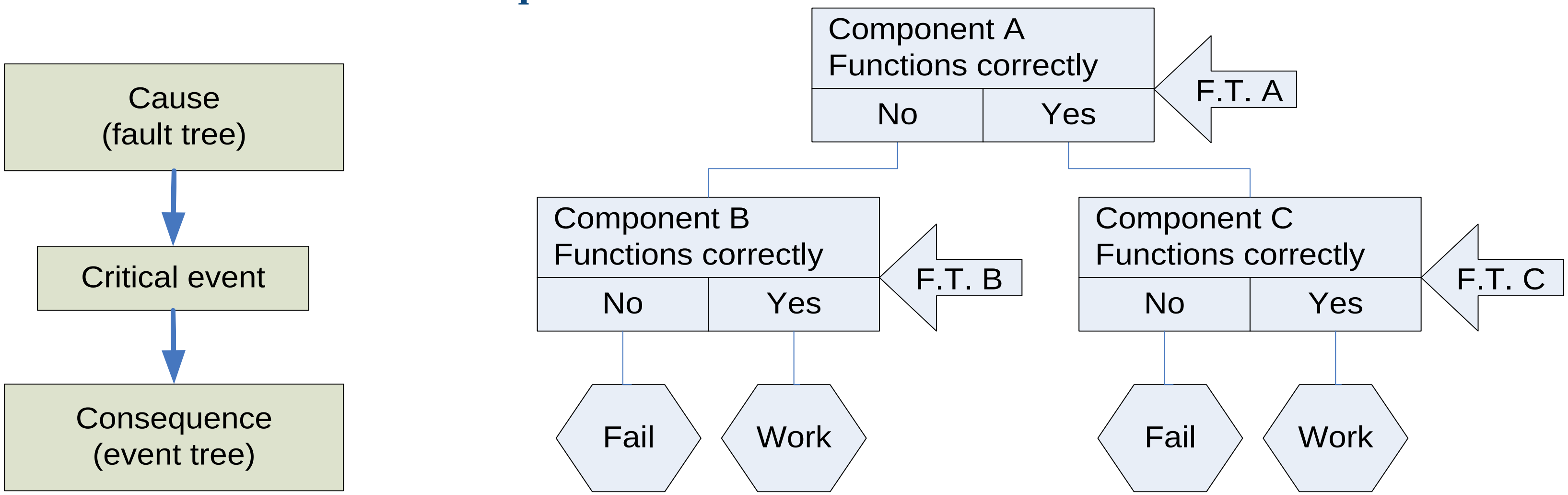
Fault Tree



Event Tree



Cause-Consequence Tree



Some types of model

- Qualitative
  - Conceptual
    - Descriptive
    - Behavioural
  - Frameworks
    - DPSIR:

Driver-Pressure-State-Impact-Response

    - S-P-R

Source-Pathway-Receptor

  - Influence & System Diagrams

- Quantitative
  - Empirical
  - Behavioural
  - Kinematic
  - I-P-O (system models)
  - Dynamic or Process
  - Statistical/Probabilistic

Quantitative Empirical Model

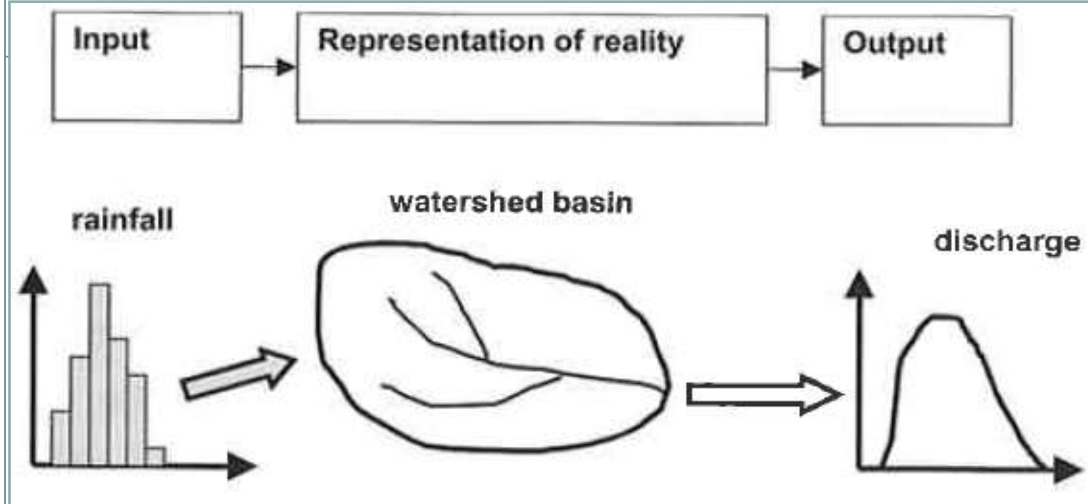


Figure 5 | Symbolic representation of a watershed basin as a system to be modelled.

Also called Black box or data driven models

See paper:

Of data and models, Cunge, 2003

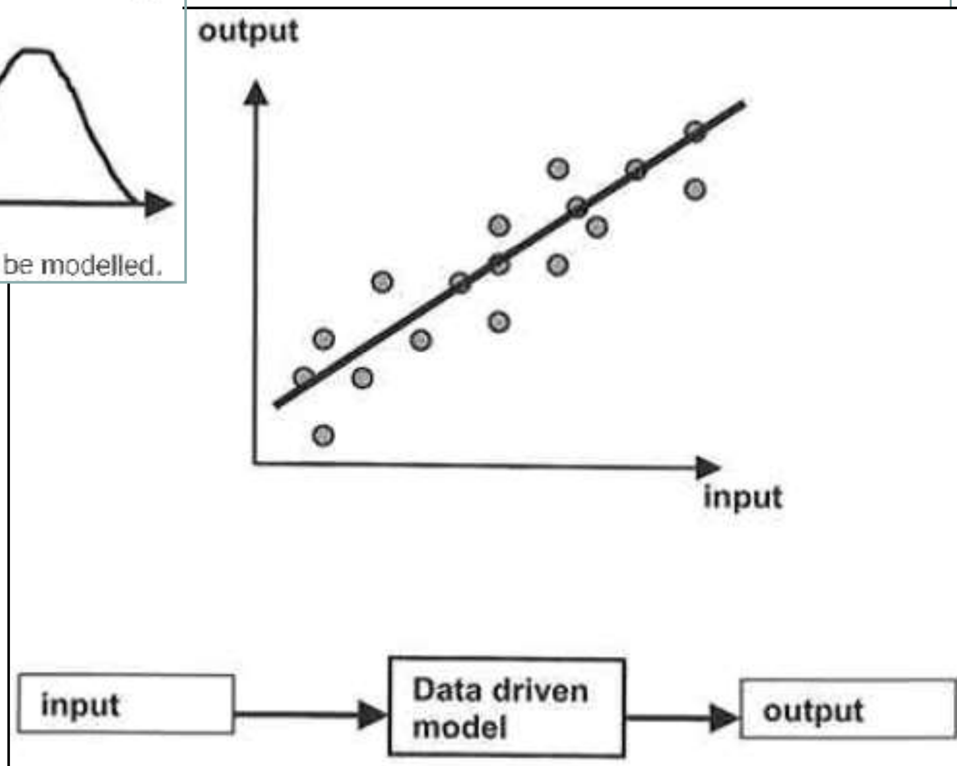
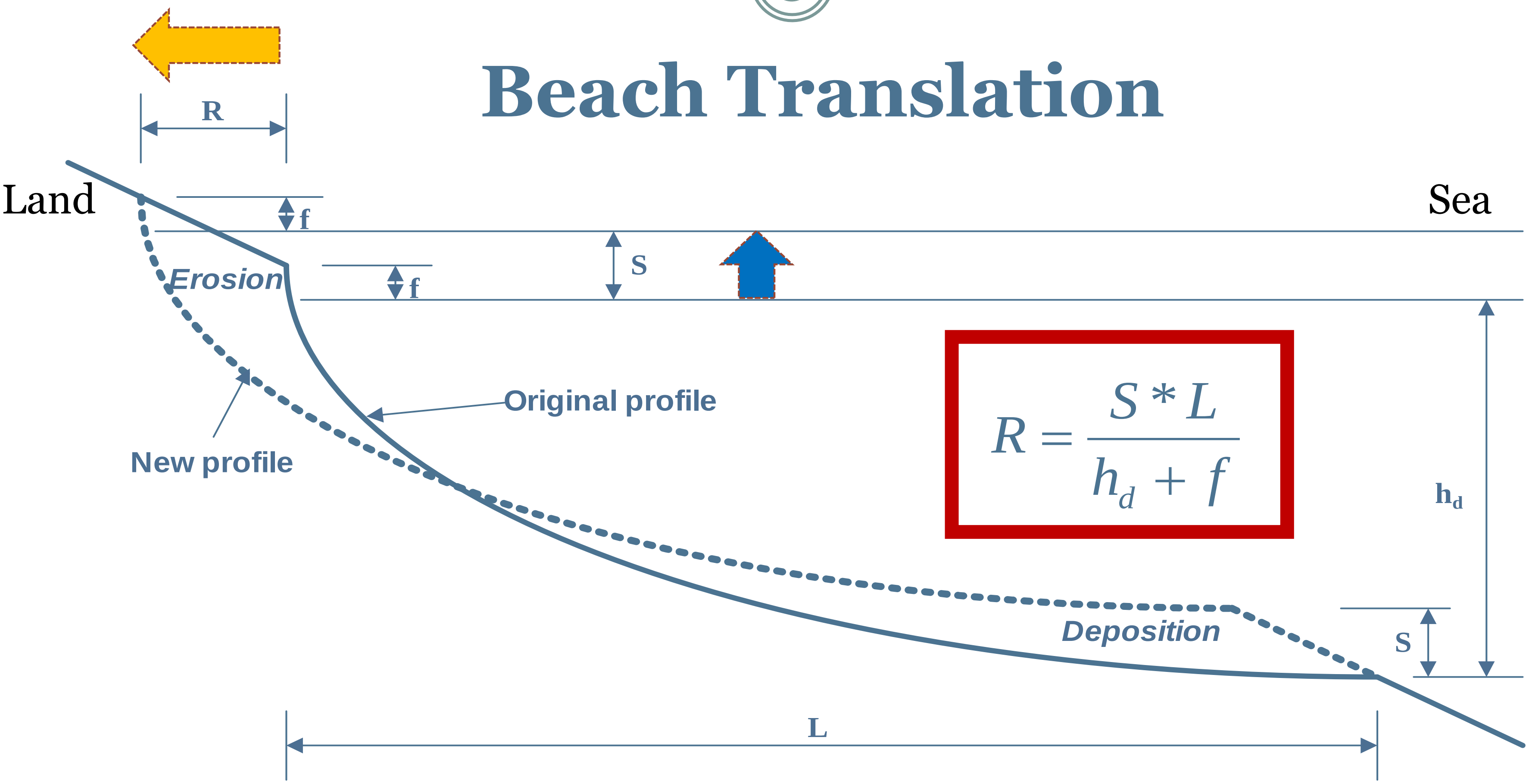


Figure 6 | Data-driven modelling—symbolic representation.

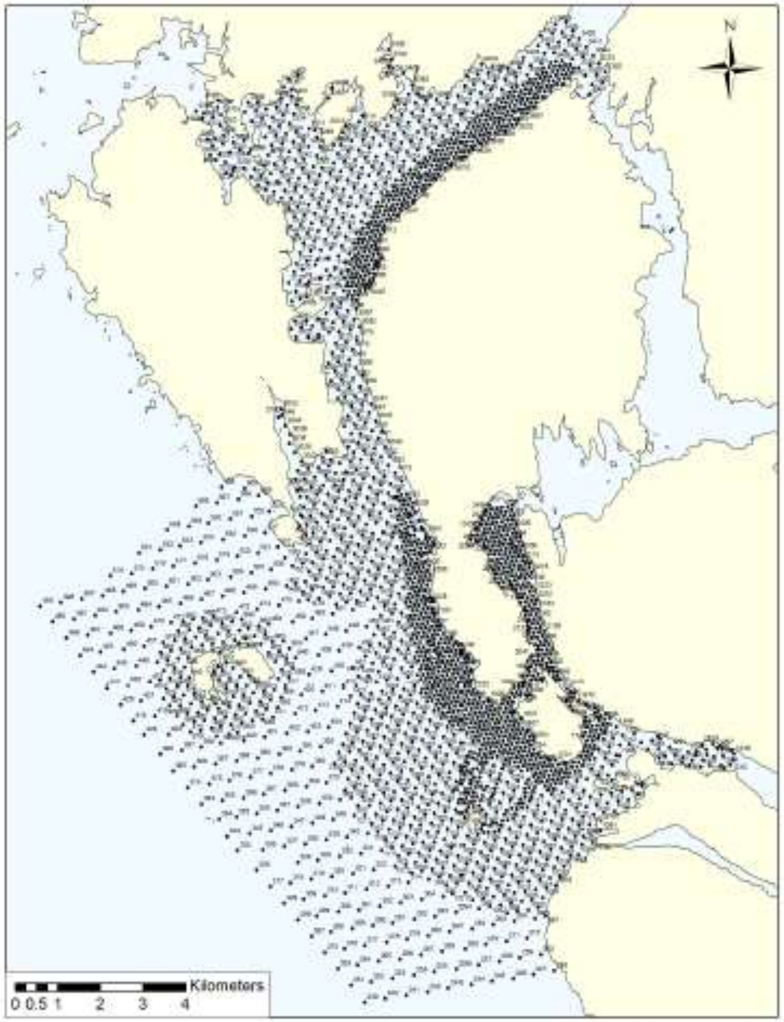
Quantitative Behavioural Model

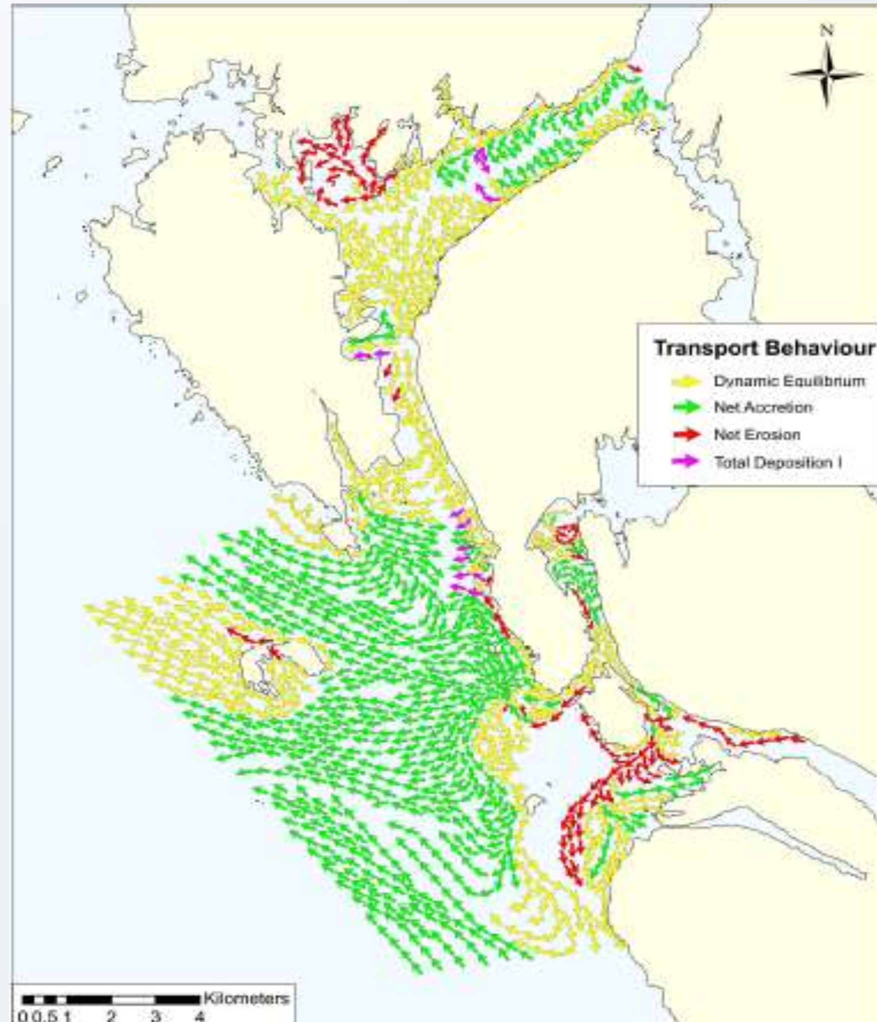
Beach Translation



$$\boxed{R = \frac{S * L}{h_d + f}}$$

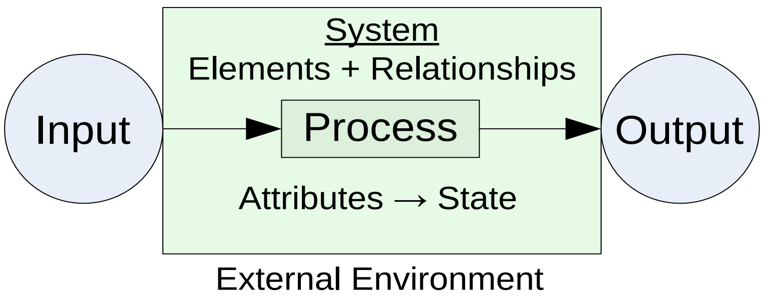
Kinematic Model – Sediment Trends Analysis



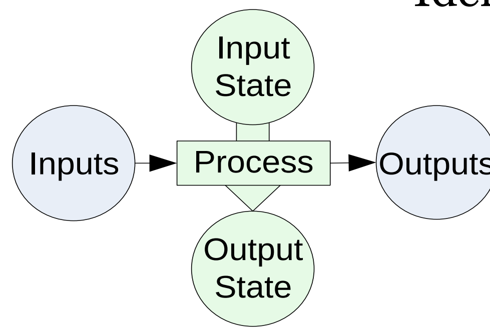


Input-Process-Output (System models)

Components of a system



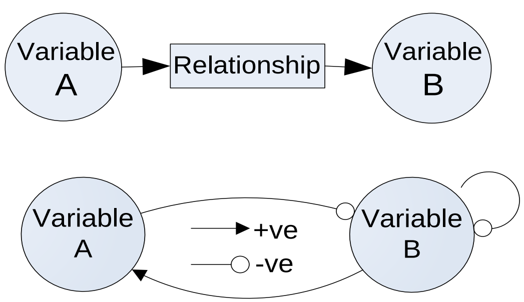
Identifying change



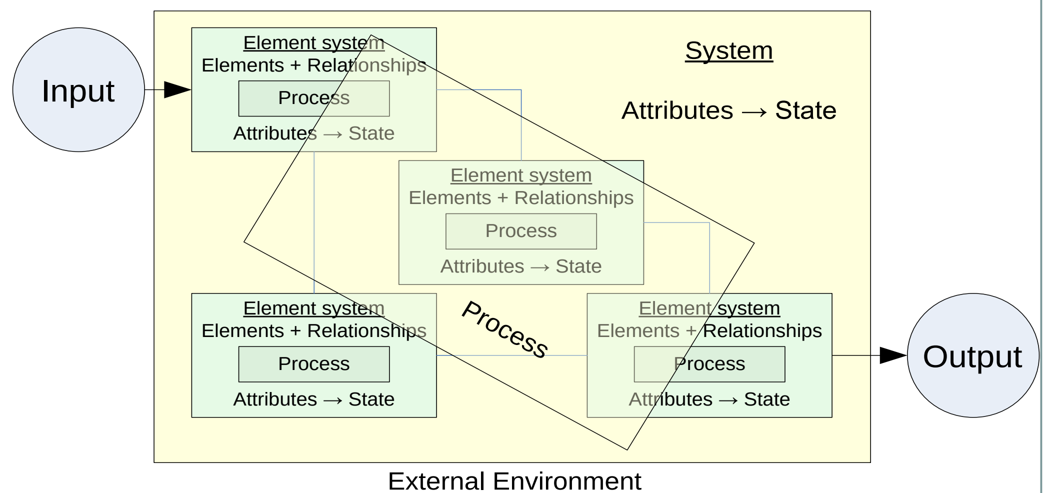
- outputs

- system state

Representations of Relationships between Elements

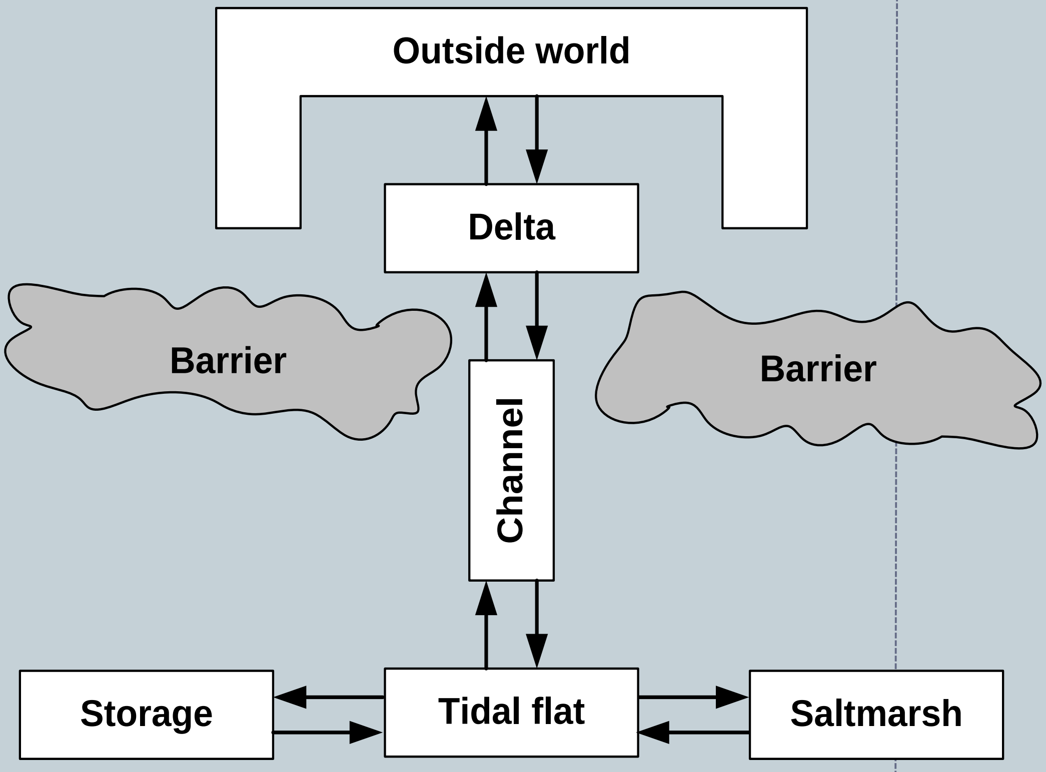


Complex multi-process system

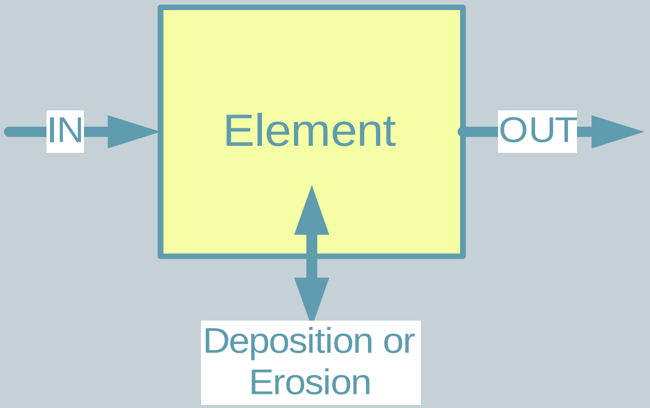


Estuary System Model

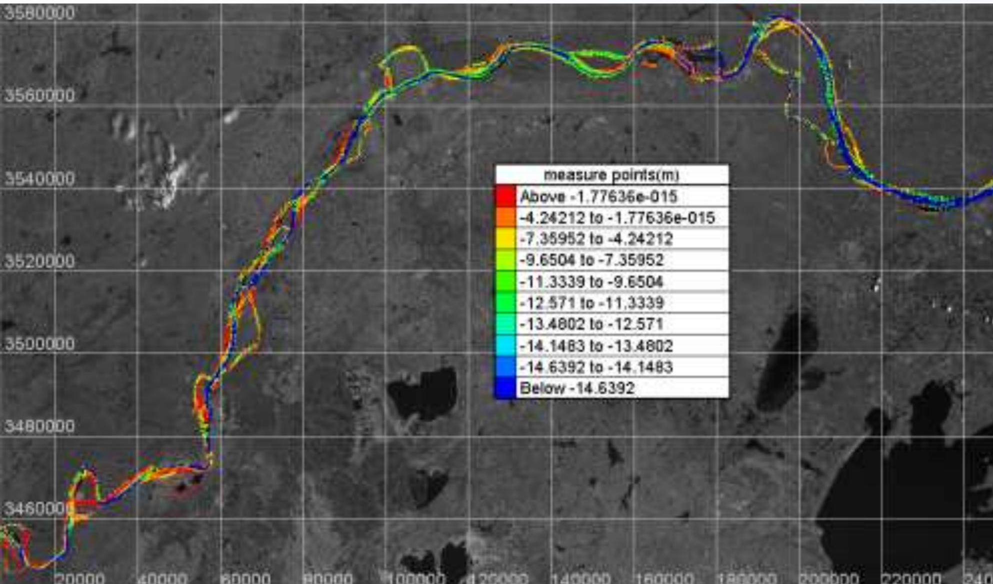
Aggregated **S**cale **M**orphological **I**nteraction between a **T**idal inlet and the **A**djacent coast

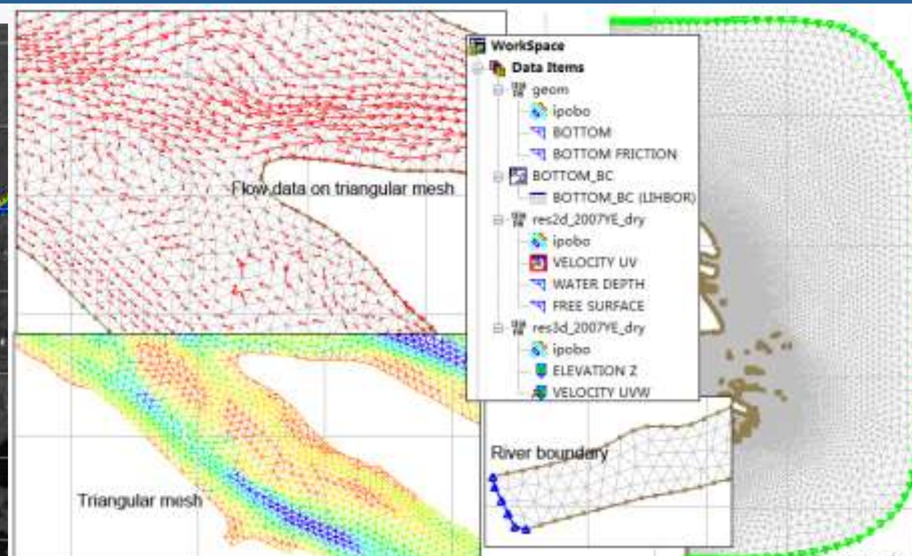


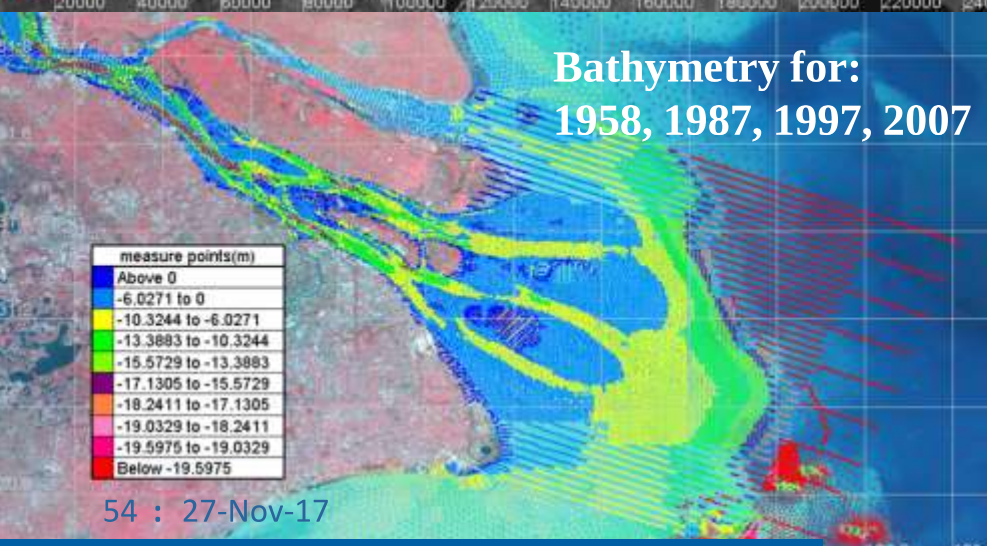
Model volume of sediment exchanges between elements

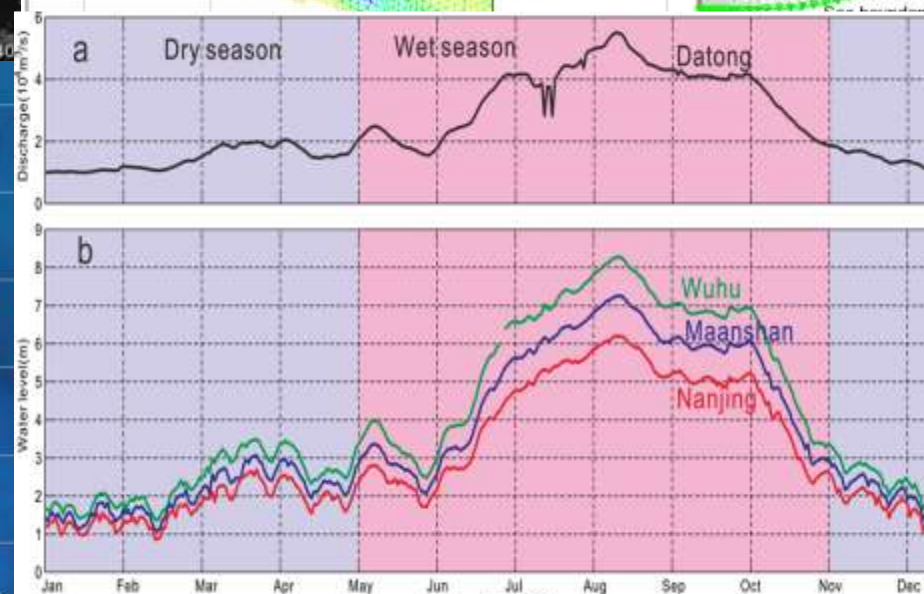


Dynamic or Process Model: Flow, Sediment Transport, etc

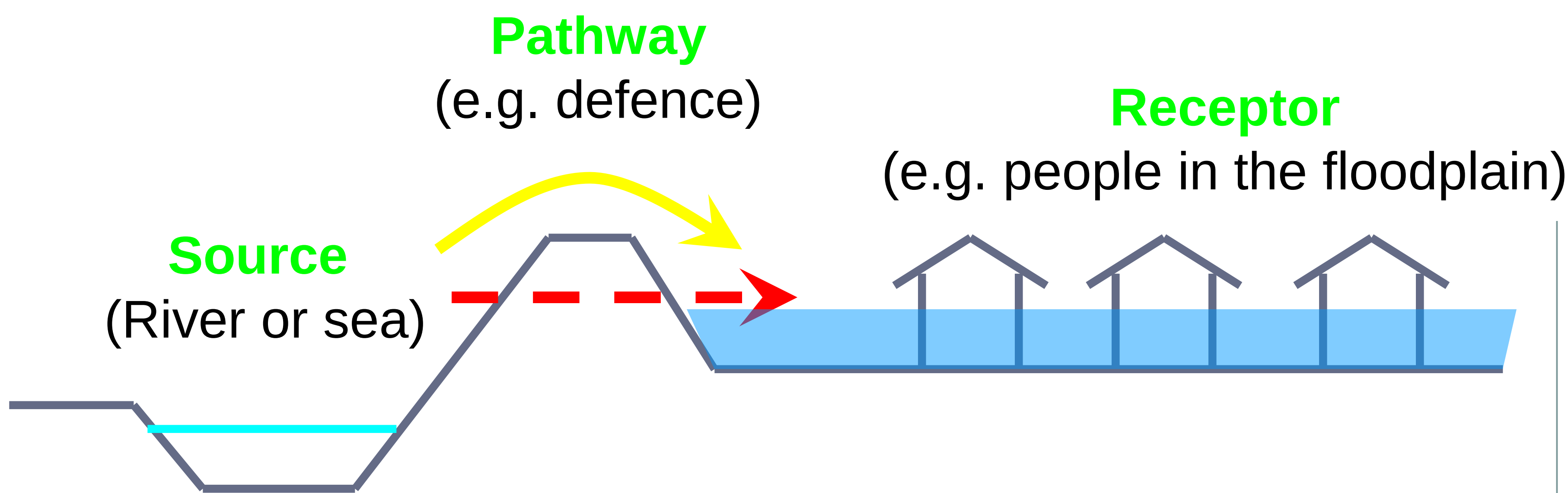


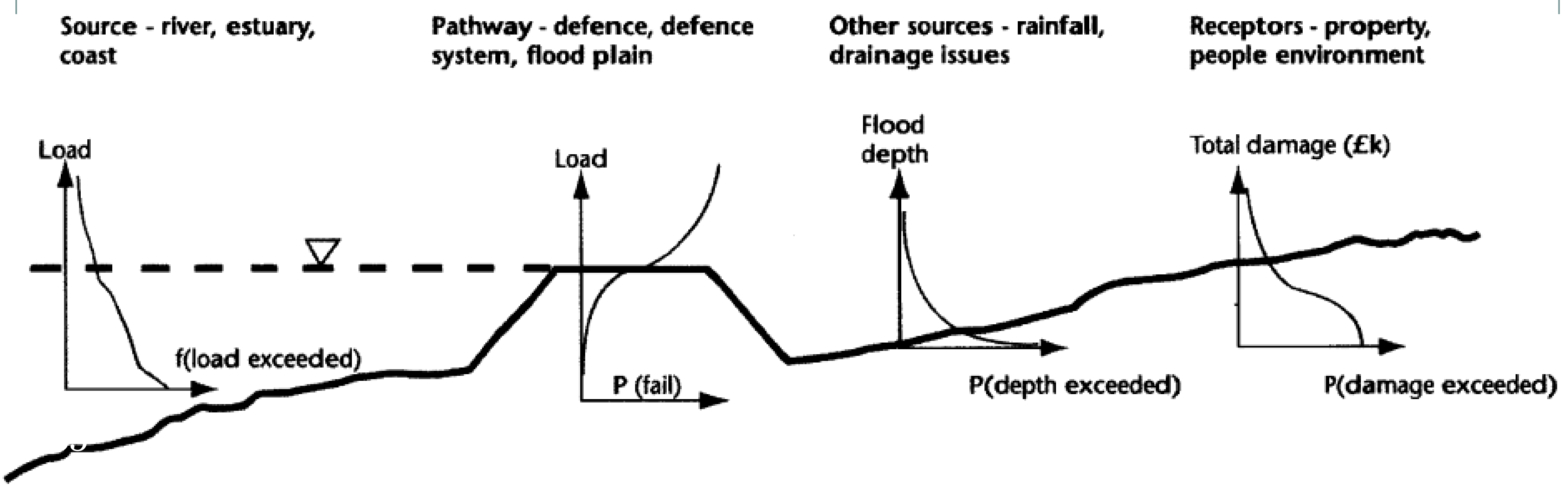






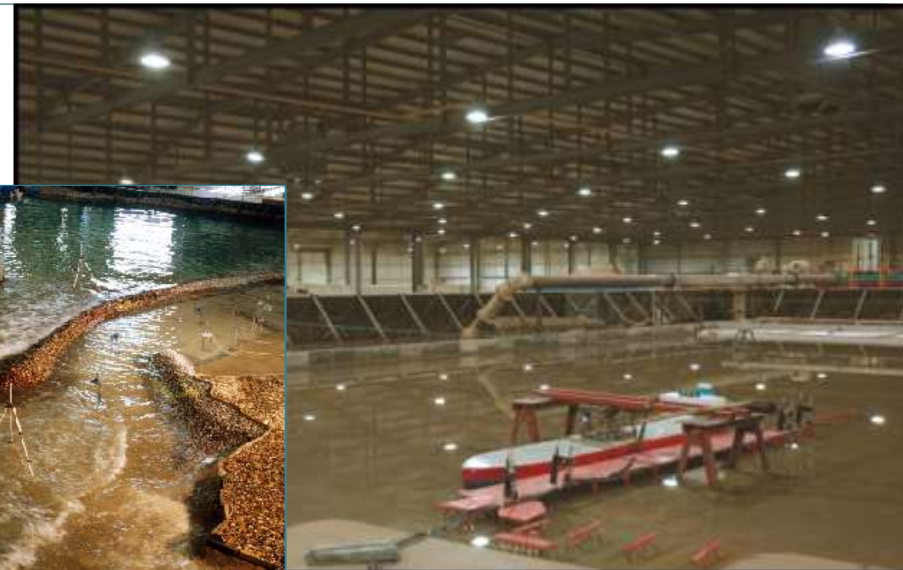
Probabilistic Model of flooding
Using Source-Pathway-Receptor Framework

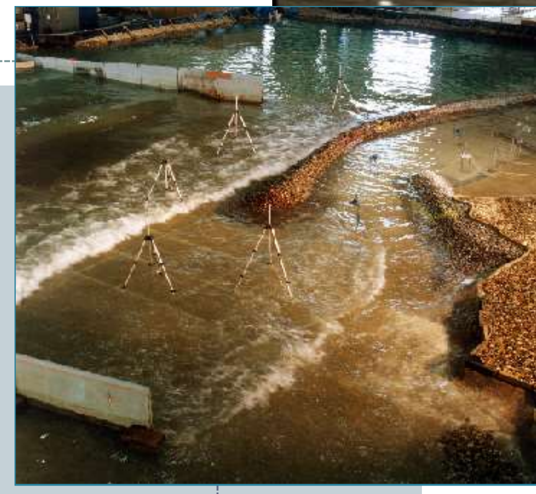


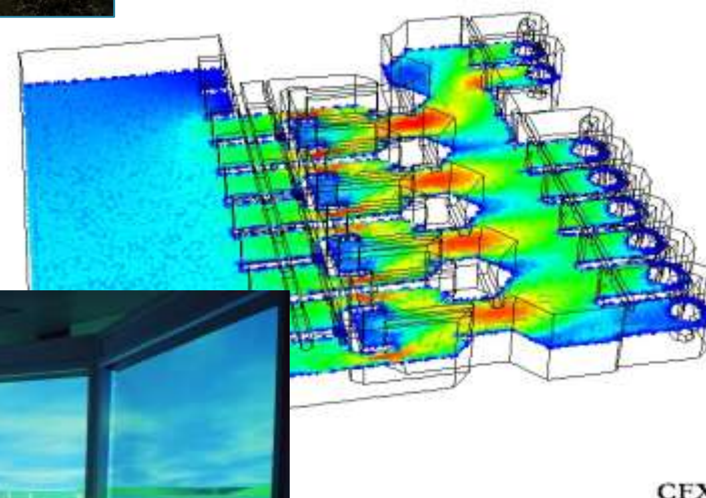


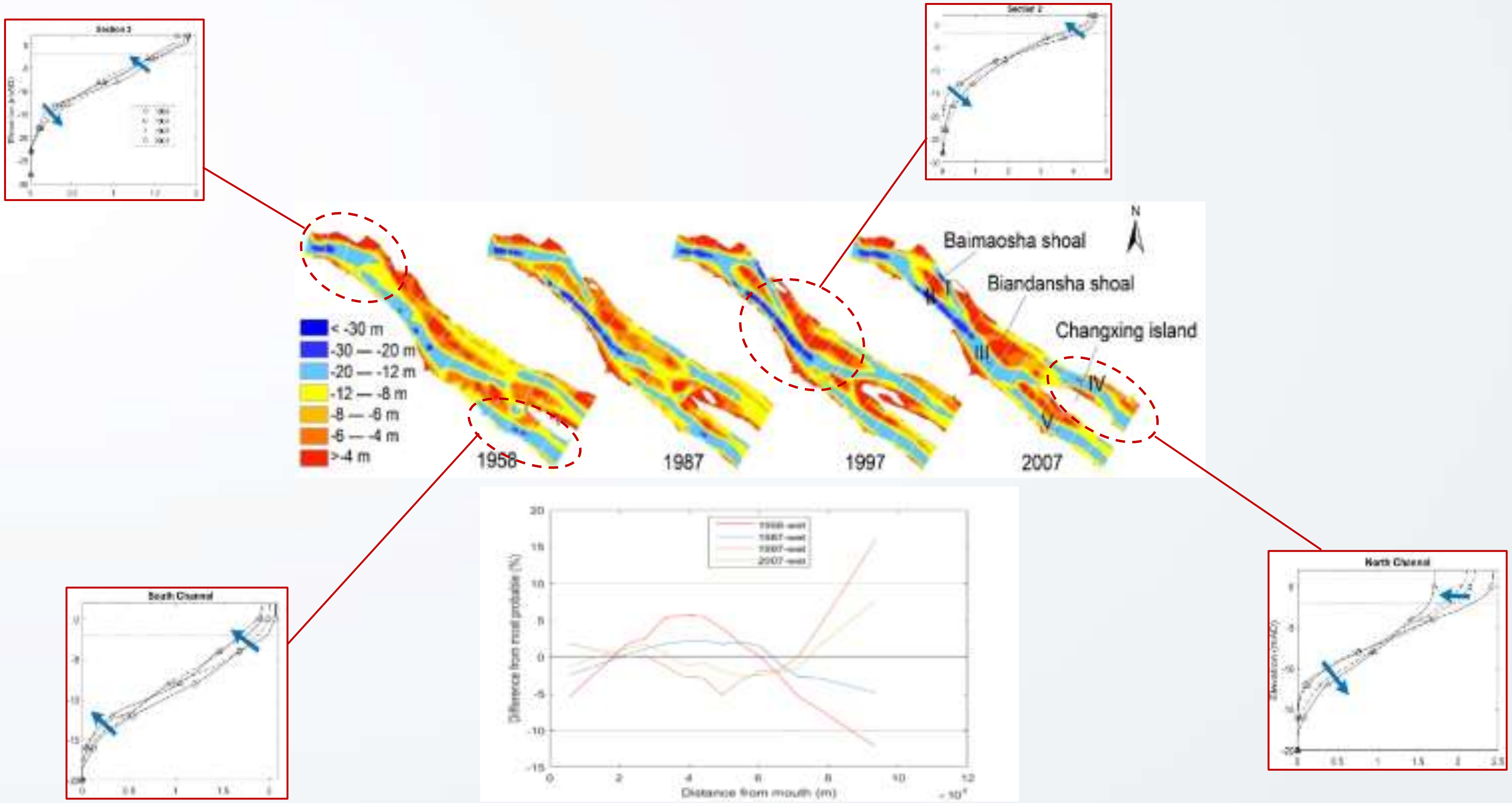
Modelling methods

- Physical
- Numerical
- Rule based (agent)
- Genetic algorithm
- Network, loop, Boolean
- Monte Carlo simulation
- Fault, Event and Cause-Consequence
- Neural network
- Fuzzy



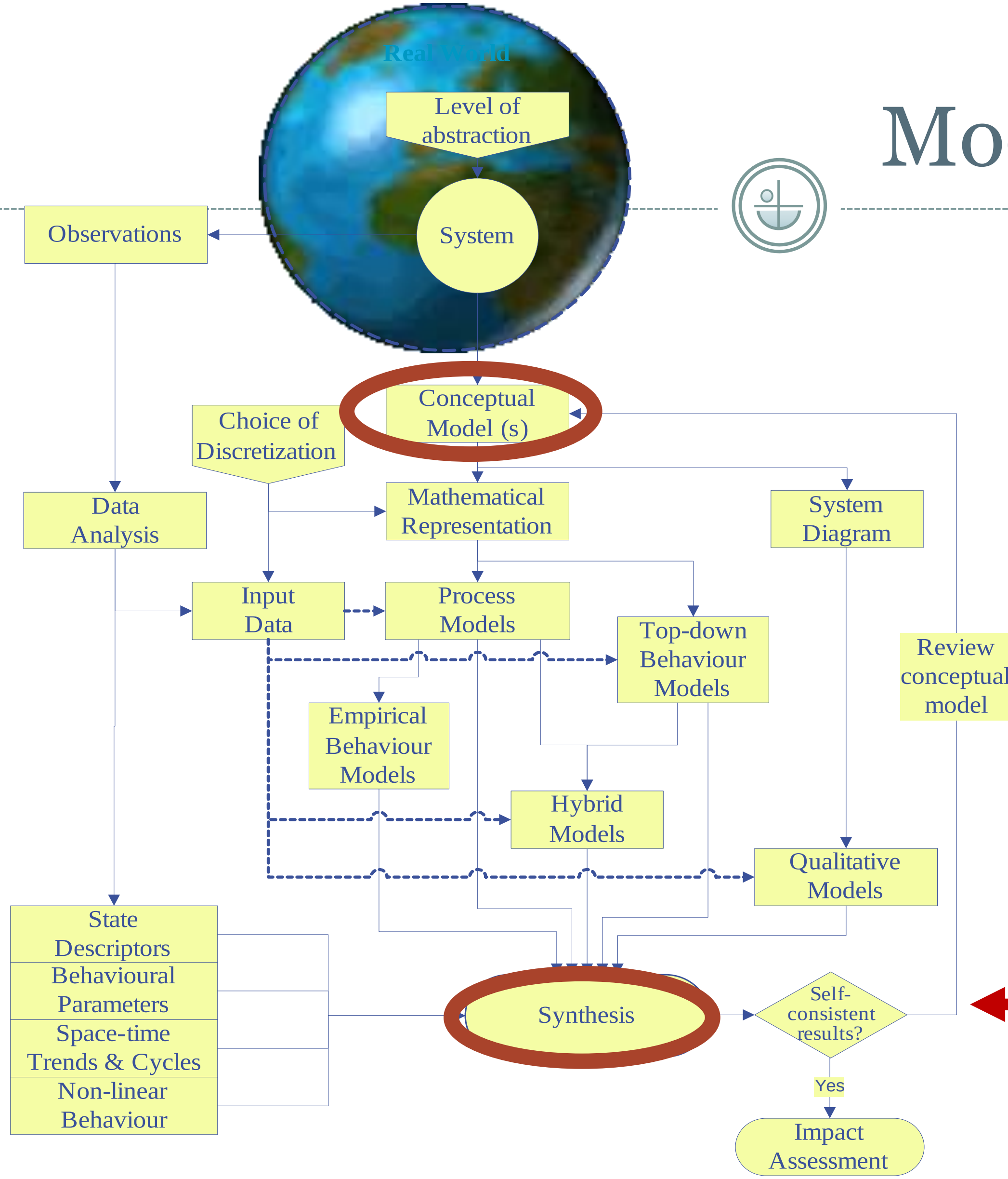






Synthesis – making sense of it all

Model Abstraction



Often use:

Data analysis + several models

=

Multiple lines of evidence

So need to interpret results

Assumptions and Simplifications

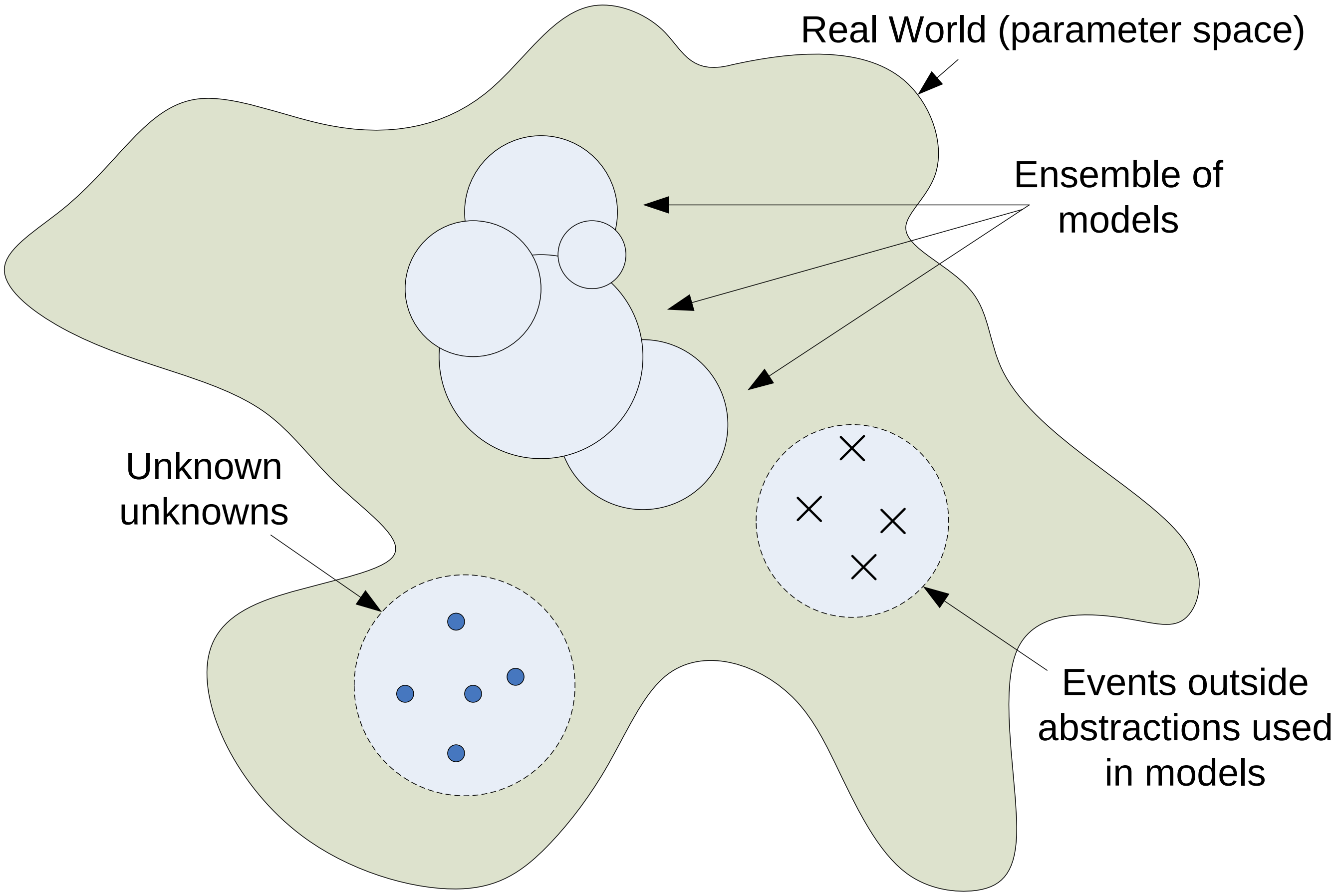
- Theoretical idealisation (eg. Navier-Stokes eqns)
- Simplifications (eg. incompressible fluid, 1 or 2-D)
- Phenomenological parameterisation (eg. turbulence closure)
- Discretisation in space and time (model and measurements)
- Adequacy of boundary conditions and constraints (eg. geology in morphological model)
- => Errors in model and measurements

Uncertainty

- Natural variability
  - refers to the randomness observed in nature
    - referred to as: Aleatory (meaning to ‘gamble’); External; Inherent; Objective; Random; Stochastic; Irreducible; Fundamental; and Real World *uncertainty*

- Knowledge uncertainty
  - refers to the state of knowledge of a physical system and our ability to measure and model it
    - referred to as: Epistemic (meaning ‘knowledge’); Functional; Internal; Subjective *uncertainty*; and Incompleteness

The limits to "completeness"

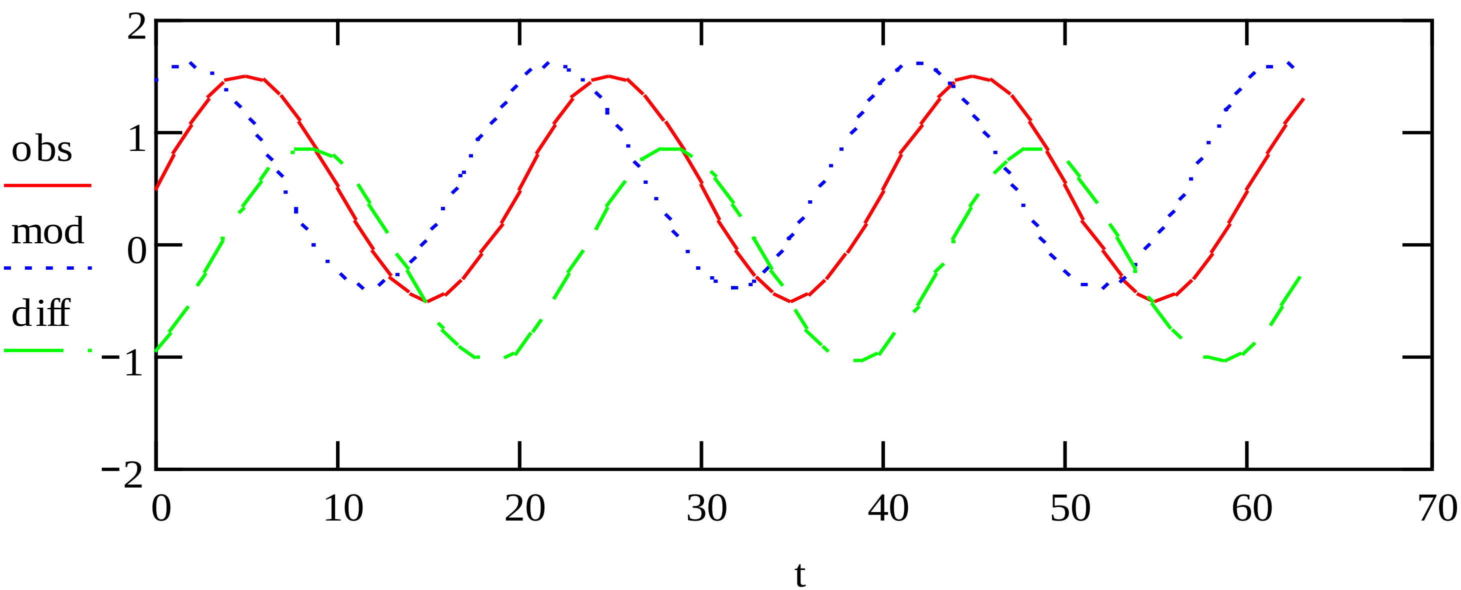


Model Performance

Root Mean Square (RMS) error

$$\text{RMS\_absolute}(obs, mod) := \sqrt{\text{mean}\left[(obs - mod)^2\right]}$$

$$\text{RMS\_relative}(obs, mod) := \sqrt{\text{mean}\left(obs^2\right)} - \sqrt{\text{mean}\left(mod^2\right)}$$



'Good Modelling Practice' paradigm

Data Driven or Black Box Approach

Can be probabilistic or fuzzy

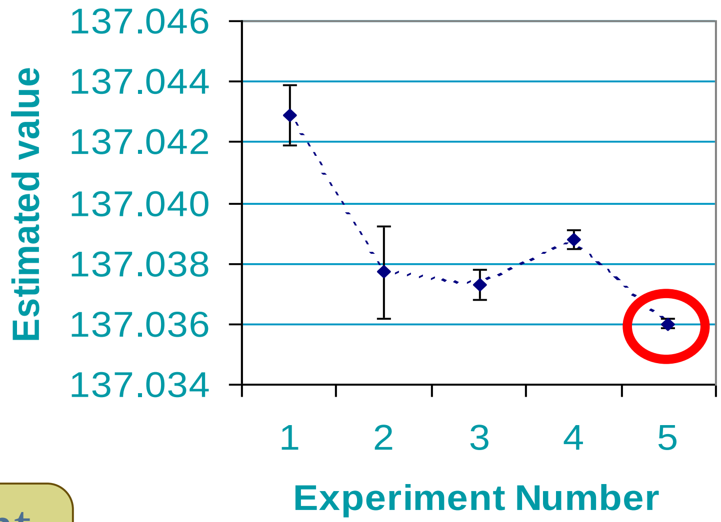
Physics-Based ~~'Deterministic'~~ Model Approach

- Set-up model
- ~~Calibrate - using model parameters that are invariant in the proposed application~~
- Validate ~~- u~~
- Run model

- Better measure of uncertainty. If error
  < acceptable range – apply model
  > acceptable range – investigate reasons

➢ Sensitivity analysis and synthesis to reduce uncertainty

Uncertainty notation



Pedigree (score 0-4):
- a – Theory
- b – Data input
- c – Peer acceptance
- d - Consensus

Significant digits

Units

Assessment

Spread (st.dev.)

Inactive digits

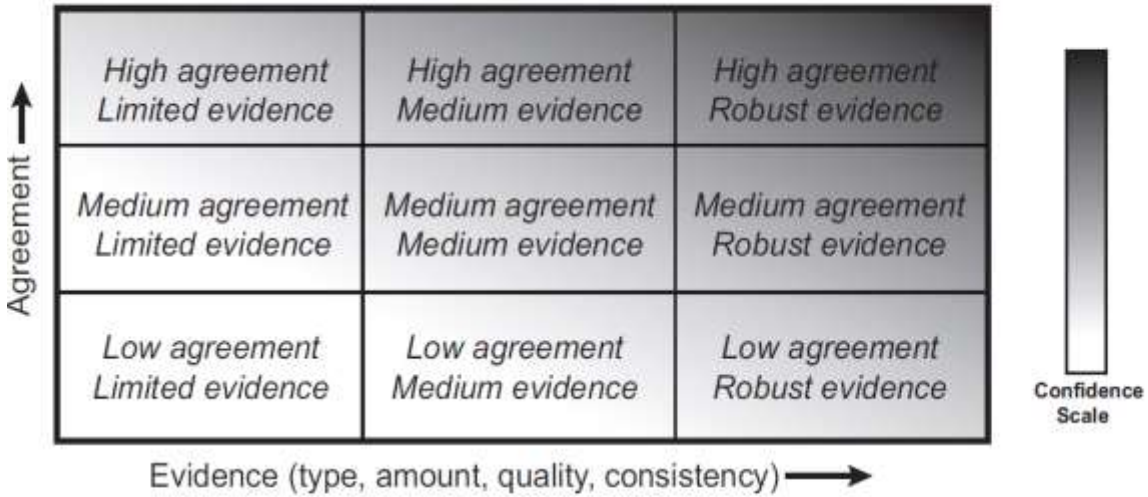
$$C + x : E\text{-}n : \pm\sigma : \pm 2\sigma_{previous} : (a,b,c,d)$$

$$137 + 36 : E\text{-}4 : \pm 1 : \pm 2.6 : (4,4,3,4)$$

Example of Pedigree Score Guide

	Score	Information or data	Theory and Method	Peer Acceptance	Consensus
“strength of evidence – scientific pedigree” →	**4**	**Comprehensive information** with sound data and good quality control	**Best available practice** and well established theory	**Absolute** – peer reviewed evidence from research literature.	**Accepted as ‘an ideal approach**.’
	3	**Reliable analysis** of the available data	**Reliable method** commonly accepted	**High** – peer reviewed evidence	**Accepted as ‘fit for purpose.**’
	2	**Calculation or estimation** of values	**Accepted method**, partial theory but limited consensus	**Medium** – some agreement accepting that there are some contradictory views	**Some consensus** but different ‘schools of thought’
	1	Education opinion. **Expert view** based on limited information	**Preliminary method** unknown reliability	**Low** – no agreement	‘**New approach’** un- tested
	0	Non-expert view/**guess**	**Crude speculation** - No discernable rigour	**None**	**None** – inappropriate use of data/information/ modelling

Pedigree as used by IPCC for AR5 and UK CCRA



Confidence based on subjective assessment

4	**Very high**	Comprehensive evidence using the best practice and published in the peer reviewed literature; accepted as a sound approach.
3	**High**	Reliable analysis and methods, with a strong theoretical basis, subject to peer review and accepted as 'fit for purpose'.
2	**Medium**	Estimates grounded in theory, using accepted methods and with some agreement.
1	**Low**	Expert view based on limited information, e.g. anecdotal evidence.
0	**Very low**	Non-expert opinion, unsubstantiated discussion with no supporting evidence.

Comparison of Alternatives

Pedigree		Method 1		Method 2
Theory		H		L
Data Input		H		L
Peer Acceptance		M		M
Consensus		L		M

Robust Evidence Based Policy

- Credible/valid - *sound line of argument?*

Line of argument not clear

- Transferable - *can the specific be generalised?*

Data inconclusive

- Reliable - *can the evidence be depended upon?*
- Objective - *has residual bias been acknowledged?*

Evidence conflicts

- Well founded - *have the right question been posed?*
- + an assessment of associated uncertainties

Comparison of Alternatives

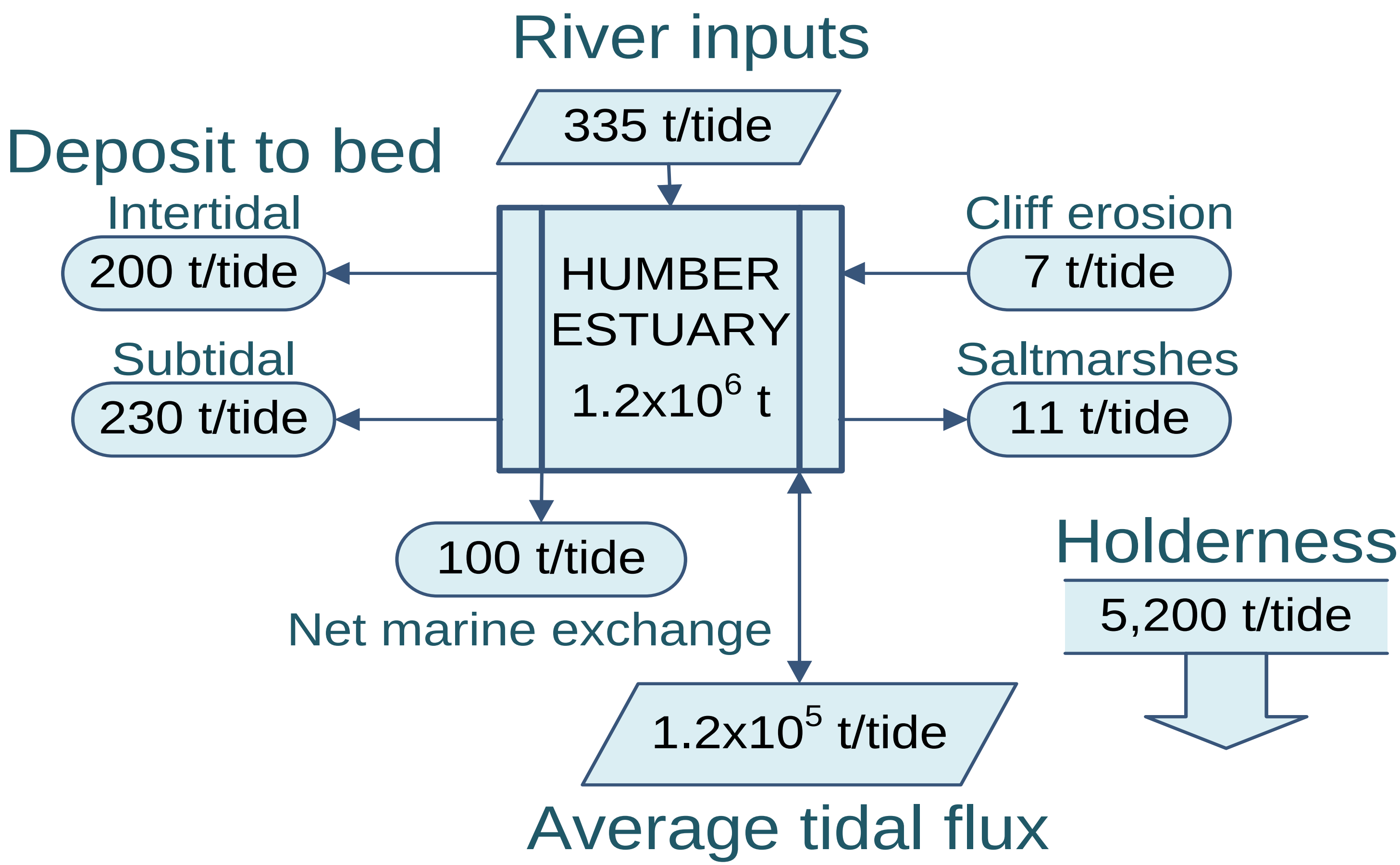
Pedigree		Method 1		Method 2
Theory		H		L
Data Input		H		L
Peer Acceptance		M		M
Consensus		L		M

Evidence Base		Method 1		Method 2
Credible		H		M
Reliable		M		L
Objective		H		M
Well founded		H		L
Transferable		H		L

Process of Synthesis

- Multiple strands of evidence
- Processes reasonably well understood
- Behaviour & dynamic states less so
- Synthesis should aim to
  - differentiate between fact & interpretation
  - test findings against conceptual model
  - identify behaviour in transparent way
  - recognise uncertainties
- The synthesis should also confirm or amend the conceptual model

Sediment Budget for Humber



Where am I? > Home > News > Environment

From The Sunday Times

November 29, 2009

The great climate change science scandal

Leaked emails have revealed the unwillingness of climate change scientists to engage in a proper debate with the sceptics who doubt global warming

Jonathan Leake, Environment Editor

TIMES RECOMMENDS

140 COMMENT

The storm began
happened," annou
devoted to criticis

"RC" said nothing
anyone who click

There, on the mo
a thousand or so
director of the cli
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Dibden Bay: The new environmental battlegrou

By Michael McCarthy, Environment Correspondent

Monday, 15 January 2001

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Proposals to build a giant deep-water container port within the proposed New Forest National Park are expected to unleash one of the most bitter planning battles seen in Britain for years.

Proposals to build a giant deep-water container port within the proposed New Forest National Park are expected to unleash one of the most bitter planning battles seen in Britain for years.

Associated British Ports, the biggest ports business in the UK, wants to site more than a mile of shipping berths, an array of big cranes and a 500-acre terminal at Dibden Bay on the west side of Southampton Water, to form one of the largest dock areas in Europe, whose 24-hour operation is expected to generate more than 3,000 heavy lorry journeys a day.

The company says the £600m, nine-year development is essential to maintain the prosperity of the port of Southampton,

guardian.co.uk

News | Sport | Comment | Culture | Business | Money | Life & style | T

Environment > Climate change

Tibet temperature 'highest since records began' say Chinese climatologists

Average Tibet temperatures in 2009 increased 1.5C, with rises noted in both winter and summer at 29 monitoring sites

Jonathan Watts, Asia environment correspondent, and agencies
guardian.co.uk, Friday 5 February 2010 13.31 GMT
Article history

tibet boy r

Communication

COASTAL SCIENCE & ENGINEERING APPLICATIONS

COASTALSEA.CO.UK

Space-Time Matrix

		Time Scale		
		Short-term	Decadal	Holocene
Spatial Features	Adjacent coast			
	Mouth Ebb/flood delta			
	Estuary			
	Rivers			

Descriptive Text

Assessment of Change

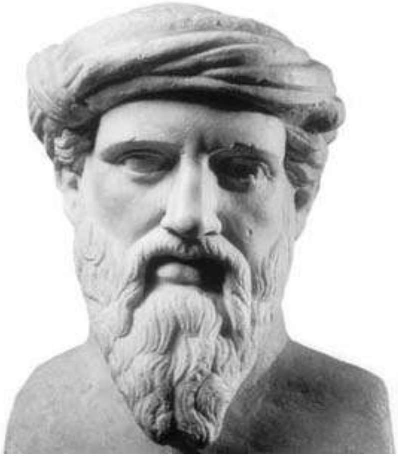
		Time Scale		
		Short-term	Decadal	Holocene
Spatial Features	Adjacent coast			
	Mouth Ebb/flood delta			
	Estuary			
	Rivers			

Before

		Time Scale		
		hort-term	Decadal	Holocene
Spatial Features	Adjacent coast			
	Mouth Ebb/flood delta			
	Estuary			
	Rivers			

After

What or Who to believe?

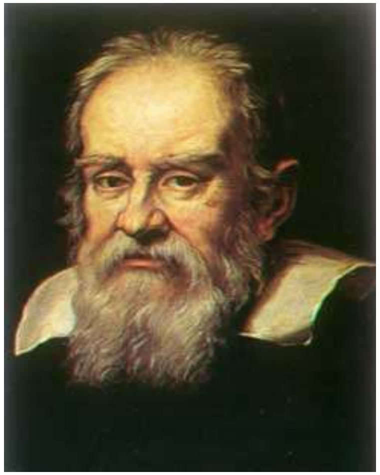


Pythagoras

The world is round?

Earth goes round the sun?

Copernicus



Galileo

Trust to tell the truth in 2000

	%
Doctors	89
Teachers	88
Clergymen or priests	86
Television news readers	75
The Police	70
The ordinary man or woman in the street	58
Civil servants	52
Trade Union Officials	40
Government Scientists	38
Business leaders	35
Politicians generally	19
Government Ministers	17
Journalists	10

Selective Reporting

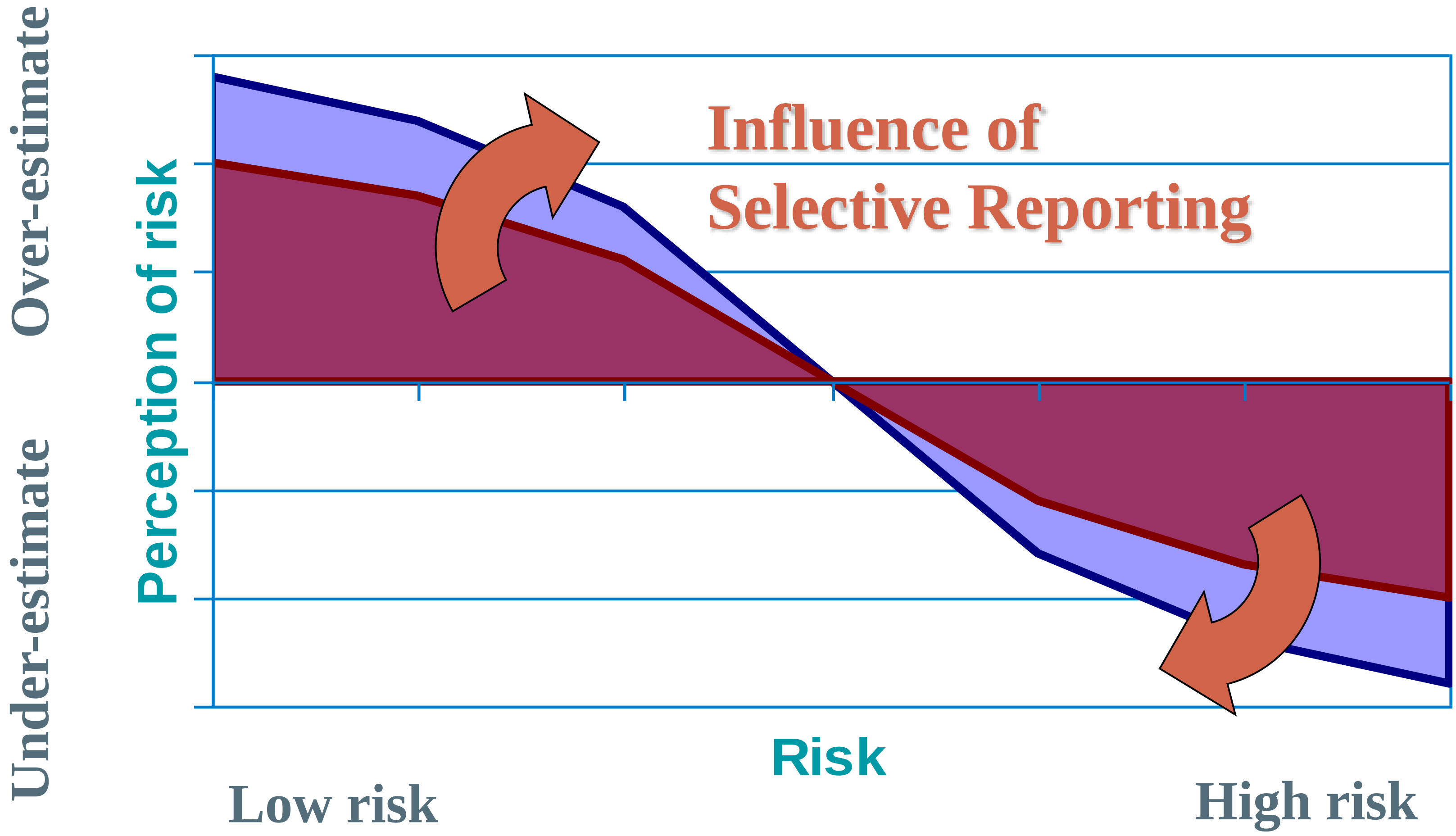
"It is the Historian who decides what facts to give the floor to and in what order and context"

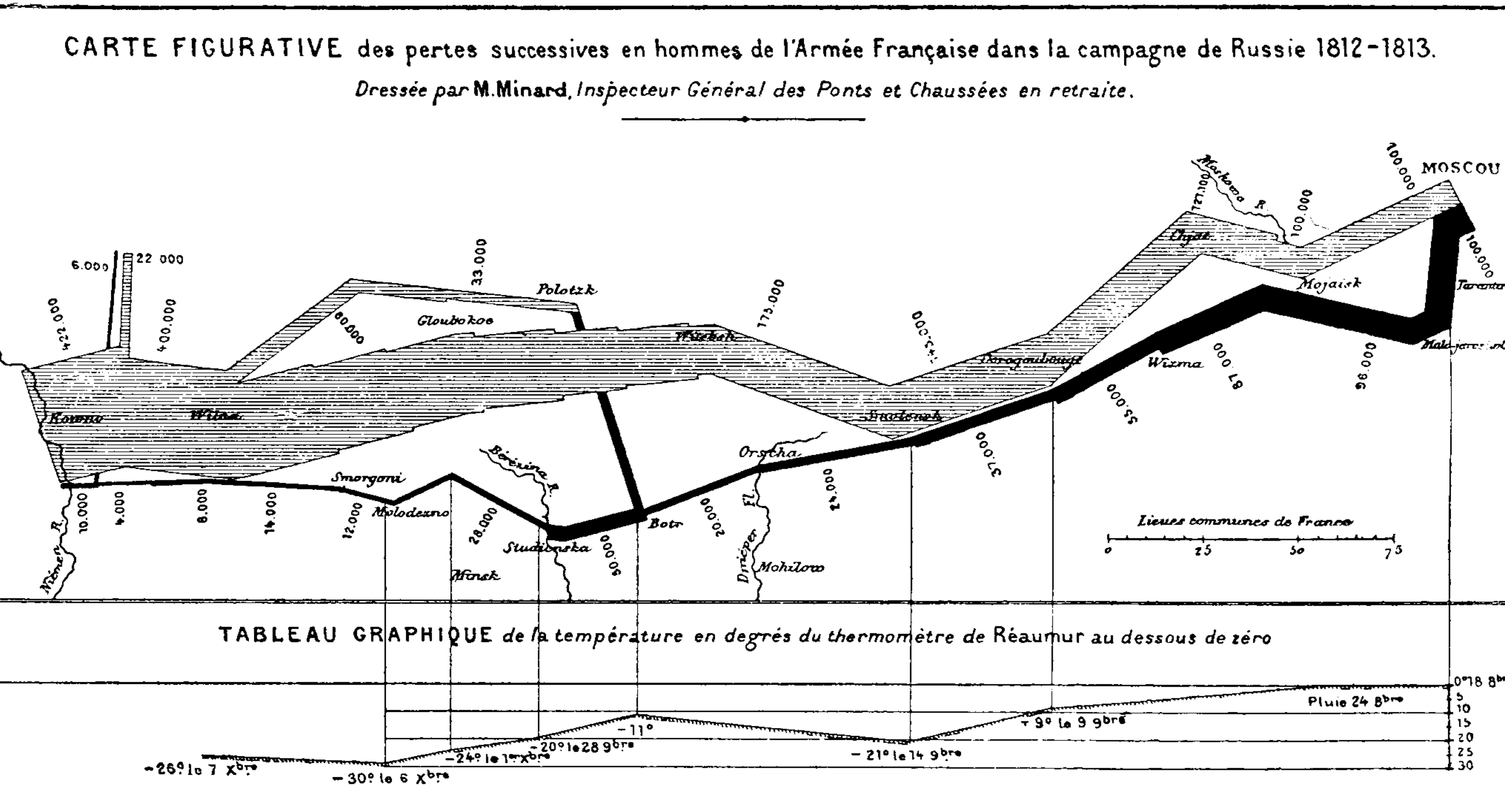
E H Carr, Historian

"That's amazing isn't it? – Why is intuition worst than useless when it comes to spotting real coincidences?"

Jack Cohen and Ian Stewart, New Scientist, 1998

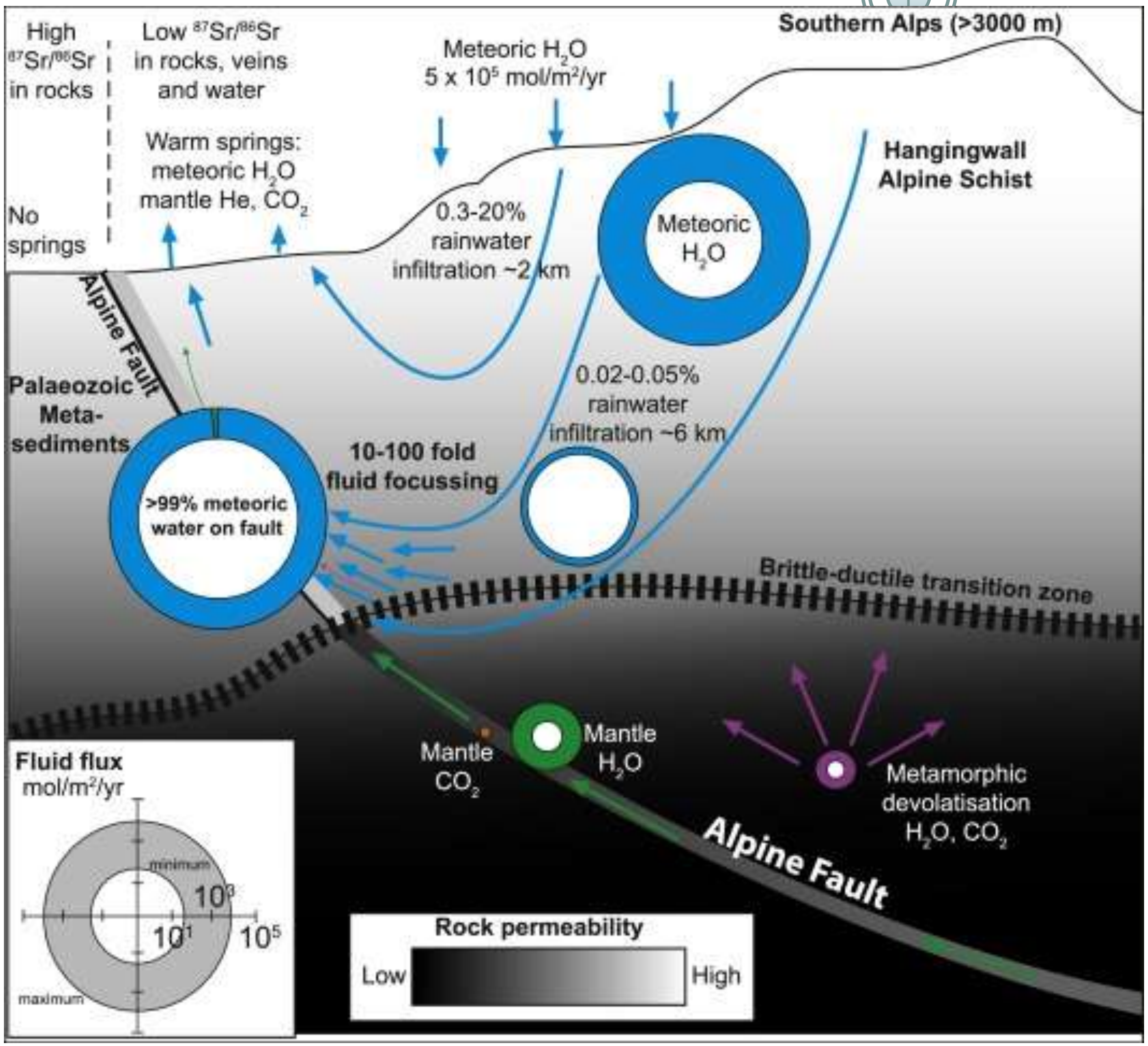
Weighing Risks





Xbre = December 9bre = November 8bre = October

Fluid budget of continental plate boundary fault



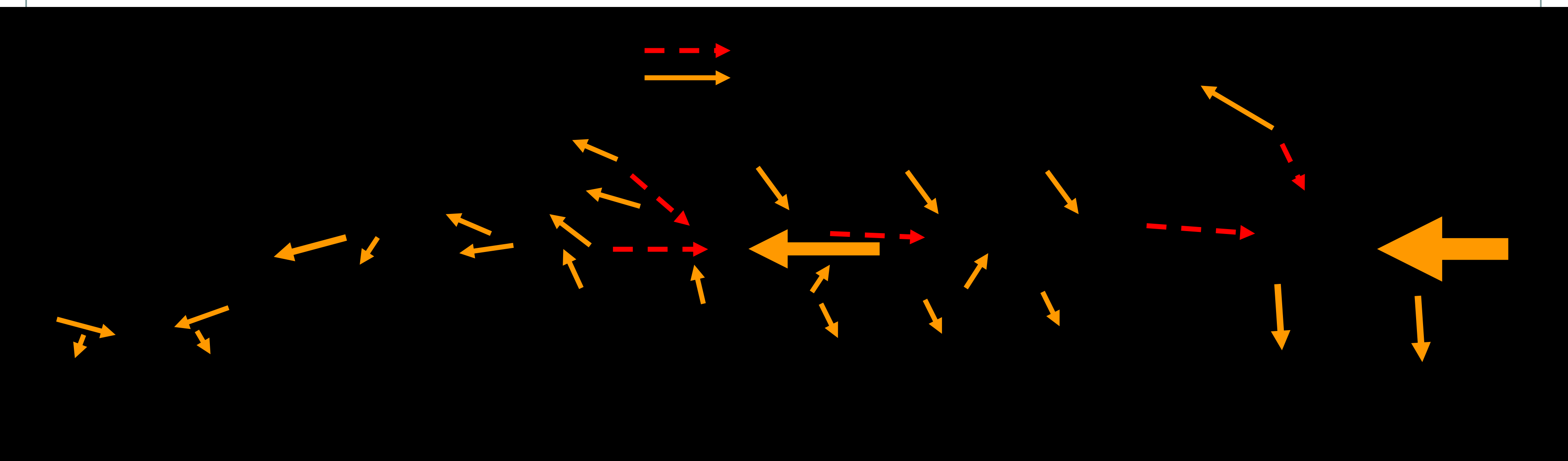
Estimated fluxes of meteoric, metamorphic and mantle fluids are shown as coloured circles, with the inner and outer circles representing minimum and maximum estimates respectively. The proportion of each end member fluid that constitutes the flux up the Alpine Fault is illustrated as a proportional circle, meteoric water making up >99% of the total flux up the Alpine Fault.

The Sediment Budget Concept

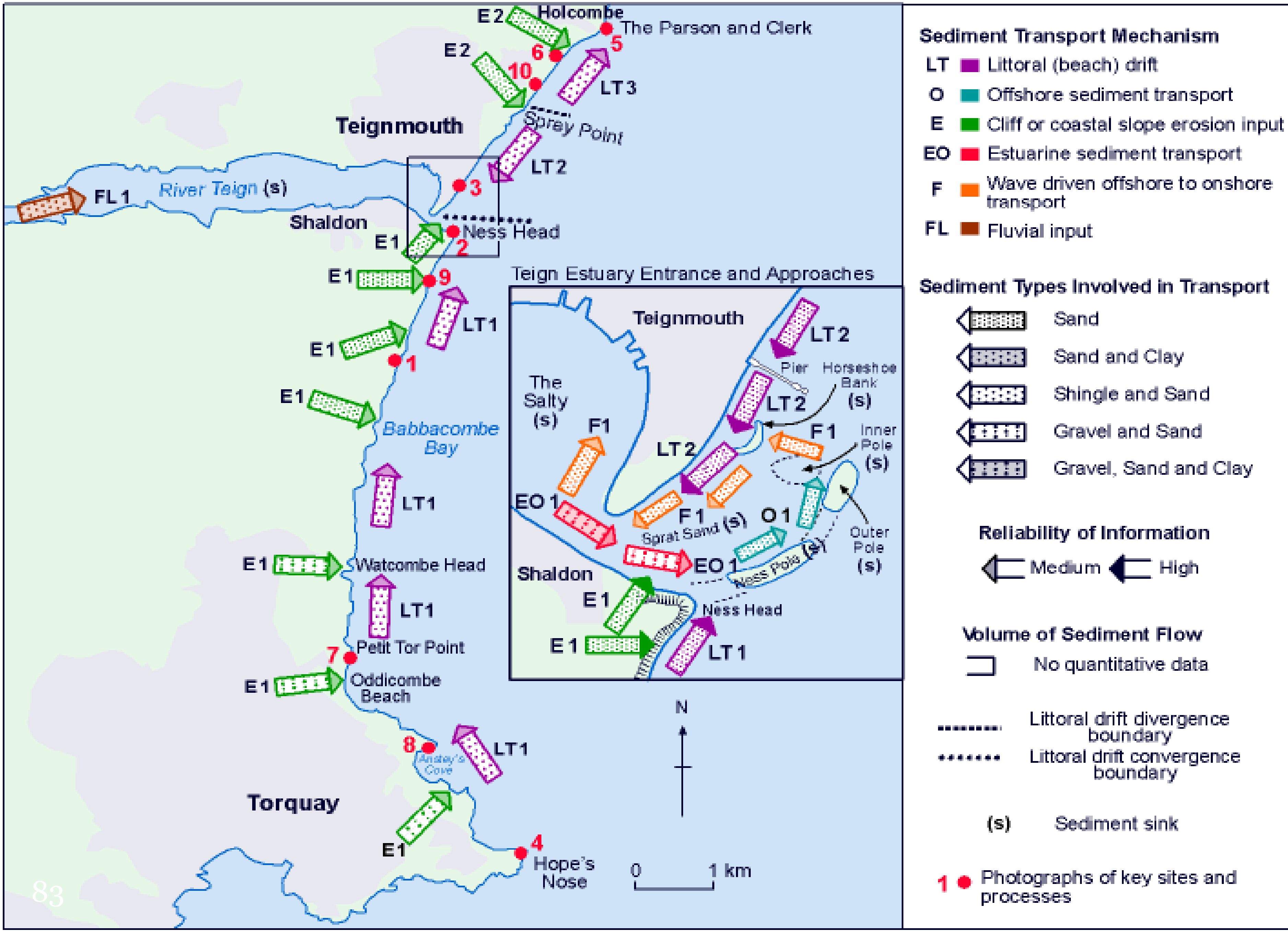
- Allows key elements of coastal system to be identified:
  - Sources of sediments
  - Sediment transport pathways
  - Sediment sinks

- Allows controls on sedimentary processes to be identified

Sediment Pathway Schematic



Hope's Nose, Torquay to Holcombe: Sediment Transport



The Art of Modelling

"The art of modelling
is to develop new insights
or understanding
that you did not have at the outset"

“Tides”

There are some coasts
Where the sea comes in spectacularly
Throwing itself up gullies, challenging cliffs,
Filling the harbours with great swirls and flourish,
A theatrical event that people gather for
Curtain up twice a day. You need to know
The hour of its starting, you have to be on guard.

There are other places
Places where you do not really notice
The gradual stretch of the fertile silk of water
No gurgling or dashings here, no froth no pounding
Only at some point the echo may sound different
And looking by chance one sees ‘Oh the tide is in’.

“Tides” by Jenny Joseph, Selected Poems, 1992