Introduction to integrated modeling

Terminology, approaches and tools

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weftec 2015
the water quality event™
WORKSHOP

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Content

- Introduction
- Integrated Urban Water Systems (IUWS) modeling in general
- Integrated Urban Drainage Models (IUDM) in particular
- Conclusions

Introduction

- Models
- Integration
- Integrated modeling

A few key definitions

“...Model *\/ˈmɒd(ə)l/*

~~(1) a thing used as an example to follow or imitate~~

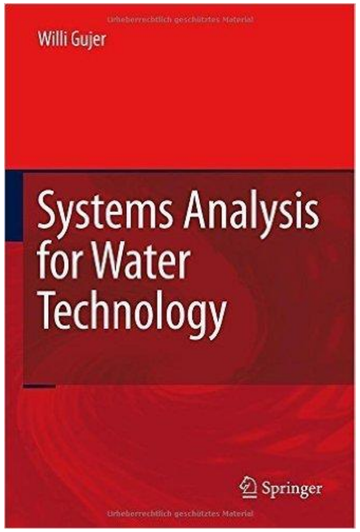
(2) a **simplified** description, especially a **mathematical** one, of a **system** or **process**, to assist calculations and **predictions**

~~(3) a person employed to display clothes by wearing them~~

...”

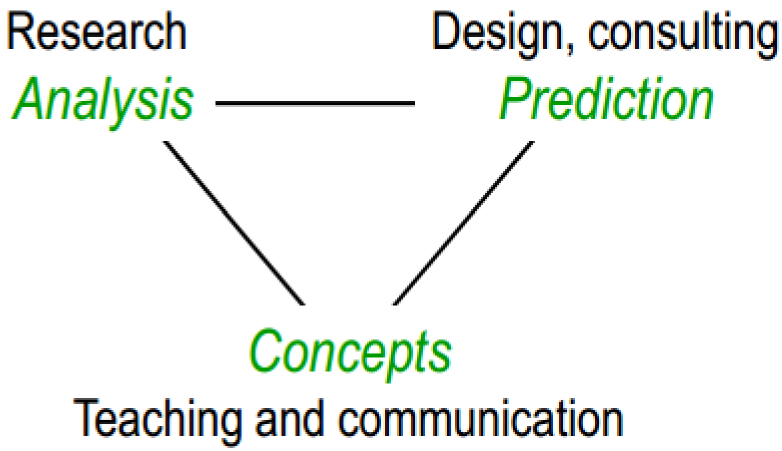
(Source: Oxford Dictionary)

...from the literature...



"A model is an abstract description of reality, which is developed in order to understand better some defined aspects of the system to be analyzed or designed."

– W. GUJER, 2008 , SPRINGER

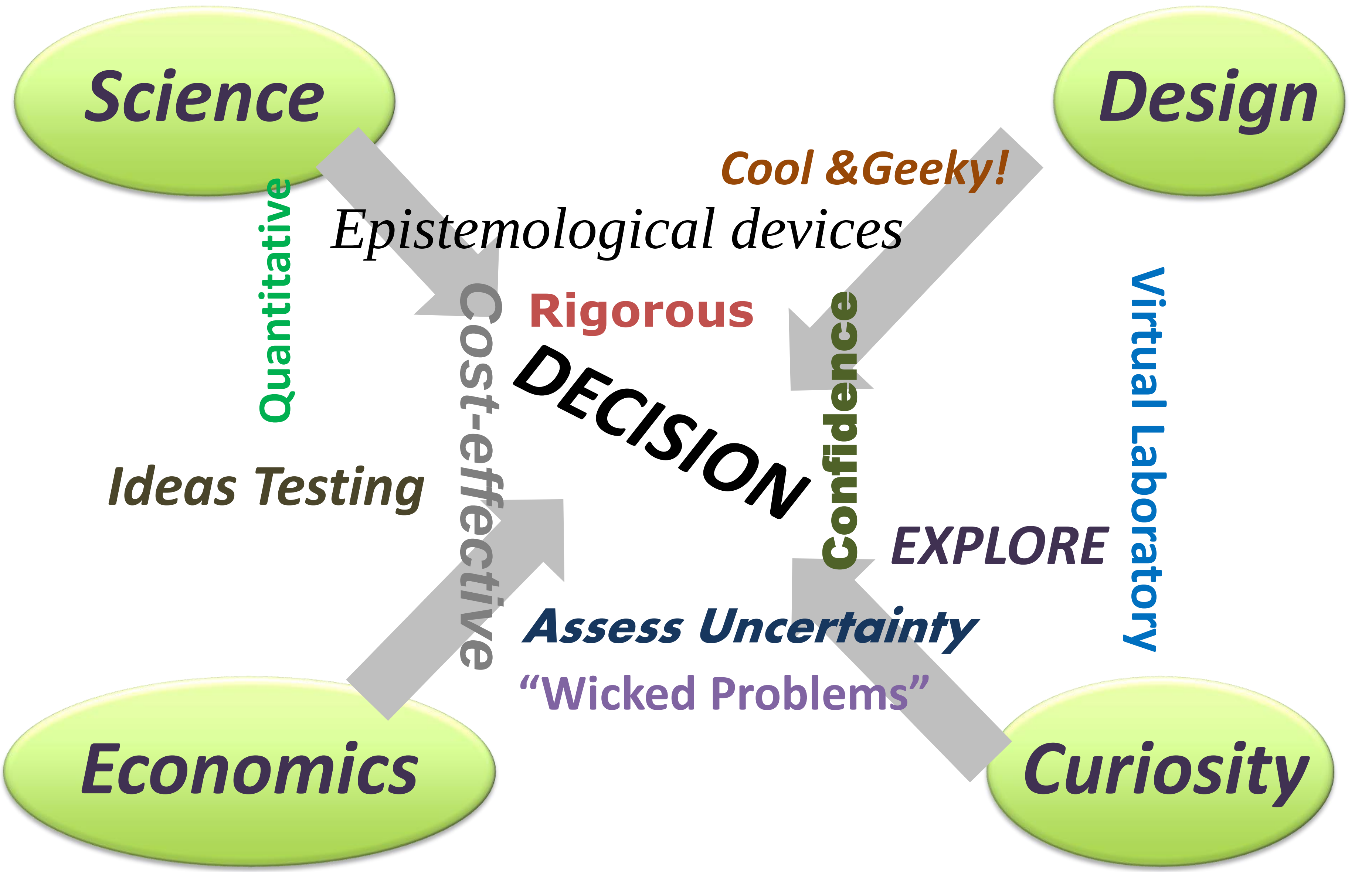


Natural sciences:
Create and communicate understanding, improve understanding of the real world:
The model is the goal of the work

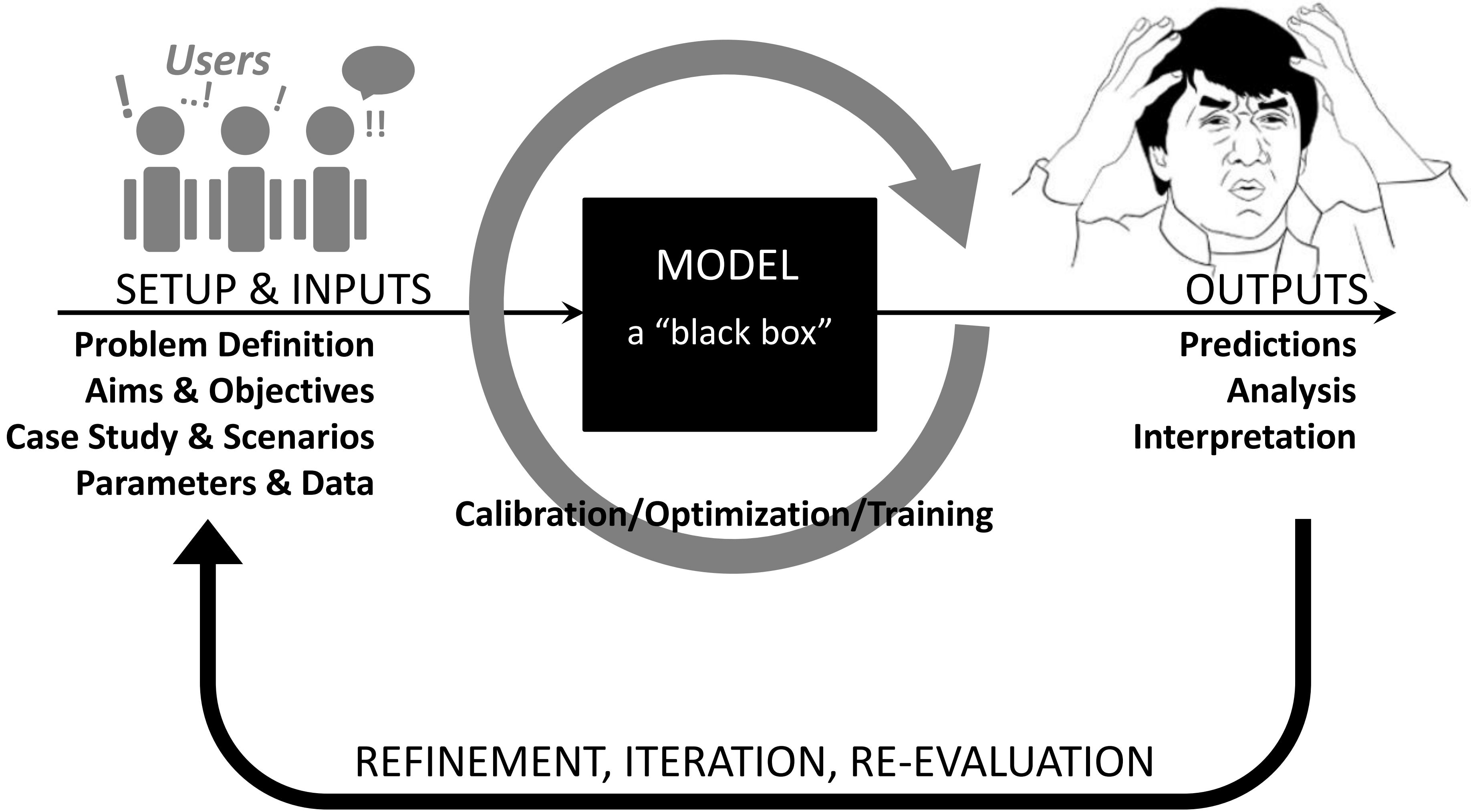
Engineering sciences:
Models should help to make valid statements with the least effort:
The model is the means to an end.

- Models allow us to communicate in a structured way what we know about a system or a process.
- Models define a common base in communication between experts.
- Models allow us to follow the historic development of our process understanding.

Why use models in engineering?



Modelling – A “Not-So-Complex” Illustration



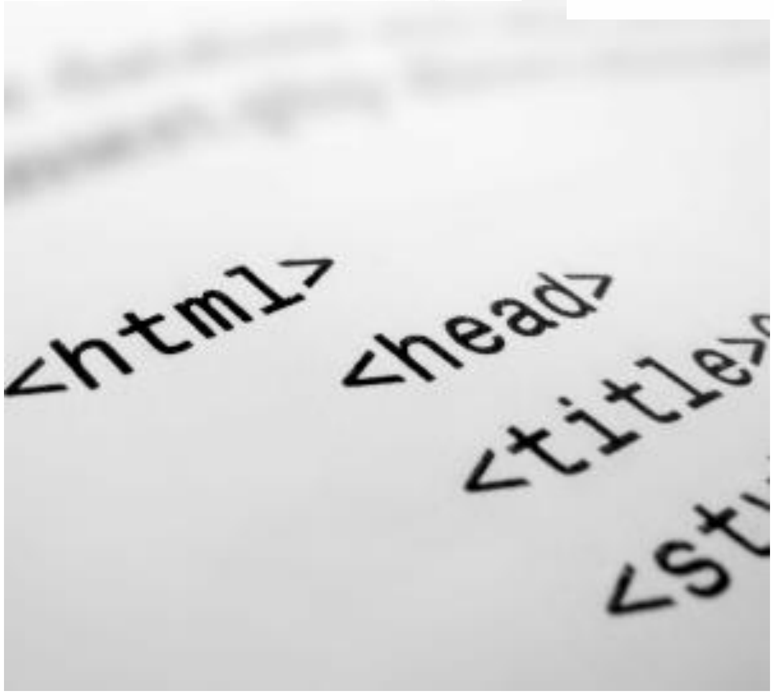
“…**Integration** /ɪntɪˈɡreɪʃ(ə)n/

the linking and coordination of various parts or aspects

…”

(Source: Oxford Dictionary)

Examples of ‘Integration’



Our journey begins around the late 1970s

905

Von der Kanalisation ins Grundwasser – Charakterisierung eines Regenereignisses im Glattal

EAWAG, 8600 Dübendorf, in Zusammenarbeit mit der Abt. Stadtentwässerung des Tiefbauamtes der Stadt Zürich

Bericht:
W. Gujer, V. Krejci, R. Schwarzenbach, J. Zobrist

Für alle diese Phänomene, die typisch sind für Regenereignisse, interessieren sich mit unterschiedlicher Gewichtung verschiedene am Gewässerschutz beteiligte Fachleute. Nur selten gelingt es aber, einen umfassenden Überblick über die Zusammenhänge und Auswirkungen dieser Phänomene zu erhalten.

Verschiedene Forschungsprojekte der EAWAG befassen sich mit Teilaspekten des generellen Problemkreises «Gewässerschutz bei Regenereignissen». Gemeinsam decken diese Projekte den ganzen Bereich, von der Quelle der Schmutzstoffe bis zur Senke respektive zum Abfluss aus einem ganzen Einzugsgebiet eines Fliessgewässers. Es war daher naheliegend, dass die verschiedenen Arbeitsgruppen in einer gemeinsamen Aktion versuchten, ein Regenereignis im Detail so zu untersuchen, dass für ausgewählte Schmutzstoffe Ursprung, Verhalten und Auswirkungen auf die Wasserzusammensetzung in einem

Our journey begins around the late 1970s

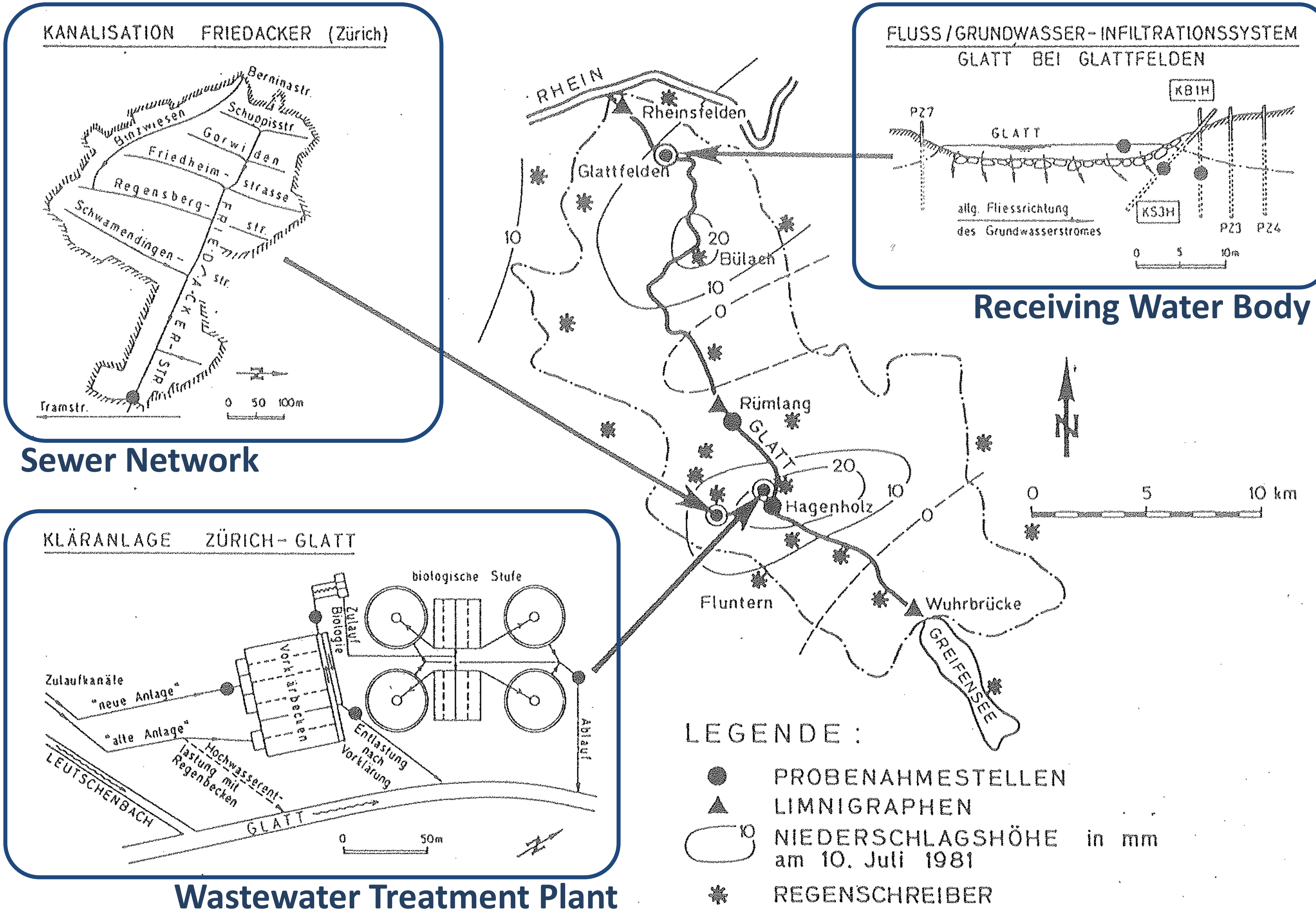
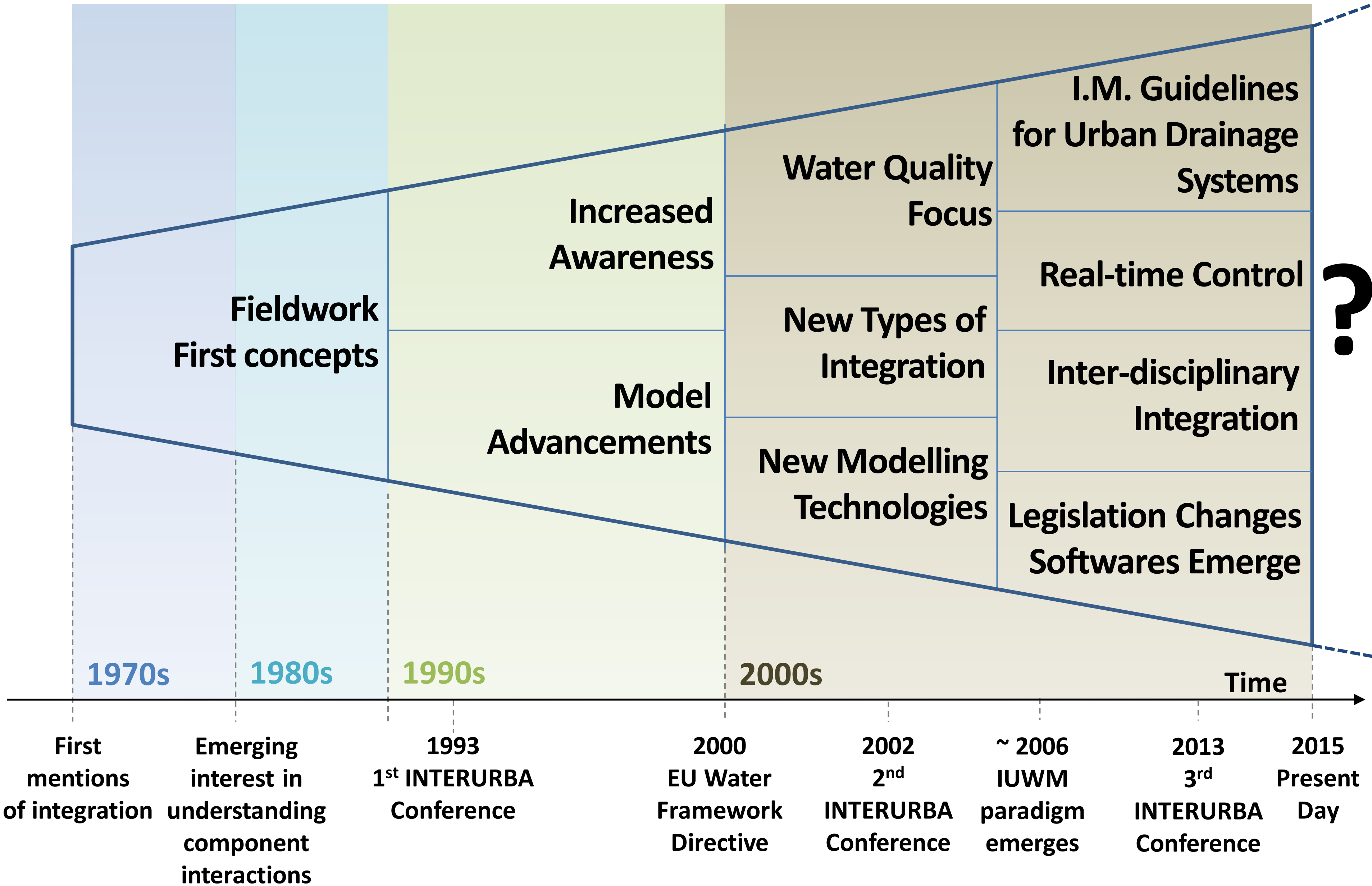


Fig. 1 Untersuchungsgebiet im Glattal: Messstellen und Niederschlagshöhen.

and since then...



So what is "Integrated Modelling"?

"...modelling of interactions between two or more urban water system components..."

– Rauch et al., 2002, Olsson and Jeppsson, 2006

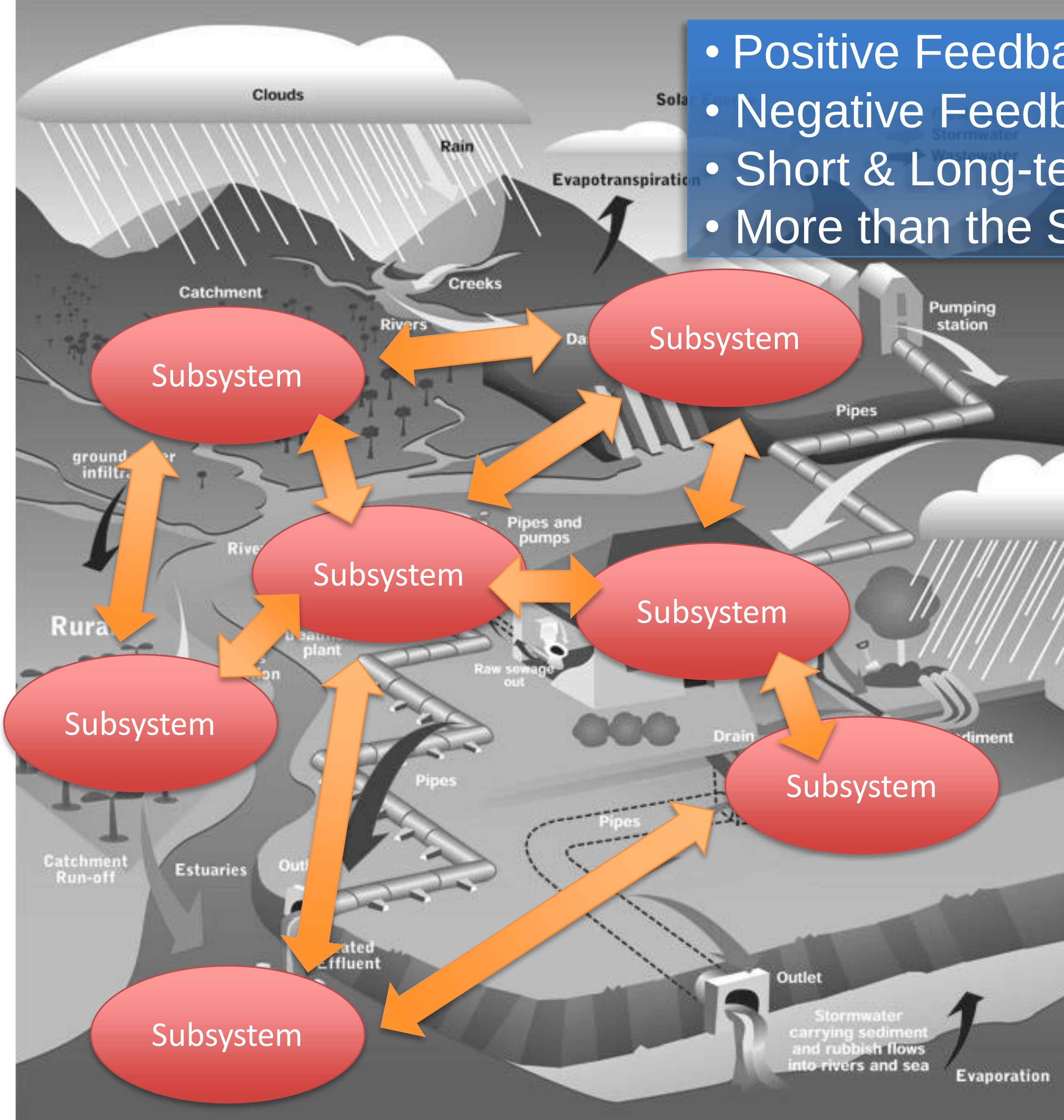
"...ability to focus on understanding the behaviour of parts of the system with respect to the broader picture..."

– Beck, 1976

"... recognises both the positive and negative feedbacks between components and exploits these for significantly more efficient solutions..."

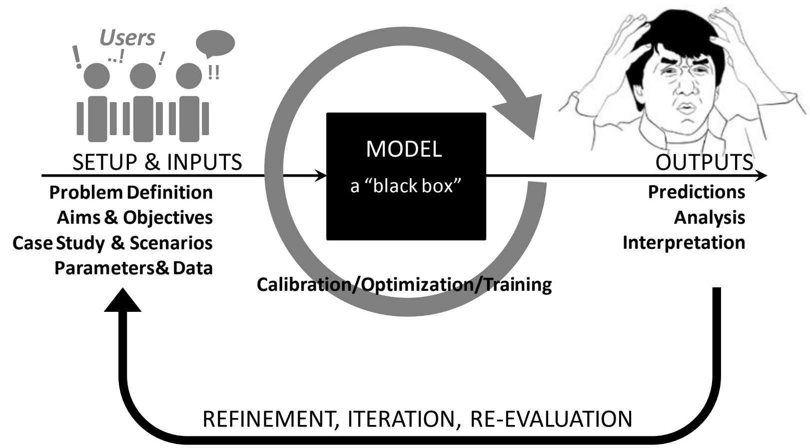
– Marsalek et al., 1993, Mitchell et al., 2007

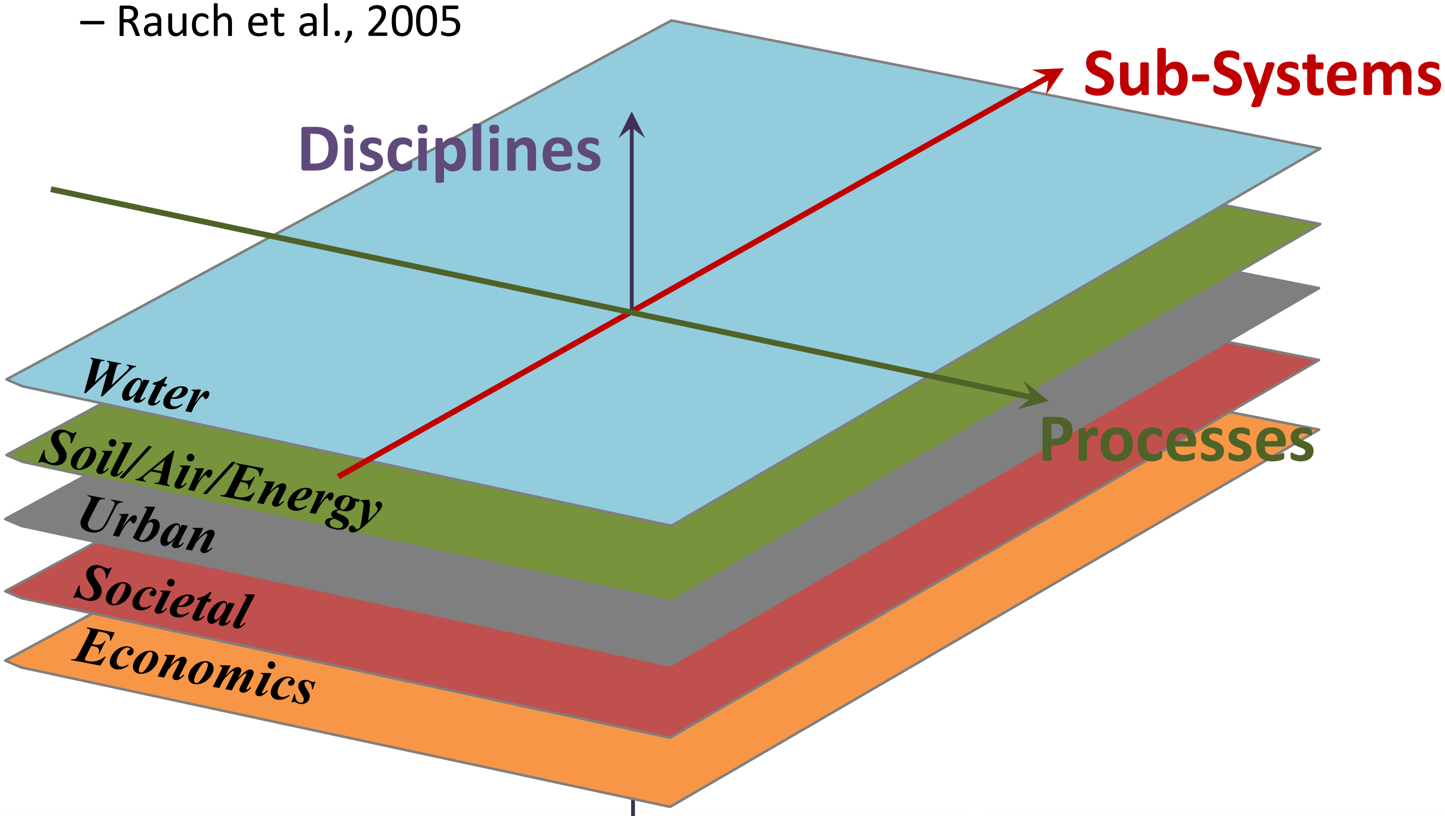
- Positive Feedback
- Negative Feedback
- Short & Long-term Effects
- More than the Sum of Parts



"...the prerequisite to an integrated approach is the identification of the "axes and planes" in which integration needs to take place..."

– Rauch et al., 2005

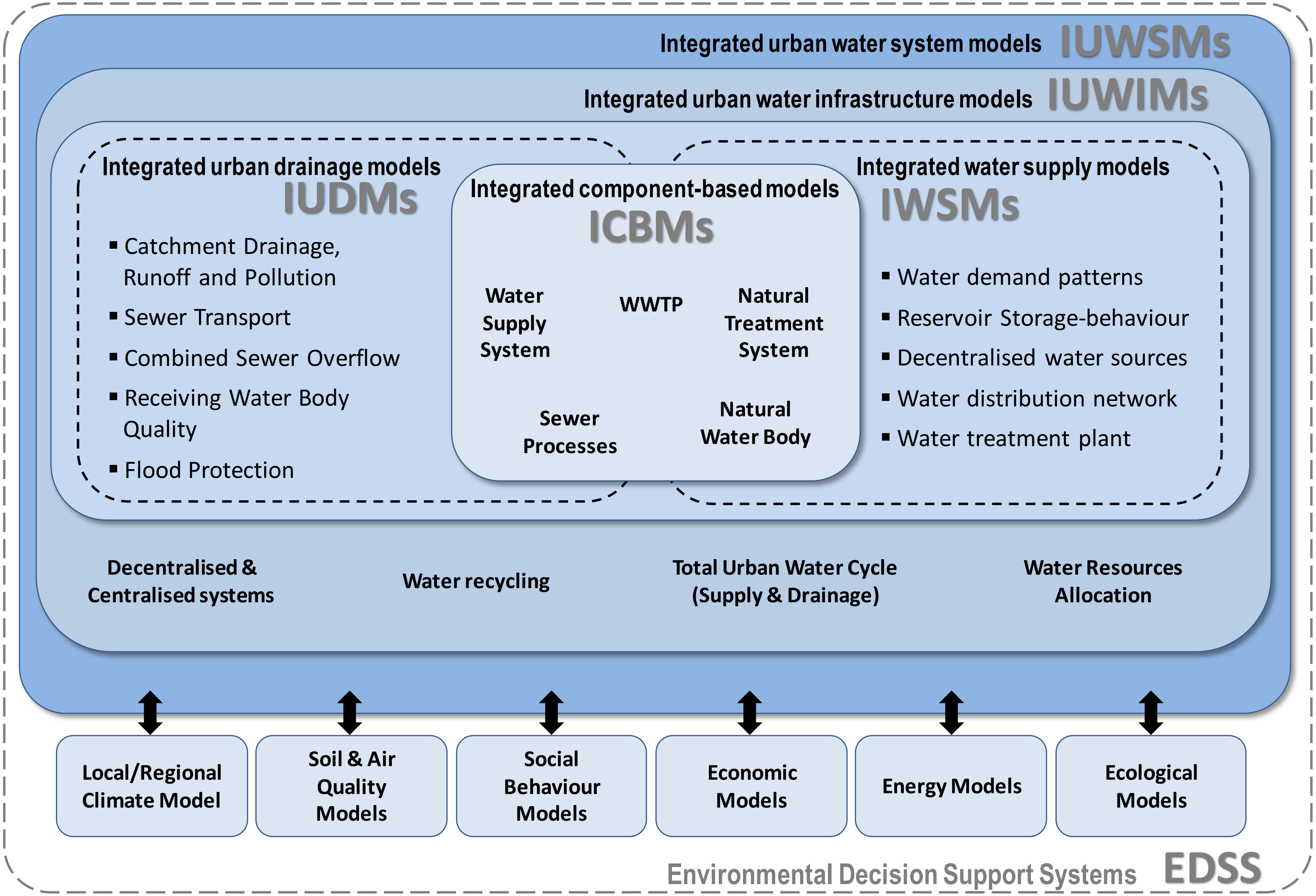




IUWS modeling in general

- Classification
- Issues (and dangers)
- Tools
- Ways of interfacing models
- Calibration and uncertainty

Organising Integrated Modelling in UWS



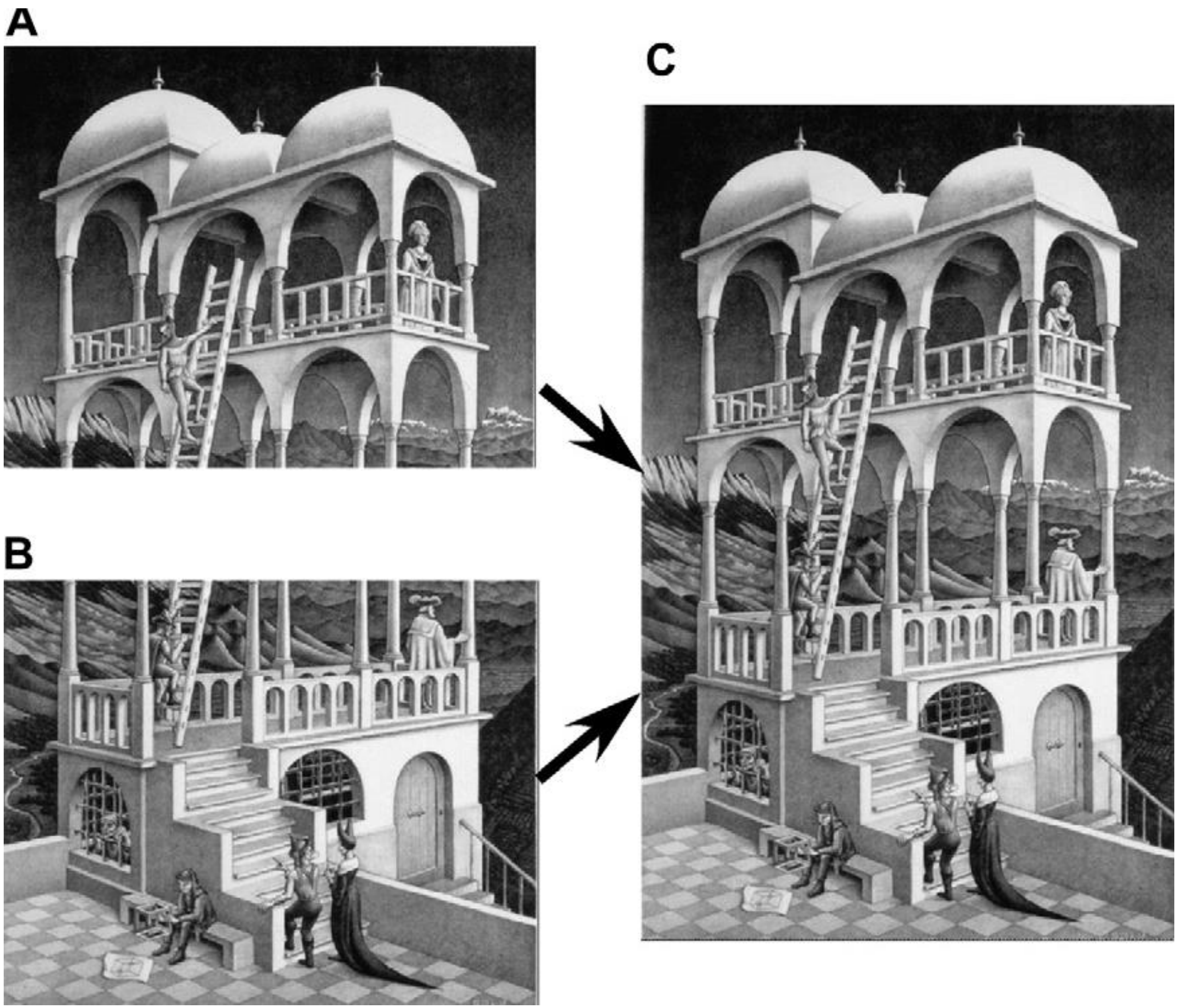
Key Considerations

Model Structure	Empirical vs. Conceptual vs. Mechanistic Deterministic vs. Stochastic
Simulation Config.	Sequential vs. Parallel Online vs. Offline
Spatial Detailing	Branched vs. Looped Distributed vs. Lumped
Temporal Detailing	Continuous vs. Discontinuous Simulation Uniform vs. Variable Time Step
Process Nature	Water Quantity (Hydrologic & Hydraulic) Water Quality (Physical, Biological, Chemical)
Computation	Single Core vs. Multi-Core Processing Single run vs. Optimisation vs. Monte Carlo
Software	Supermodel vs. Interface vs. Hybrid

Integronsters – ugly constructions

adapted from Voinov and Shugart (2013)

Integronsters – skewed geometry



adapted from Voinov and Shugart (2013)

Integronsters – mismatched scales

adapted from Voinov and Shugart (2013)

Integronsters – overwhelming complexity

adapted from Voinov and Shugart (2013)

Integronsters – overwhelming complexity

adapted from Voinov and Shugart (2013)

Integronsters – confusion of tongues

adapted from Voinov and Shugart (2013)

Tools: Some Examples

- Integrated Component-Based Model (ICBM):
  - Benchmark Simulation Model No. 2
    (whole of wastewater treatment plant model)

- IUDMs (drainage) & IWSMs (supply):
  - SIMBA (IFAK), WEST (DHI)
    (sewer system, wastewater treatment plant, receiving waters in single model)
  - SAMBA, RUMBA, FOXTROT
    (linkage of sewer system, wastewater treatment plant, receiving waters)
  - EPANET (Rossman, 2000)
    (simulation of water distribution networks & storages)

Tools: Some Examples

- IUWIMs (water infrastructure):
  - MUSIC (eWater)
  - UrbanDeveloper (eWater)
  - Aquacycle (Mitchell et al., 2001)
  - MIKE URBAN, WEST (DHI)

- IUWSMs (water systems): current only sparse
  - Work by Fagan et al., 2010
  - VIBe (Sitzenfrei et al., 2010)
  - OpenMI (OpenMI Association, 2010)
  - DAnCE4Water & UrbanBEATS

Integration

I'm providing discharge every minute in l/s

Model 1

State Variable

My state variable is the flow of a non-compressible fluid with a density of 1000 kg/m^3

Model 3

State Variable

Model 2

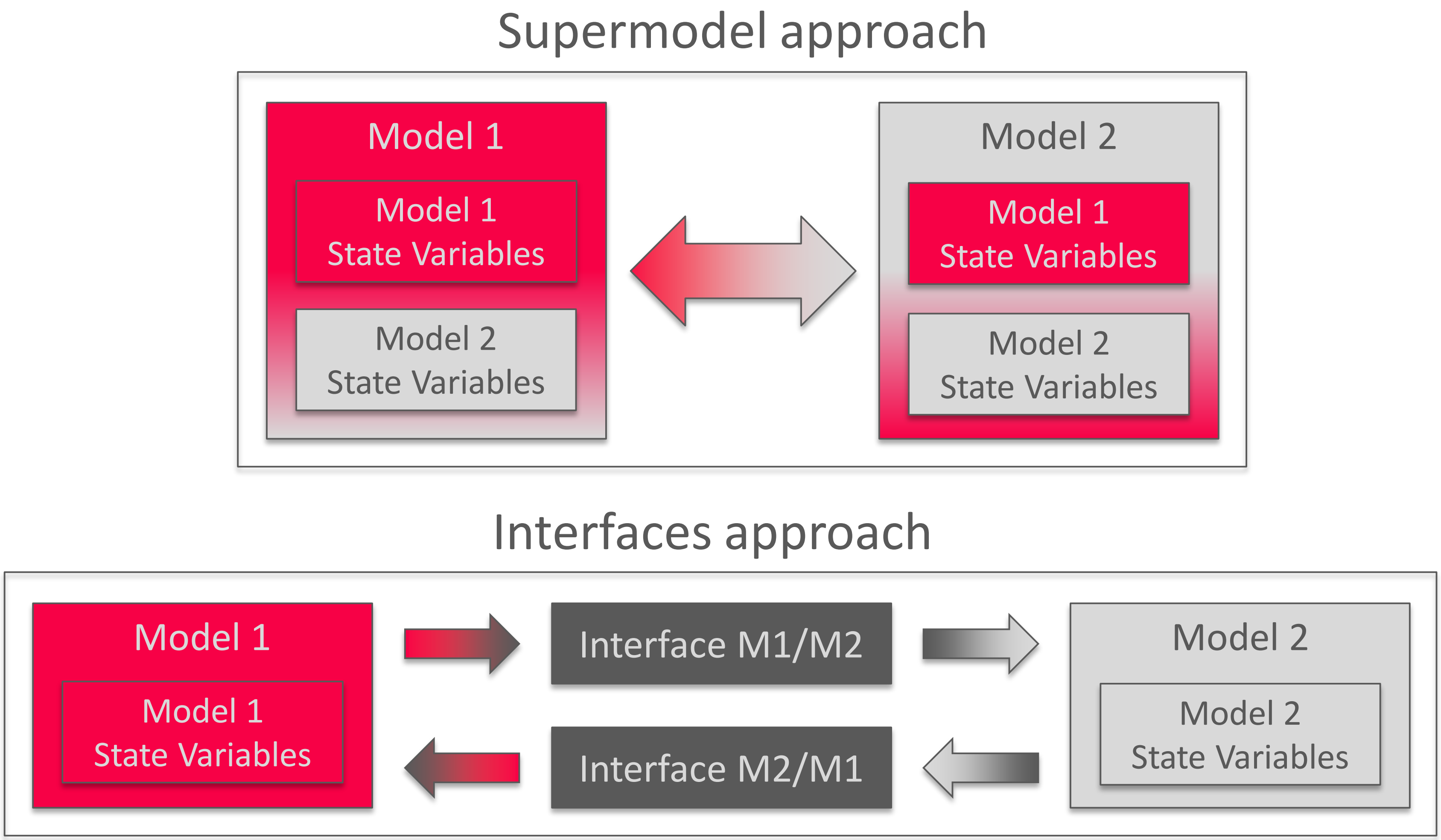
State Variable

I'm expecting the amount of inflowing sewage in gallons per day

Interfacing and Integration

- Methodological integration
  - Data produced by one model are a meaningful input to another model
- Technical integration
  - Automating data exchange between models, making them jointly executable

Methodological Integration

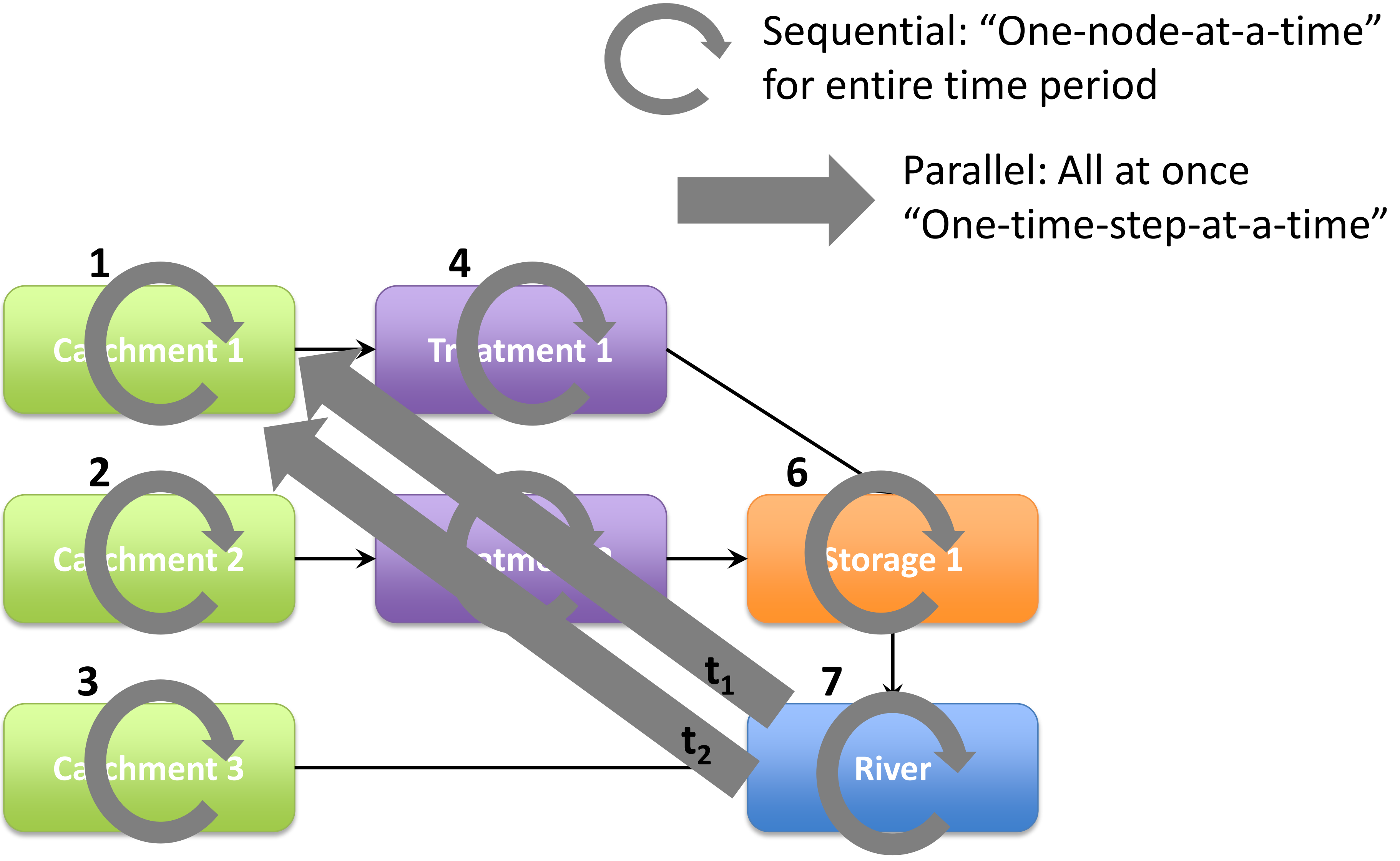


(Vanrolleghem, 2005)

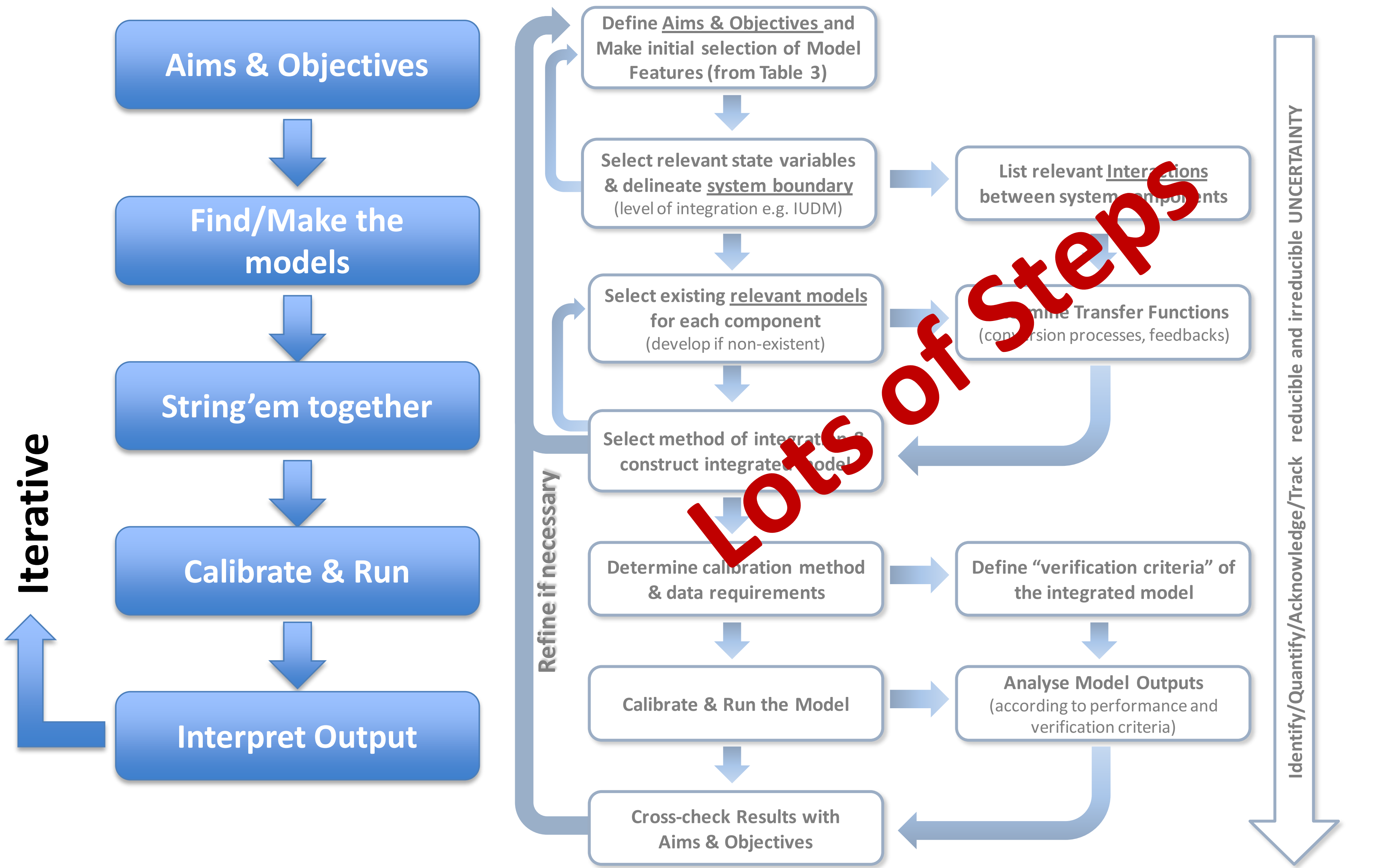
Technical Integration

- Scripts
- Integration in a proprietary method
- Integration using a modelling framework based on open standards

Sequential vs. Parallel



Developing Integrated Models



Calibrating and Validating these Beasts

- Three methods identified:

#1 :: calibrate the whole integrated model at once

#2 :: start upstream, then gradually move downstream, quantity before quality

#3 :: calibrate individual models first, then integrate them

Calibrating and Validating these Beasts

- Integrated models as "unwieldy" and "highly complex" – a technical and logistical challenge!

- Error propagation, equifinality and sometimes unavoidable auto-correlation more pronounced with increasing complexity

- Calibration/Validation feasibility decreasing with larger integrated models – still useful?

- Overcome data limitations with semi-hypothetical case studies and exploration

- Overcome overparametrisation by using simpler surrogate models

Uncertainty

- Types:
  - Statistical (outcomes known and quantifiable)
  - Scenario (outcomes known but not quantifiable)
  - Qualitative (not all outcomes known nor quantifiable)
  - Recognised Ignorance

- Statistical received great attention (many methods to quantify)

- Scenario partly explored

- Should integrated modelling field rely on classical uncertainty estimation methods?
  - EU QUICS project

IUDMs in particular

- Drivers (wet-weather effects on receiving water ➔ UPM)
- Concepts

Effects of wet weather discharges on river quality

- **Reduction in Dissolved Oxygen (DO) due to:**
  - Degradation of dissolved BOD & BOD attached to sediment
  - Resuspension of polluted bed sediments exerting an oxygen demand
  - Low DO levels in spilled storm sewage
- **Rapid increase in river concentrations of:**
  - Ammonia, bacteria, COD, suspended sediments, heavy metals etc.

Effects of wet weather discharges on river quality

- **Magnitude of impact depends on:**
  - River flow (dilution)
  - Chanel gradient (slope)
  - Channel geometry & roughness
  - In-river structures (velocity & depth)
  - pH (high pH increases proportion of *un-ionised ammonia* for a given conc. of total ammonia)
  - Temperature
  - Ecology (macrophytes, algae, fish & invertabrates)

Urban Pollution Management – a short (UK) history

" The failure to relate overflow to river needs ....puts at hazard the attainment of target quality for the river system (and) distorts the correct pattern of investment in the sewerage system"

Technical Committee on Storm Overflows and the Disposal of Storm Sewage, 1970

" We would like to have been able to recommend a Formula for overflow setting that took account of river quality flow and use……but there are too many unknown factors to make it workable"

Technical Committee on Storm Overflows and the Disposal of Storm Sewage, 1970

Dry weather flow

DWF = PG + I + E

E (industrial flow)

P (population)
G (water consumption)

Infiltration

CSO Setting = DWF + 1360P + 2E litres/day

> *"We consider that there is an urgent need for a study to be made of the effect of intermittent discharges of storm sewage on streams".*

Royal Commission on Environmental Pollution 16th Report 1992

6,500 WWTP

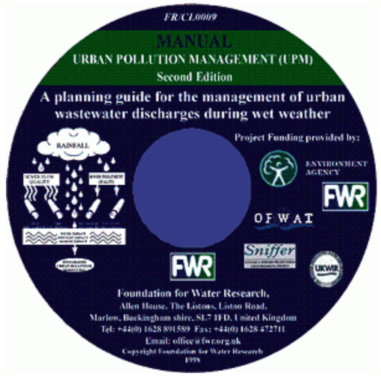
25,000 CSOs

In 1990 8,000 CSOs = significant pollution

50% of all bathing waters

320 inland waterbodies

Urban Pollution Management Manual
(I) 1995, (II) 1998, (III) 2013



Environment Agency

UKWIR

CIWEM Chartered Institution of Water and Environmental Management

Urban Drainage Group

PHASE A — **INITIAL PLANNING**

↓

PHASE B — **CONSTRUCT UPM TOOLS**

↓

PHASE C — **TESTING COMPLIANCE**

↓

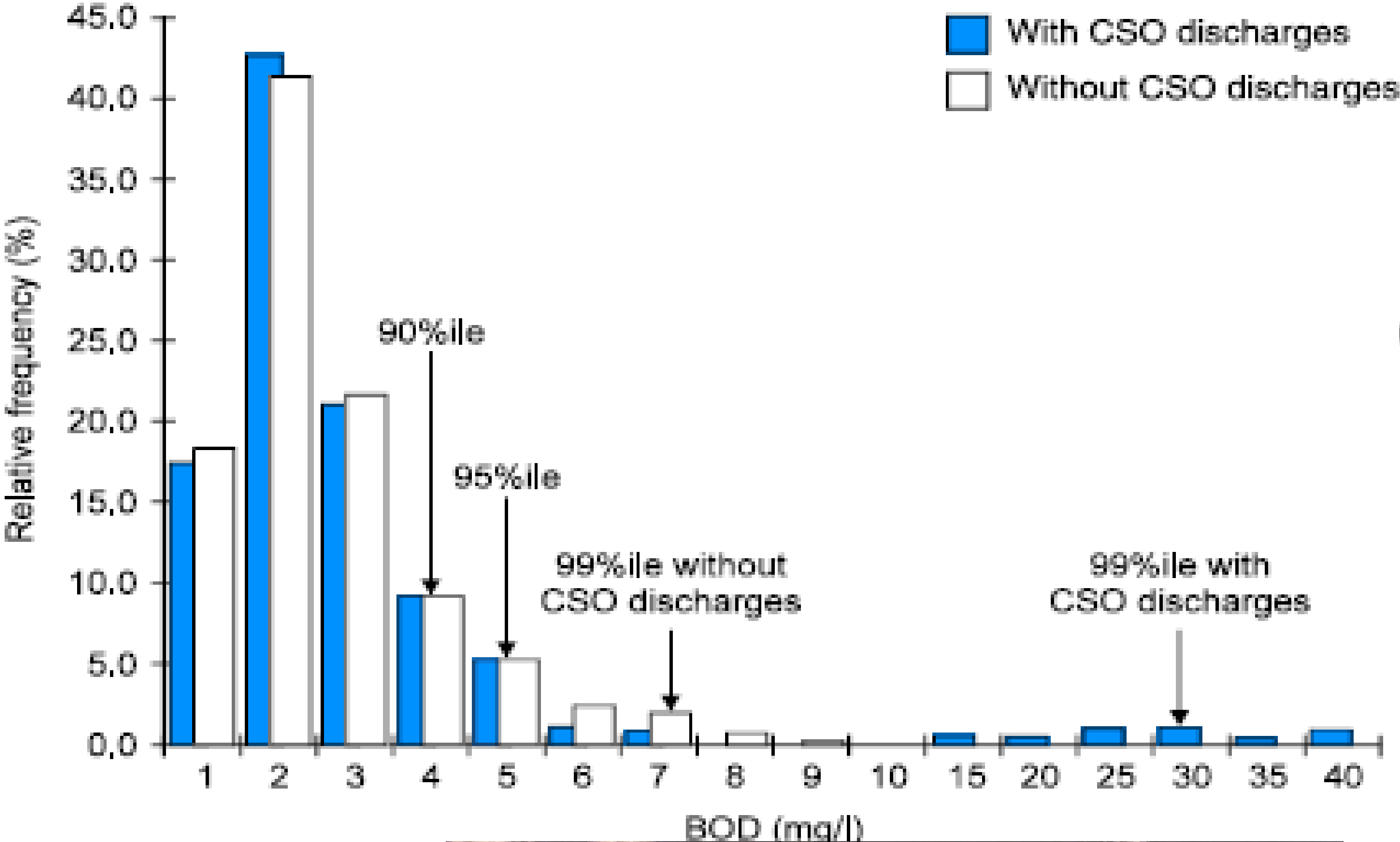
PHASE D — **POST PLANNING STUDY ISSUES**

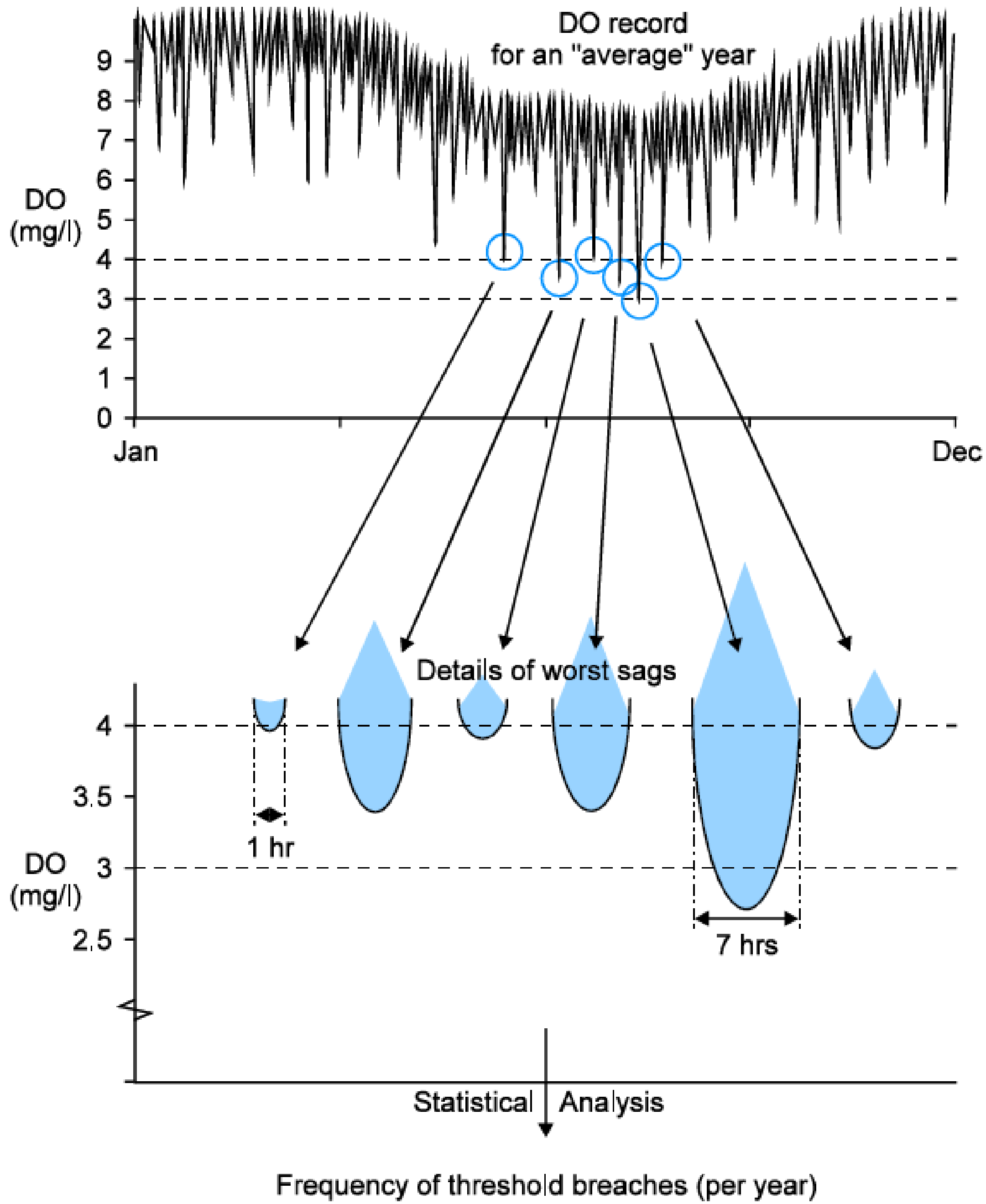
"The management of wastewater discharges from sewerage and sewage treatment systems under wet weather conditions such that the requirements of the receiving water are met in a cost-effective way"

Environmental Quality Standard (EQS) – Environmental Quality Objective (EQO) principle

- EQOs are used to specify the desired use of the water body (e.g. Good Ecological Status)
- The performance of individual discharges (e.g. CSOs & WRRF%) should be set by reference to the ability of receiving waters to accommodate contaminants without detriment to the desired use of the water (the EQO)
- EQSs are the concentrations of target substances (e.g. dissolved oxygen) which if achieved enable the desired use to be protected.
- EQSs can be used in monitoring to judge water quality
- **EQSs can be used in planning and design to test whether a proposed infrastructure configuration will deliver an EQO**

Why special standards are needed for 'wet weather'




DO record
for an "average" year
DO
(mg/l)
9
8
7
6
5
4
3
2
1
0
Jan
Dec
Details of worst sags
4
3.5
DO
(mg/l)
3
2.5
1 hr
7 hrs
Statistical Analysis
Frequency of threshold breaches (per year)

UPM2 Fundamental Intermittent Standards DO

Ecosystem suitable for a sustainable salmonid fishery			
Return period	Dissolved oxygen concentration (mg/l)		
	One hour	Six hours	24 hours
One month	5.0	5.5	6.0
Three months	4.5	5.0	5.5
One year	4.0	4.5	5.0

≡ British Columbia (Canada) MoE instantaneous min value

≡ USEPA warm water 1 day value

- Other values for cyprinids
- Same concept for NH_3
- Cross-corrections DO-NH_3

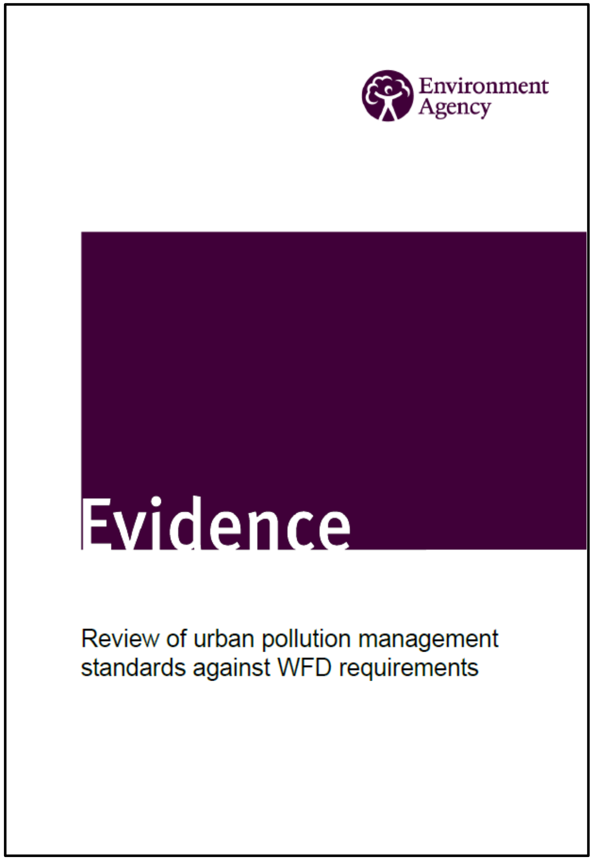
Are UPM2 FIS consistent with needs of Water Framework Directive (2000/60/EC) (WFD)?

New data on:

- sensitivity of aquatic organisms to dissolved oxygen and/or unionised ammonia (1992 onwards)
- repeated exposure to pulses of unionised ammonia

"the UPM2 FIS provide protection against both short-term mortality and longer term effects on the physiology, growth and reproduction of the fish"

"meeting the UPM2 FIS should ensure that the good quality status of a water body is not compromised"



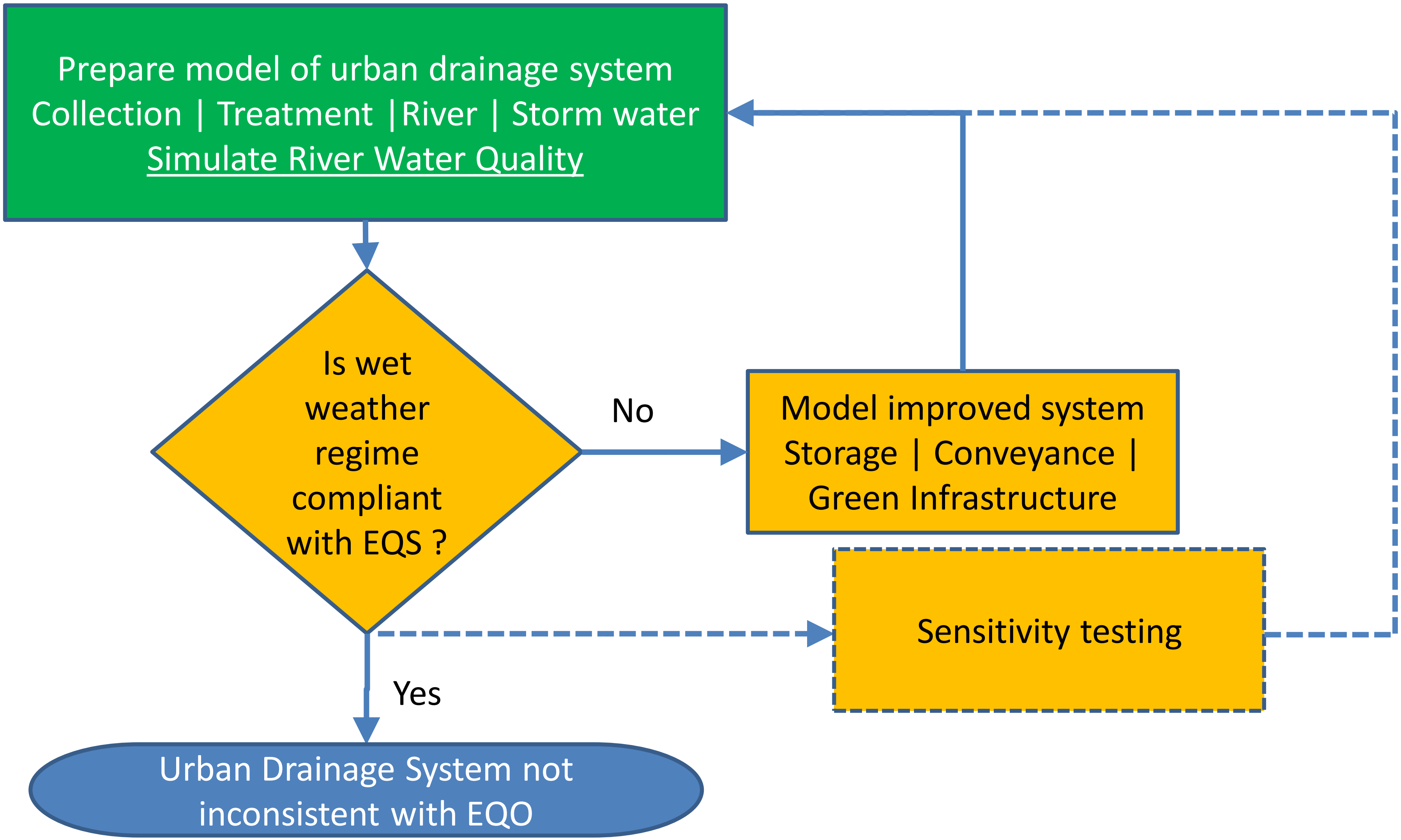
Environment Agency

Evidence

Review of urban pollution management standards against WFD requirements

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291495/LIT_7372_bec80a.pdf

UPM modelling approach (IUDM)



Conclusions (UPM)

- UPM FIS are **design** criteria – not a classification system
- Developed for use in modelling studies to check that '**wet weather**' regime is consistent with delivering a EQO
- Re-evaluation in 2012 confirmed that using FIS design criteria for wet weather impacts (CSOs, WWTP, storm water) **protects** Good Ecological Status

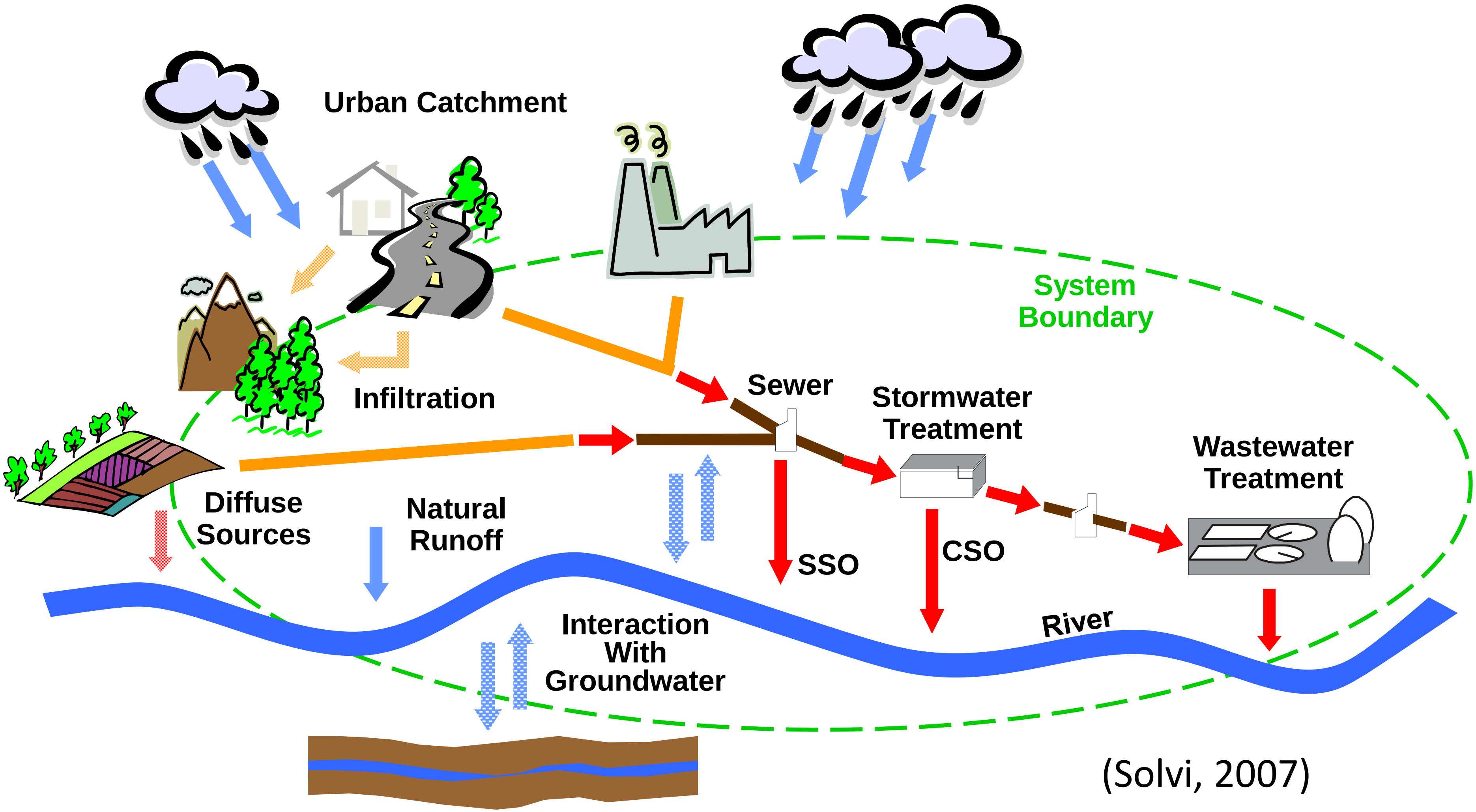
Conclusions (UPM)

- Track record
  - UPM used as basis of **£3.5 billion** programme to 'improve' c. 8,000 UK CSOs since 1995
  - Customised UPM FIS used to support development of **£4 billion** Thames Tideway Tunnel programme (20km 8m dia. tunnel intercepting 30+ CSOs on tidal River Thames)
- Regulatory policy
  - UK regulators fully **endorse** use of UPM approach
  - FIS are science based but usage is **site** specific
  - Regulator reserves right to **vary** values
  - **Partnership** approach in 'initial planning' stage

IUDMs

- Limited to urban wastewater system detailed vs. simplified
  - Catchment/sewer
  - WWTP
  - River

System boundaries



(Solvi, 2007)

Catchment/sewer – detailed

- High level of spatial detail (down to 20 cm diameters and many small catchments)
- Can have up to 1000s network elements
- Use of some version of the hydrodynamic Saint-Venant equations (PDE: 1-D, 2-D, 3-D)
- Needed if velocity, water levels are important
- Rainfall/runoff same models as simplified

Catchment/sewer – detailed

- Long tradition and wide diffusion of detailed modeling
- Many software tools (inside models do not change much, solvers may):
  - InfoWorks, MIKE URBAN, SWMM, …

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{gh^2}{2}\right) + \frac{\partial(huv)}{\partial y} = S_{0,x} - S_{f,x} + q_{1D}u_{1d}$$

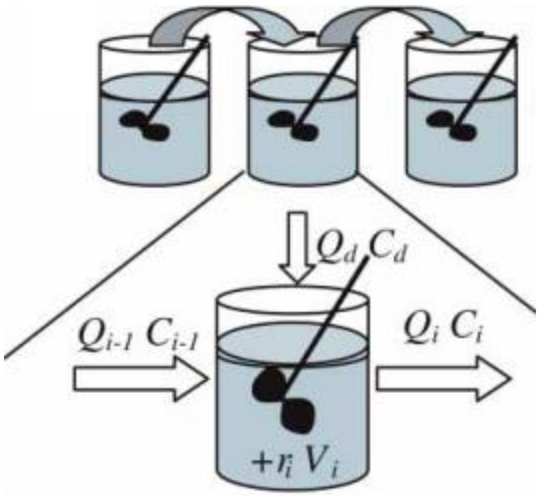
$$\frac{\partial(hv)}{\partial t} + \frac{\partial}{\partial y}\left(hv^2 + \frac{gh^2}{2}\right) + \frac{\partial(huv)}{\partial x} = S_{0,y} - S_{f,y} + q_{1D}v_{1d}$$

Catchment/sewer – simplified

- Low level of spatial detail (down to 50-100 cm pipe diameters and lumped catchments)
- Can have up to 100s network elements
- Use of tanks-in-series approach (ODE)
- Sufficient when flows and/or water volumes are important (water quality)
- Solutions for backwater are available (Vanrolleghem et al., 2009)

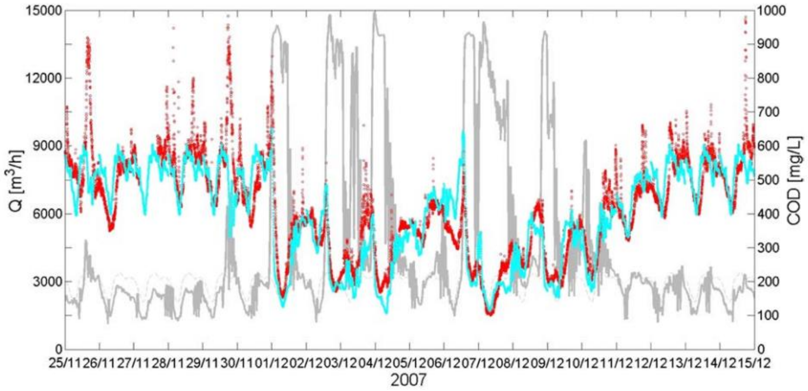
Catchment/sewer – simplified

- Developed mostly in countries where regulation allows/promotes it
- Model more important than software around it
  - KOSIM, SMUSI, MUSIC, …



Catchment/sewer – quality

- Water quality usually included (solids, pollutants) but not very reliable
- Specific models for specific applications, difficult to generalize to other systems
  - Reaeration
  - Sulphide production
  - Methanogenesis
  - Chemical dosage



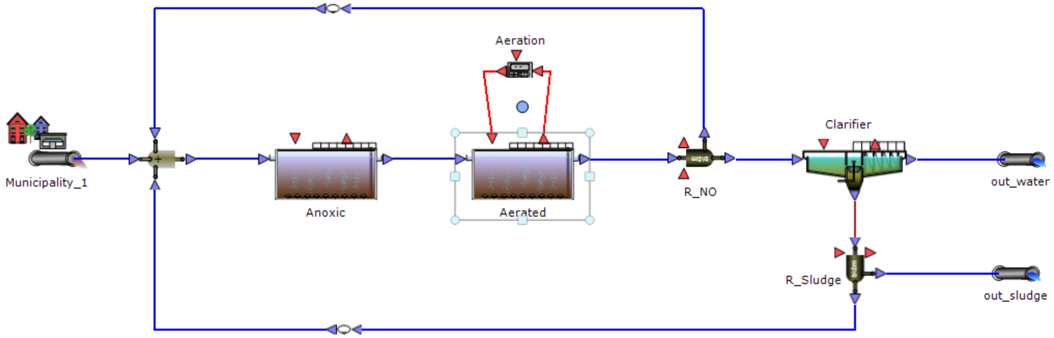
- With more use of sensors in sewers, use of such data or derived data-driven models

Catchment/sewer – quality

- Dry weather flow relatively easy to model
  - Per capita flow and loads
  - Infiltration rate (from WRRF influent data)
  - Processes?
- Wet-weather more difficult
  - Accumulation / Wash-off in catchment
  - Sedimentation / Resuspension in pipes and tanks
  - CSOs concentrations

WRRF

- Tanks-in-series
- No simplification needed
- Still issues with wet-weather modeling
  - Primary and secondary settlers
  - Influent fractionation
  - Mixing



River – detailed

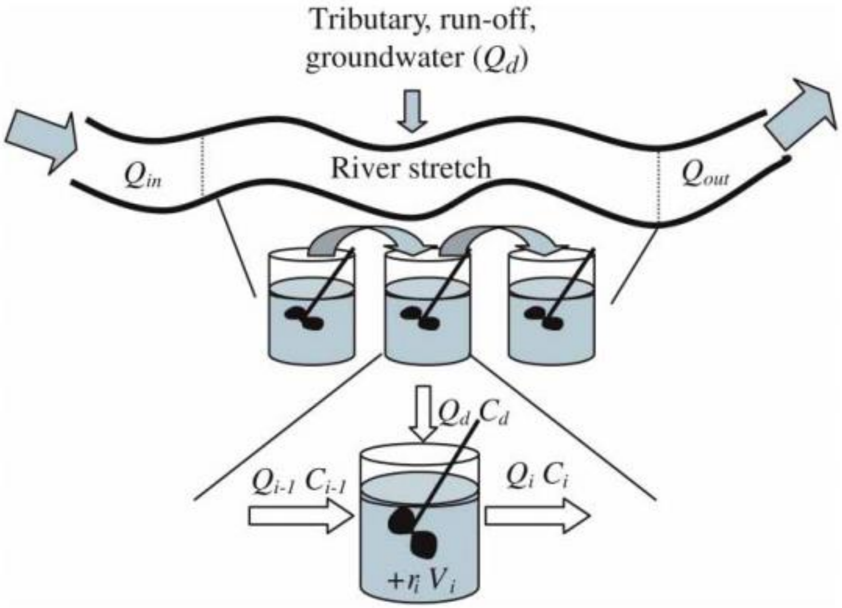
- Used when velocities, water levels are important (solids transport, flooding)
- Often used for water quality
- Inputs are measured or from basin hydrologic models
- Many software tools available:
  - InfoWorks, MIKExx, DUFLOW, SOBEK, …

$$\frac{\partial(hu)}{\partial t} + \frac{\partial}{\partial x}\left(hu^2 + \frac{gh^2}{2}\right) + \frac{\partial(huv)}{\partial y} = S_{0,x} - S_{f,x} + q_{1D}u_{1d}$$

$$\frac{\partial(hv)}{\partial t} + \frac{\partial}{\partial y}\left(hv^2 + \frac{gh^2}{2}\right) + \frac{\partial(huv)}{\partial x} = S_{0,y} - S_{f,y} + q_{1D}v_{1d}$$

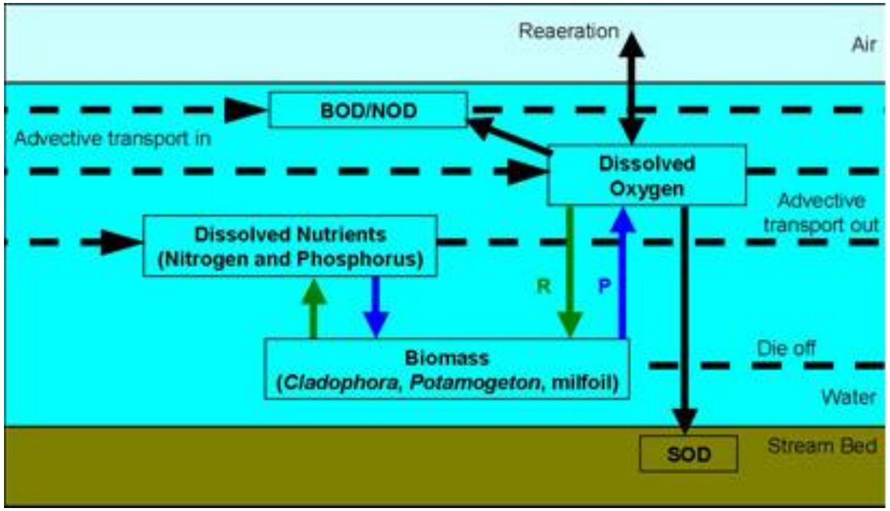
River – simplified

- Same as for sewers
- Used when quality is more important than (some details of) quantity, e.g. in SWAT et similia…



River – quality

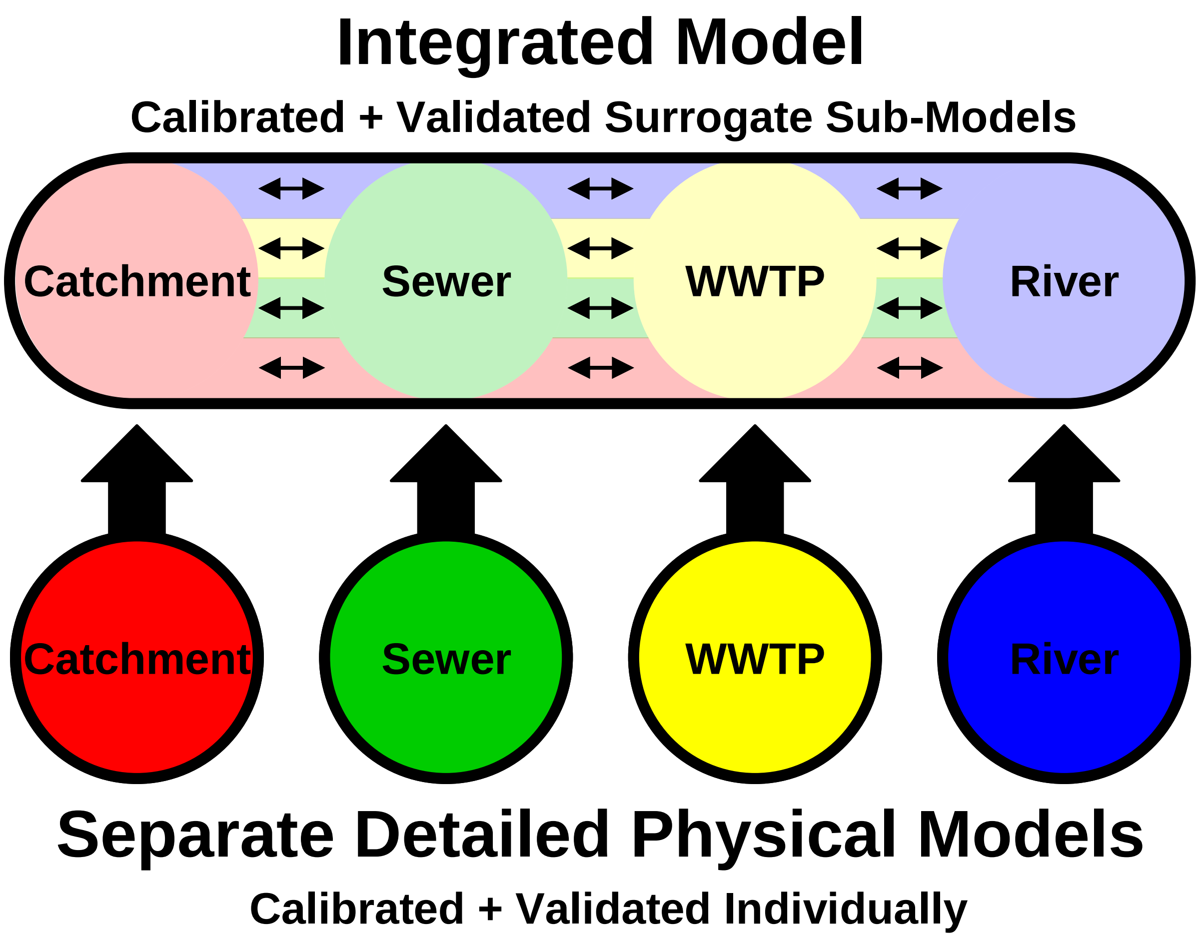
- Wide and old use of water quality (from S&P)
- Many possible processes can be included
  - DO-BOD, solids, C-N-P cycles, algae, eutrophication, sediment, chemical equilibria, …
- Difficult to predict ecological quality
  - Interface can be UPM FIS
- Several models currently used in many forms
  - RWQM1, QUAL2E, QUAL2K, DUFLOW, …



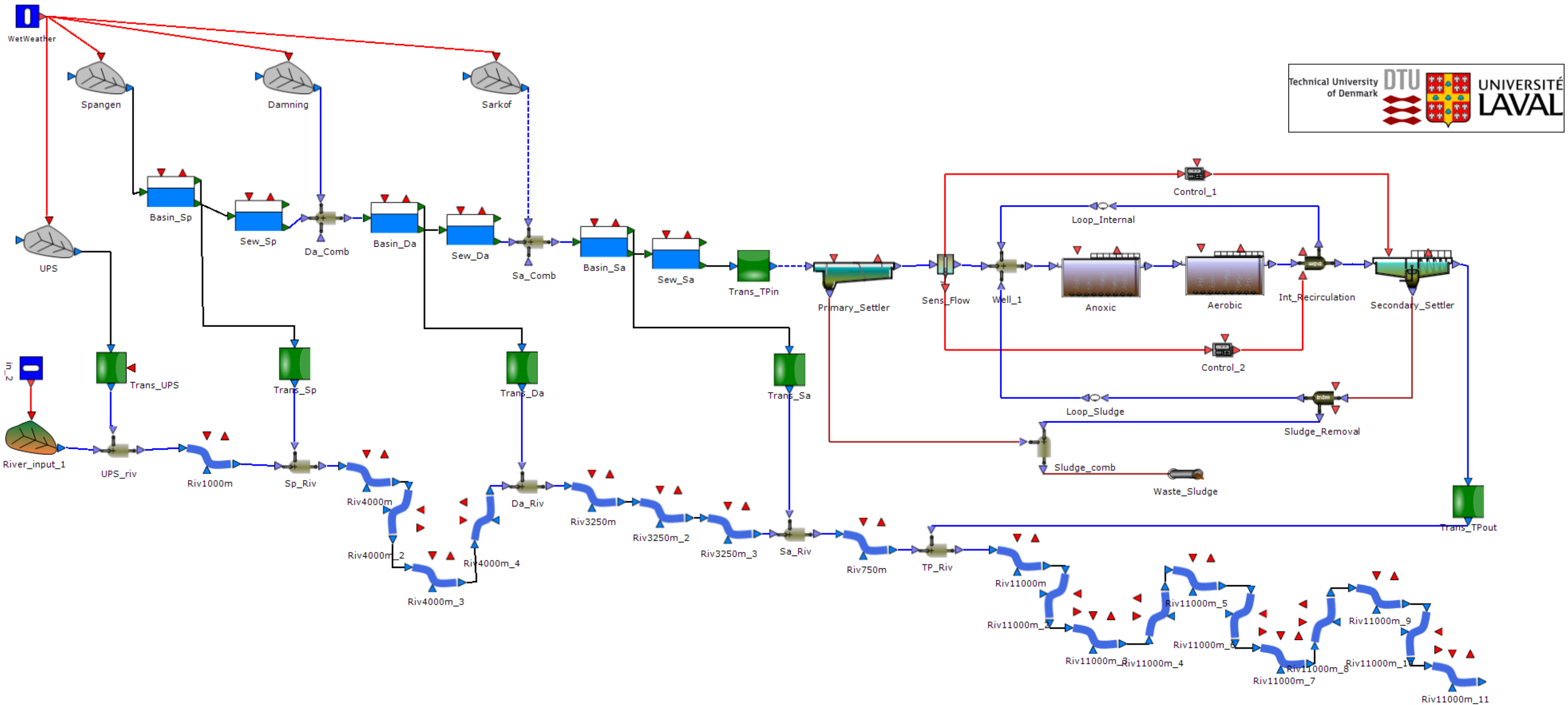
Integration – OpenMI

- Standard interface
- It allows models to exchange data with each other
- On a time step by time step basis
- It is defined by a set of software interfaces that a compliant model or component must implement
- www.openmi.org

Integration – single platform



Integration – single platform

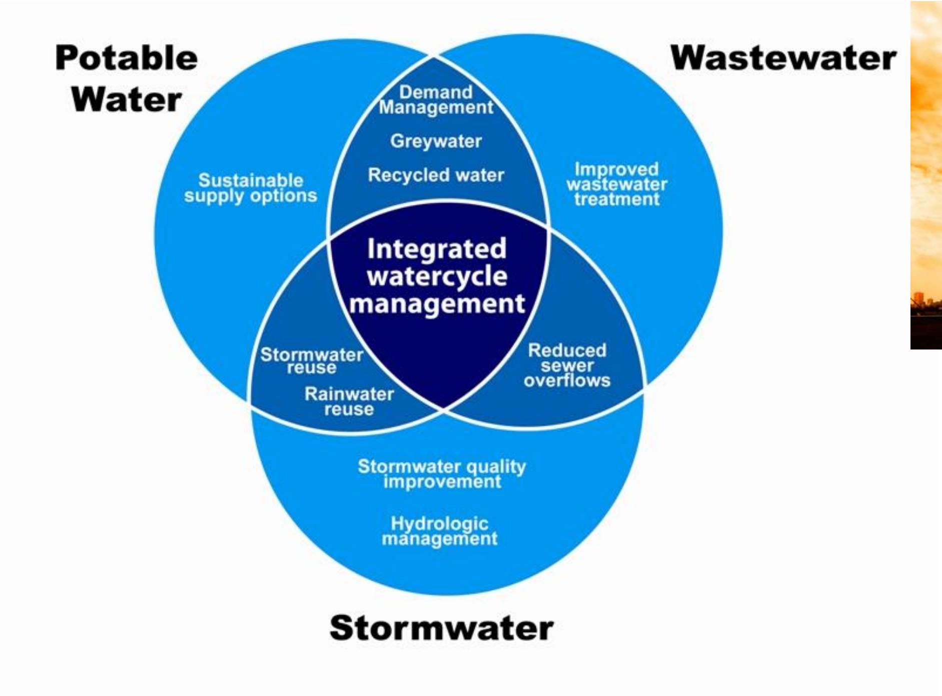


Integration – software

- Commercial
  - WEST, SIMBA
- Non-commercial
  - City-Drain (Matlab), SYNOPSIS, …

Conclusions

Driving the Adoption of Integrated Models

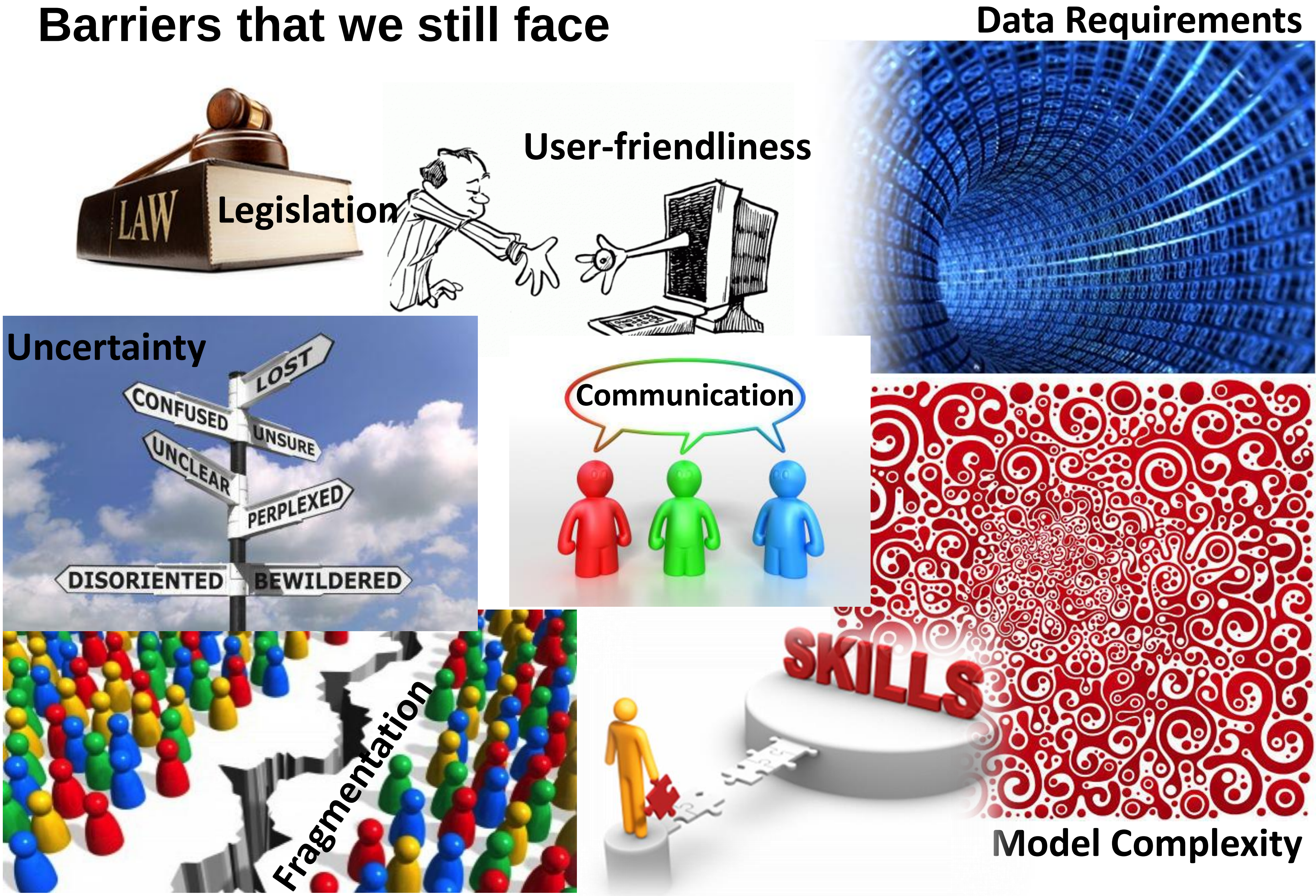


(1) Global Change & the IUWM Paradigm

(2) Changing Legislation

(3) Diversity of Integrated Model Use

Barriers that we still face



So what does the future hold?

- The literature's Key goals
  - More 'now-casting'
  - More transparent process in using integrated models
  - More interdisciplinary work
- The direction of future research(?) - "Virtual Playgrounds" encompassing the technical and non-technical
- Fragmentation in practice needs to be overcome
- Legislation needs to evolve more than it has
- Participatory approach

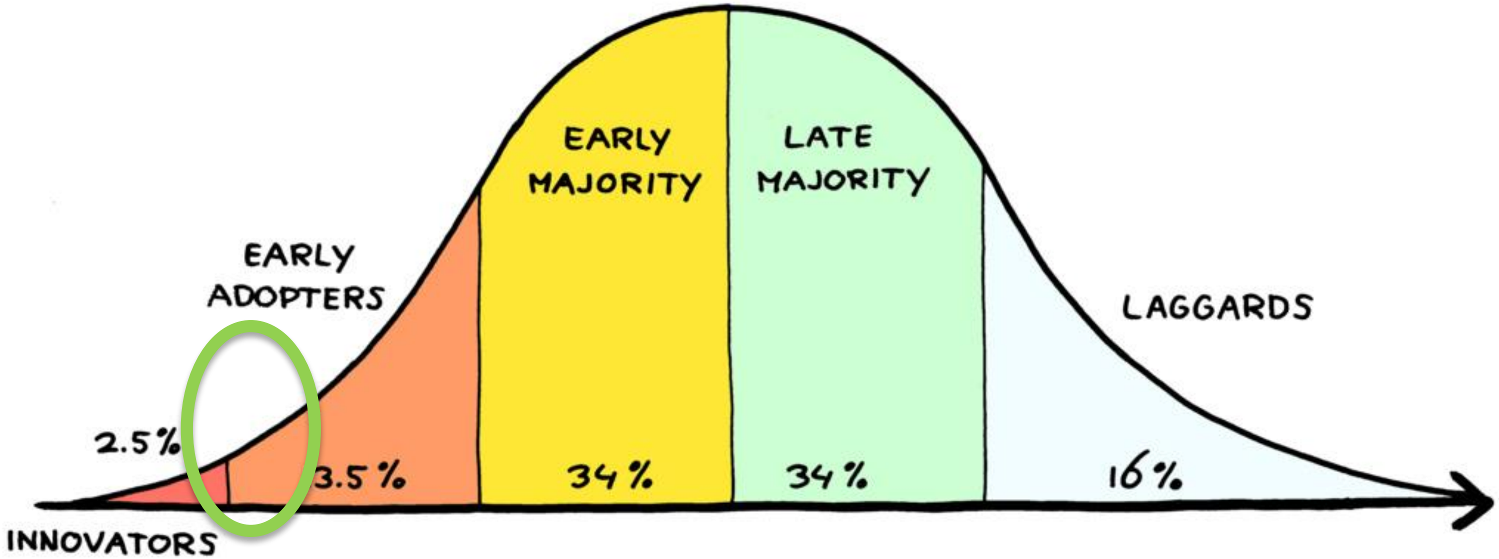
Open questions

- Can we describe all processes of interest? Do we have suitable models?
- Is the linkage of socio-economic models with hydraulic, water quality and bio-process models feasible?
- Do we have to integrate physically (detailed) models or can we answer our question also with simplified (conceptual) models?
- How to deal with the uncertainty caused by the model structure (detailed versus simplified model), the interfaces (conversion of state variables), spatial and temporal integration?

Open questions

- Is it realistic to measure all the data needed for calibration of integrated models?
- Which type of issues we would like to address or what type of problems we would like to solve with integrated model? Which degree of integration and which type of models are needed for this?
- Can we sufficiently connect model predictive control or other optimisation/analysing tools with integrated models?

Slow uptake in practice, but there is progress



(Rogers, 1962)