Hydrological Modelling

CT 4431

Prof. dr. ir. H.H.G. Savenije

Course Contents

1. Modelling of Hydrological Processes. Lecturer: Savenije
2. Conceptual modelling. Lecturers: Savenije, Hrachowitz
3. Calibration and Uncertainty, Hrachowitz
4. Distributed modelling. Lecturers: Savenije, Euser

Course Contents (cont.)

5. Groundwater modelling. Lecturer: Bakker
6. Flexible modelling (Bateau), <u>Fenicia</u>
7. Comparison of modelling approaches. Lecturers, pitfalls: Savenije, <u>Hrachowitz</u>
8. Individual study on:
   - Conceptual modelling (Hrachowitz, Coenders, Euser)
   - Distributed modelling (Euser, Coenders, Euser)
   - Analytical elements GW modelling (Bakker)

Examination

- Oral, mainly based on Individual Study
- But also addressing the full material of the lecture:
  - Powerpoint on Blackboard
  - Lecture note
  - Reader related to individual study
- Recommended: Keith J. Beven (2001)

  "Rainfall-Runoff Modelling; The Primer" (Wiley)

Modelling Hydrological Processes

1. Why model?
2. Modelling Process
3. Equifinality
4. Perceptual Model
5. Model classification
6. Conceptual models

1. Why model?

- To encapsulate our knowledge
  - to prove a hypothesis wrong
- Extrapolate in time (forecast) and/or space (ungauged basin)
  - otherwise it is curve fitting
- As a mathematical laboratory
  - “virtual reality”

2. Modelling Process

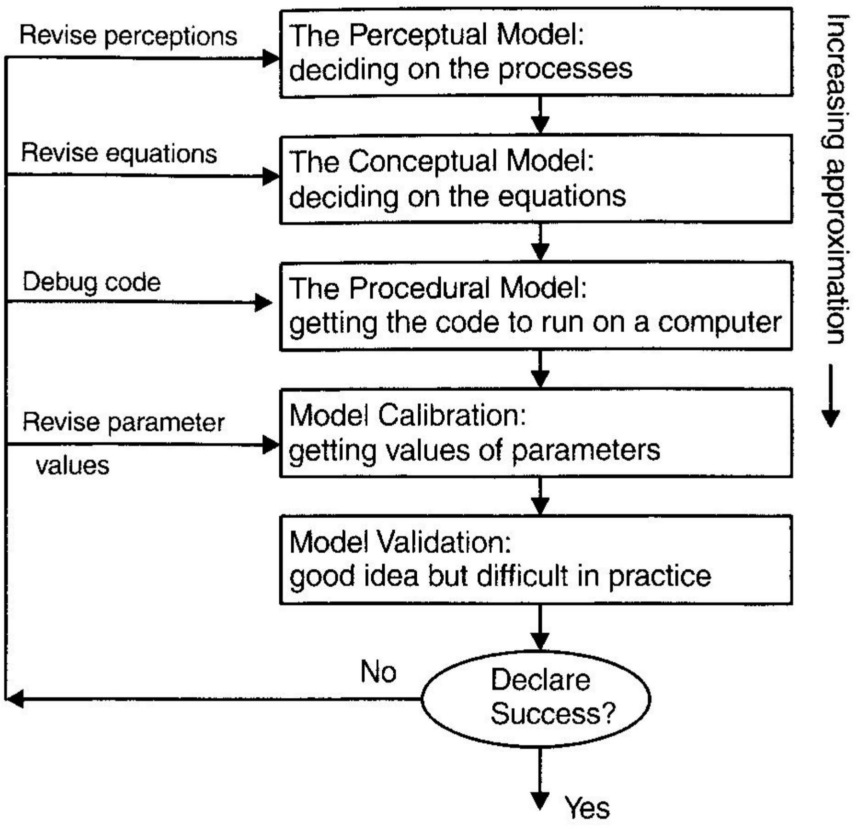

Figure 1.2 *A schematic outline of the different steps in the modelling process*

Art versus Science

Hydrol. Earth Syst. Sci., 13, 157–161, 2009
www.hydrol-earth-syst-sci.net/13/157/2009/

Hydrology and Earth System Sciences

HESS Opinions
"The art of hydrology"*

H. H. G. Savenije

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*Invited contribution by H. H. G. Savenije, EGU Henry Darcy Medal award 2008.

Received: 23 September 2008 – Published in Hydrol. Earth Syst. Sci. Discuss.: 14 November 2008
Revised: 2 February 2009 – Accepted: 2 February 2009 – Published: 18 February 2009

Art of Modelling
Savenije (2009), HESS

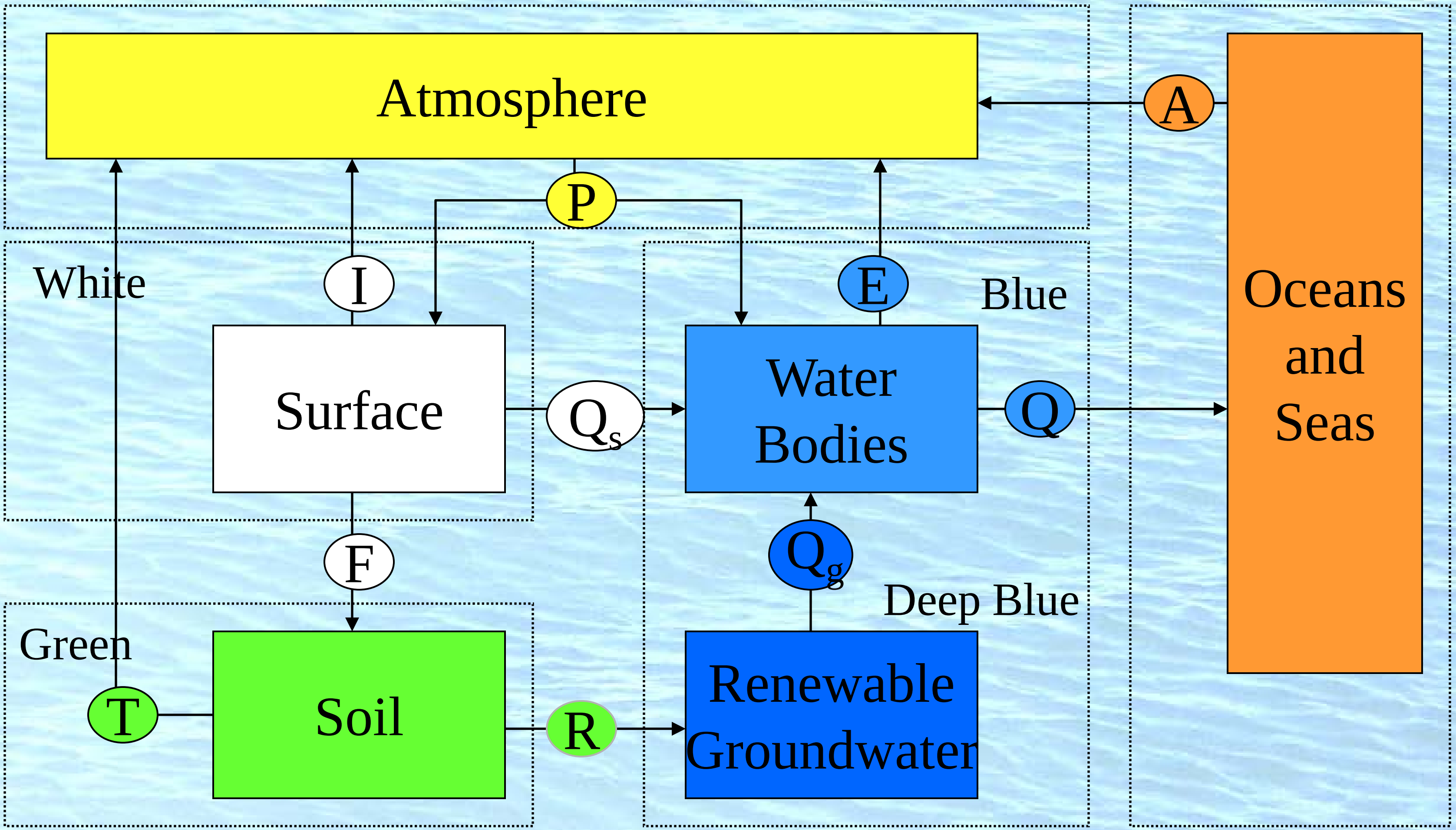
Hydrol. Earth Syst. Sci., 13, 157–161, 2009

- Creativity: figuring out how it works
- Experience: know how
- Insight
- Intuition
- Artful design of experiments
- Fenicia *et al*. (Water Resources Research, 44, 2008)

Basic rules of modelling

1. Make sure you use correct dimensions in the equations, e.g.: include d*t*
2. make a schematic picture of the conceptual framework (different ways to close a balance)
3. distinguish between stocks and fluxes
4. test and evaluate your model

Global Water Resources



What consists a model?

- equations, procedures and rules
  - differential equations
  - boundary conditions (fluxes, states, geometry)
  - initial conditions
- time-varying input: drivers and boundary conditions (e.g. atmospheric fluxes)
- fixed input: geometry (boundary conditions)
- model parameters (generally calibrated):
  - time invariant (e.g. conductivity, porosity)
  - time variant (e.g. interception capacity)
- state variables (stocks and fluxes) : internal and external (output)

Determination of model parameters

- from the literature (science)
- from experience (art)
- through calibration (art or science?)
  - manual
  - automatic
  - stepped (Fenicia *et al*., 2007)

WATER RESOURCES RESEARCH, VOL. 44, W01402, doi:10.1029/2006WR005563, 2008

Click Here for Full Article

Understanding catchment behavior through stepwise model concept improvement

Fabrizio Fenicia,[1,2] Hubert H. G. Savenije,[2] Patrick Matgen,[1] and Laurent Pfister[1]

Received 26 September 2006; revised 4 August 2007; accepted 21 September 2007; published 3 January 2008.

[1] Lack of data is one of the main limitations for hydrological modeling. However, it is often used as a justification for over simplifying, poorly performing models. If we want to enhance our understanding of hydrological systems, it is important to fully exploit the information contained in the available data, and to learn from model deficiencies. In this paper, we propose a methodology where we systematically update the model structure, progressively incorporating new hypotheses of catchment behavior. We apply this methodology to the Alzette river basin in Luxembourg, showing how stepwise model improvement helps to identify the behavior of this catchment. We show that the most significant improvement of the evolving model structure is associated to the characterization of antecedent wetness. This is improved accounting for interception, which affects vertical storage distribution, and accounting for rainfall spatial heterogeneity, which influences storage variations in the horizontal dimension. Overall, our results suggested that, due to the damping effect of the basin, the description of fast catchment response benefits more from spatially distributed information than that of slow catchment response.

Citation: Fenicia, F., H. H. G. Savenije, P. Matgen, and L. Pfister (2008), Understanding catchment behavior through stepwise model concept improvement, *Water Resour. Res.*, *44*, W01402, doi:10.1029/2006WR005563.

Relevance of Hydrological Modelling

1. IAHS-PUB: prediction in ungauged basins
2. Analysing effects of land-use change, climatic change
3. Water Resources Assessment
4. Flood analysis

What is IAHS?

- IUGG association with >3500 individual members
  - (at least) 65 member counties
- Programmatic alignment with UN agencies: WMO, UNESCO, etc.
- Conferences, red books, Hydrological Sciences Journal
- Governance via 7 Commissions (ICWRS)
- Biannual meetings, IUGG-IAHS
  Perugia, Italy, July 2007,

  Hyderabad, India, 2009

  Melbourne, 2011

  Delft, 2012 !!

First Announcement of the IAHS symposium on the

Completion of the IAHS decade on Prediction in Ungauged Basins and the way ahead

Delft, The Netherlands, 23-24 October 2012

In October 2012 we celebrate the 90th anniversary of IAHS and the completion of the IAHS decade on Prediction in Ungauged Basins (PUB). The conference will report on the scientific achievements that were made during the decade and the insights that were gained. We also look ahead to identify the major scientific challenges for the coming period.

During the conference we invite contributions from all scientists that have worked on the main themes of PUB to share their conclusions and views on the advances made during the decade and the remaining research questions. The conference has a general part which provides a summary of the PUB decade, presentations on the Synthesis report and the PUB manual, as well as a visionary session on the future challenges. Subsequently there are thematic sessions organised around the 6 research themes of PUB, as listed below.

Scientific organising committee:

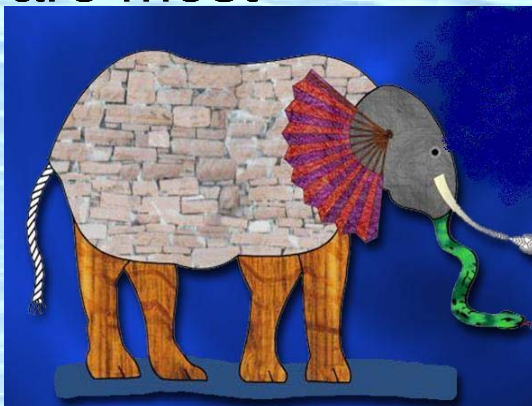
- Hubert Savenije (chair)
- Murugesu Sivapalan
- Jeff McDonnell
- Guenter Bloeschl
- John Pomeroy

Local organising committee:

- Hubert Savenije
- Nick van de Giesen
- Stefan Uhlenbrook
- Markus Hrachowitz
- Saket Pande

What is PUB?

- A **movement** to change the way that we do hydrological science
- Our focus and reason for being is **uncertainty reduction** in all its forms
- 10-yr scientific goal to **shift hydrology** from calibration reliant models to new and rich understanding-based models
- Why is PUB within IAHS?
  - To use these new approaches in parts of the world where predictions in ungauged basins are most pressing - the **developing world**
- **PUB Science Plan, Sivapalan *et al*., Hydrol. Sciences Journal, Dec 2003**



Thematic Sessions:

Theme 1: Catchment classification

- *Convener*: Peter Troch
- *Co-convener*: Markus Hrachowitz, Ross Woods

Theme 2: Conceptualisation of process heterogeneity

- *Convener*: Guenter Bloeschl
- *Co-convener*: Stefan Uhlenbrook, Doerthe Tetzlaff, Erwin Zehe

Theme 3: Uncertainty analysis and model diagnostics

- *Convener*: Hoshin Gupta
- *Co-convener*: Thorsten Wagener, Saket Pande, Jim Freer

Theme 4: New Approaches to Data-Collection

- *Convener*: Erwin Zehe
- *Co-convener*: Nick van de Giesen, Vincent Fortin

Theme 5: New Hydrological Theory

- *Convener*: Murugesu Sivapalan
- *Co-convener*: Hessel Winsemius, Alexander Gelfan

Theme 6: New Approaches to Modelling

- *Convener*: Hubert Savenije
- *Co-convener*: Fabrizio Fenicia, Martyn Clark

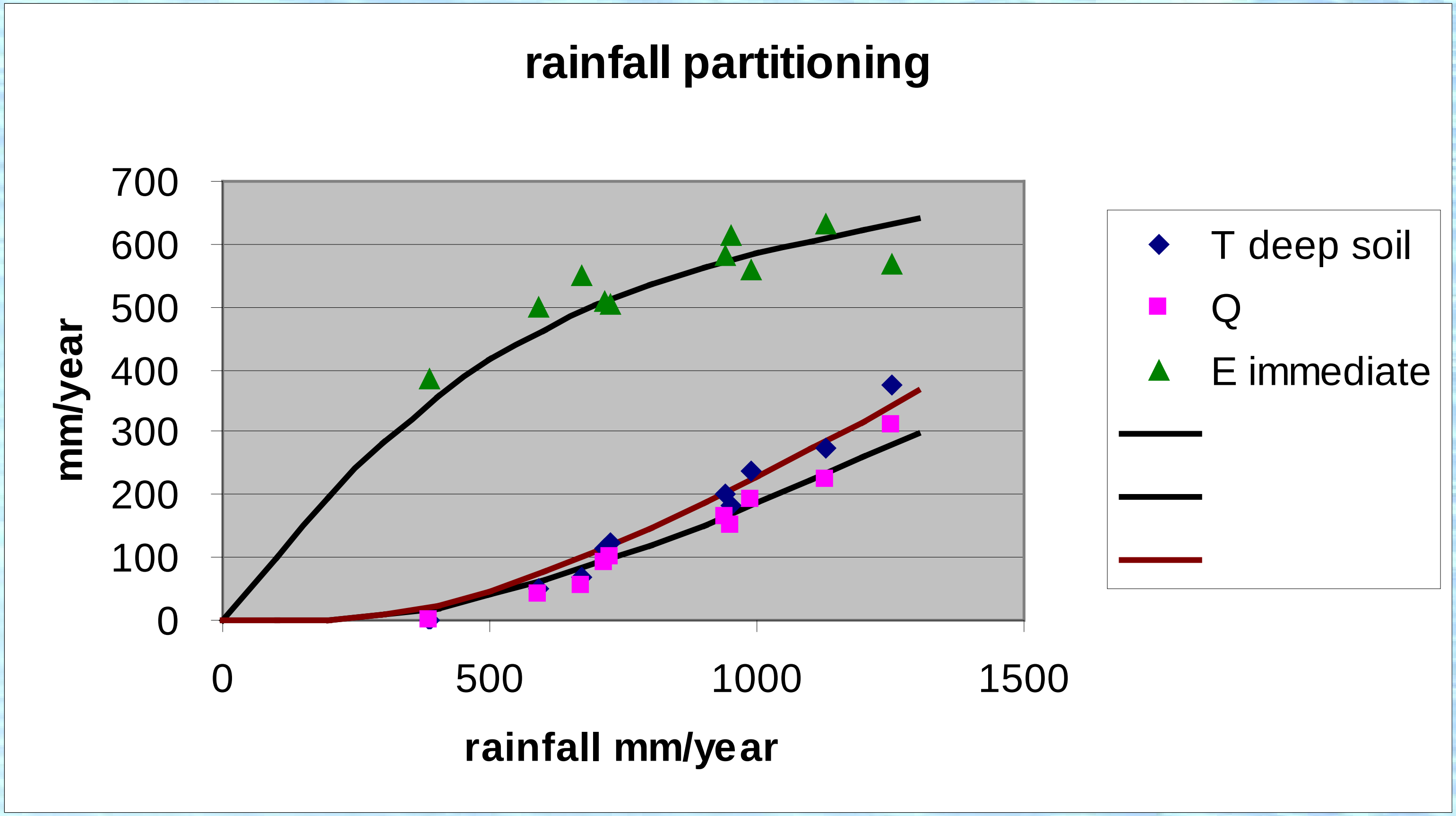
Main issues in Modelling

- Non-linearity
- Heterogeneity
- The issue of scale
  - the problem of the ant
- Equifinality
  - infinite parameter sets perform equally well
- Physically based or conceptual?
- Lumped or distributed?

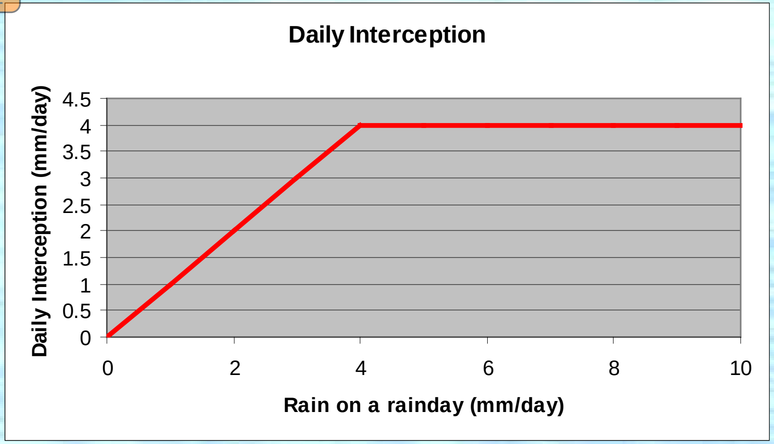
Non-Linearity

- Non-linear differential equations
- Hysteresis
  - flood wave
  - soil wetting and drying (pF-curve)
- Threshold behaviour
  - ANN’s are not capable of mimicking hydrological models

Non-linearity due to thresholds



From Threshold to Non-linearity

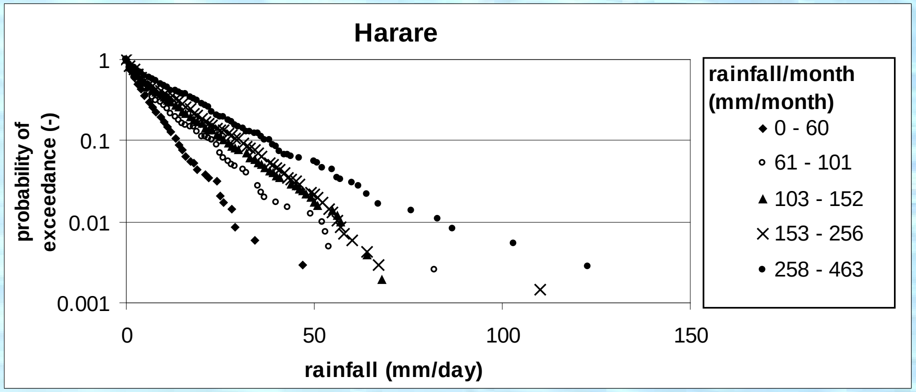


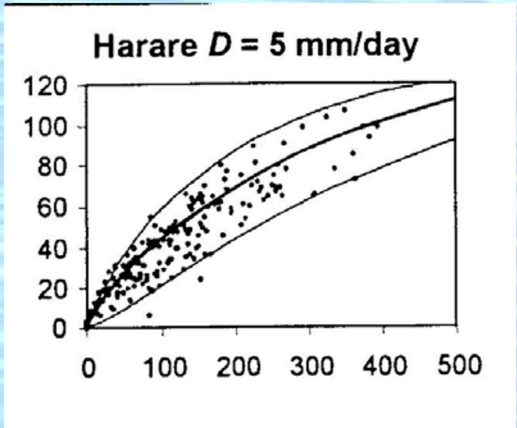
De Groen & Savenije (2006), Water Resources Research

$$I_r = \mathrm{Min}\left(D, P_r, E_p\right)$$

$$1 - \mathrm{F}(P_r) = \exp\left(\frac{-P_r}{\beta}\right)$$

$$I_m = P_m\left(1 - \exp\left(\frac{-D}{\beta}\right)\right)$$





P_r rainfall on a rainday (mm/day)

β the average amount of rainfall on a rainday = P_m/n_r (mm/day)

WATER RESOURCES RESEARCH, VOL. 42, W12417, doi:10.1029/2006WR005013, 2006

A monthly interception equation based on the statistical characteristics of daily rainfall

Marieke M. de Groen[1] and Hubert H. G. Savenije[2]

Received 3 March 2006; revised 13 July 2006; accepted 16 August 2006; published 21 December 2006.

[1] This paper presents a simple analytical equation for monthly interception on the basis of the combination of a daily threshold model with the probability distribution of daily rainfall. In this paper, interception has a wider definition than merely canopy interception. It is the part of the rainfall that evaporates after it has been stored on the wetted surface, which includes the canopy, the understory, the bottom vegetation, the litter layer, the soil, and the hard surface. Interception is defined as the process of evaporation from intercepted rainfall. It is shown that this process has a typical timescale of 1 day. Monthly interception models can be improved by taking the statistical characteristics of daily rainfall into account. These characteristics appear to be less variable in space than the rainfall itself. With the statistical characteristics of daily rainfall obtained at a few locations where reliable records are available (for example, airports) monthly models can be improved and applied to larger areas (20–200 km). The equation can be regionalized, making use of the Markov property of daily rainfall. The equation obtained for monthly interception is similar to Budyko's curve.

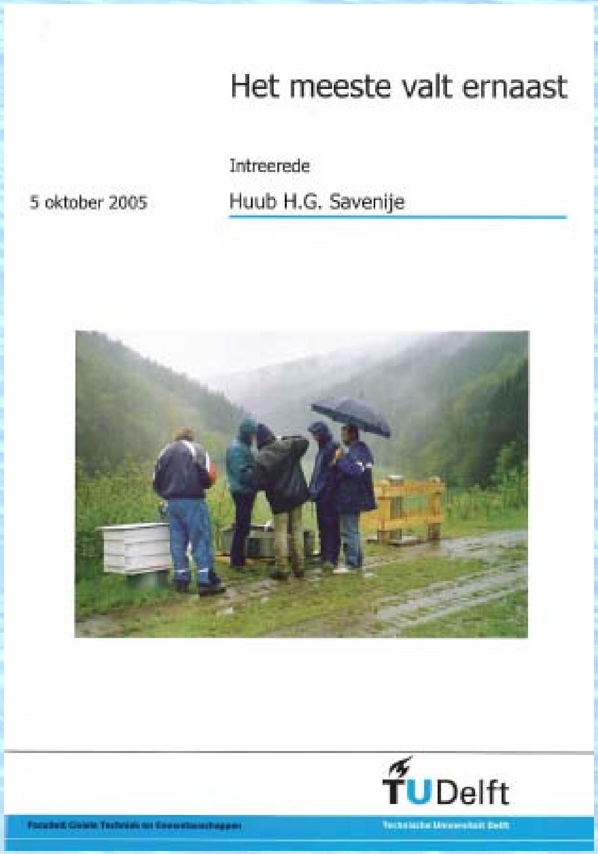
Citation: de Groen, M. M., and H. H. G. Savenije (2006), A monthly interception equation based on the statistical characteristics of daily rainfall, *Water Resour. Res.*, *42*, W12417, doi:10.1029/2006WR005013.

From Threshold to Non-linearity

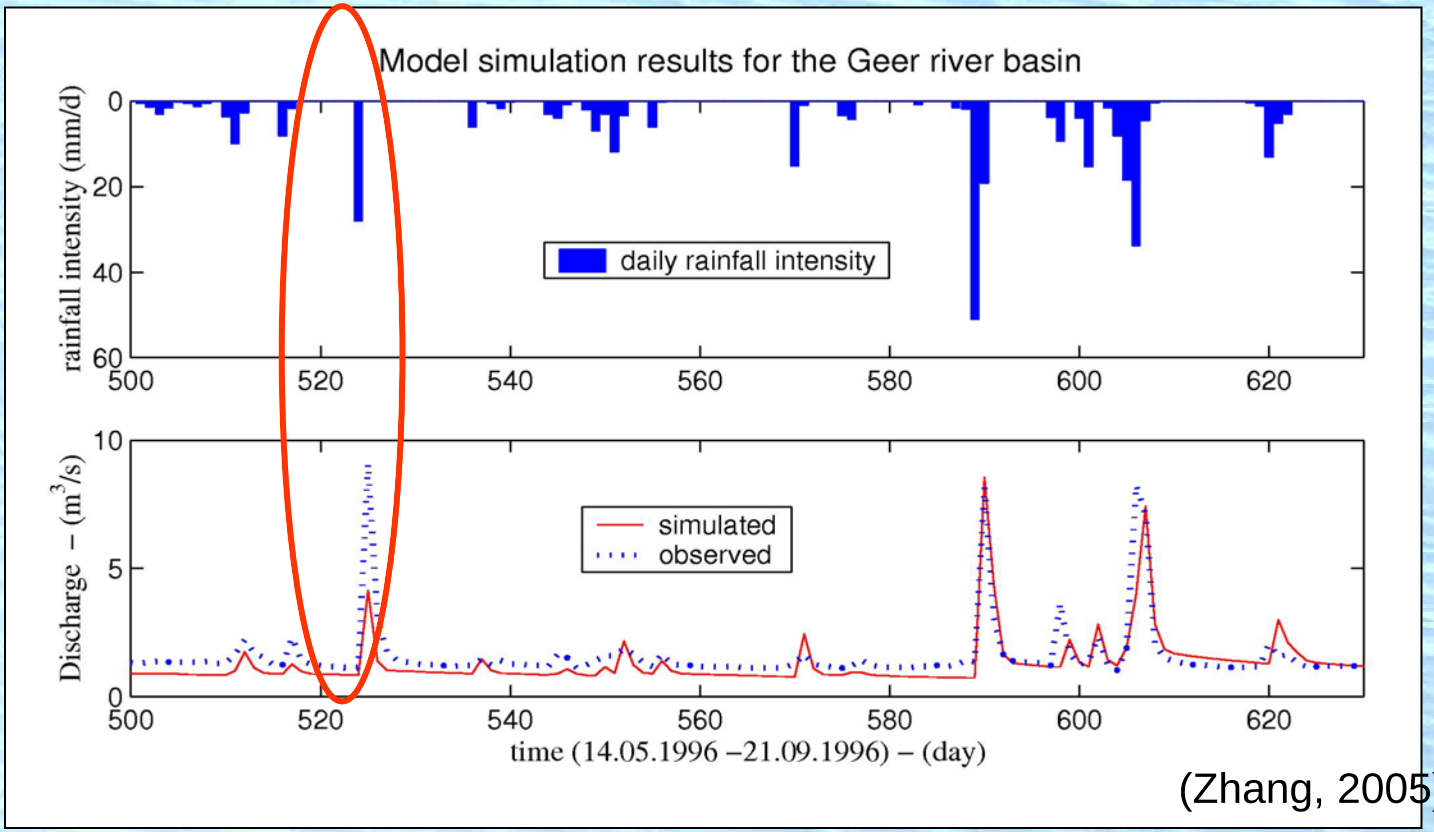
- Linear threshold process
- Plus probability distribution of system driver (e.g. rainfall)
- Plus probability distribution of threshold
- Results in non-linear behaviour

Heterogeneity

- “het meeste valt ernaast”
  - spatial distribution of rainfall
- spatial distribution of topography
- spatial distribution of soil depth
- spatial distribution of land cover

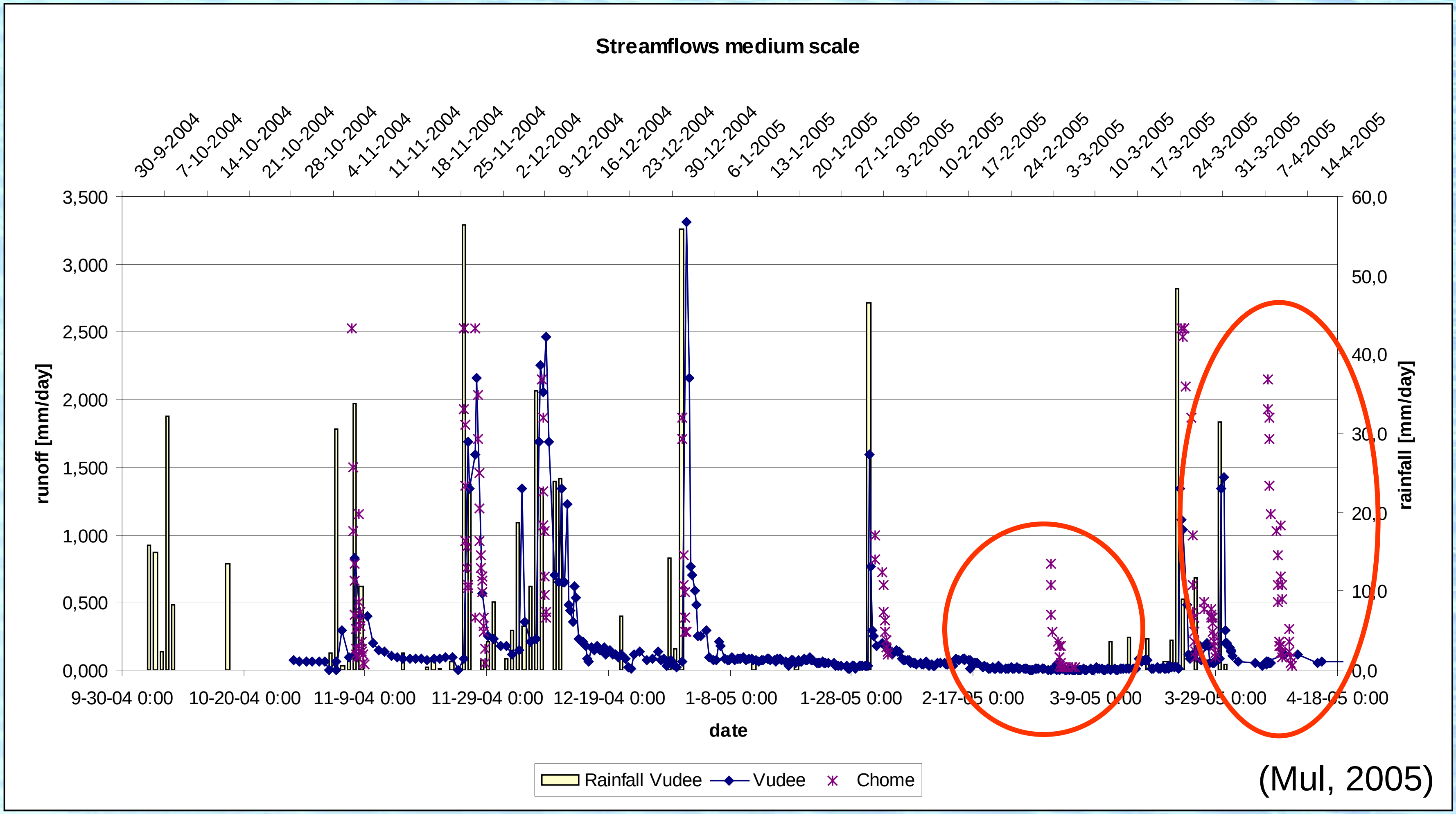


Het meeste valt ernaast



(Zhang, 2005)

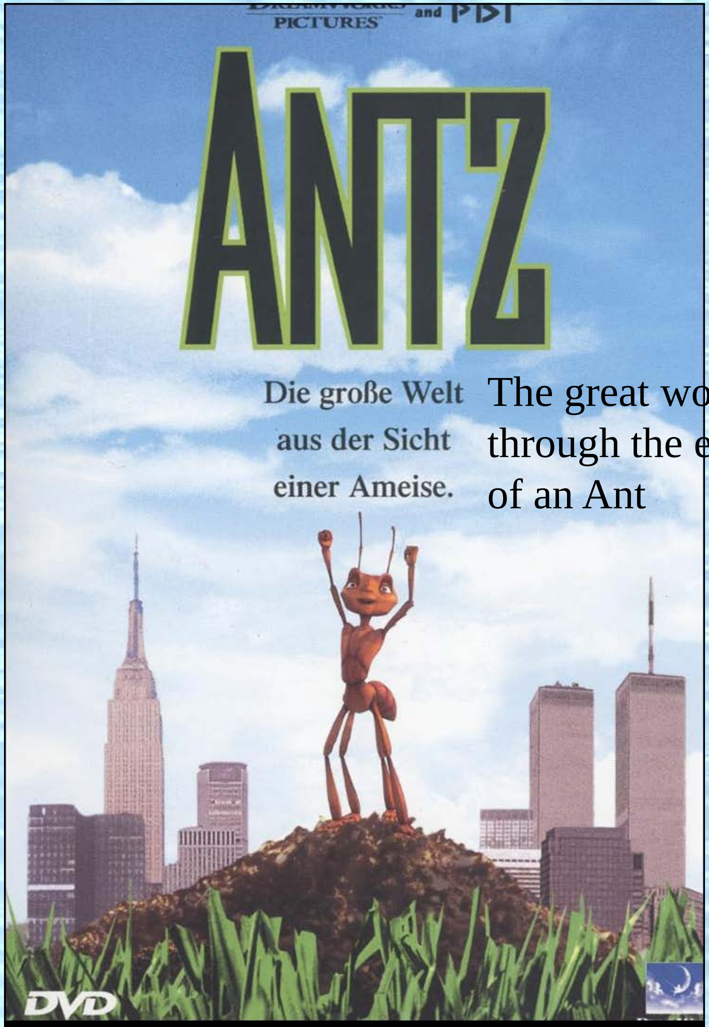
Het meeste valt ernaast



(Mul, 2005)

The issue of Scale

- better understanding through zooming in
  - mainstream
- better understanding through zooming out
  - holistic empirism



The great world
through the eyes
of an Ant

3. Equifinality

- makes validation and evaluation difficult
- is the result of over-parameterization
- the “curse” of distributed and physically based modelling
- asks for parsimonious conceptual models
- “equifinality is a blessing in disguise”
  - – the world is simpler than we think

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **15**, 2835–2838 (2001)
DOI: 10.1002/hyp.494

Equifinality, a blessing in disguise?

Hubert H. G. Savenije

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Correspondence to:

Since Beven (1993, 1996, 2001) introduced the concept of equifinality, it appears that it has become the curse of hydrology, or at least the curse of distributed hydrological modelling. In this comment it is argued that equifinality is indeed at the heart of our hydrological 'laws' and that without it many of these hydrological laws would not exist. So, as the argument goes, equifinality is a blessing rather than ... tification for many of the hydrological ... n a hydrological model many different

Hydrol. Earth Syst. Sci., 10, 339–352, 2006
www.hydrol-earth-syst-sci.net/10/339/2006/

Hydrology and Earth System Sciences

Comparison of two model approaches in the Zambezi river basin with regard to model reliability and identifiability

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[1]Water Resources Section, Faculty of Civil Engineering and Applied Geosciences, Delft University of Technology, Stevinweg 1, P.O. Box 5048, 2600 GA Delft, The Netherlands
[2]Institute of Earth Observation and Space Systems (DEOS), Physical and Space Geodesy group, Delft University of Technology, Kluyverweg 1, P.O. Box 5058 2600 GB, Delft, The Netherlands

Received: 16 September 2005 – Published in Hydrol. Earth Syst. Sci. Discuss.: 7 December 2005
Revised: 21 February 2006 – Accepted: 13 March 2006 – Published: 11 May 2006

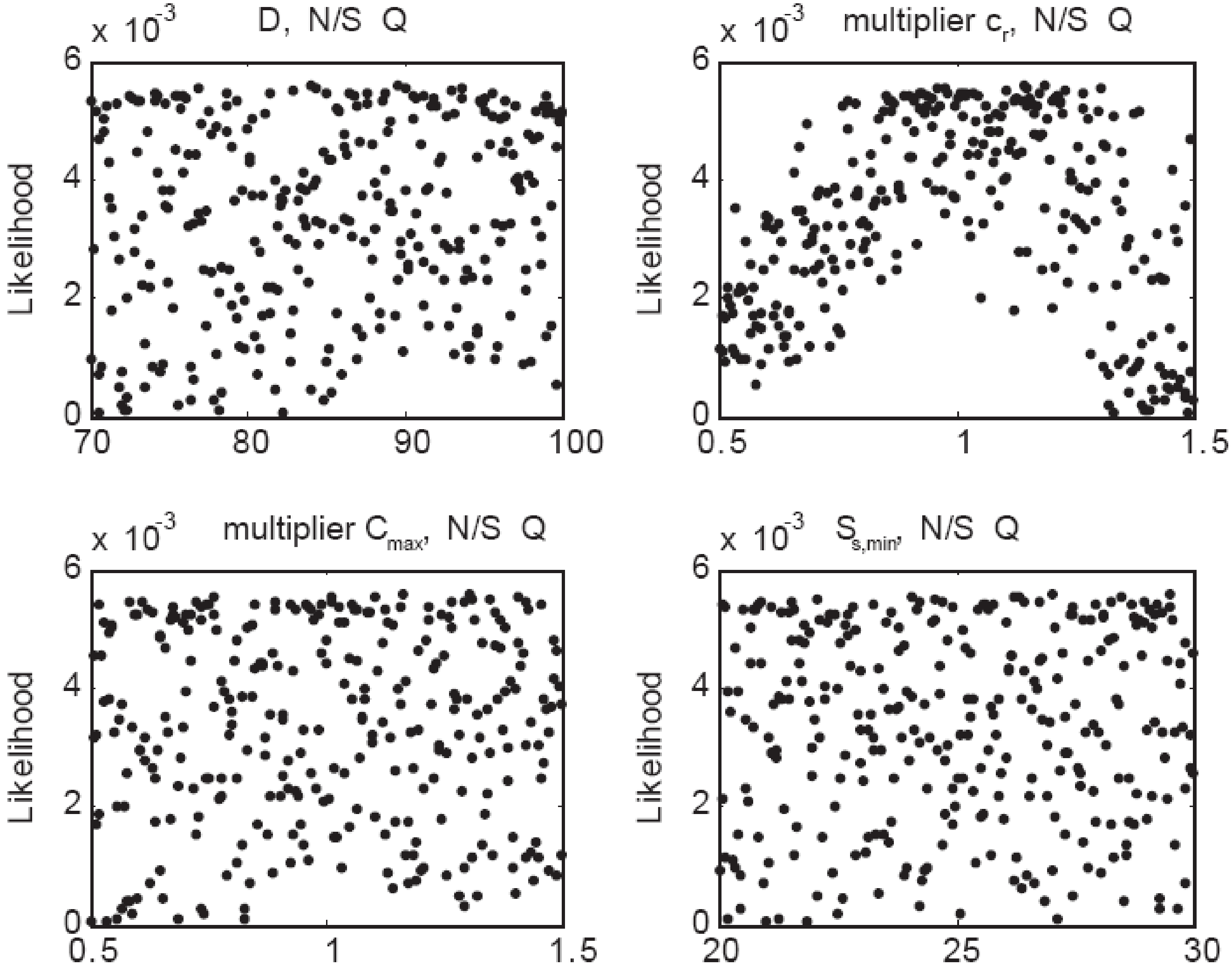
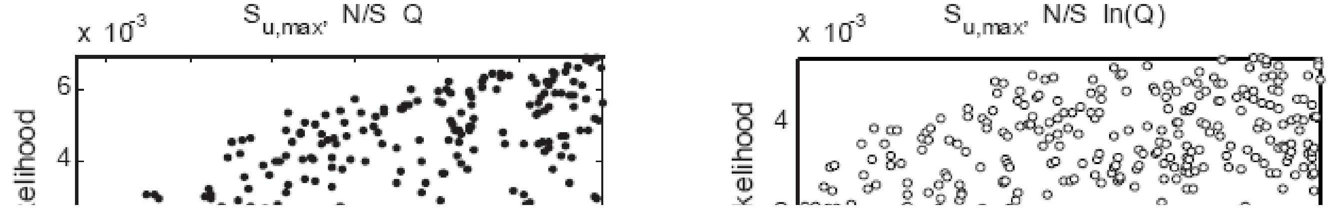


Fig. 7. GLUE likelihood dotty plots on Lukulu watershed using the STREAM model. D [mm month^{-1}] is the interception threshold, c_r [- separates effective rainfall in percolation and storage in the unsaturated zone, $C_{\max}$ [mm month^{-1}] is the maximum capillary rise and $S_{s,\mathrm{mi}}$ [mm] is the dead-storage level. c_r and $C_{\max}$ were variable over the sub-basins and therefore multiplied by a constant for each run.



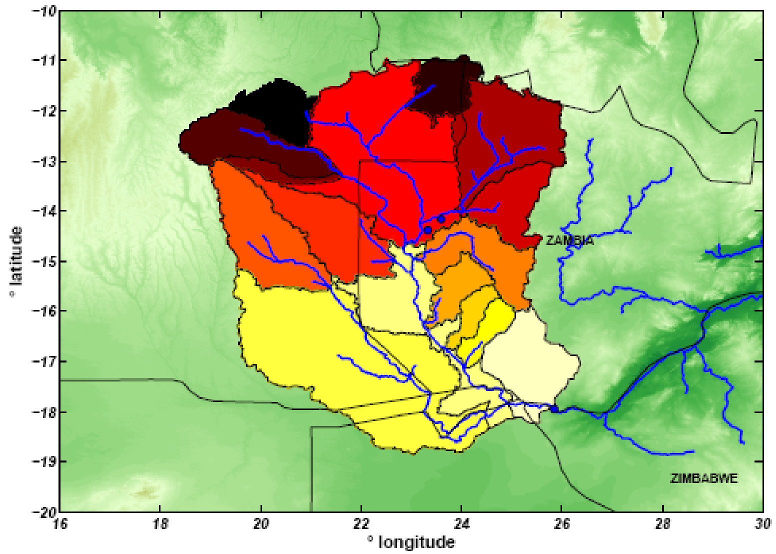


Fig. 8. The 16 delineated sub-catchments used in the LEW model.

It is in this approach acknowledged that the hydrology of the Zambezi river cannot be treated as uniform. Field observations (e.g. Bastiaansen, 1990) showed that the upper Zam-

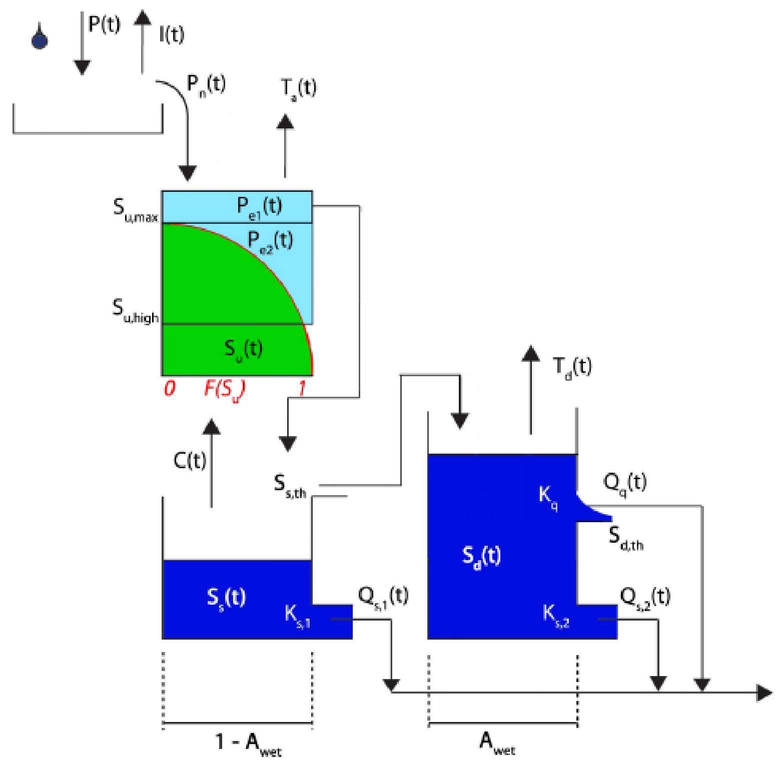
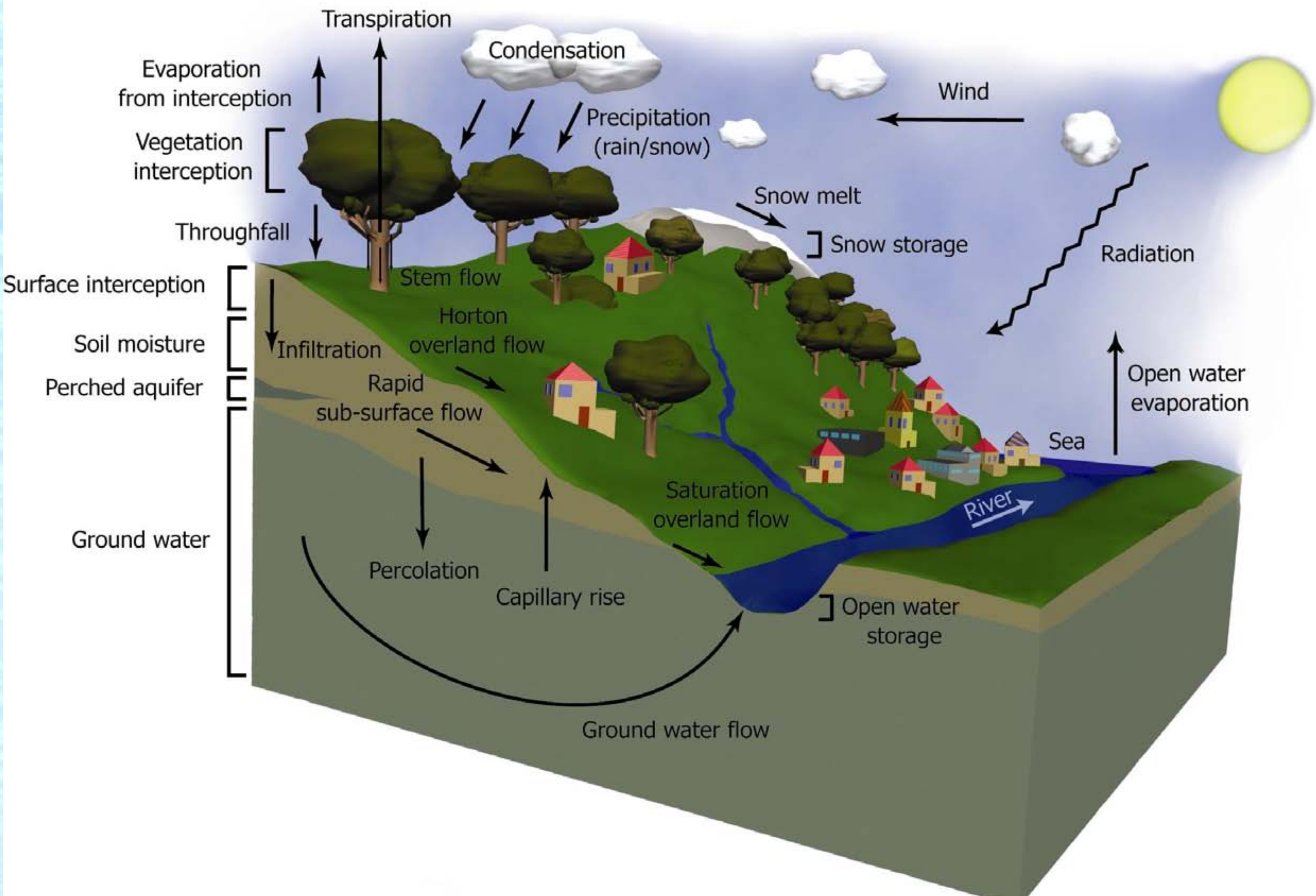


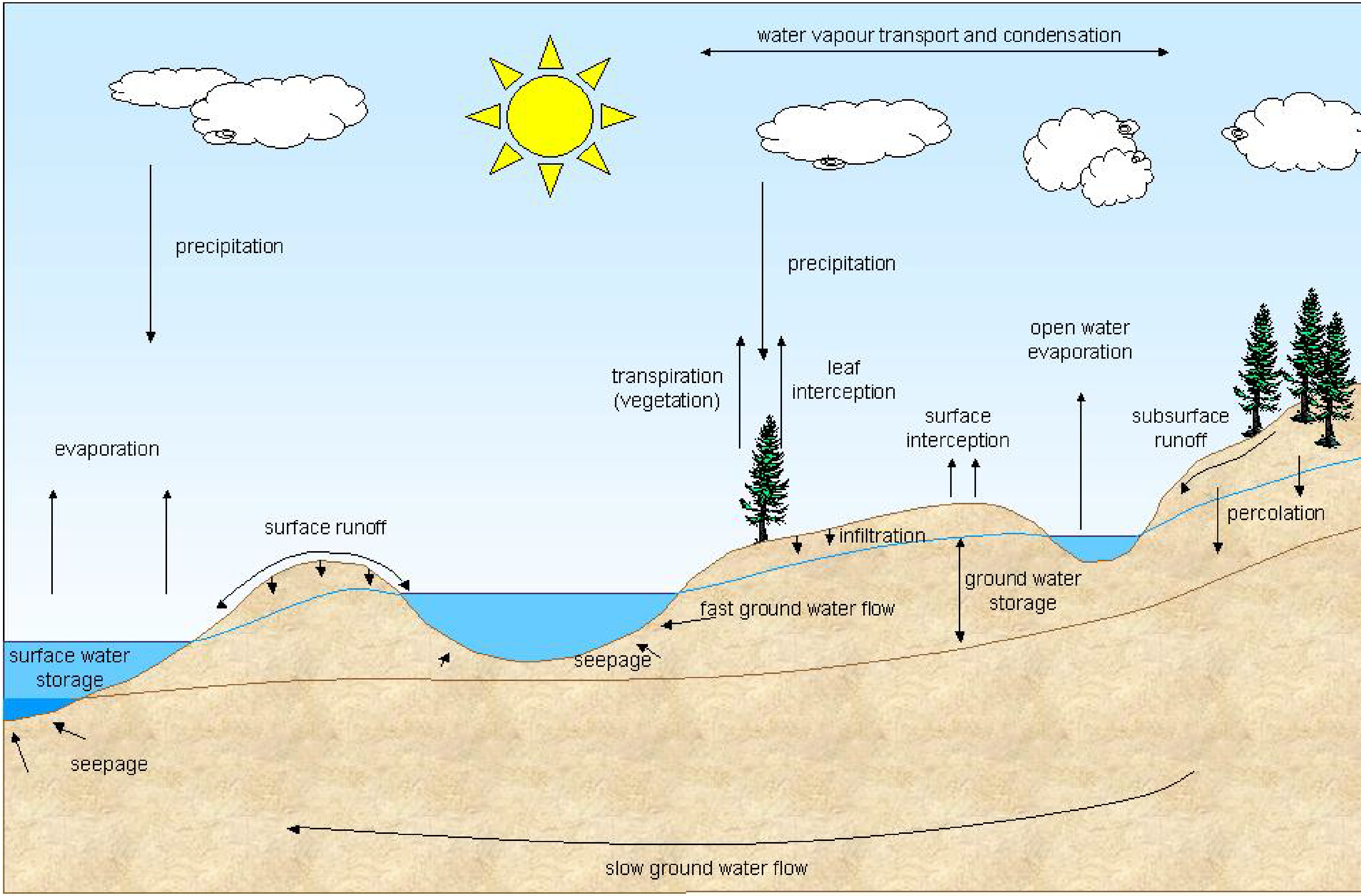
Fig. 9. LEW conceptual model structure.

ig. 10. GLUE likelihood dotty plots on Kabompo watershed. Filled dots: likelihoods for discharge. Open dots: likelihoods for the natural ogarithmic of discharge. $S_{u,\max}$ [mm] is the maximum field capacity, B [–] is the power that describes the soil moisture capacity function nd $S_{d,th}$ [mm] is the drainage network threshold.

4. Perceptual model



4. Perceptual model



Saturation overland flow

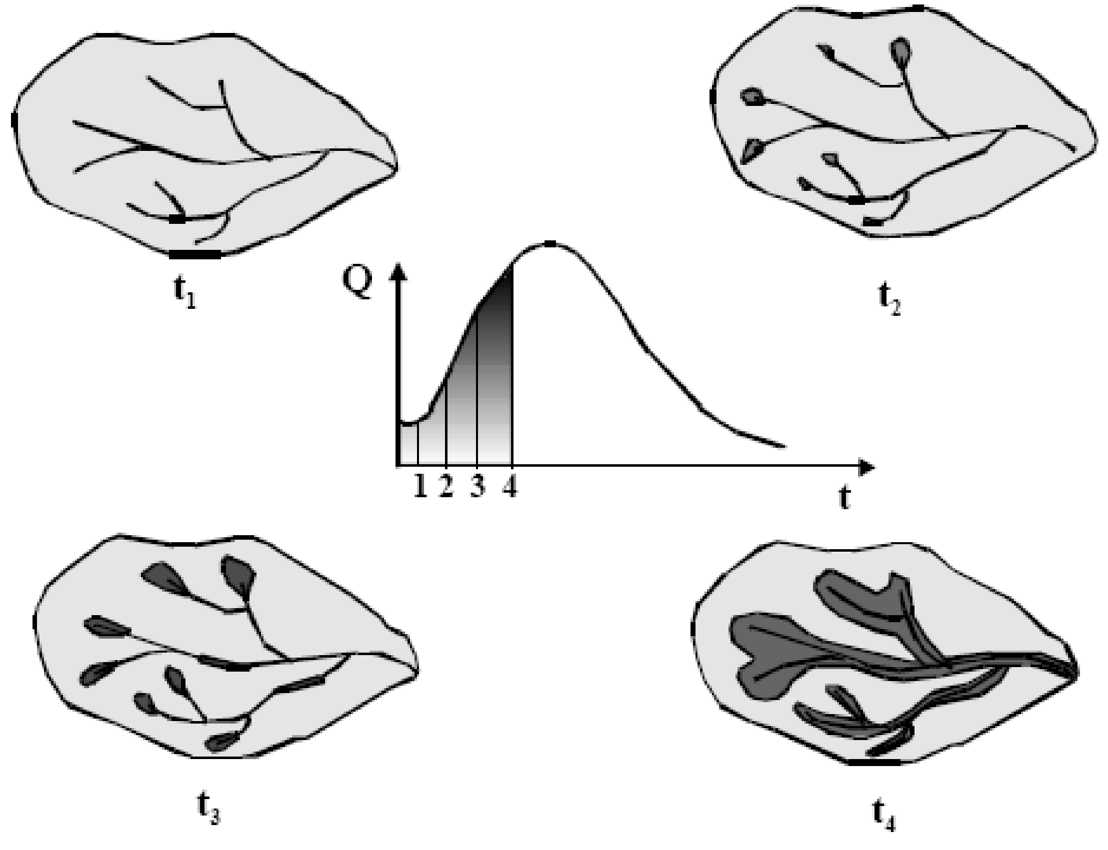


Figure 12.5: *Expansion of the saturation overland flow source area during a storm event [modified after Dunne, 1978]*

Processes

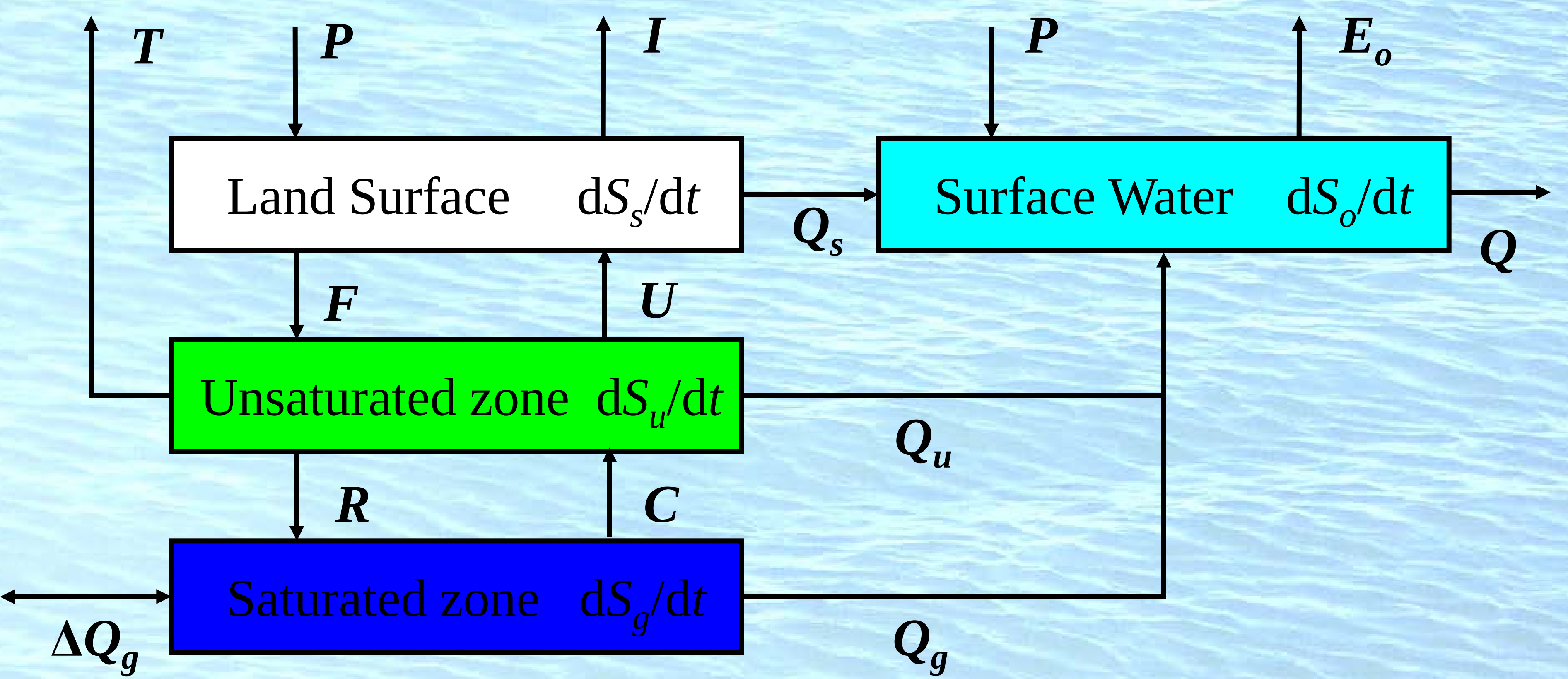
Table 12.1: *Spatial and temporal process scales of the rainfall-runoff processes*

Process	Spatial scale	Temporal scale
Rainfall (convective ⇒ depression)	100 m – 100.000 m	1 min. –days
Hortonian overland flow	10 m - 100 m	1 min - 15 min.
Saturation overland flow	10 m - 1.000 m	5 min - hours
Stream flow	10 m - 100 m	1 min - hours
Unsaturated subsurface flow	1 m - 100 m	10 min. - days
Perched subsurface flow	10 m - 1.000 m	10 min. - 1 day
Macro pore flow	1 m - 100 m	1 min. - 1 hour
Groundwater flow	100 m - 100.000 m	1 day - years
Channel flow	100 m - 10.000 m	10 min - days
Interception	as rainfall	S_s/I 1 min – 1 day
Transpiration	catchment	S_u/T weeks - months
Open water evaporation	water body	S_o/E_o months - years

Processes

- All processes can occur at the same time
  - but keep it as simple as possible (parsimony)
- Rapid sub-surface flow can act as a pressure wave with old water
- Old-new water paradox
  - use of tracers and geo-chemical characteristics (signatures)

Model Scheme



5. Model Classification

- Lumped *versus* Distributed
- Deterministic *versus* Stochastic
- Bottom-up *versus* Top-down
- Conceptual *versus* Physically-Based

5. Model Classification

	Lumped	Distributed
Physically-based Freeze-Harlan (1969) “blue print”	REW	SHE, Thales, IHDM
Conceptual (ESMA, explicit soil moisture accounting)	LEW	STREAM
Stochastic	Transfer functions ANN (artificial neural networks)	Network width functions GUH (geomorphological UH)

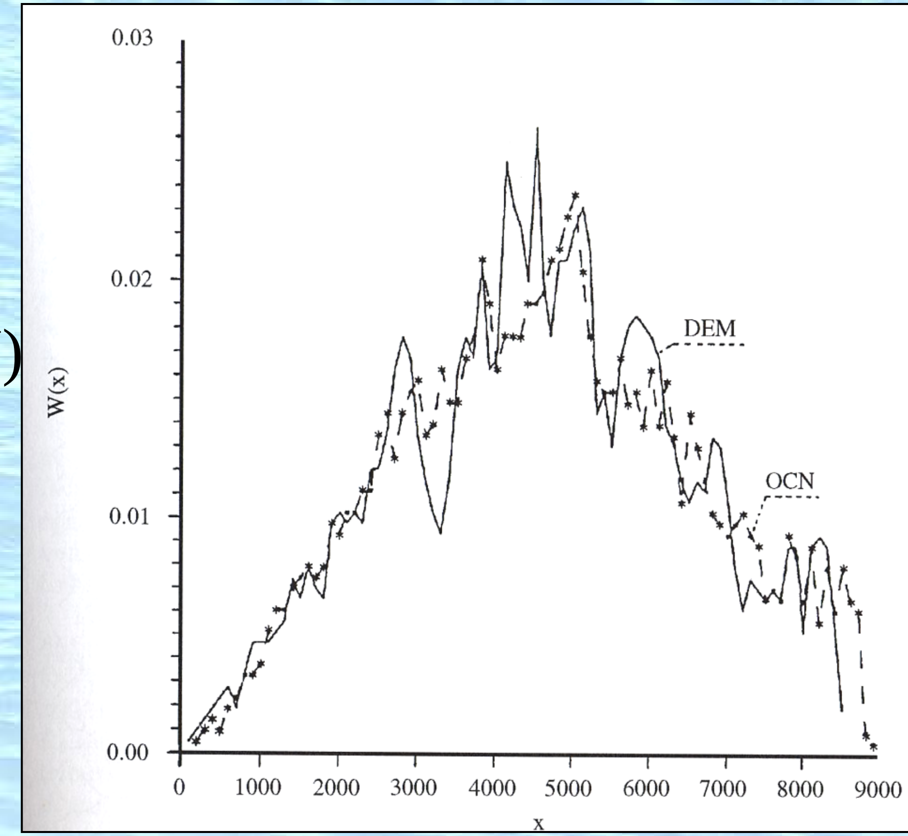
Stochastic Distributed

examples: GUH, width function

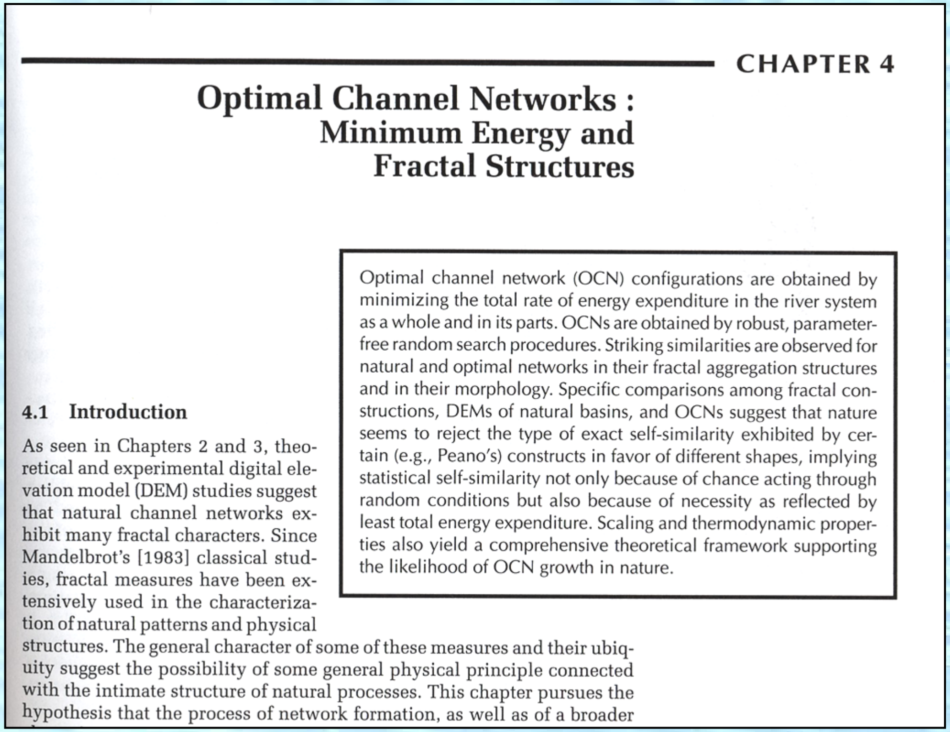
Optimum Channel Network (OCN)
from fractal analysis

Width Function from DEM

Self-organisation !!



Self-organisation



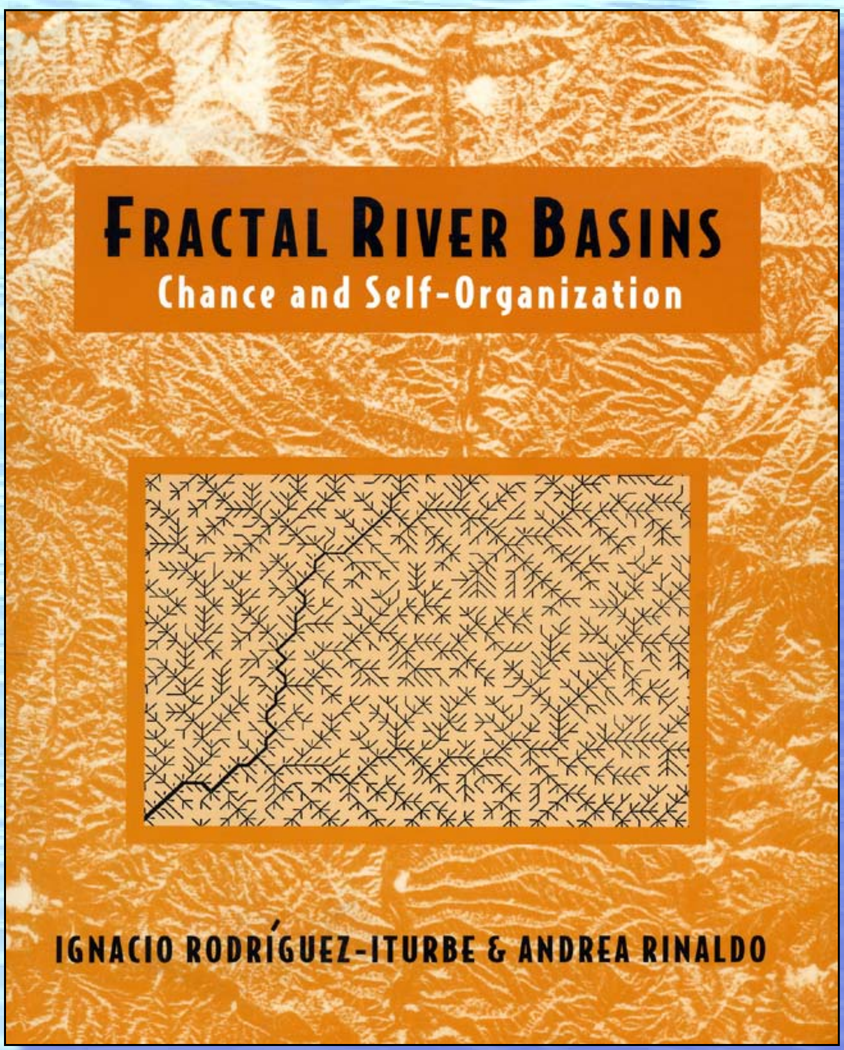
CHAPTER 4

Optimal Channel Networks : Minimum Energy and Fractal Structures

Optimal channel network (OCN) configurations are obtained by minimizing the total rate of energy expenditure in the river system as a whole and in its parts. OCNs are obtained by robust, parameter-free random search procedures. Striking similarities are observed for natural and optimal networks in their fractal aggregation structures and in their morphology. Specific comparisons among fractal constructions, DEMs of natural basins, and OCNs suggest that nature seems to reject the type of exact self-similarity exhibited by certain (e.g., Peano's) constructs in favor of different shapes, implying statistical self-similarity not only because of chance acting through random conditions but also because of necessity as reflected by least total energy expenditure. Scaling and thermodynamic properties also yield a comprehensive theoretical framework supporting the likelihood of OCN growth in nature.

4.1 Introduction

As seen in Chapters 2 and 3, theoretical and experimental digital elevation model (DEM) studies suggest that natural channel networks exhibit many fractal characters. Since Mandelbrot's [1983] classical studies, fractal measures have been extensively used in the characterization of natural patterns and physical structures. The general character of some of these measures and their ubiquity suggest the possibility of some general physical principle connected with the intimate structure of natural processes. This chapter pursues the hypothesis that the process of network formation, as well as of a broader



Why is there so much scope for different models?

- our inability to calculate the spatial and temporal variability of the rainfall accurately ("het meeste valt ernaast")
- our deficient ability to conceptualise (Art)
- over-parametrisation

Can we do without calibration?

- If a model were entirely physically-based one would not need calibration
- But that is impossible !! (equifinality, data requirements)
- So we need aggregated, effective parameters
- Effective parameters need to be calibrated
  - they cannot be measured directly
  - fortunately there are patterns and there is self-organisation

Reasons for distributed modelling

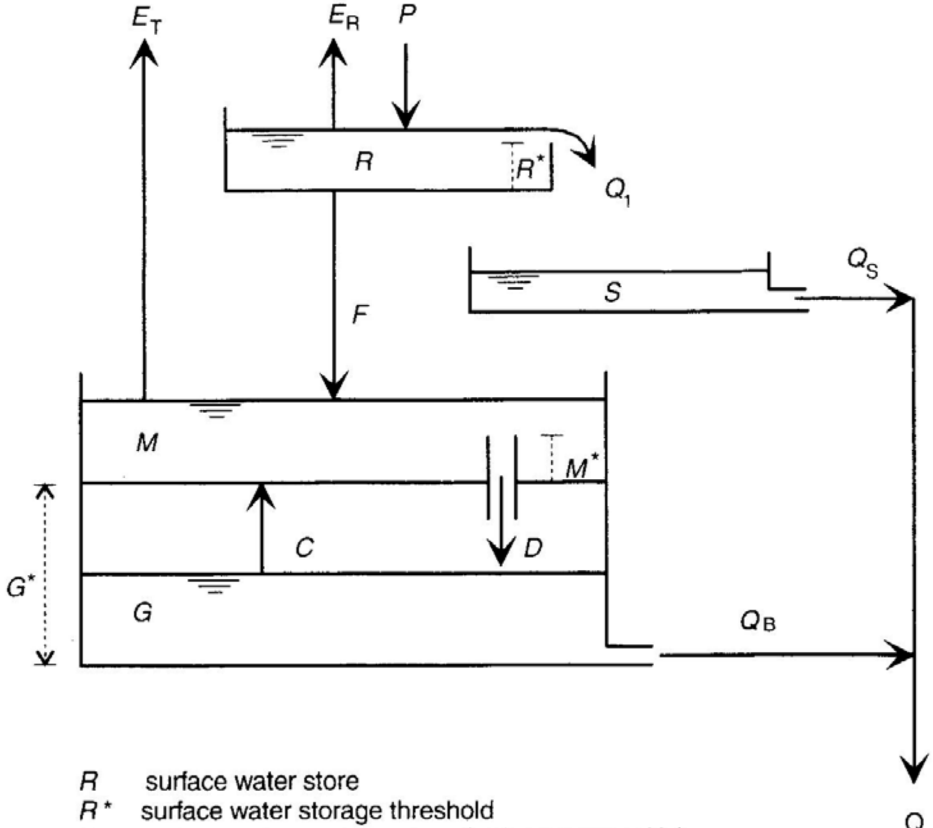
- modelling flow pathways
  - water
  - erosion, sediment transport
  - contaminant transport
- modelling land use change
- rainfall is spatially distributed
- there are spatially distributed data sources: DEM, RS
- Often lacking in these models:
  - interception !
  - macro-pore flow
  - concentrated overland flow (sheetflow doesn't occur)

6. From Physically based to Process based

- mapping of hydrotopes (hydrological response units) or hydrological landscapes
- ESMA (explicit soil moisture accounting) models with spatial distribution functions
- Spatial accounting of moisture

Conceptual Models

- ESMA (explicit soil moisture accounting): Sacramento, HBV, FLEX (Fenicia), etc.
- VIC (Variable Infiltration Capacity): Arno, Hymod, HBV, LEW, FLEX, making use of probability distributions to account for heterogeneity
- Semi-distributed conceptual: LEW



R surface water store
R^* surface water storage threshold
S surface water routeing store (with parameter K_S)
F infiltration to soil moisture store (with parameters f_o, f_c, k)
M soil moisture store
M^* soil moisture storage threshold
D recharge to groundwater store
C maximum rate of capillary rise
G groundwater store (with parameter K_g)
G^* groundwater storage threshold
P precipitation input
E_T evapotranspiration from soil water store
E_R evaporation from surface water store
Q_1 surface runoff
Q_S outflow from surface water routeing store
Q_B outflow from groundwater store
Q total stream discharge

Figure 2.8 *Schematic diagram of the Dawdy and O'Donnell (1965) conceptual or explicit soil moisture accounting (ESMA) rainfall–runoff model*

ESMA

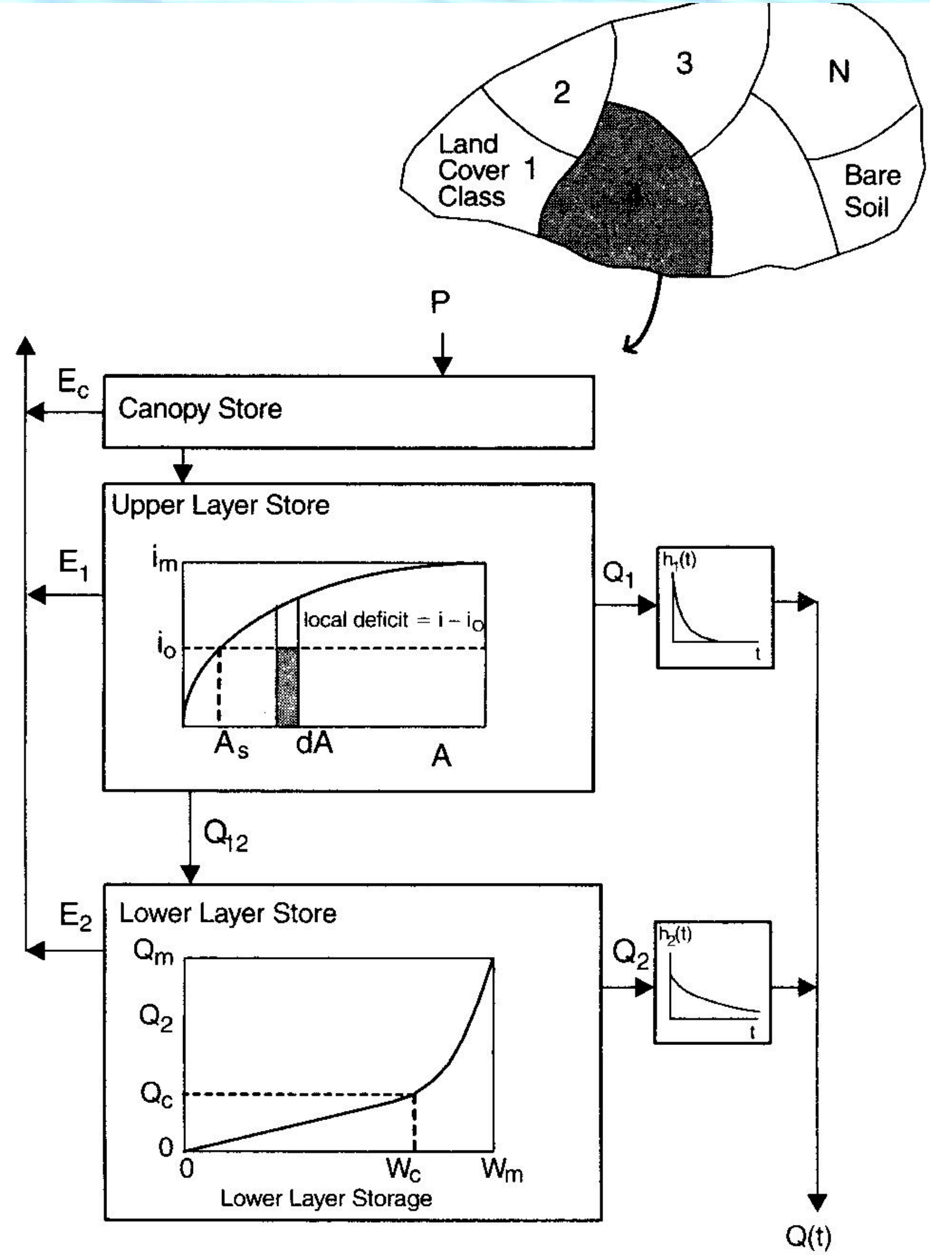
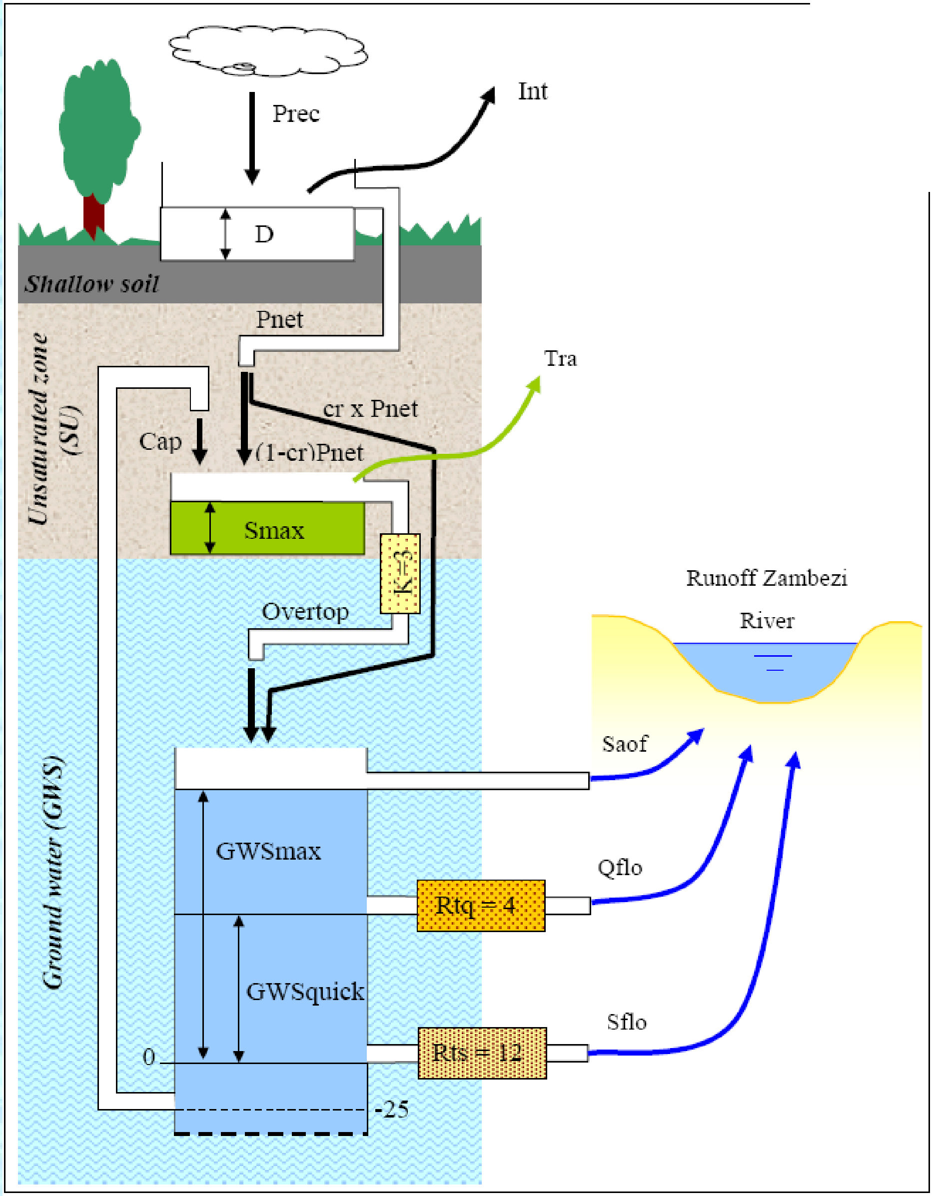
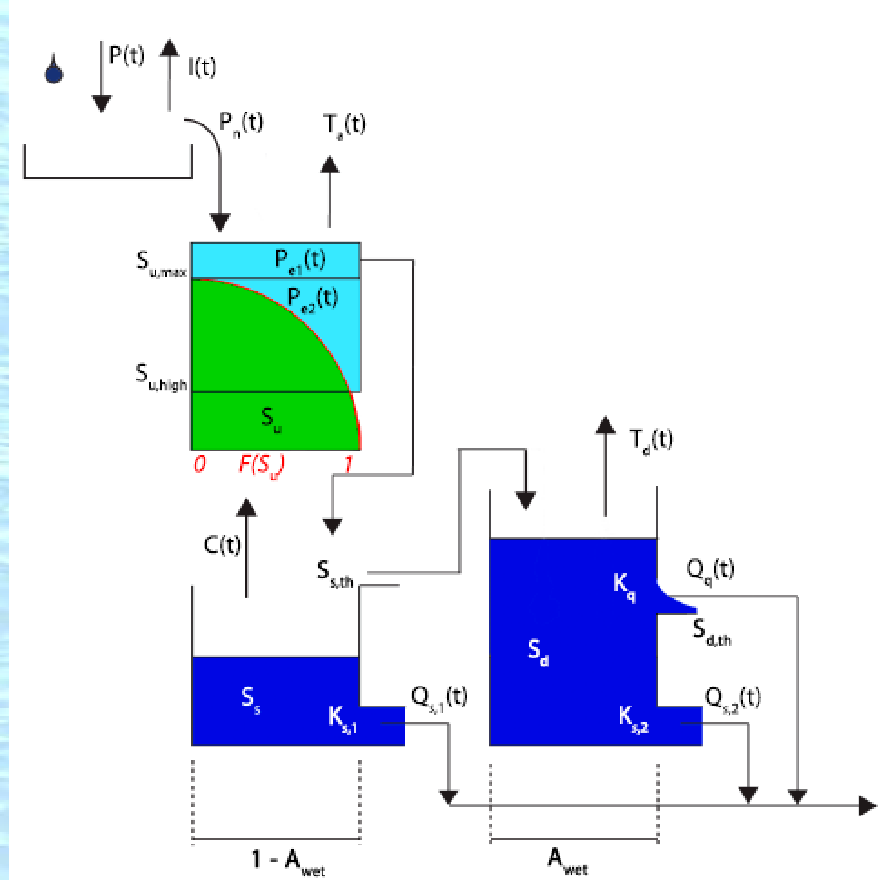


Figure B2.2.1 *Schematic diagram of the VIC-2L model (after X. Liang et al. 1994)*

VIC

Conceptual models





LEW conceptual model structure.

Conceptual Models (cont.)

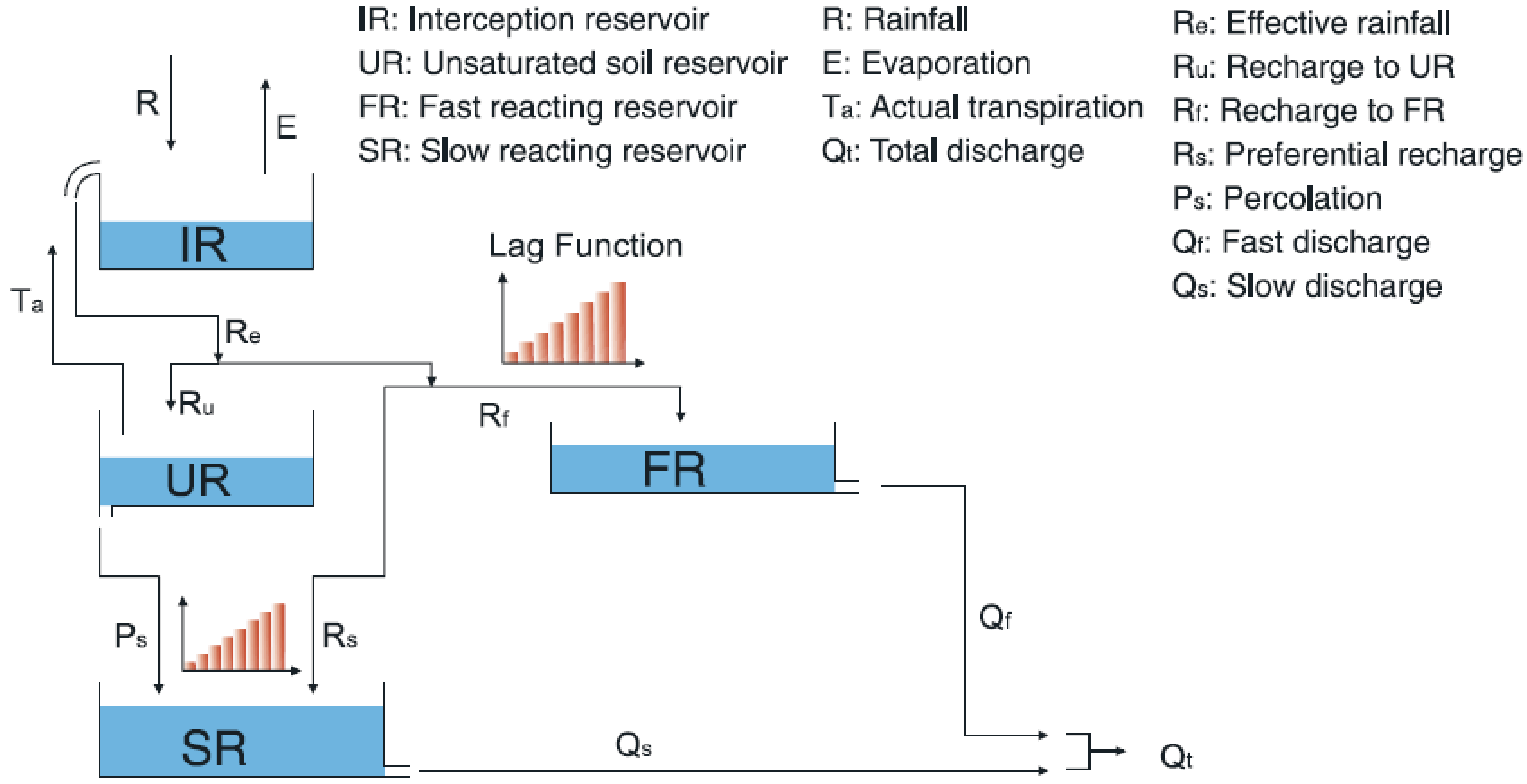
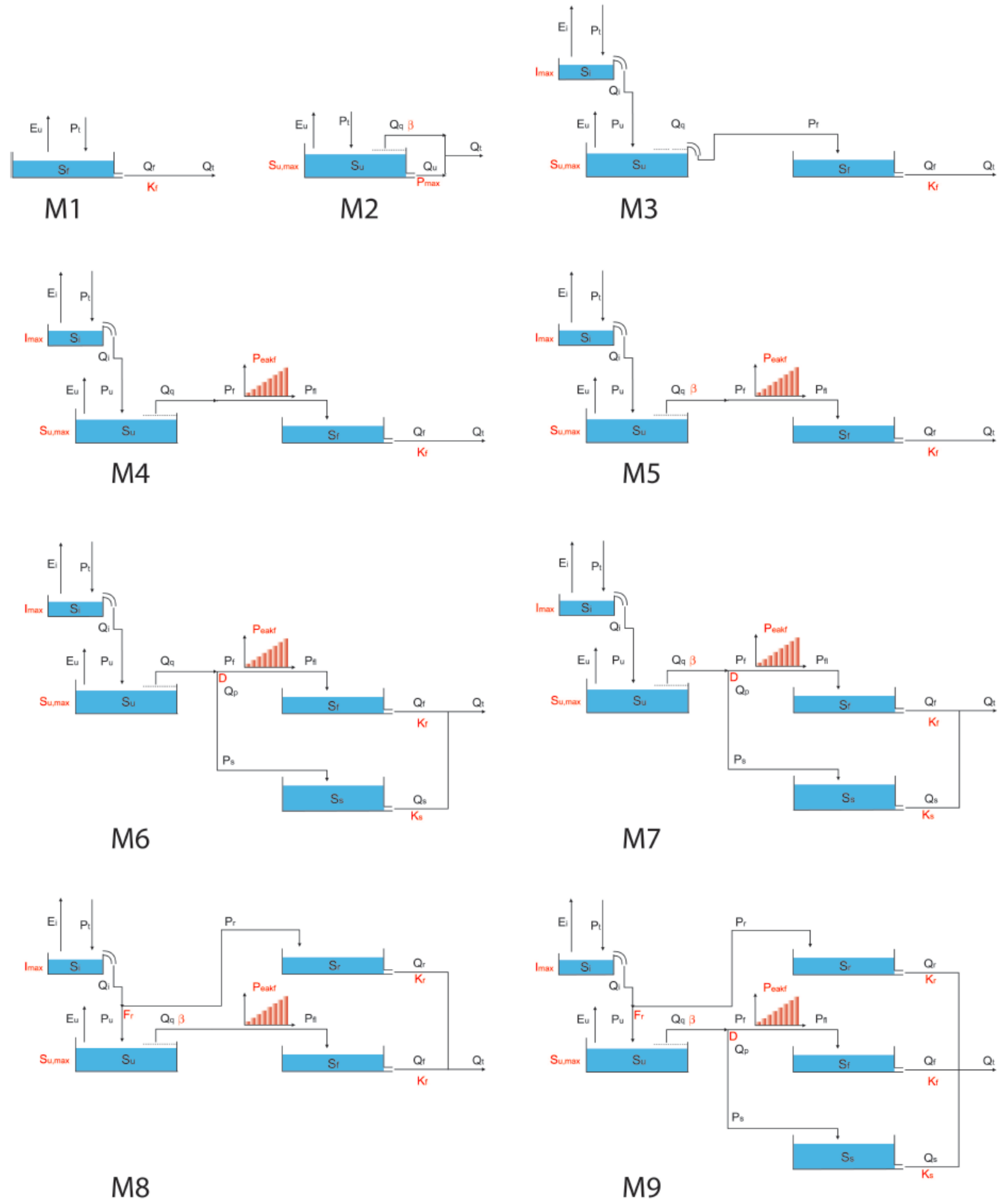


Figure 10. Structure schematization of the FLEX^{B} model.

Flexible Model Structures



Flexible model structures

- Topography driven conceptual modelling
- Identifying dominant runoff mechanisms and modelling these in a flexible model framework

see: http://www.hydrol-earth-syst-sci-discuss.net/7/4635/2010/hessd-7-4635-2010-discussion.html

Hydrol. Earth Syst. Sci., 14, 2681–2692, 2010
www.hydrol-earth-syst-sci.net/14/2681/2010/
doi:10.5194/hess-14-2681-2010

Hydrology and Earth System Sciences

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Received: 3 July 2010 – Published in Hydrol. Earth Syst. Sci. Discuss.: 15 July 2010
Revised: 3 December 2010 – Accepted: 20 December 2010 – Published: 23 December 2010

Hydrol. Earth Syst. Sci. Discuss., 7, 4635-4656, 2010
www.hydrol-earth-syst-sci-discuss.net/7/4635/2010/
doi:10.5194/hessd-7-4635-2010

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Abstract   Discussion Paper (PDF, 530 KB)   Final Revised Paper (HESS)   Special Issue

Interactive Discussion

Status: Closed

AC: Author Comment | **RC**: Referee Comment | **SC**: Short Comment | **EC**: Editor Comment

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RC C2827: 'Review Comments', Anonymous Referee #1, 11 Oct 2010
  AC C3185: 'How to test and falsify our new ideas?', Hubert H.G. Savenije, 27 Oct 2010

RC C2940: 'Review comments', Anonymous Referee #2, 14 Oct 2010
  AC C3228: 'Reply to Referee # 2', Hubert H.G. Savenije, 28 Oct 2010

SC C3489: 'Comments by L. Pfister, F. Fenicia, J. Frentress, L. Gourdol, C. Hissler, J.-F. Iffly, J. Juilleret, R. Krier, N. Martínez-Carreras and S. Wrede', Laurent Pfister, 17 Nov 2010
  AC C3796: 'About scale and connectivity', Hubert H.G. Savenije, 01 Dec 2010

RC C3553: 'Review', Andràs Bàrdossy, 22 Nov 2010
  AC C3788: 'It is a new approach rather than a new conceptual model', Hubert H.G. Savenije, 01 Dec 2010

EC C3556: 'EC', Erwin Zehe, 22 Nov 2010
  AC C3801: 'About the link between topography and soil, scale, connectivity and realism.', Hubert H.G. Savenije, 01 Dec 2010