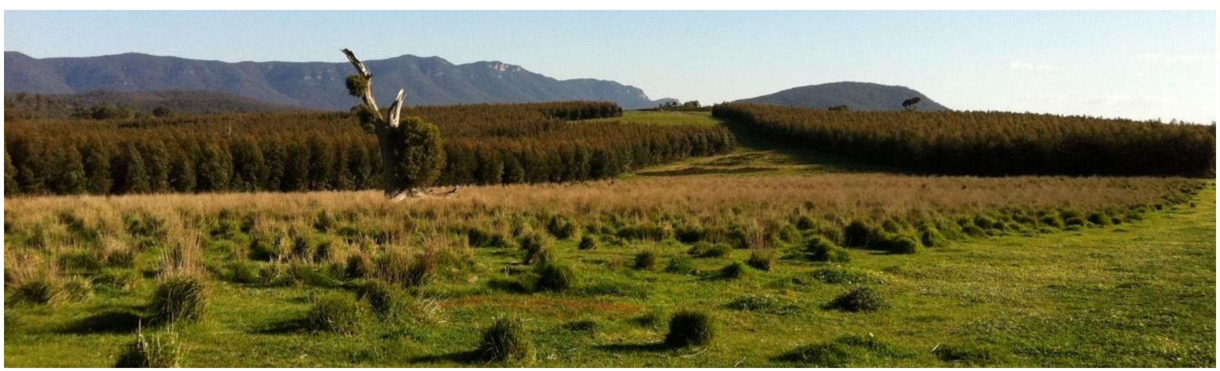
MONASH University

Catchment-scale water balance

Lumped models and hydrologic spaces

Edoardo Daly

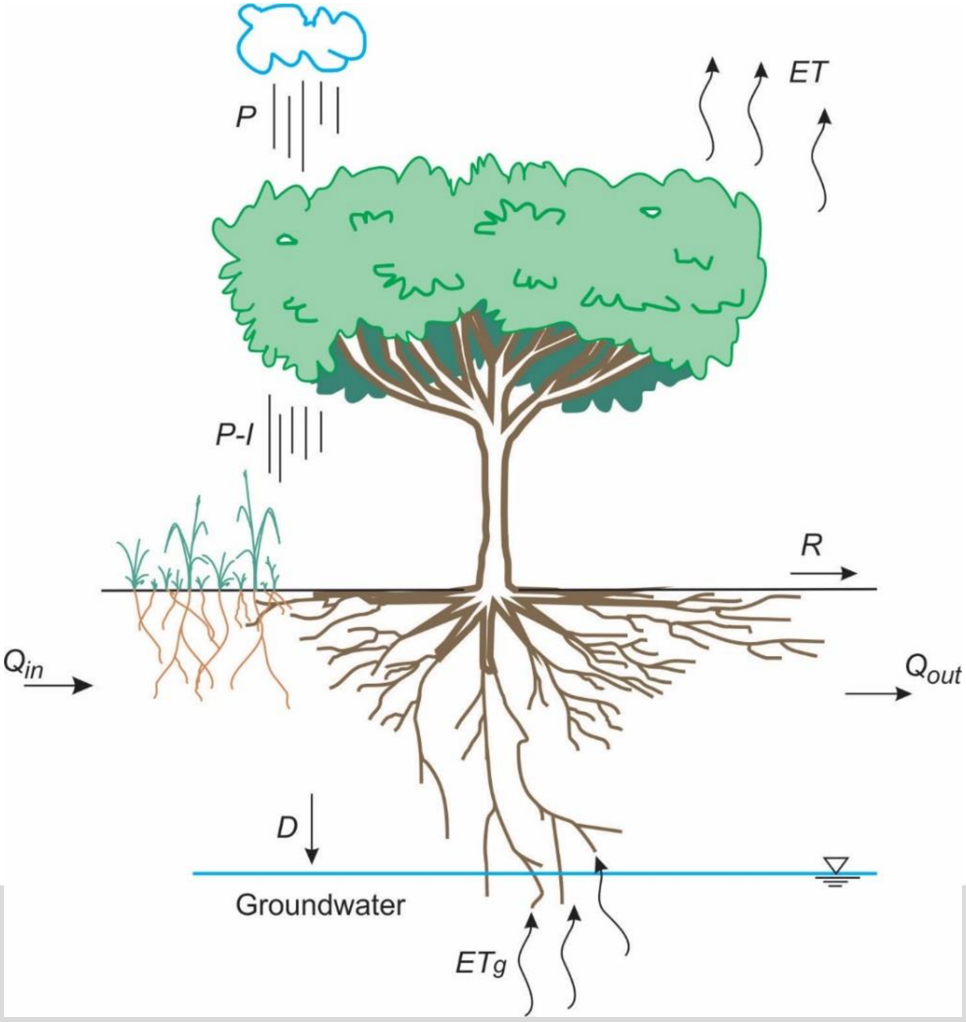
Firenze, 21 October, 2019



GROUP OF EIGHT AUSTRALIA

Eco-hydrology

The science which seeks to describe the hydrologic mechanisms that underlie ecologic patterns and processes (Rodriguez-Iturbe, *Water Resour. Res.*, 2000)



MONASH University

WATER-CARBON TRADE-OFFS IN PRODUCTIVE RURAL CATCHMENTS

Understand how different land uses affect catchment water balance and biomass productivity

- to estimate the trade-off between carbon sequestration and water resources related to pasture and blue gum plantation
- to develop hydrological models at both plot and catchment scales for land-use planning and water management

MONASH University

Australian Government
Australian Research Council

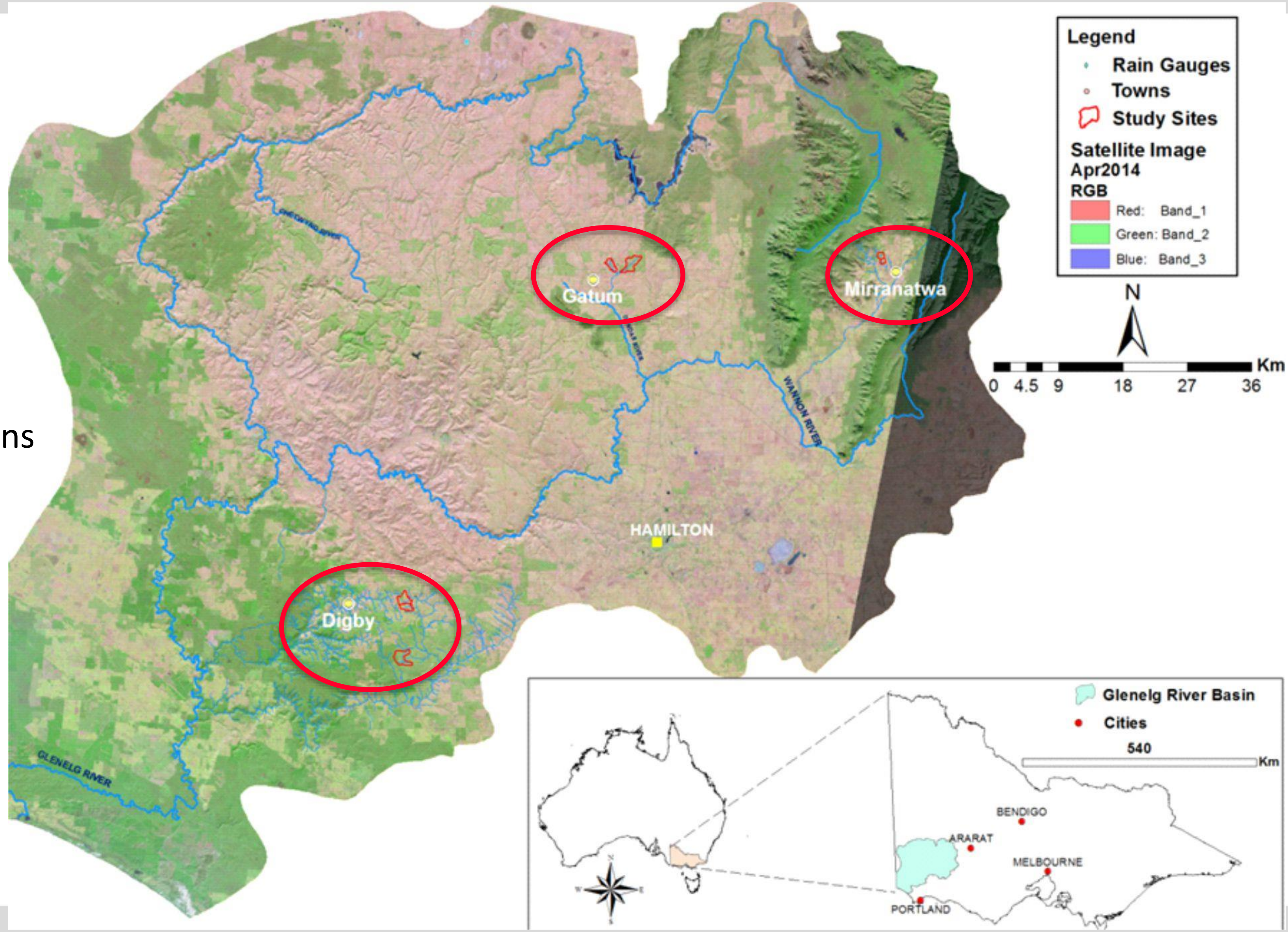
VICTORIA State Government | Economic Development, Jobs, Transport and Resources

LA TROBE UNIVERSITY AUSTRALIA

UNIVERSITÀ DEGLI STUDI DI PADOVA

CATCHMENT STUDY

- 4 pastures
- 3 plantations



Natural urban reserves

- Link water resources and vegetation health in native, urban reserves
  - Test a set of measurement methods (in-situ and remote sensing) to relate water use with tree growth and biodiversity in urban reserves
  - Develop models to assist with the management of urban reserves and parks

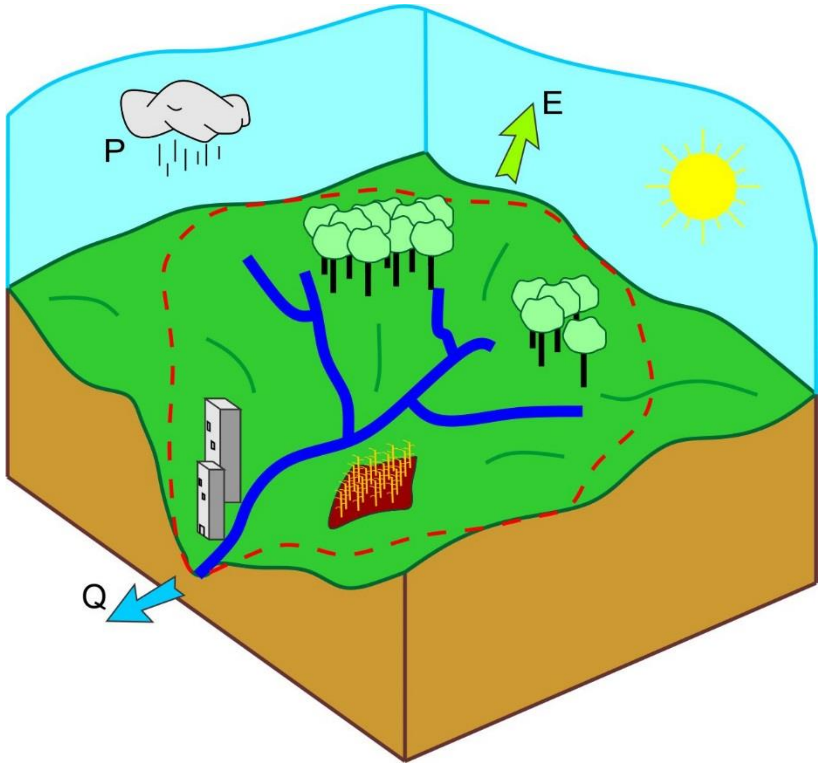
Workshop on Thursday, October 24, 11 am

MONASH University

Catchment water balance

Beyond current frameworks

- Catchment water balance is a key issue
  - Understanding and predicting how catchments store and release water



On the long term, the water balance becomes

$$P = E + Q$$

HYDROLOGY – NEED FOR LAWS

WATER RESOURCES RESEARCH, VOL. 22, NO. 9, PAGES 46

Looking for Hydrologic La

JAMES C

Department of Engineering Hydrology,

The search for regularities in hydrologic relat

INVITED COMMENTARY

HP TODAY

HYDROLOGICAL PROCESSES
Hydrol. Process. **17**, 871–874 (2003)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5108

A double paradox in catchment hydrology and geochemistry

WATER RESOURCES RESEARC

Moving beyond heterogeneity and
A new vision for watershed hydr

J. J. McDonnell,[1,2] M. Sivapalan,[3] K. Vaché,
C. Hinz,[8] R. Hooper,[9] J. Kirchner,[10] M. L. R

Received 28 August 2006; revised 14 March 2007; accepted 1

[1] Field studies in watershed hydrology co
enormous heterogeneity and complexity of ra
watersheds, in different hydroclimatic regime
ability to generalize these findings to ungaug

from small-scale theories. *Doog*
change was equivalent to a comb
now call top-down and bottom-up
2005]. His vision was a search fo
dependence of landscape pr
responses. Some twenty years la
positive vision presented in that p
relevant and, unfortunately, very

Hydrol. Earth Syst. Sci., 21, 3701–3713, 2017
https://doi.org/10.5194/hess-21-3701-2017

Hydrology and Earth System Sciences
Open Access
EGU

Scaling, similarity, and the fourth paradigm for hydrology

Christa D. Peters-Lidard[1], Martyn Clark[2], Luis Samaniego[3], Niko E. C. Verhoest[4], Tim van Emmerik[5], Remko Uijlenhoet[6], Kevin Achieng[7], Trenton E. Franz[8], and Ross Woods[9]

[1]Earth Sciences Division, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
[2]Research Applications Laboratory, National Center for Atmospheric Research, Boulder, CO 80301, USA
[3]UFZ-Helmholtz Centre for Environmental Research, Leipzig, 04318, Germany
[4]Laboratory of Hydrology and Water Management, Ghent University, Coupure links 653, 9000 Ghent, Belgium
[5]Water Resources Section, Delft University of Technology, Delft, 2628 CN, the Netherlands
[6]Hydrology and Quantitative Water Management Group, Wageningen University, 6700 AA Wageningen, the Netherlands
[7]Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY 82071, USA
[8]School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68583, USA
[9]Department of Civil Engineering, University of Bristol, Bristol, BS8 1TR, UK

Abstract. In this synthesis paper addressing hydrologic scaling and similarity, we posit that roadblocks in the search for universal laws of hydrology are hindered by our focus on computational simulation (the third paradigm) and assert that it is time for hydrology to embrace a fourth paradigm of data-intensive science. Advances in information-based hydrologic

- Mikhail Ivanovich Budyko (1920–2001)
- Developed a framework for long-term catchment-scale water balance
  - Two assumptions
    1. Steady state
    2. Very large catchments

Advanced Review

Mikhail Budyko's (1920–2001) contributions to Global Climate Science: from heat balances to climate change and global ecology

Jonathan D. Oldfield*

Edited by Matthias Heymann, Domain Editor, and Mike Hulme, Editor-in-Chief

WIREs Clim Change 2016, 7:682–692. doi: 10.1002/wcc.412

$$P = E + Q$$
$$E = f(P, E_0)$$

P – average annual precipitation
E – average annual evapotranspiration
Q – average annual streamflow
E_0 – average annual potential evapotranspiration

$$E = f(P, E_0)$$

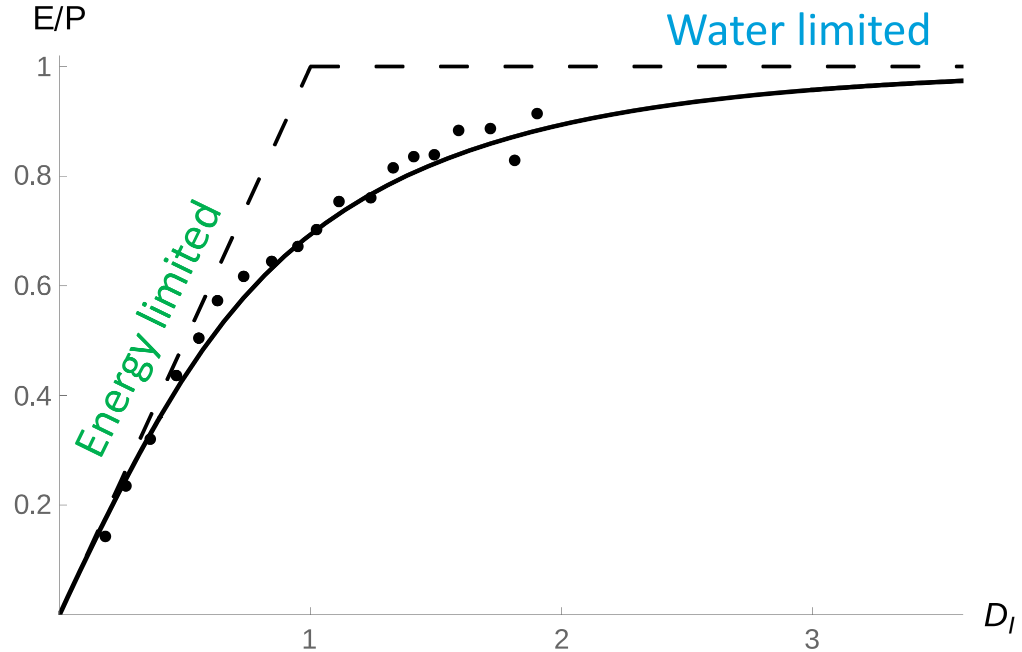
Dimensional analysis
(Buckingham-Π theorem)

$$\frac{E}{P} = f_B\left(\frac{E_0}{P}\right) = f_B(D_I)$$

Dryness Index

$$D_I \rightarrow +\infty; \quad \frac{E}{P} \rightarrow 1$$

$$D_I \rightarrow 0; \quad \frac{E}{P} \rightarrow D_I$$



$$E = f(P, E_0)$$

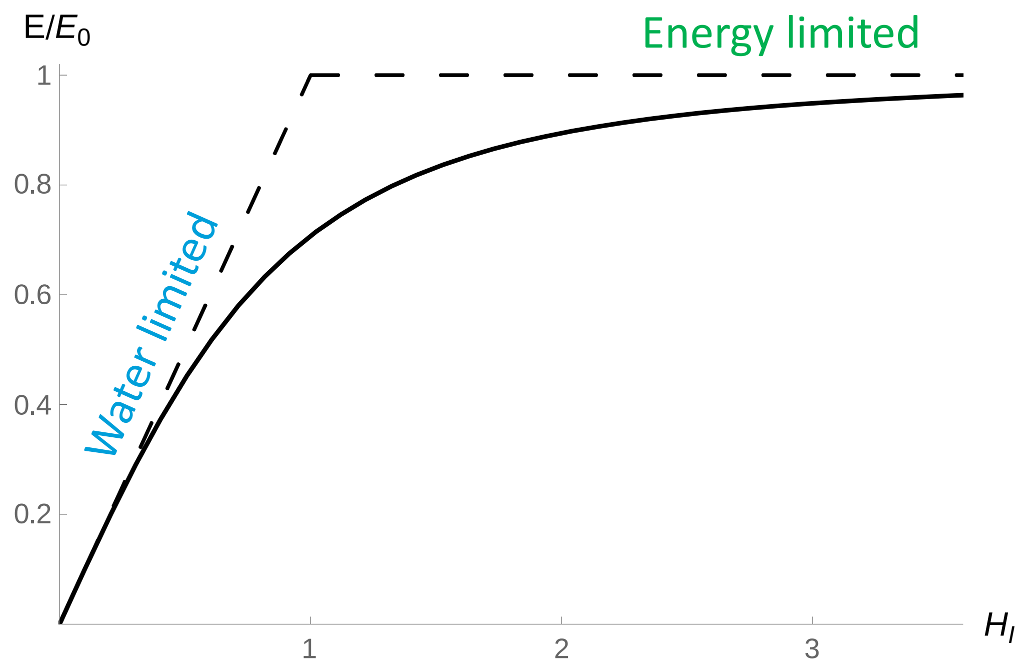
Dimensional analysis
(Buckingham-Π theorem)

$$\frac{E}{E_0} = f_T\left(\frac{P}{E_0}\right) = f_T(H_I)$$

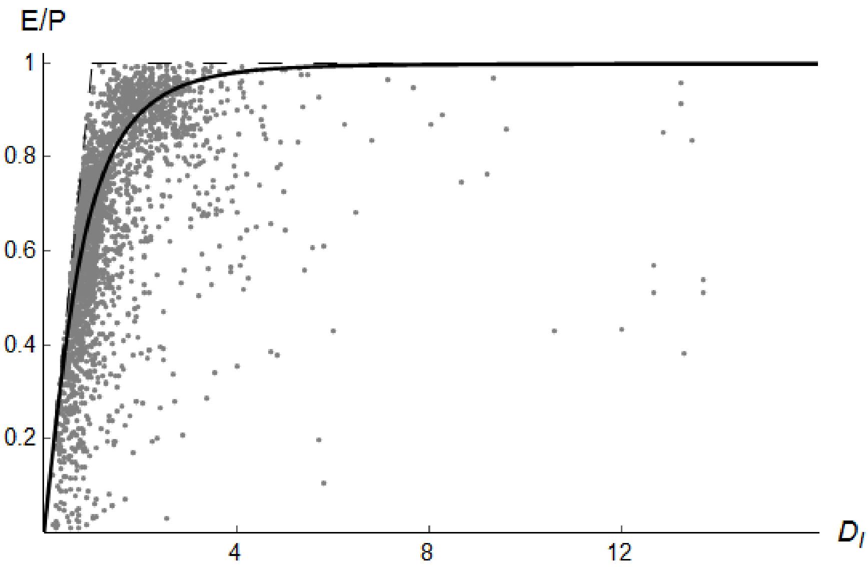
Humidity Index

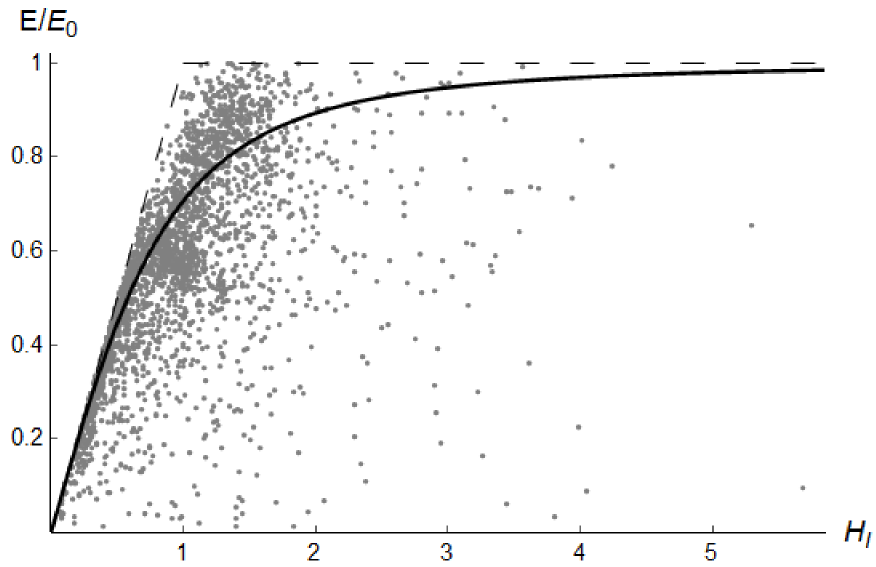
$$H_I \rightarrow +\infty; \quad \frac{E}{E_0} \rightarrow 1$$

$$H_I \rightarrow 0; \quad \frac{E}{E_0} \rightarrow H_I$$



- Data from catchments worldwide do not follow the theoretical frameworks
- Climatic factors are not the only ones driving the water balance of small catchments





Padron et al., *Water Resources Research*, 2017

CURRENT POPULAR MODELS

Fu (Zhang et al., *Water Resources Research*, 2004)

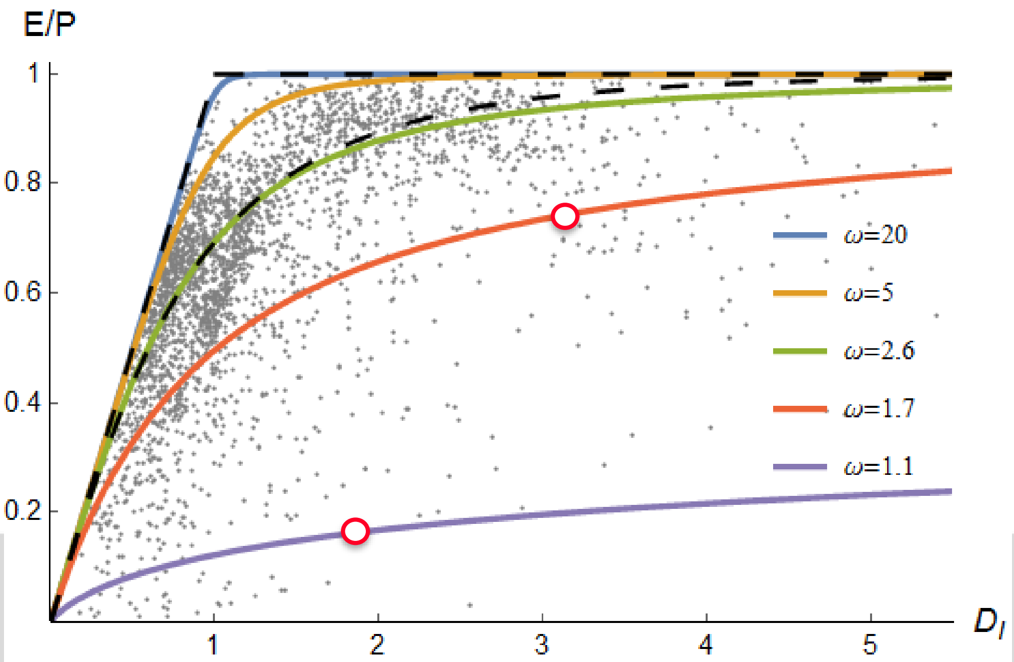
$$\frac{E}{P} = 1 + D_I - (1 + D_I^{\omega})^{\omega}$$

$$\frac{E}{E_0} = 1 + H_I - (1 + H_I^{\omega})^{\omega}$$

MCY (Choudhury, *Journal of Hydrology*, 1999)

$$\frac{E}{P} = \frac{1}{(1 + D_I^{-n})^{1/n}}$$

$$\frac{E}{E_0} = \frac{1}{(1 + H_I^{-n})^{1/n}}$$



AIM

- Can we improve the Budyko and Turc frameworks?
- Can we overcome limitations of current approaches?
  - Climate is the only forcing of the water balance
  - Parameters in current models do not have a clear physical meaning and thus cannot be measured or estimated from measurements

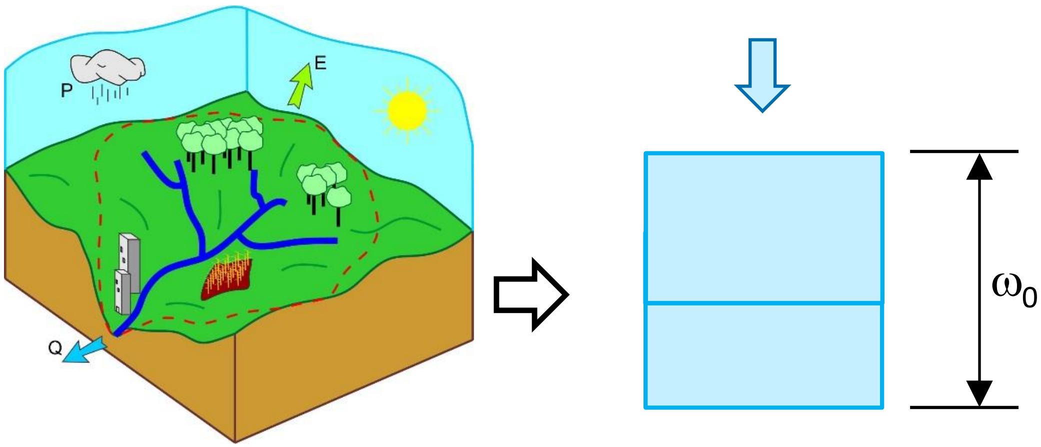
Amilcare Porporato

Salvatore Calabrese

Jun Yin

ADDING STORAGE TO THE FRAMEWORK

- Long-term water balance (steady state)
- Consider a catchment as a finite capacity
- Key factors driving E
  - P: on the long term is the only supply of water
  - E_0: is the maximum demand of water from the atmosphere
  - **Φ**: maximum amount of water that can be stored within the catchment to supply E (**Maximum Storage Rate**)



$$\Phi = N_P \omega_0$$

- ω_0 is a depth representing the maximum storage, calculated from soil type and land use
- N_P is the average number of rainfall events in a year

$$E = f(P, E_0, \Phi)$$

Dimensional analysis
(Buckingham-Π theorem)

$$\frac{E}{P} = f_B\left(\frac{E_0}{P}, \frac{\Phi}{P}\right) = f_B(D_I, \gamma_P)$$

$$\frac{E}{E_0} = f_T\left(\frac{P}{E_0}, \frac{\Phi}{E_0}\right) = f_T(H_I, \gamma_E)$$

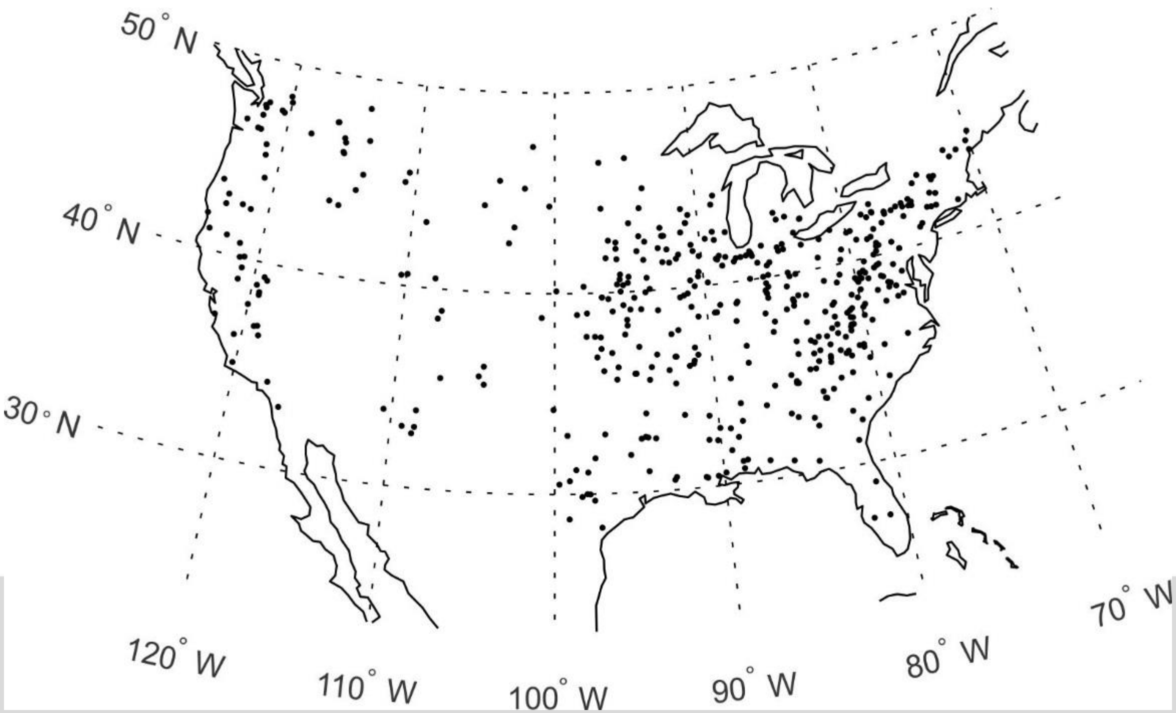
$$\frac{E}{\Phi} = f_\Phi\left(\frac{P}{\Phi}, \frac{E_0}{\Phi}\right) = f_\Phi(\gamma_P, \gamma_E)$$

γ_P – how much water can be stored with respect to P

γ_E – frequency of rainfall with respect to the frequency at which E_0 can deplete the storage

APPLICATION – MOPEX CATCHMENTS

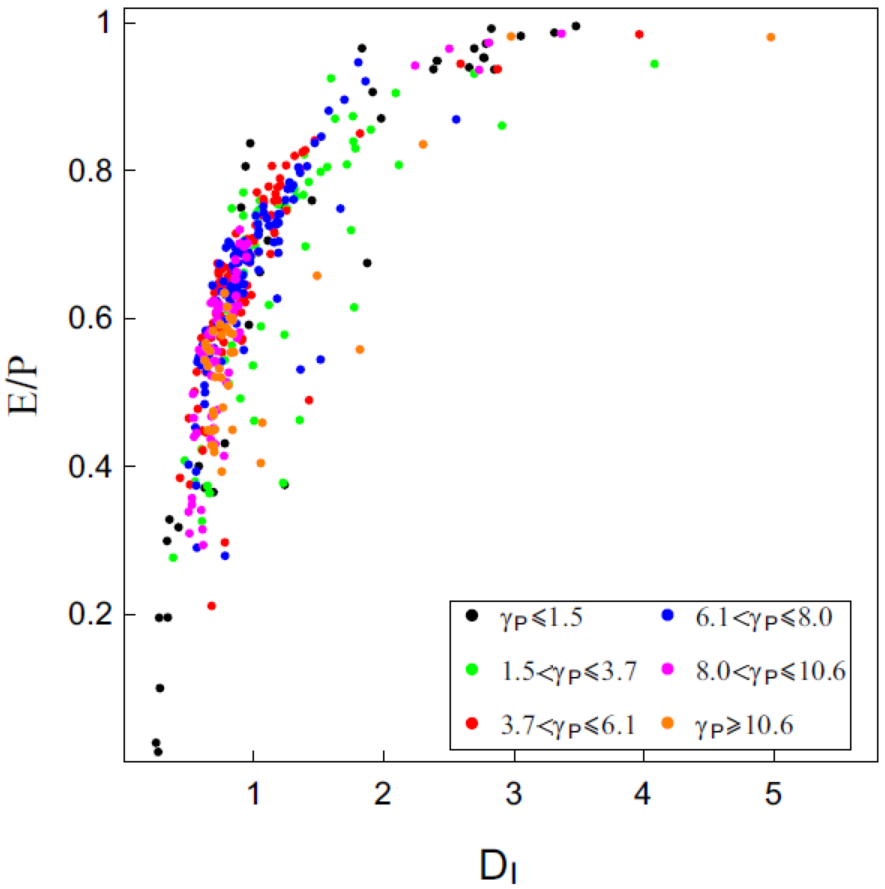
- 438 catchments across the continental USA
- Data of P, E_0, and Q (E=P-Q) in the period 1948-2003
  - 28 did not have at least 25 years of data of Q and E_0
  - 5 had $E>E_0$ (other factors are affecting the water balance)
  - 21 catchments are mostly (>80%) covered by wetlands, ice, and water bodies

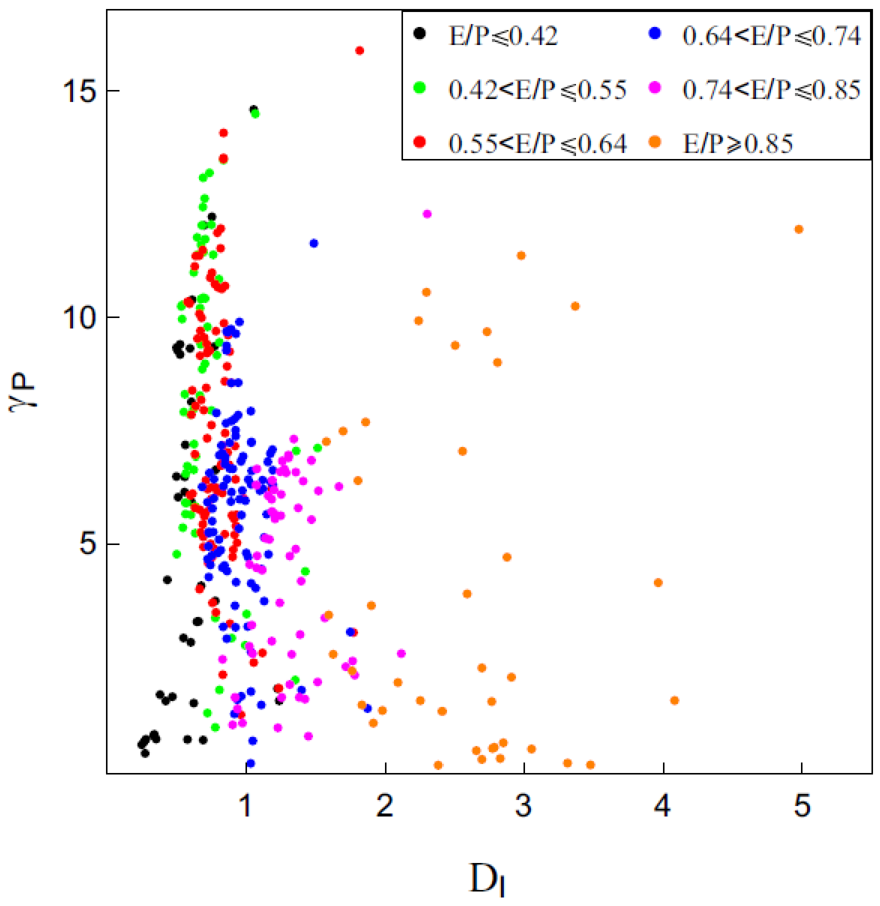


- Rainfall data
  - Average annual rainfall (P)
  - Average annual number of rainfall events (N_P)
- Potential evapotranspiration
  - Average annual potential evapotranspiration (E_0)
- Land cover (International Geosphere-Biosphere Programme, IGBP)
  - Maximum storage, ω_0

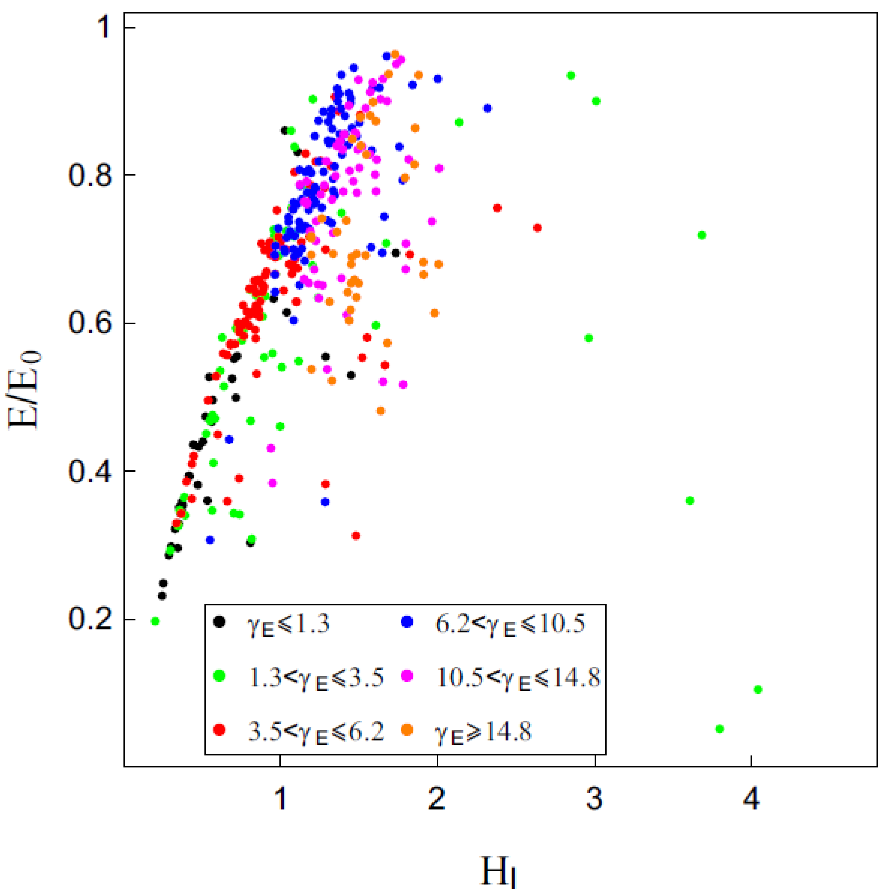
$$D_I = E_0/P \qquad H_I = P/E_0$$

$$\Phi = N_P\,\omega_0 \qquad \gamma_P = \Phi/P \qquad \gamma_E = \Phi/E_0$$

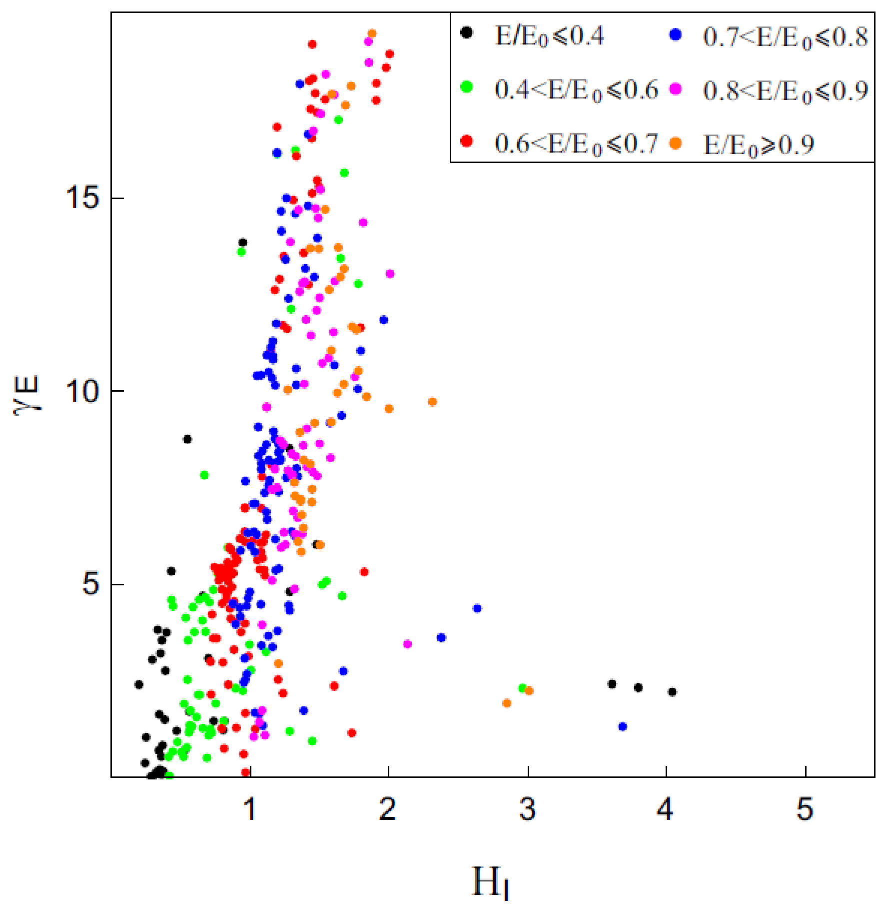

E/P
D_I
$\gamma_P \leqslant 1.5$
$1.5<\gamma_P \leqslant 3.7$
$3.7<\gamma_P \leqslant 6.1$
$6.1<\gamma_P \leqslant 8.0$
$8.0<\gamma_P \leqslant 10.6$
$\gamma_P \geqslant 10.6$


γ_P
D_I
E/P≤0.42
0.42<E/P≤0.55
0.55<E/P≤0.64
0.64<E/P≤0.74
0.74<E/P≤0.85
E/P≥0.85

Turc space

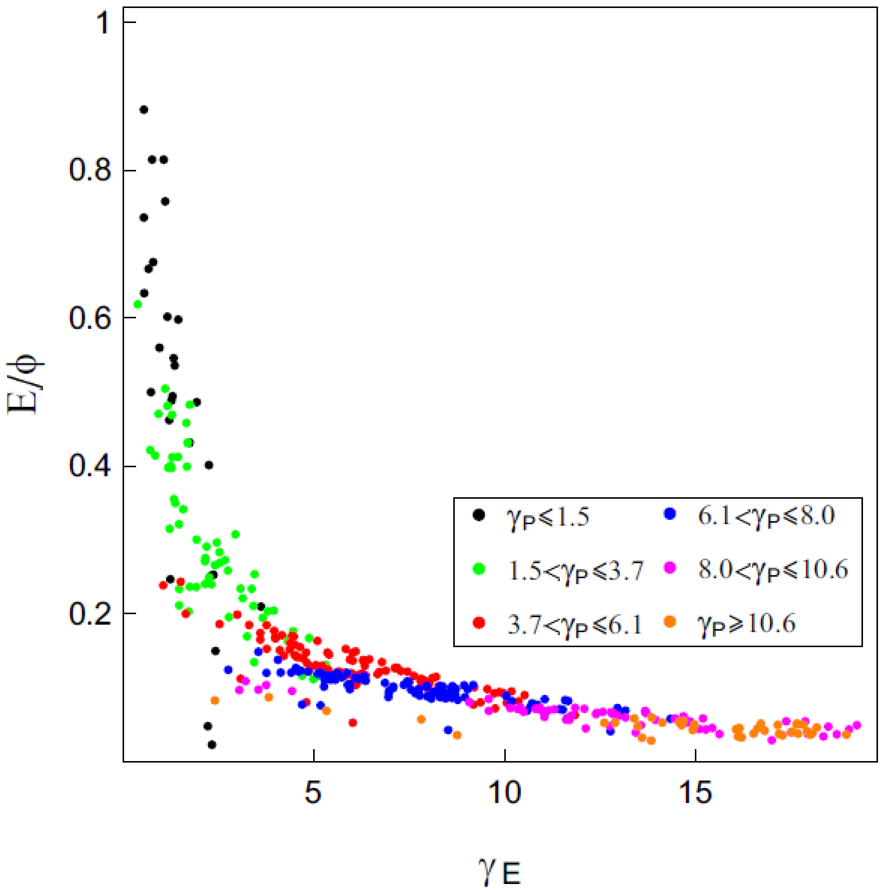


E/E0
H_I
γE≤1.3
1.3<γE≤3.5
3.5<γE≤6.2
6.2<γE≤10.5
10.5<γE≤14.8
γE≥14.8

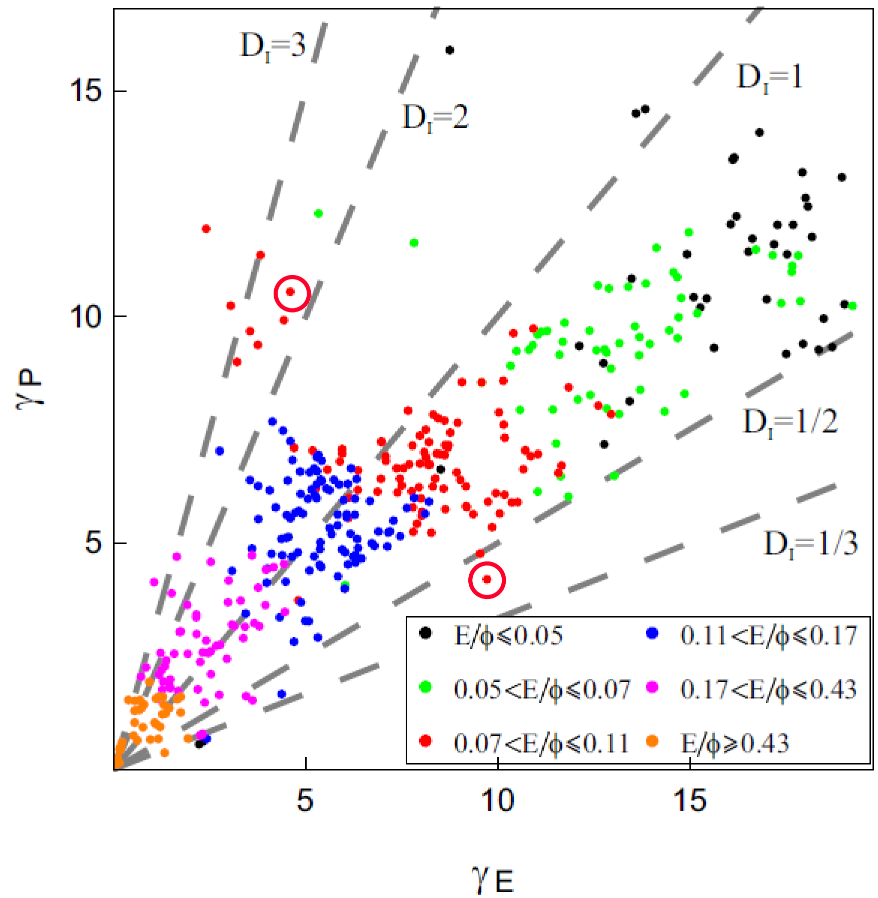


γE
H_I
E/E0≤0.4
0.4<E/E0≤0.6
0.6<E/E0≤0.7
0.7<E/E0≤0.8
0.8<E/E0≤0.9
E/E0≥0.9

Φ-SPACE



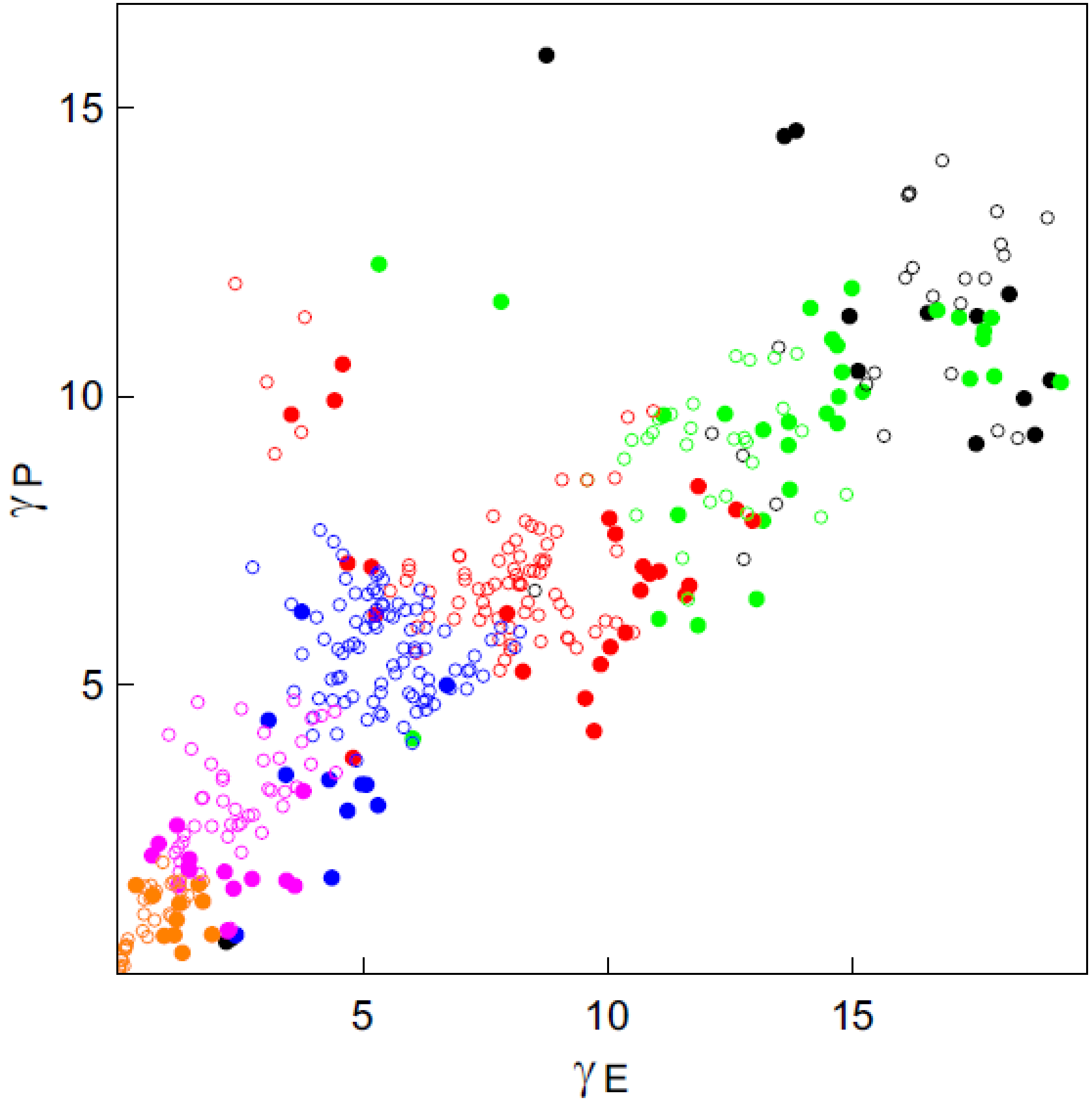
1
0.8
0.6
0.4
0.2
E/ϕ
5
10
15
γE
γP≤1.5
1.5<γP≤3.7
3.7<γP≤6.1
6.1<γP≤8.0
8.0<γP≤10.6
γP≥10.6



D_I=3
D_I=2
D_I=1
D_I=1/2
D_I=1/3
15
10
5
γP
5
10
15
γE
E/ϕ≤0.05
0.05<E/ϕ≤0.07
0.07<E/ϕ≤0.11
0.11<E/ϕ≤0.17
0.17<E/ϕ≤0.43
E/ϕ≥0.43

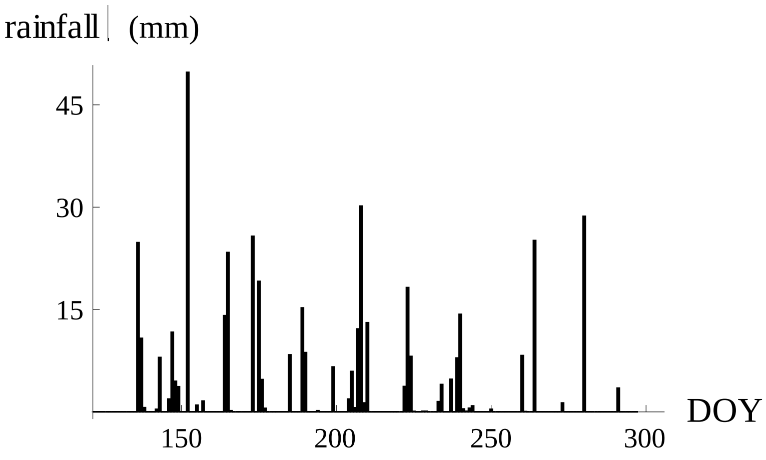
SLOPE

105 catchments with slope steeper than 10°

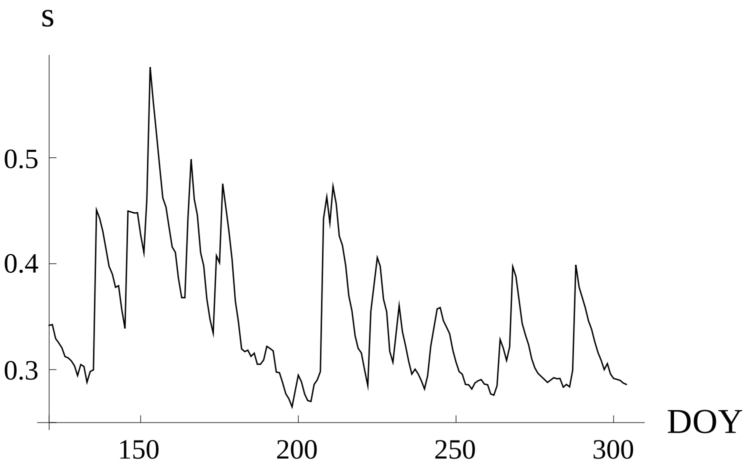


Stochastic model for daily soil water balance

Marked Poisson process (λ, α)



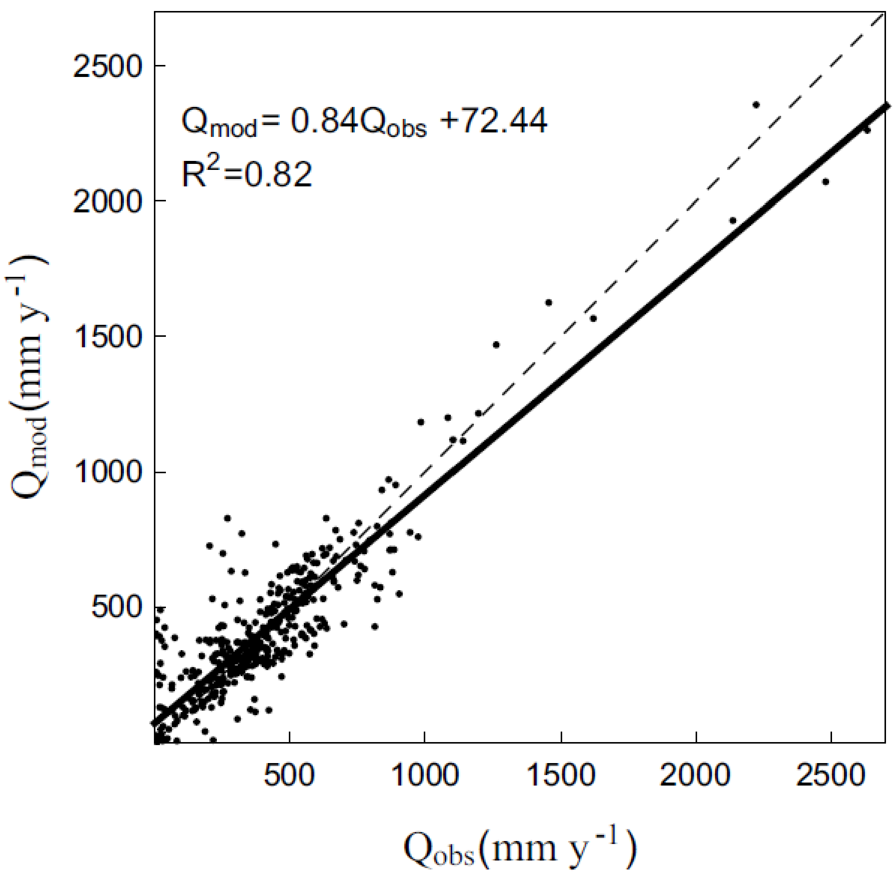
Filtered Poisson process (λ, α, η)



$$p(x) = \frac{N}{\eta} x^{\lambda/\eta - 1} e^{-\gamma x} \longrightarrow p(x) = \frac{N}{\eta} x^{\lambda/\eta - 1} e^{-\gamma x}$$

$$x = \frac{s - s_w}{s_{fc} - s_w}$$

$$\frac{E}{\Phi} = \frac{1}{\gamma_P} - \frac{1}{\gamma_E} \frac{\gamma_P^{\gamma_E - 1} \, e^{-\gamma_P}}{\Gamma(\gamma_E) - \Gamma(\gamma_E, \gamma_P)}$$



- New framework for long-term catchment water balance
  - **Climatic conditions** and key **catchment characteristics**
  - **Parameters** have clear physical meaning
  - Parameters can be estimated from measureable environmental variables
- Hydrologic spaces
  - The new framework includes **Budyko** and **Turc** as limits for large catchments
  - **Φ-space** helps classify catchments in relation to land use and rainfall (both amounts and frequency of occurrence)
- Future
  - Test against global data sets
  - Include changes in storage (i.e., short-term water balance)