



Integrated Water Management

Week 2:

Scenarios and Tools

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Water Management

Civil Engineering and Geosciences

Technical University Delft



Week 2: Scenarios & Tools

Course Outline

Day		Subject	Teacher
1-9	Morning Afternoon	1. Introduction Introduction course and IWRM Challenges of the 21st Century Computer lab WEAP: WEAP River	Van de Giesen Van de Giesen/ Mostert Van de Giesen
8-9	Morning Afternoon	Scenarios and tools Computer lab WEAP: Rhine & Volta	Van de Giesen Van de Giesen
15-9	Morning Afternoon	Role-play transboundary water management Computer lab WEAP: Rhine & Volta	Mostert Van de Giesen
22-9	Morning Afternoon	Governance and stakeholders: case study from The Netherlands Computer lab WEAP: Rhine & Volta	Mostert Mostert
29-9	Morning Afternoon	Water, food and energy (Discussion) Computer lab: actor analysis Rhine & Volta	Van de Giesen/ Mostert Mostert
6-10	Morning Afternoon	IWRM revisited Work on Rhine & Volta	Van de Giesen Van de Giesen
13-10		No lecture. Work on draft report	
20-10	Morning	Draft final report ready. Presentation	Van de Giesen/ Mostert
29-10		Before 9.00 am: Handing in final report and indication of everybody's contribution to it.	



Week 2: Scenarios & Tools

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1: Introduction

2: Scenarios & Tools

IWM Fall 2013



Week 2: Scenarios & Tools

Outline

- **What do we want to achieve?**
- Strategies to deal with multiple futures
- Inputs: Climate (+population, economic growth, ...)
- Sub-models:
 - Hydrology
 - Irrigation
 - Hydropower
 - Heat
- Data sources (Volta&Rhine)
- Graph Theory & WEAP



Week 2: Scenarios & Tools

What do we want to do?

- Model for stakeholders => optimal decisions



Week 2: Scenarios & Tools

IWM Fall 2013



Source: au.video.yahoo.com



Week 2: Scenarios & Tools

What do we want to do?

- Model for stakeholders => optimal decisions

- Objective function:
 - Nature / physics
 - Stakeholders



Week 2: Scenarios & Tools

What do we want to do?

- Model for stakeholders => optimal decisions
- Objective function:
 - Nature / physics => Before cookie break
 - Stakeholders => After cookie break



Week 2: Scenarios & Tools

What do we want to do: Scenarios

- Objective function
- External forcing / boundary conditions (=> week 4)
- Constraints / institutions



Week 2: Scenarios & Tools

What do we want to do: Scenarios

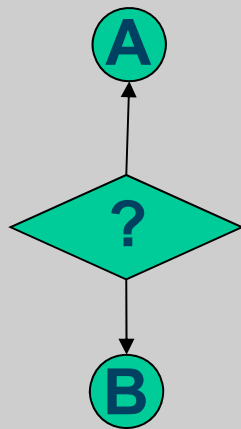
- Objective function
- External forcing / boundary conditions
- Constraints / institutions

Problem: Multiple futures!



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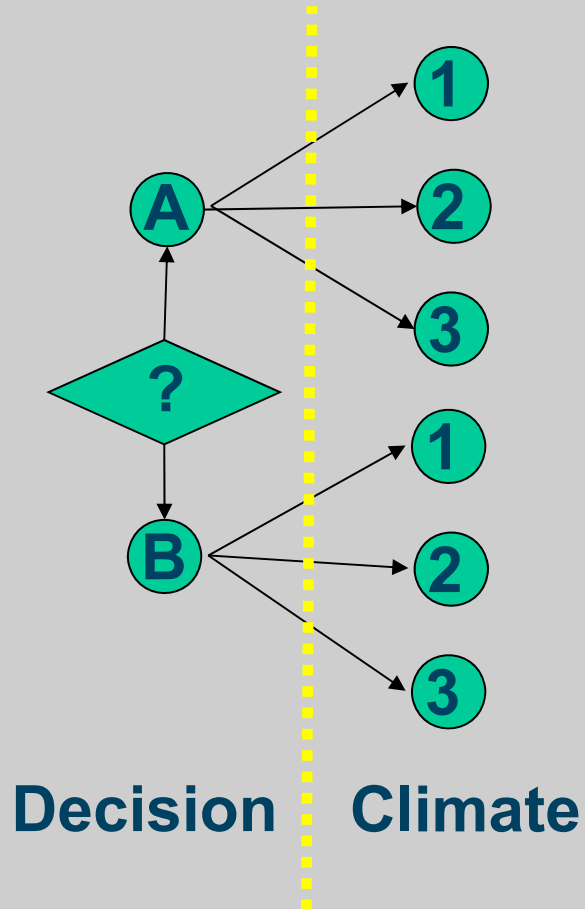
Multiple futures



source: www.deondernemer.nl

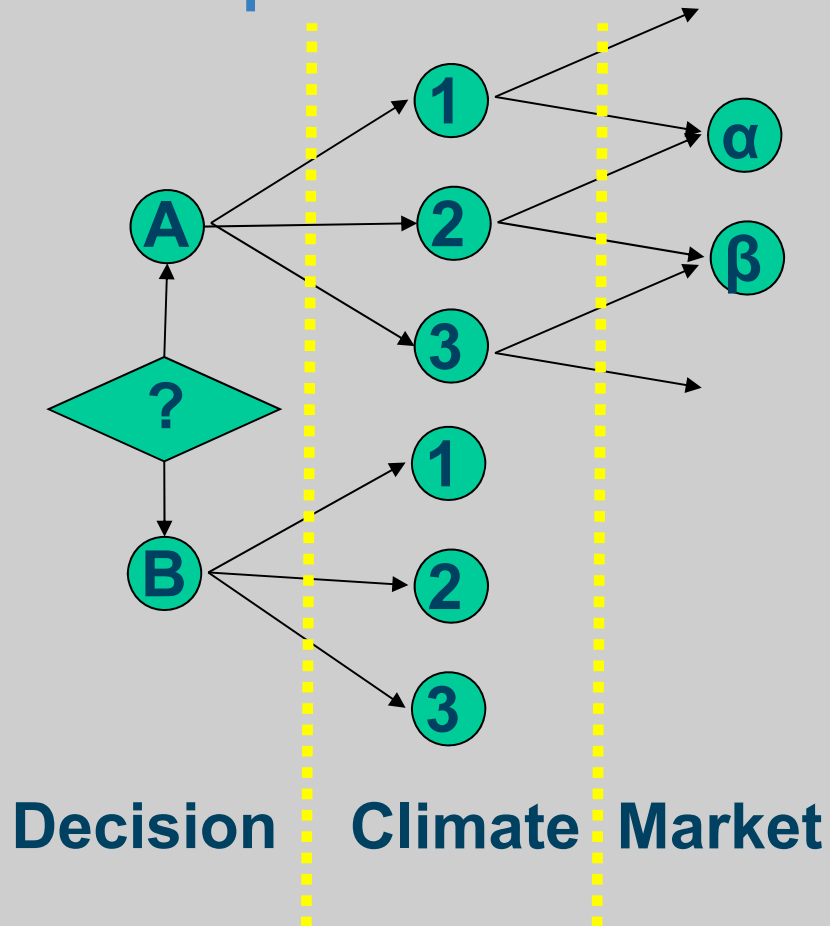
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Multiple futures



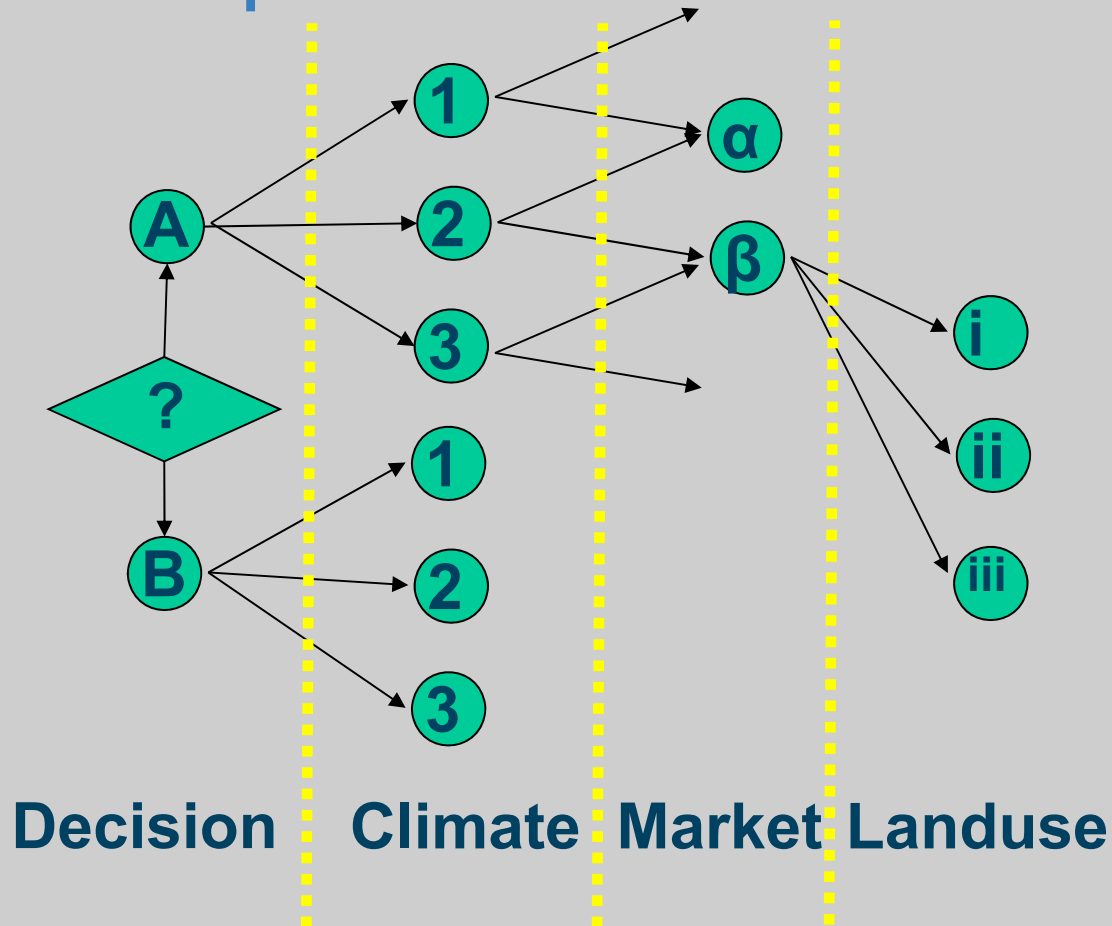
Week 2: Scenarios & Tools

Multiple futures



Week 2: Scenarios & Tools

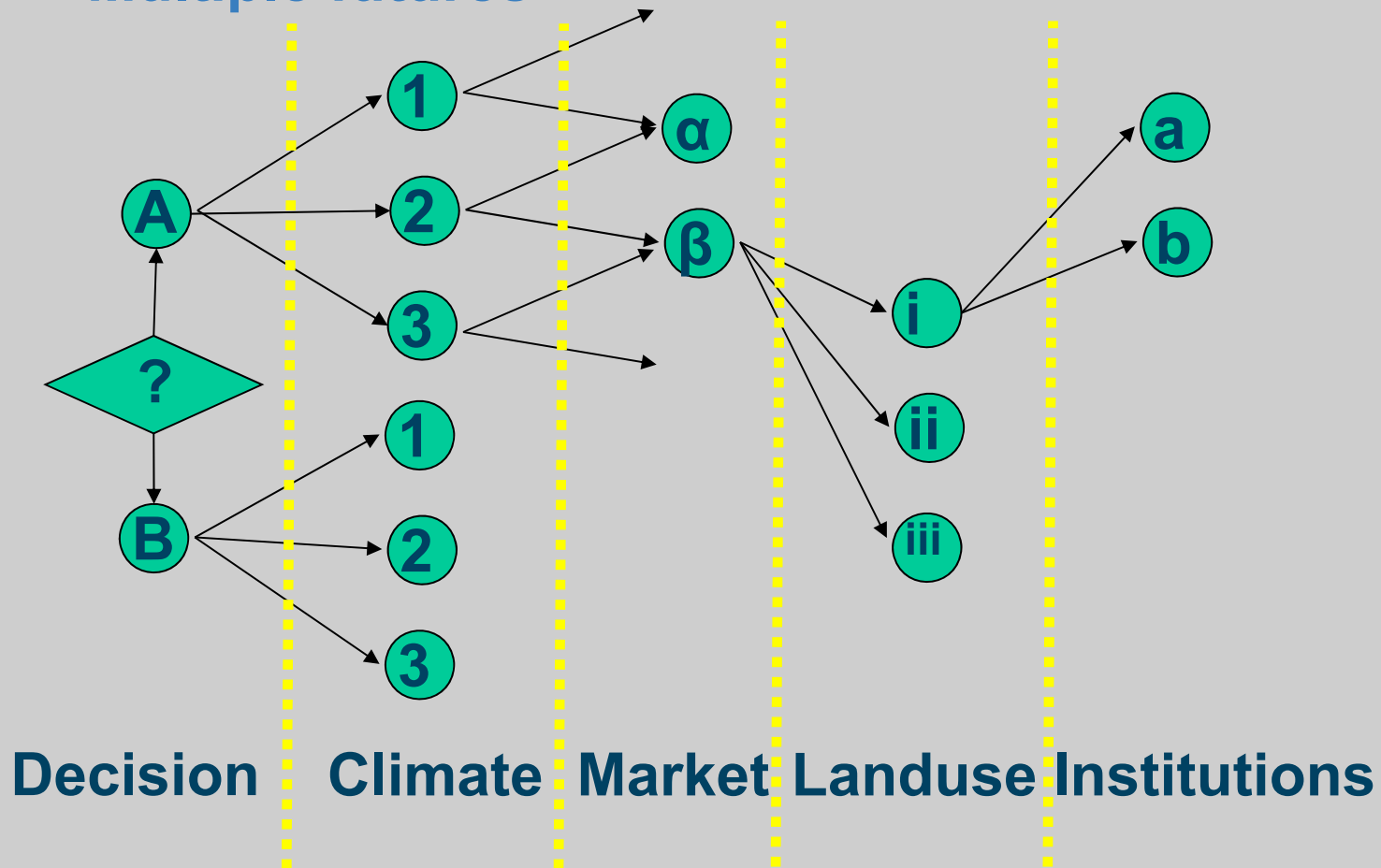
Multiple futures





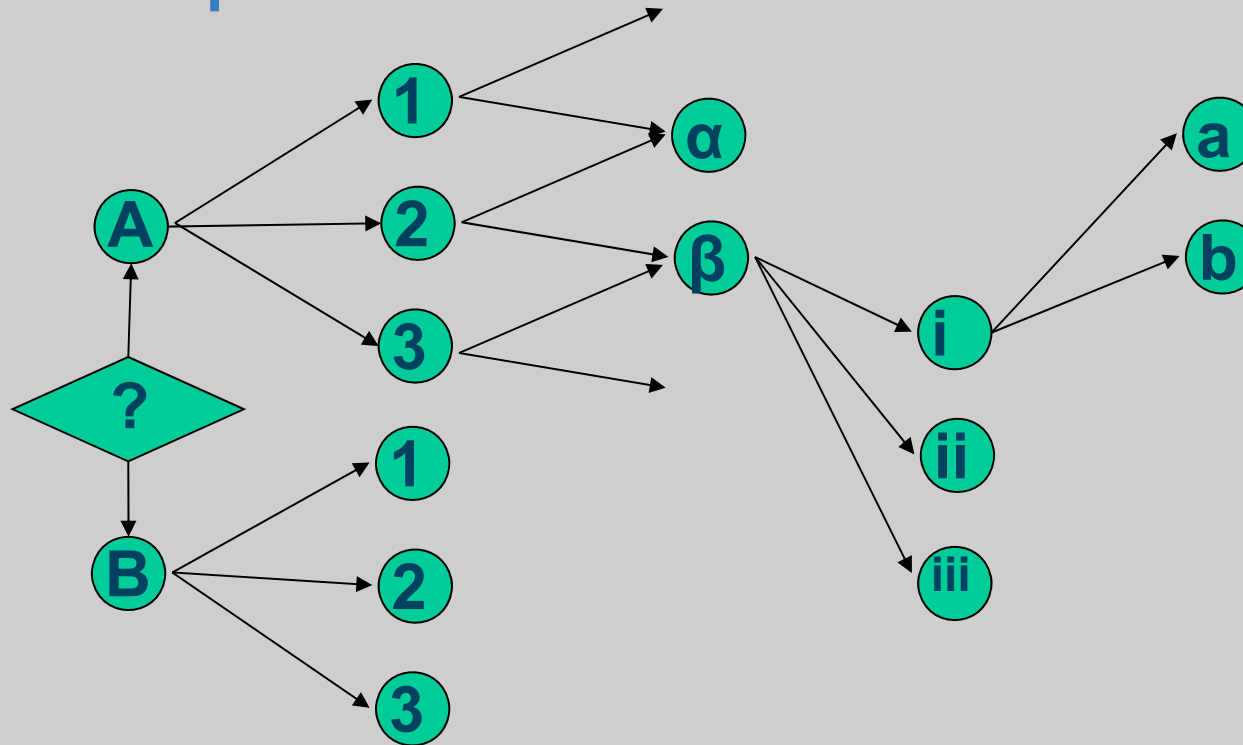
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Multiple futures



Week 2: Scenarios & Tools

Multiple futures



Decision Climate Market Landuse Institutions

Futures=2x3x2x3x2x...



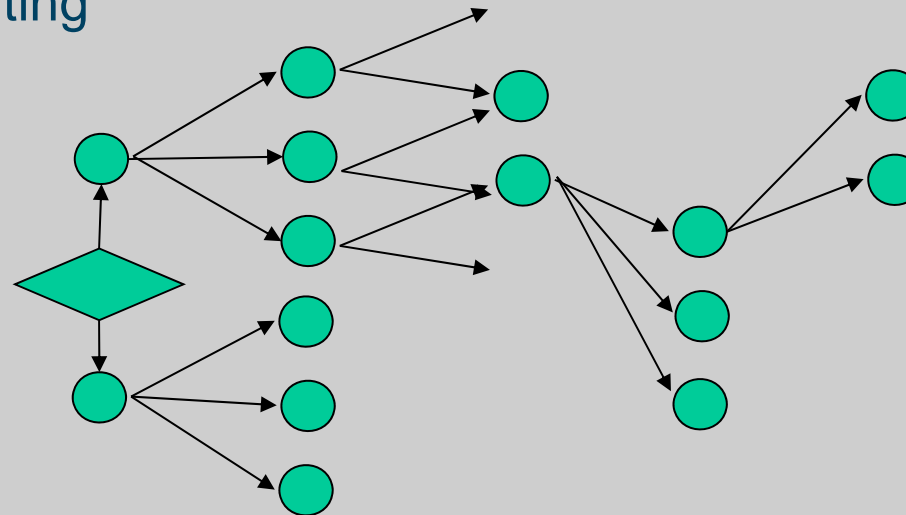
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Multiple futures

- Strategies
 - Bayesian integration
 - Consistent story-lines (Hoekstra, IPCC)
 - Common future (Yates, Siemens)
 - ...

Multiple futures

- Bayesian integration
 - Integrate along all pathways
 - Use priors to weigh decision points
 - Proper discounting
 - Robust design



Congli Dong





Week 2: Scenarios & Tools

Multiple futures

- Story lines: IPCC scenarios
 - 40 emission scenarios
 - demography
 - economic development
 - technological development



Week 2: Scenarios & Tools

Multiple futures

- Story lines: IPCC scenarios
 - A1: Globalization, rapid economic development
 - A2: Regional, low economic growth, high population
 - B1: Globalization, improved technologies
 - B2: Regional, medium economic growth, medium population

- Emissions, climate change, GCMs



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Multiple futures

- Common future
 - Especially good for stakeholders
 - Panel / forum
 - Subjectivity / perceptions



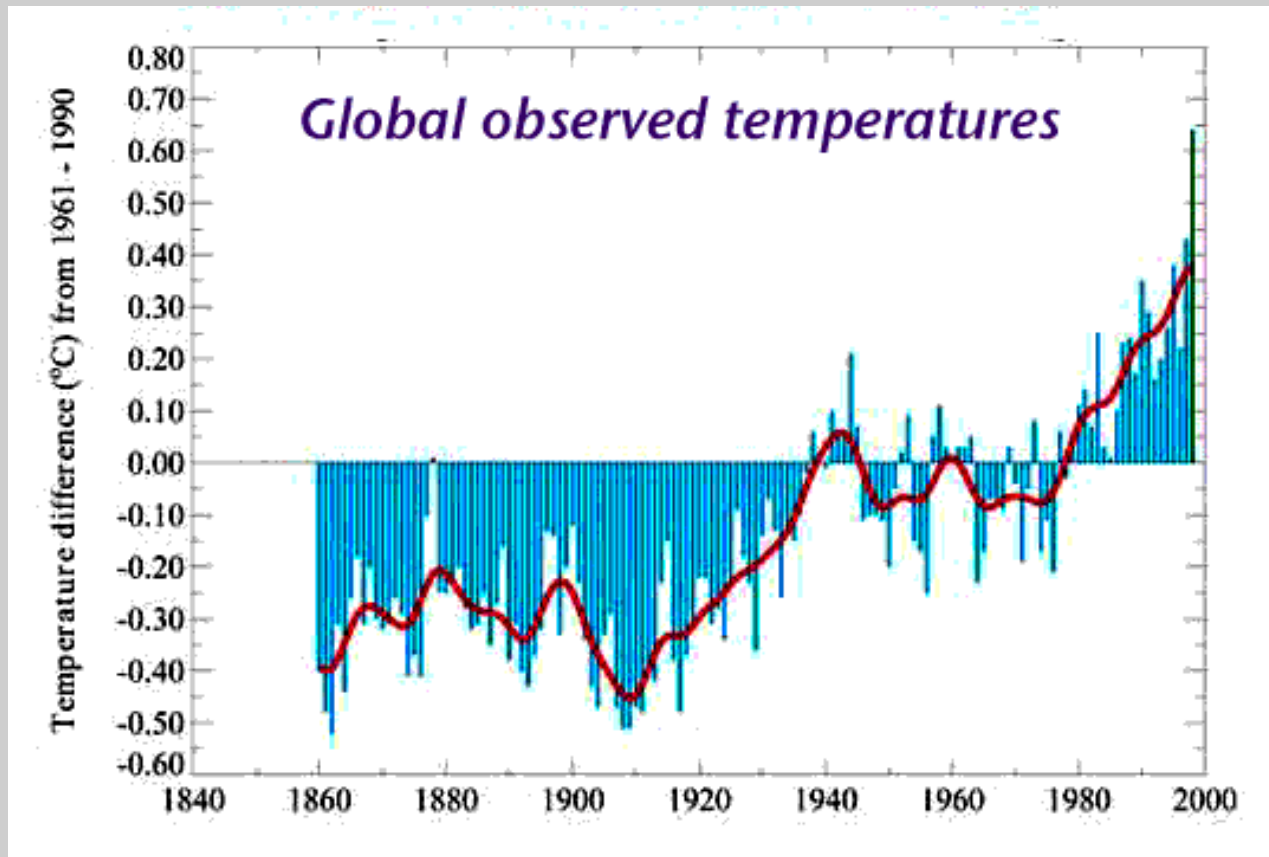
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Multiple futures: IPCC story lines

- Climate scenarios
 - General Circulation Models (GCM's)
 - GCM's & water
 - Downscaling GCM's

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GCM's & Climate Change Scenarios

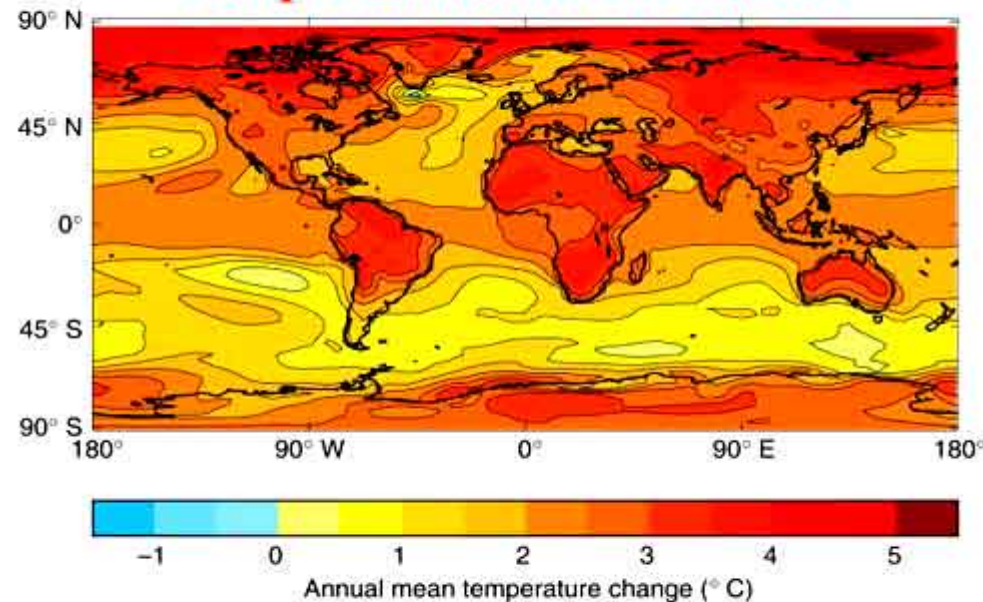


source: www.inforse.org

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GCM's & Climate Change Scenarios

Figure 11: Projected Changes in Annual Temperatures for the 2050s



The projected change in annual temperatures for the 2050s compared with the present day, when the climate model is driven with an increase in greenhouse gas concentrations equivalent to about a 1% increase per year in CO_2

The Met Office Hadley Centre for Climate Prediction and Research.

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GCM's & Climate Change Scenarios

Global Water Resources: Vulnerability from Climate Change and Population Growth

Vorosmarty et al
 Science 289
 July 2000

REPORTS

Global Water Resources: Vulnerability from Climate Change and Population Growth

Charles J. Vorosmarty,^{1,2,4*} Pamela Green,^{1,3,4} Joseph Salisbury,^{1,3,4} Richard B. Lammers^{1,2,4}

The future adequacy of freshwater resources is difficult to assess, owing to a complex and rapidly changing geography of water supply and use. Numerical experiments combining climate model outputs, water budgets, and socioeconomic information along digitalized river networks demonstrate that (1) a large proportion of the world's population is currently experiencing water stress and (2) rising water demands greatly outweigh greenhouse warming in defining the state of global water systems to 2025. Consideration of direct human impacts on global water supply remains a poorly articulated but potentially important facet of the larger global change question.

Greenhouse warming continues to dominate the world's science and policy agendas on global change. One fundamental concern is the impact of this climate change on water supply (1, 2). The question of how human society directly influences the state of the terrestrial water cycle has received much less attention, despite the presence of the socioeconomic equivalent of the Malthusian curve, namely, rapid population growth and economic development. Our goal in this report is to identify the contributions of climate change, human development, and their combination to the future state of global water resources.

Assessments of water vulnerability traditionally have been cast at the country or regional scale (2-5). Although recent work has focused on individual drainage basins and subbasins (1, 6, 7), to the best of our knowledge, no global-scale study has articulated the geographic linkage of water supply to water demand defined by runoff and its passage through river networks. We present a high-resolution geography of water use and availability, analyzing the vulnerability of water resources infrastructure (8) to future climate change, population growth and migration, and industrial development between 1985 and 2025. We consider explicitly how the topology of river systems determines the character of sustainable water supply and its use by humans.

Mean annual surface and subsurface (shallow aquifer) runoff accumulated at river discharge (9) is assumed to constitute the sustainable water supply to which local human populations have access (9). We assess the distribution of population with respect to relative

water demand (RWD) defined as the ratio of water withdrawn or water use to discharge. We consider the domestic and industrial sectors (DIW_{ij}), irrigated agriculture (AIW_{ij}), and their combination (DAW_{ij}) on a mean annual basis. Each ratio determines the degree to which humans interact with sustainable water supply and provides a local index of water stress. Values on the order of 0.2 to 0.4 indicate medium to high stress, whereas those greater than 0.4 reflect conditions of severe water limitation (10). We also constructed a water stress index (DAWA_{ij}), defined as the ratio of aggregate upstream water use relative to discharge. We consider vulnerability with respect to sustainable water resources only. We make no explicit evaluation of non-sustainable supplies or withdrawals, such as the mining of groundwater, although we can draw inferences about such activities by analyzing RWD. We do not explicitly model human adaptation to climate change or development pressure, but we do incorporate estimates of future water use efficiency offered in other studies.

A recent version of the Water Balance Model (WBM) (11) was used to compute contemporary and future runoff at 30' grid resolution (latitude by longitude). Runoff fields were constrained by monitoring data, and converted to discharge by integrating along digitalized rivers (12, 13). Climate change fields were from the Canadian Climate Center general circulation model (CCM) and Hadley Center circulation model (HadCM2) (14).

Based on Climate Change (IPCC) assessment (14), global means for contemporary (1961-99) runoff and river discharge were computed by the WBM using off-line atmospheric forcing from HadCM2 and CGCM1. Predictions were in substantial agreement with runoff fields based on observed discharge (13, 15). Results from HadCM2/WBM and CGCM1/WBM were used to predict incremental differences between contemporary and future runoff and discharge for individual grid cells. These differences were then applied to a baseline (15) to generate the future picture of runoff (16). Mean global runoff varied in response to climate change from an increase of 2.1 mm year⁻¹ (HadCM2/WBM) to a decrease of 17 mm year⁻¹ (CGCM1/WBM) (17). With each runoff field, mean substantial changes could be found at local and regional scales. CGCM1/WBM gave the strongest climate change signal, and we use it to exemplify key findings derived from both models.

Domestic and industrial water demand was determined by population and per capita use statistics. The geography of contemporary urban and rural population was developed from a 1-km data set (18). Future population distribution was determined from projections of the percent change in total, rural, and urban population from 1985 to 2025 (19) applied to the 1-km urban and rural population maps. Contemporary water withdrawal statistics (20) were used to estimate contemporary water demands, but they first required standardization and spatial disaggregation (20). The geography of agricultural water demand was computed from irrigated land areas and national use statistics (21). Future demands for all sectors were based on population growth, economic development, and projected change in water use efficiency (22). Water withdrawals at 30' resolution were geographically linked to digital river networks and corresponding discharge estimates.

The contemporary condition is represented by 1985, the year that is most compatible with the time span represented by the runoff climatology and historical water use statistics. Against this benchmark we formulated three scenarios to quantify the contributions of climate change and development pressure to the degree of relative water demand in 2025. The first scenario (Sc1) varied climate but fixed the magnitude and spatial distribution of human population and water withdrawal at 1985 levels. Sc2 applied projected water demands for 2025 but used runoff and discharge based on contemporary climate. Sc3 changed both climate and water demand. Total water use per capita is projected to decrease from 640 to 590 m³ year⁻¹ between 1985 and 2025. The impacts of human development under Sc2 and Sc3 will therefore generally reflect population growth and migration as opposed to intensification of water use, though results will be location specific. In addition to (7), our calculation of global water use in 2025 is conservative, 4700 km³ year⁻¹ compared to 5200 km³ year⁻¹.

We compared our calculations to country-level data typically applied in global water assessments. Our national-scale aggregation of gridded DAW_{ij} and a recent global assessment by the United Nations (1) place almost the same fraction of the world's 1995 population under similar levels of water stress (Table 1). In both studies, one-third of the total population of

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GCM's & Climate Change Scenarios

Global Vulnerability Change

Charles
Joseph

The future adequacy of complex and rapidly expanding water resources is a function of the proportion of the world's rising water demand that is met by the state of global water resources. This report is the first of a larger

assessment of the world's water resources and policy change. One fundamental question is the impact of climate change on water resources. The question of how climate change will affect the state of the world's water resources has been addressed in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. This report is to identify the contribution of climate change to the future water resources.

Assessments of water resources have been carried out at the global scale (2-5). Although research on individual drainage basins (6, 7), to the best of our knowledge, no global-scale study has attempted to linkage of water supply defined by runoff and its use in agriculture. We present a high-resolution study of the vulnerability of water resources to future climate change, and migration, and land-use changes. We use the topography of rivers to assess the character of sustainable water use by humans.

Global annual surface and subsurface (shallow aquifer) runoff, accumulated as river discharge (8), is assumed to constitute the sustainable water supply to which local human populations have access (9). We assess the distribution of population with respect to relative

Water Systems Analysis Group, Complex Systems Research Center, Delft University of Technology, Laboratory of Water Resources, Delft University of Technology, Delft, The Netherlands, and Space, Earth Sciences Department, University of New Hampshire, Durham, NH, USA.

*To whom correspondence should be addressed.

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Vorosmarty et al
Science 289
July 2000

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GCM's & Climate Change Scenarios

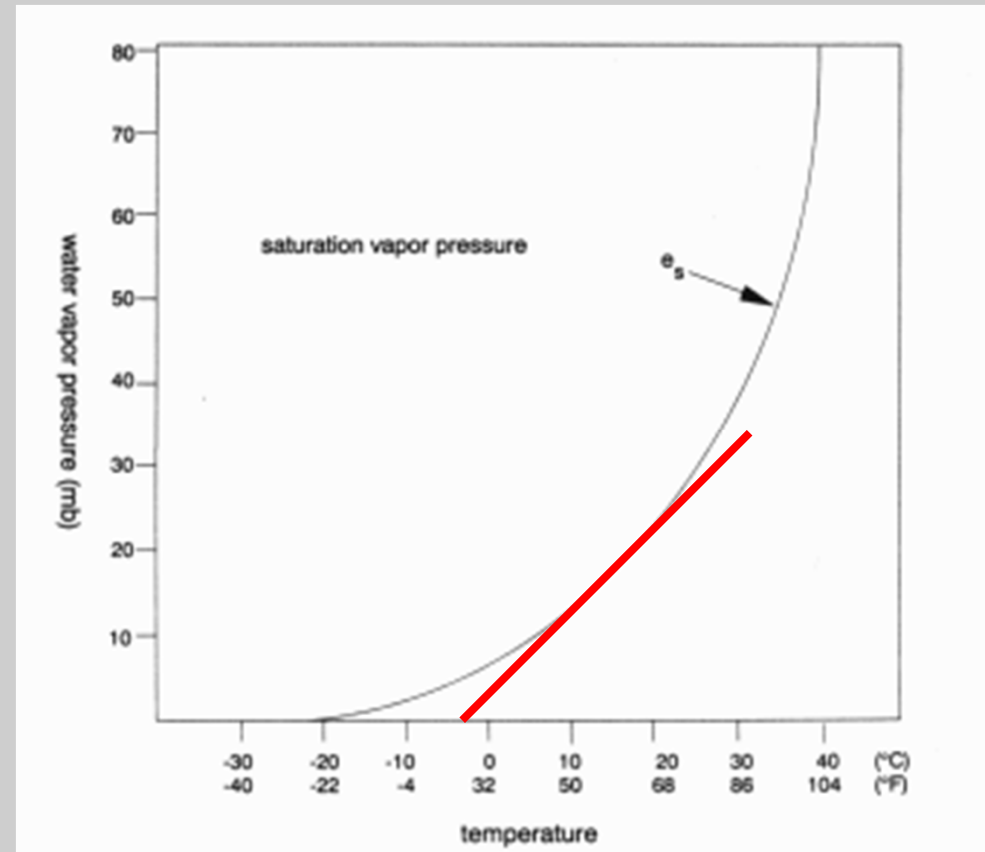
Clausius-Clapeyron

$$\frac{d \ln p}{dT} = \frac{\Delta H_{vap}}{RT^2}$$

+1°C ⇒ +7% H₂O

Probably:

+1°C ⇒ +2-4% H₂O



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GCM's & Climate Change Scenarios

Clausius-Clapeyron

$$\frac{d \ln p}{dT} = \frac{\Delta H_{vap}}{RT^2}$$

+1°C ⇒ +7% H₂O

Probably:

+1°C ⇒ +2-4% H₂O

or **7%???**

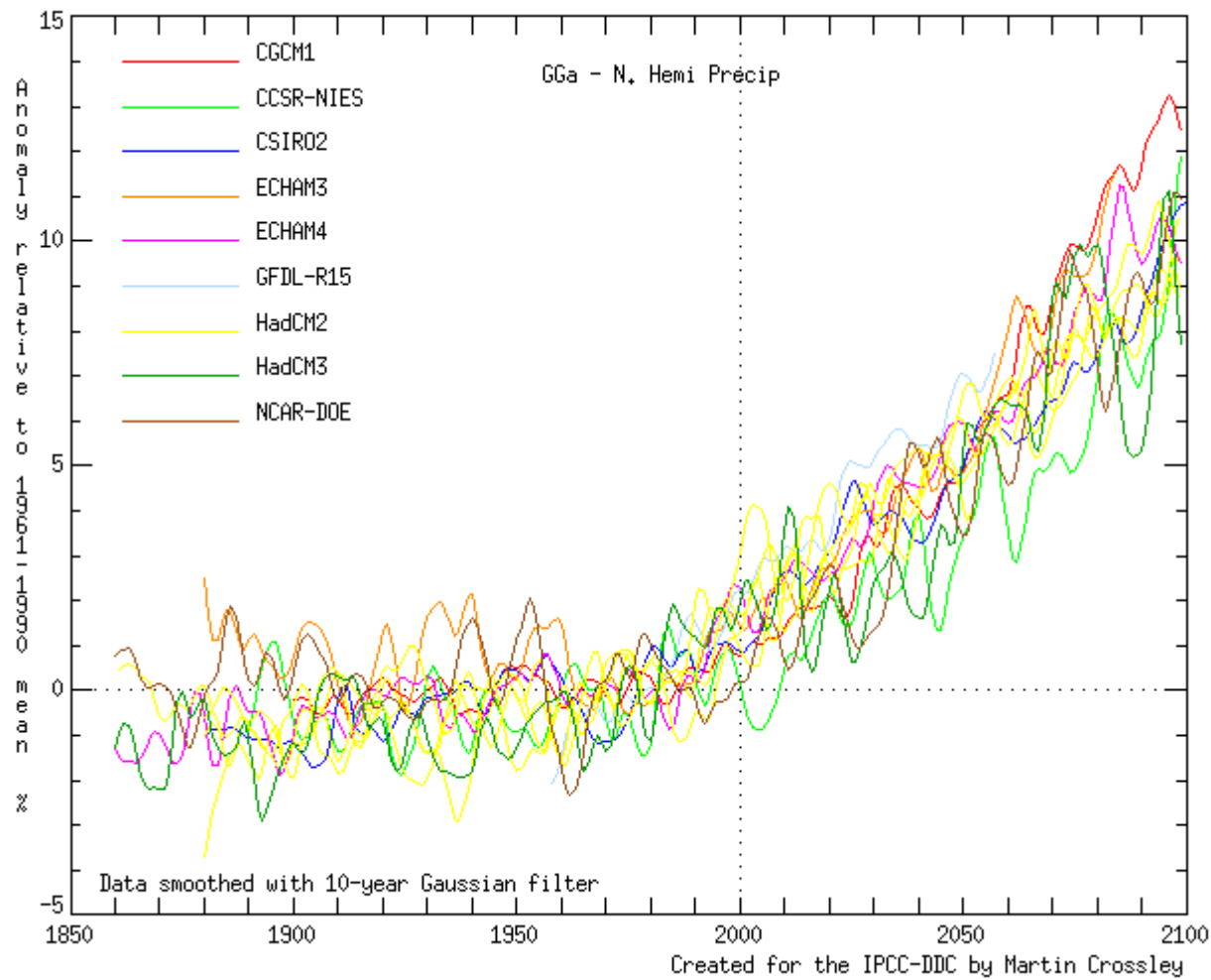


Science 289 July 2007



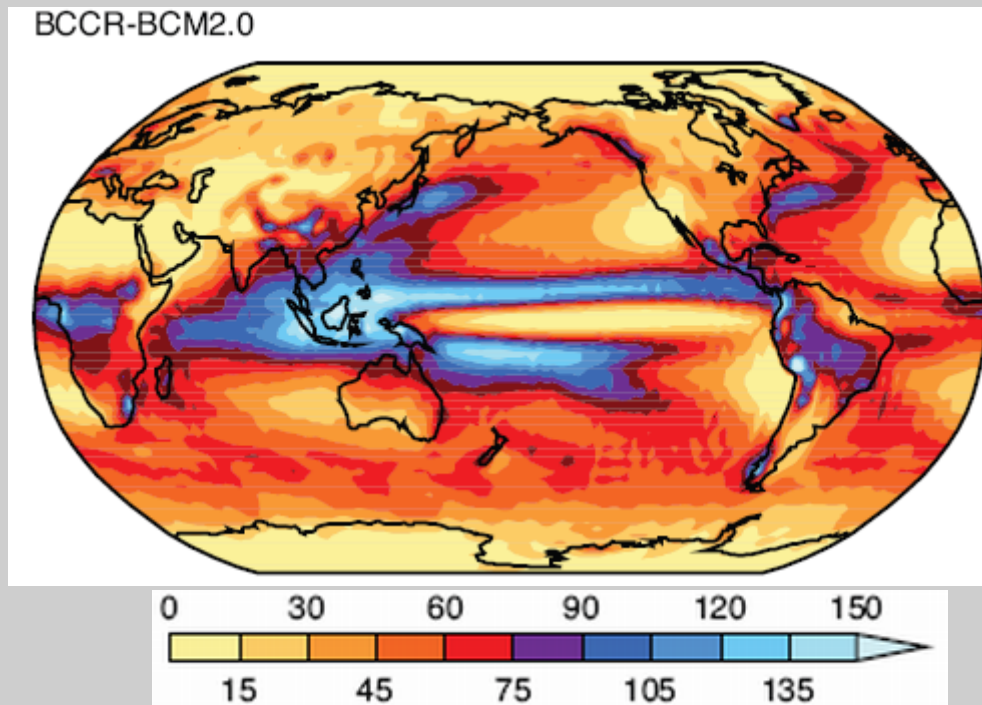
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GCM's & Climate Change Scenarios



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GCM's & Climate Change Scenarios



Error rainfall (cm)

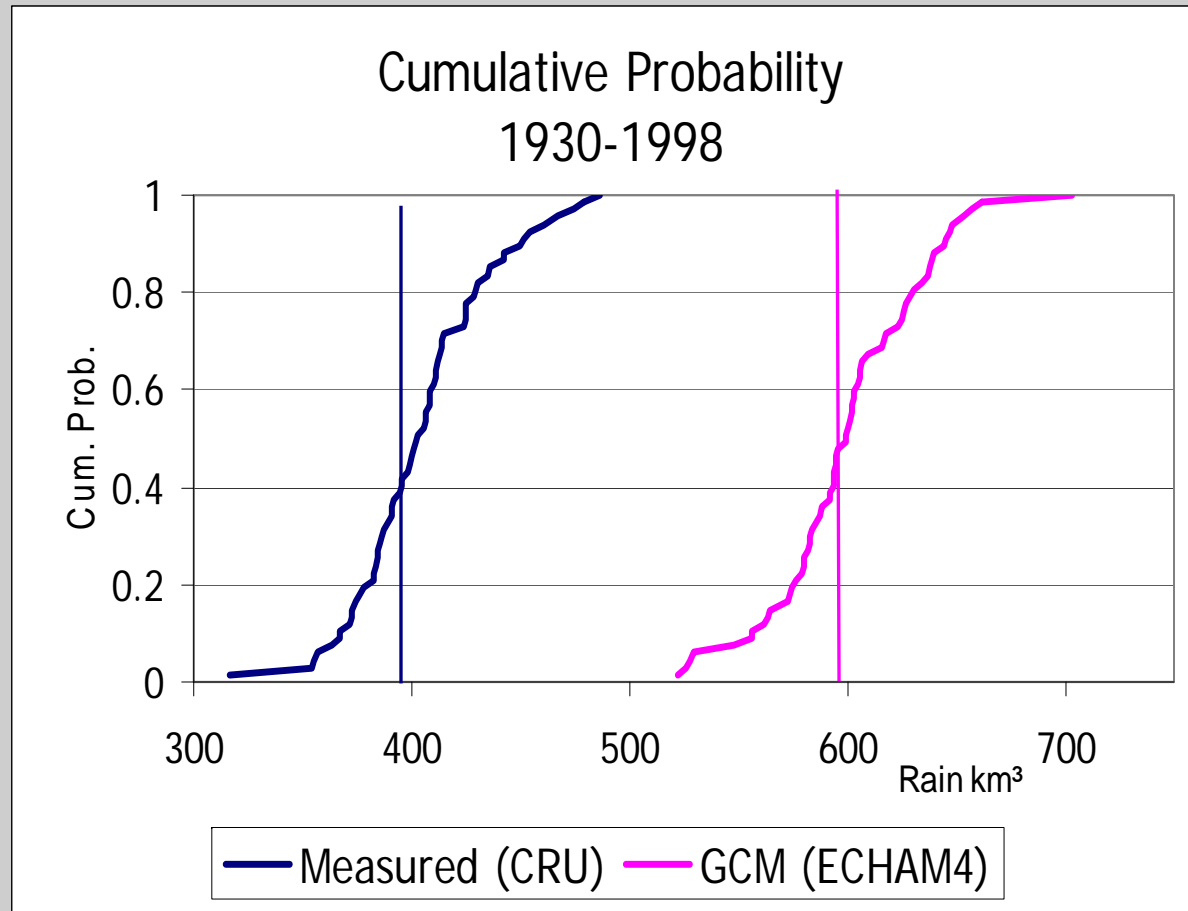


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Downscaling GCM's

- GCM's are not good for water
- GCM's are not good locally
- Strategies
 - KNMI
 - WaterGAP
 - Example Volta

Downscaling GCM's



Volta Basin



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Downscaling GCM's

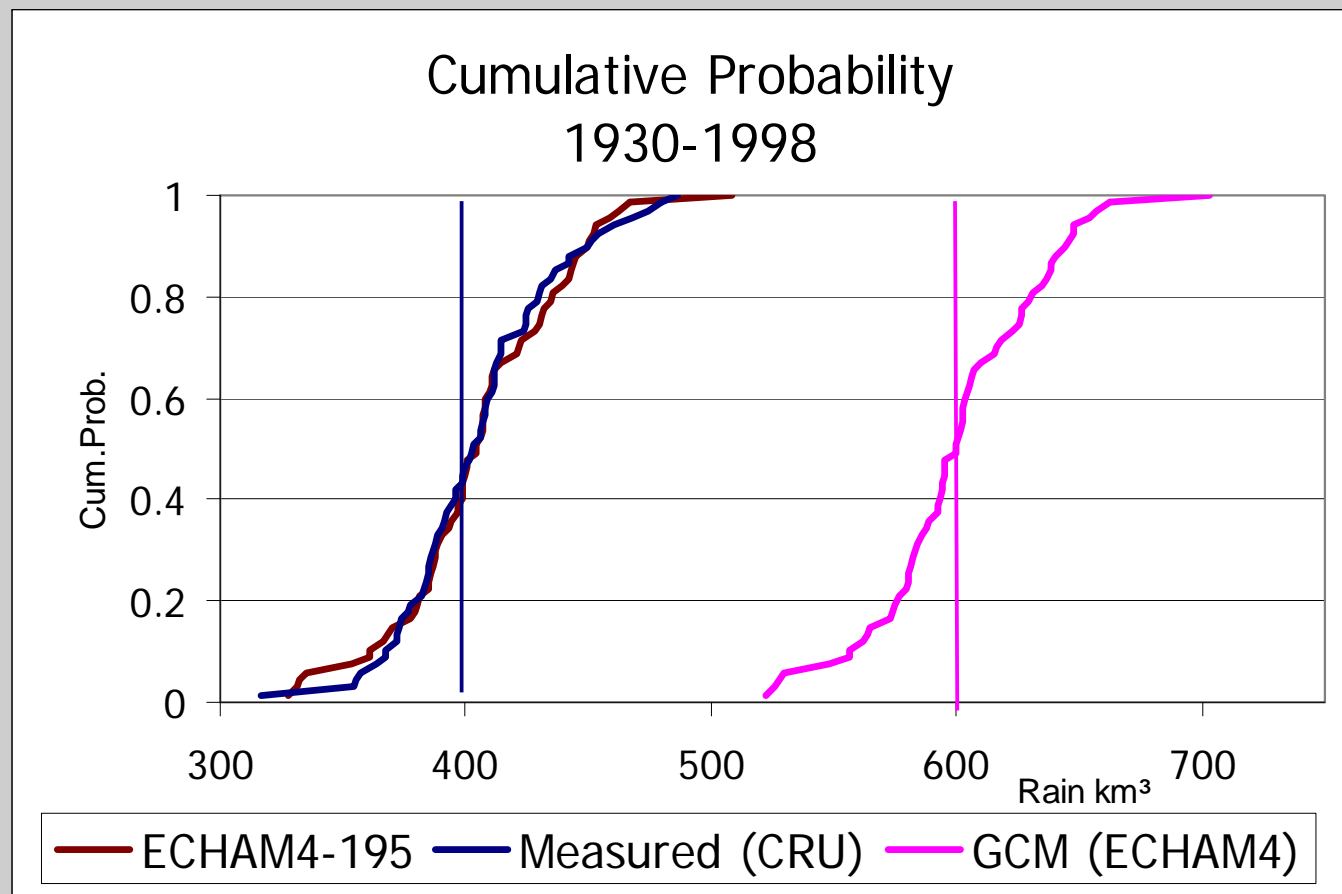
➤ Strategies

$$\hat{p}_1 \propto \mu_1 + \sigma_1 \hat{\chi}$$

$$\hat{p}_2 \propto \mu_2 + \sigma_2 \hat{\chi}$$

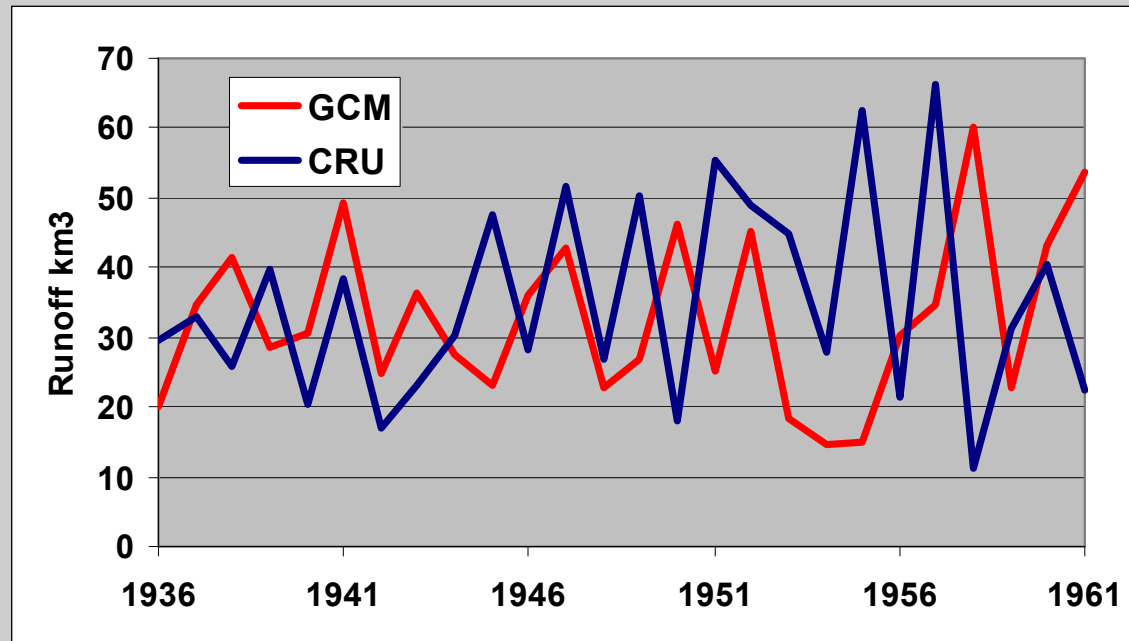
$$\hat{p}_2 \propto \mu_2 + \sigma_2 \frac{\hat{p}_1 - \mu_1}{\sigma_1}$$

Comparison Historical and GCM Rainfall, ECHAM4



Normalization: Subtract/Add Mean

Comparison GCM (ECHAM4) and Historical Runoff

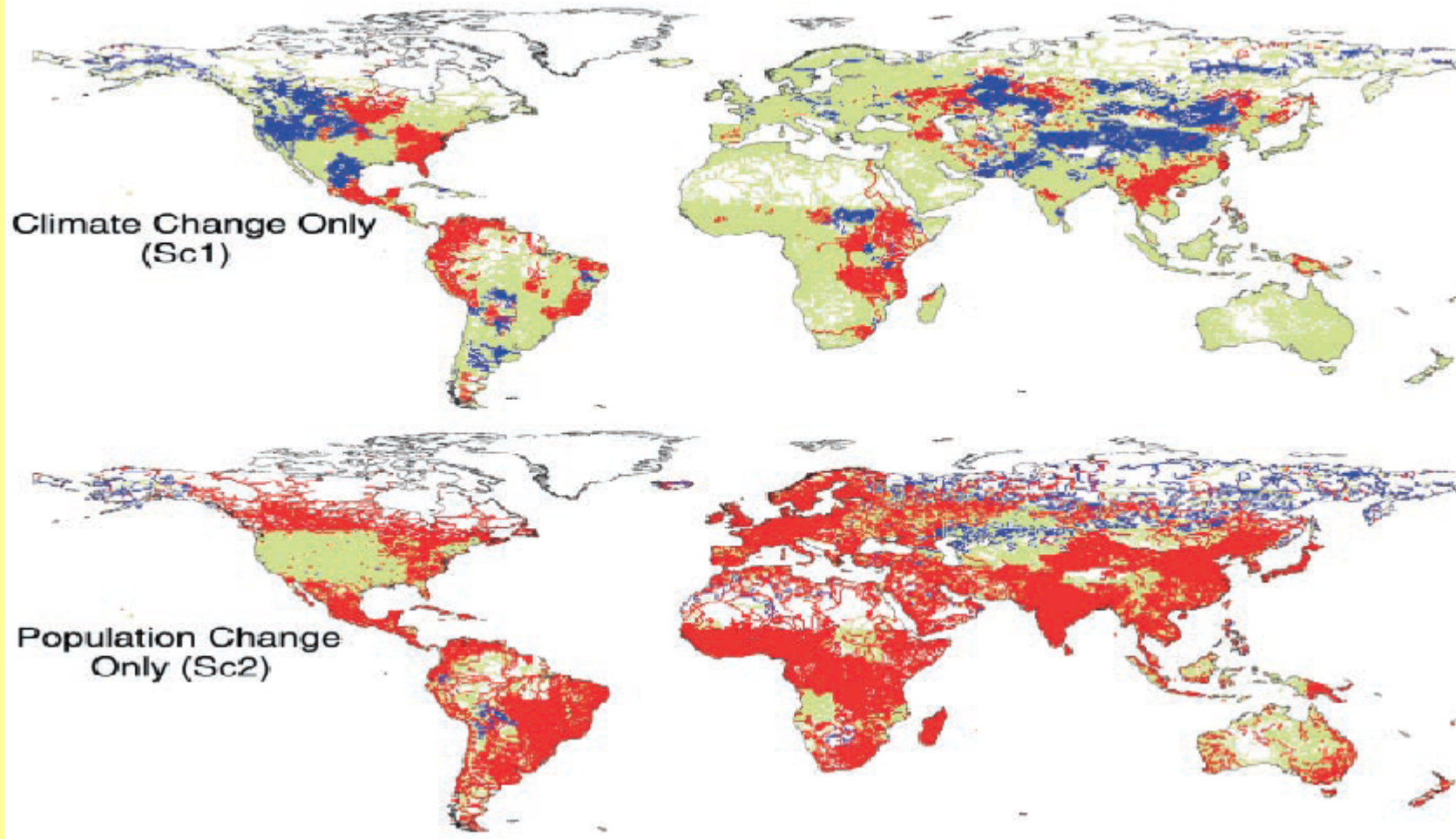


Normalization: Average Monthly Difference
Average OK (33 km^3 vs 36 km^3)
SD OK (12 km^3 vs 14 km^3)

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Climate uncertainty vs 1st order effects

Relative Change in Demand per Discharge

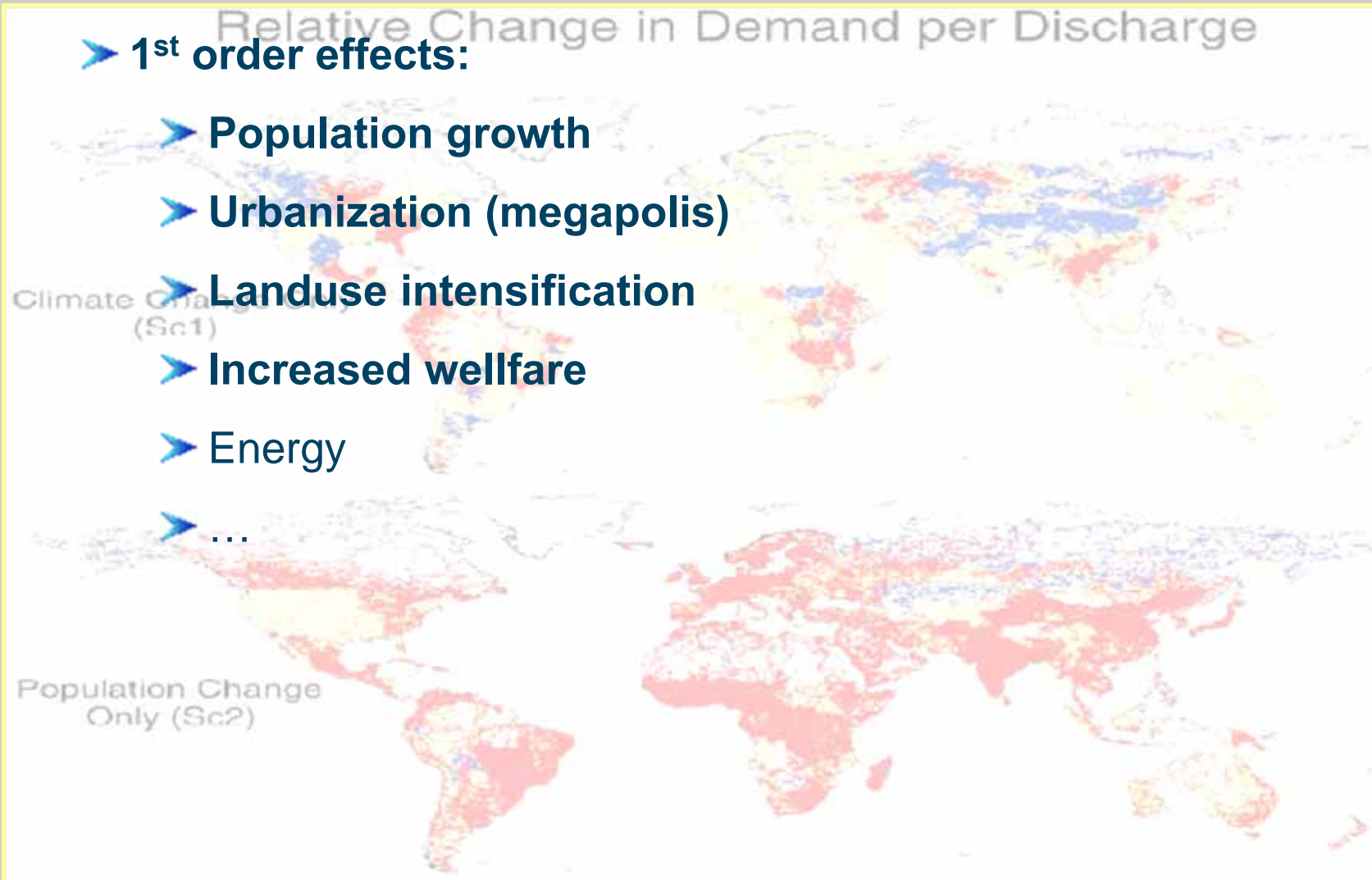


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Climate uncertainty vs 1st order effects

➤ **1st order effects:**

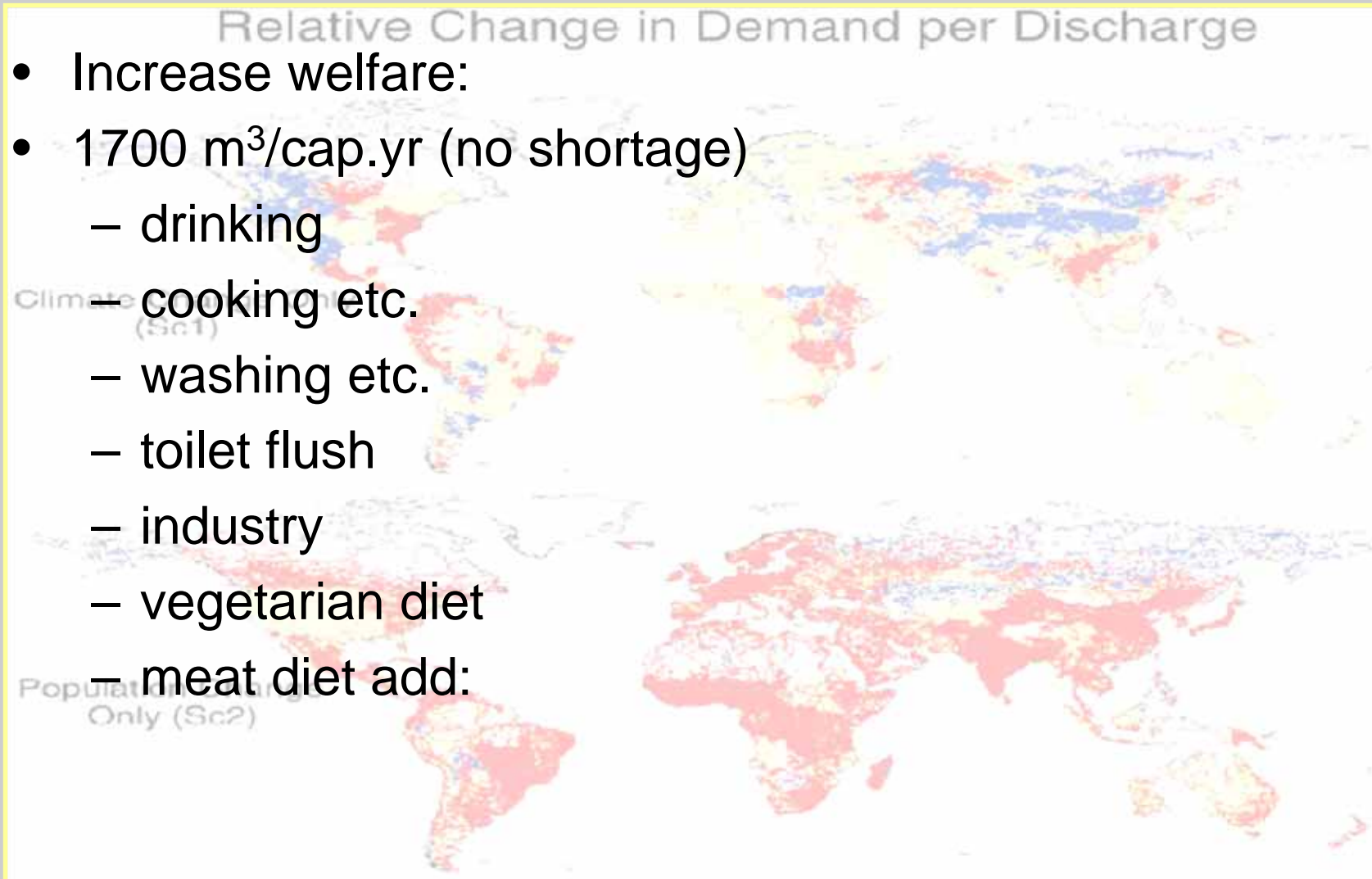
- **Population growth**
- **Urbanization (megapolis)**
- **Landuse intensification**
- **Increased welfare**
- **Energy**
- **...**



Week 2: Scenarios & Tools

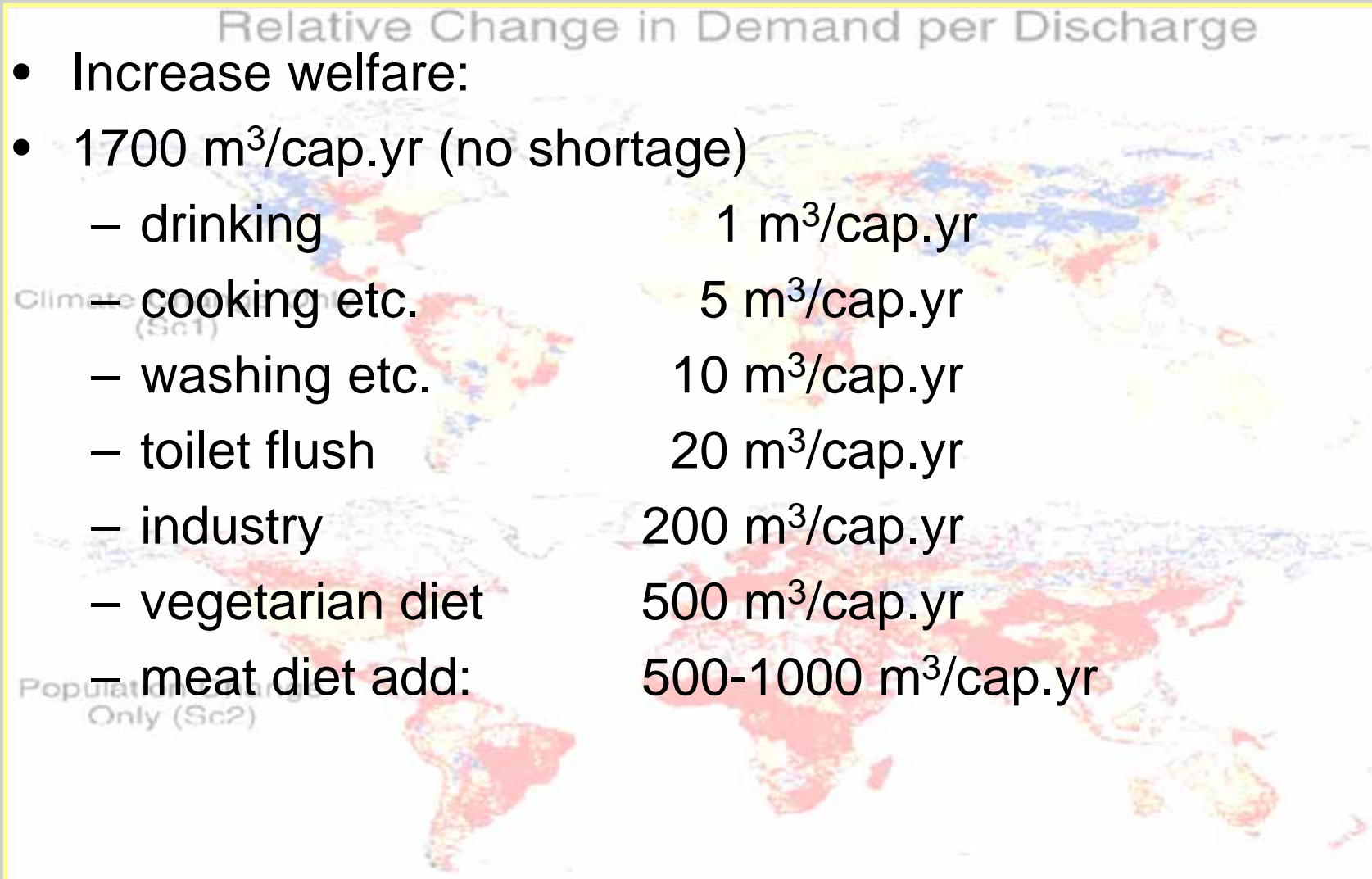
Climate uncertainty vs 1st order effects

- Increase welfare:
- 1700 m³/cap.yr (no shortage)
 - drinking
 - cooking etc.
 - washing etc.
 - toilet flush
 - industry
 - vegetarian diet
 - meat diet add:



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Climate uncertainty vs 1st order effects





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Sub-models

- Hydrology
- Water use:
 - Household
 - (Industry)
 - Irrigation
 - Hydropower
 - Ecology/temperature



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Hydrology:

Link between climate and management

- Rainfall – runoff models
 - Volta
 - Rhine
 - Bootstrap runoff records



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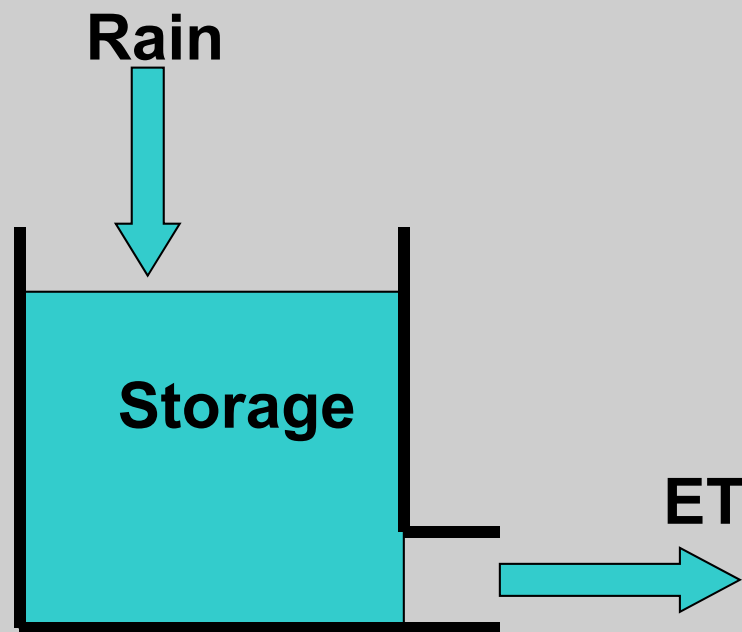
Hydrology: Data sources

- GRDC: <http://grdc.bafg.de>
- CRU: <http://www.cru.uea.ac.uk>
- GCM's: http://cera-www.dkrz.de/IPCC_DDC/
 - Volta: GLOWA Volta CD
 - Rhine: <http://www.iksr.de>

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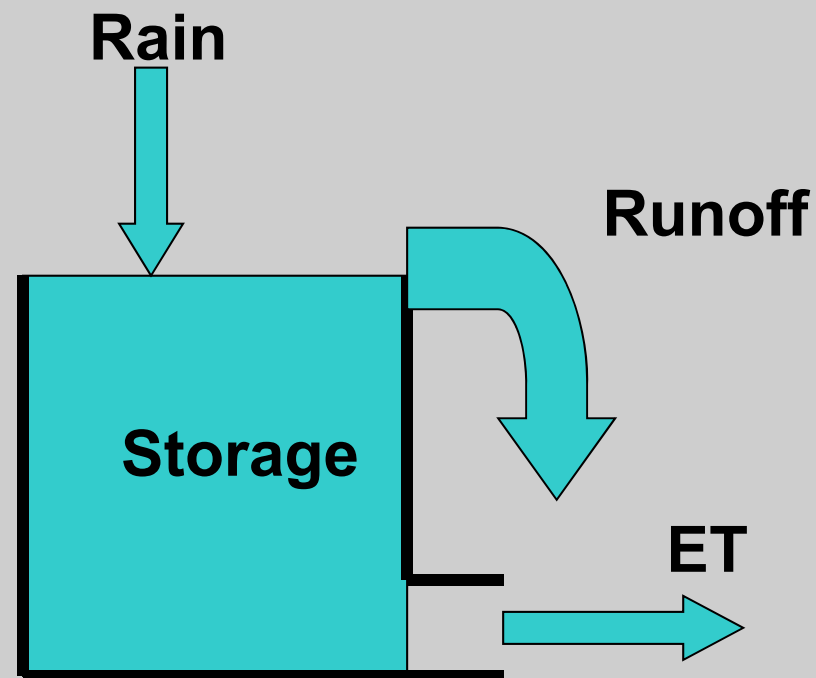
Simple hydrological models

Volta



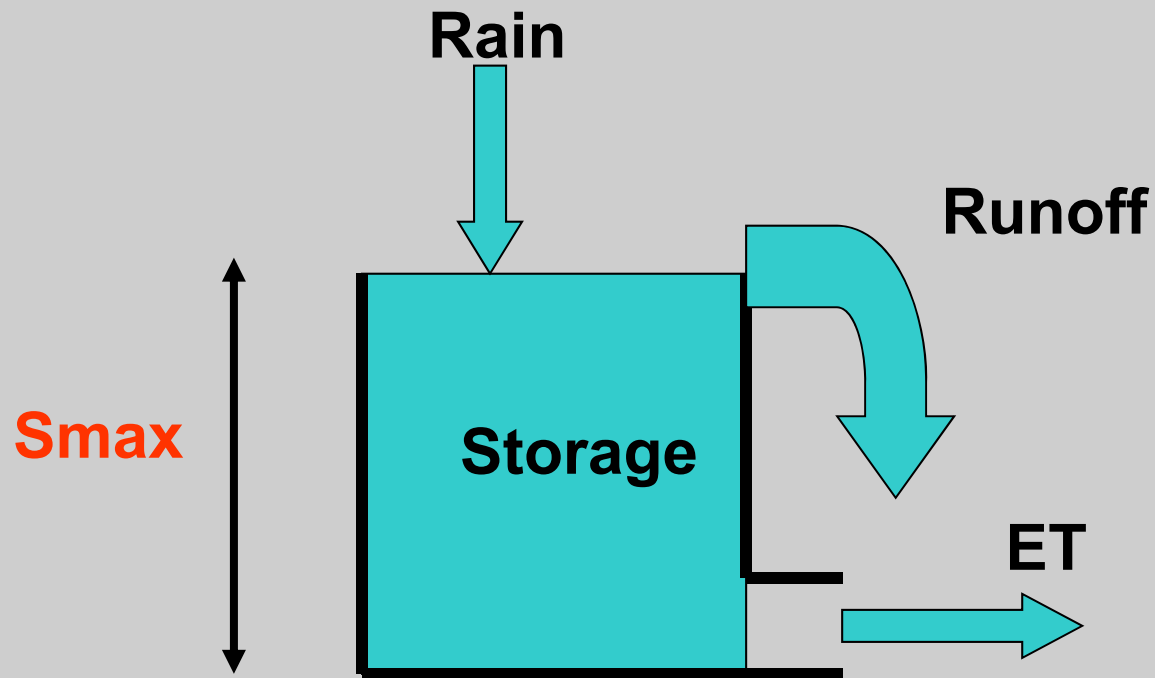
Simple hydrological models

Volta



Simple hydrological models

Volta





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Simple hydrological models

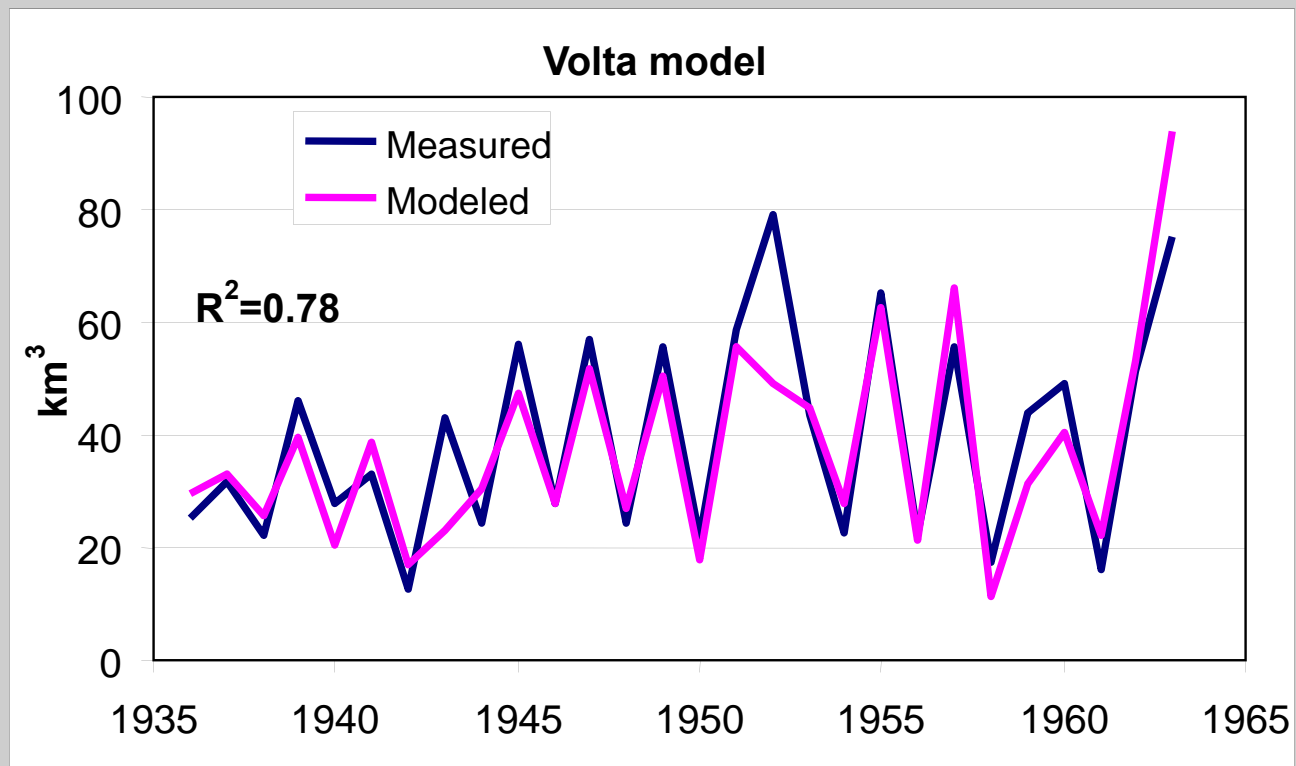
Volta

Bucket model

1. $S'_n = S_{n-1} + P_n$
2. $Q_n = \max(S'_n - S_{\max}, 0)$
3. $S''_n = S'_n - Q$
4. $E = E_{\text{pot}} * (S''_n / S_{\max})$
5. $S_n = S''_n - E$

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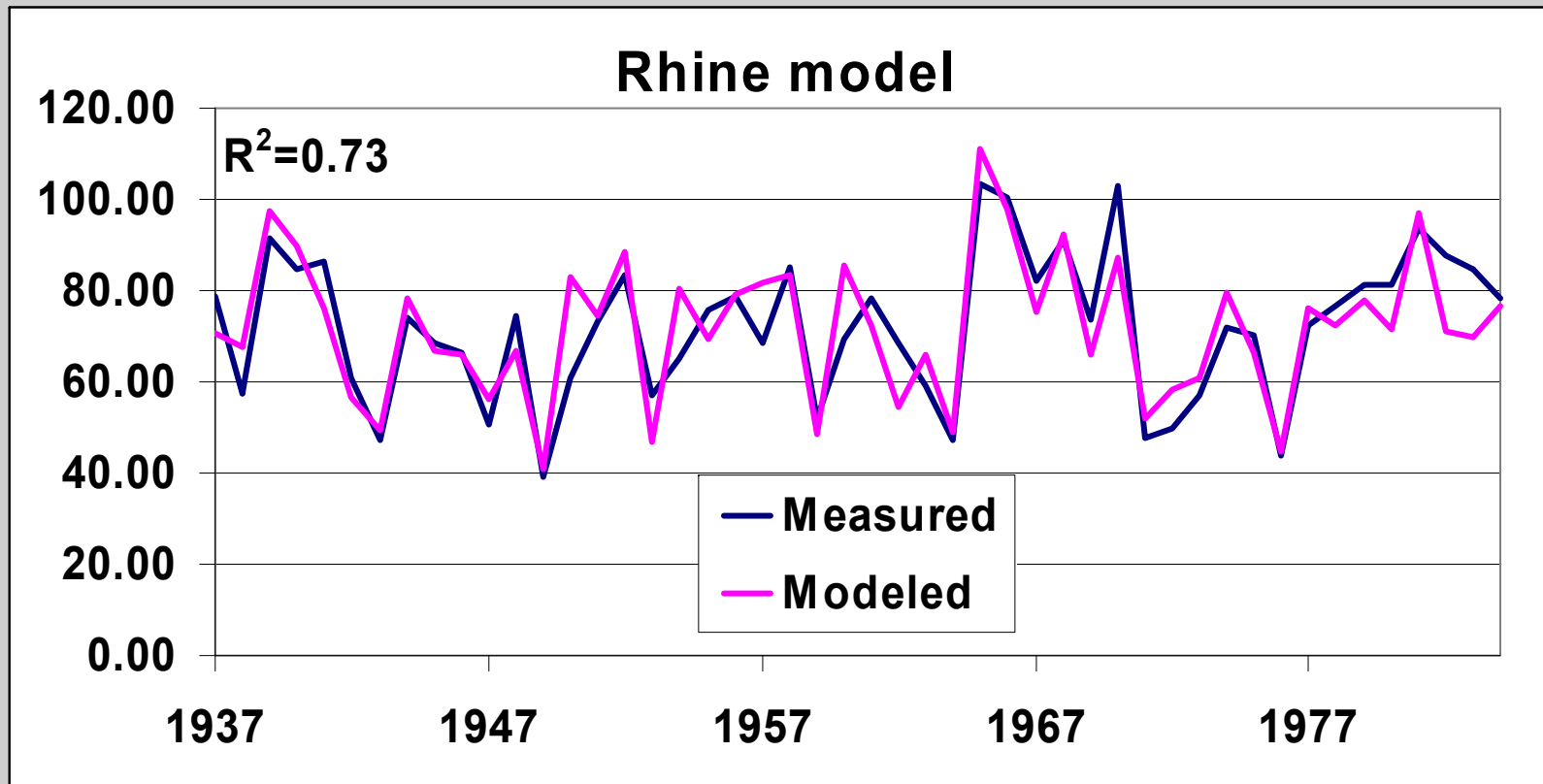
Simple hydrological models



Bucket model

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Simple hydrological models



Bucket model



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Simple hydrological models

Rhine - alternative

Bucket model

- Good for water limited evaporation
- Reaction within time step



Week 2: Scenarios & Tools

Simple hydrological models

Rhine - alternative

Moving average:

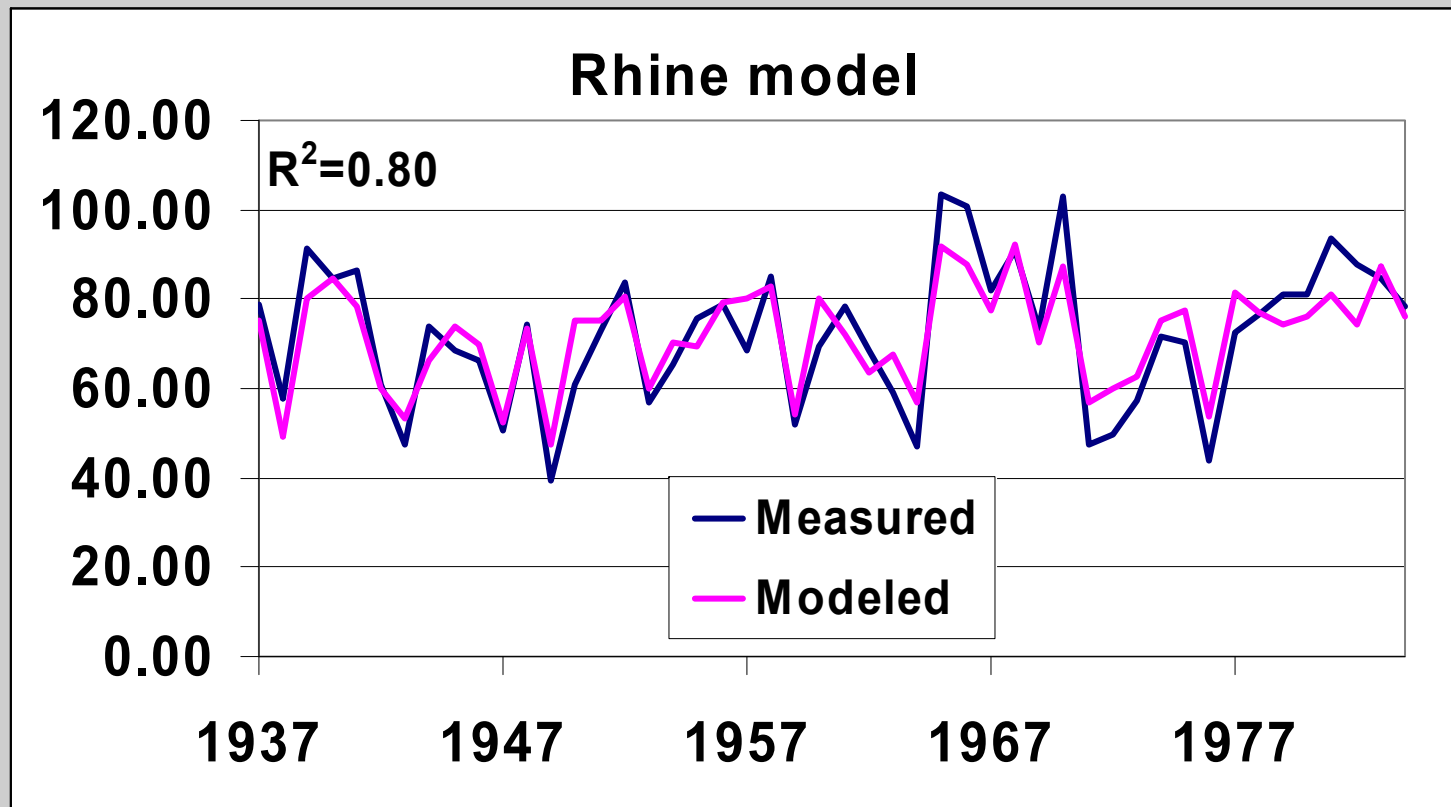
$$1. S'_n = S_{n-1} + P_n$$

$$2. Q_n = \alpha(S'_n + S_{n-1} + S_{n-2}) + \beta(S_{n-3} + \dots) + \gamma(S_{n-6}) + \delta$$

$$3. S_n = S'_n - Q$$

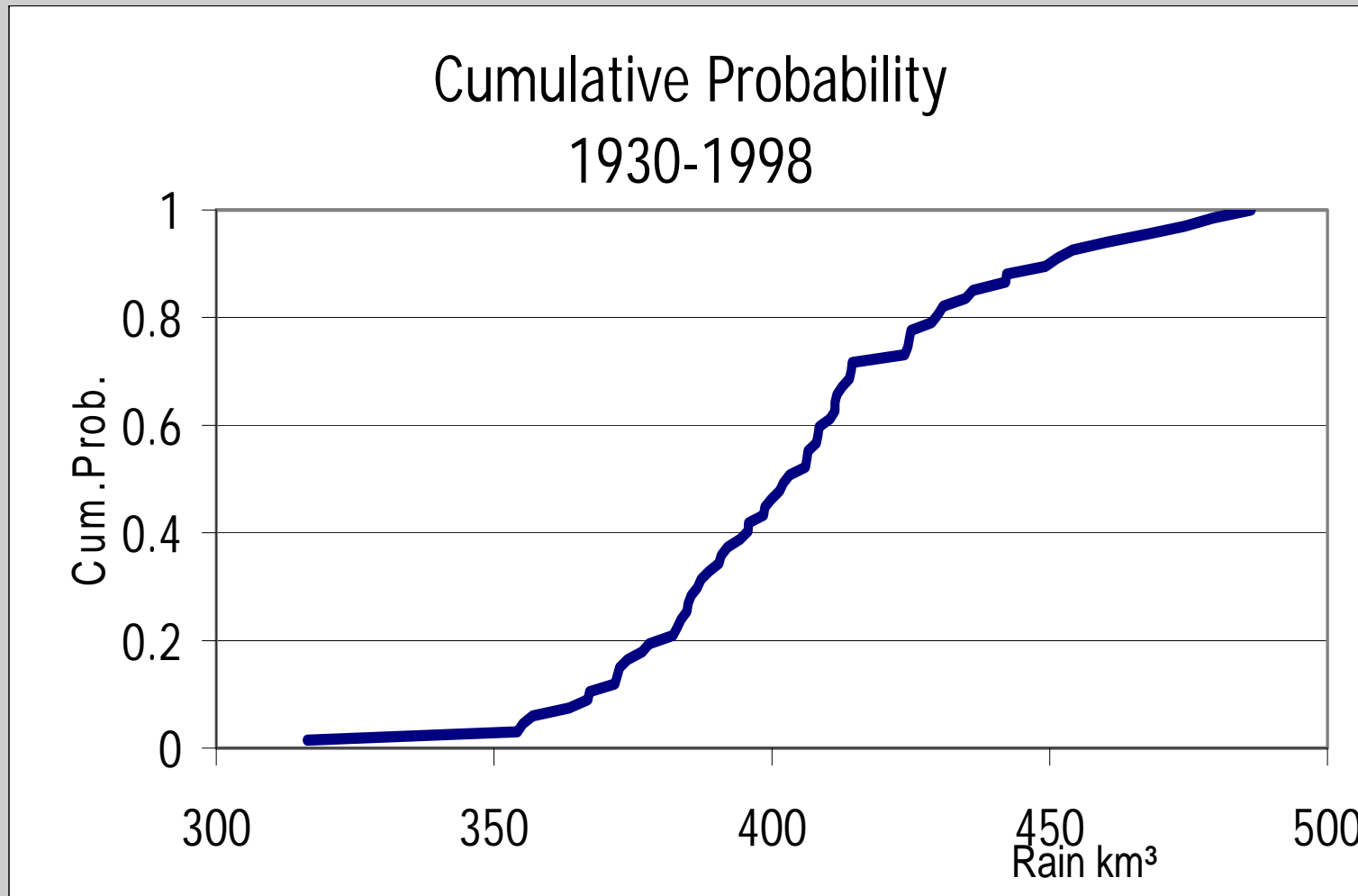
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Simple hydrological models

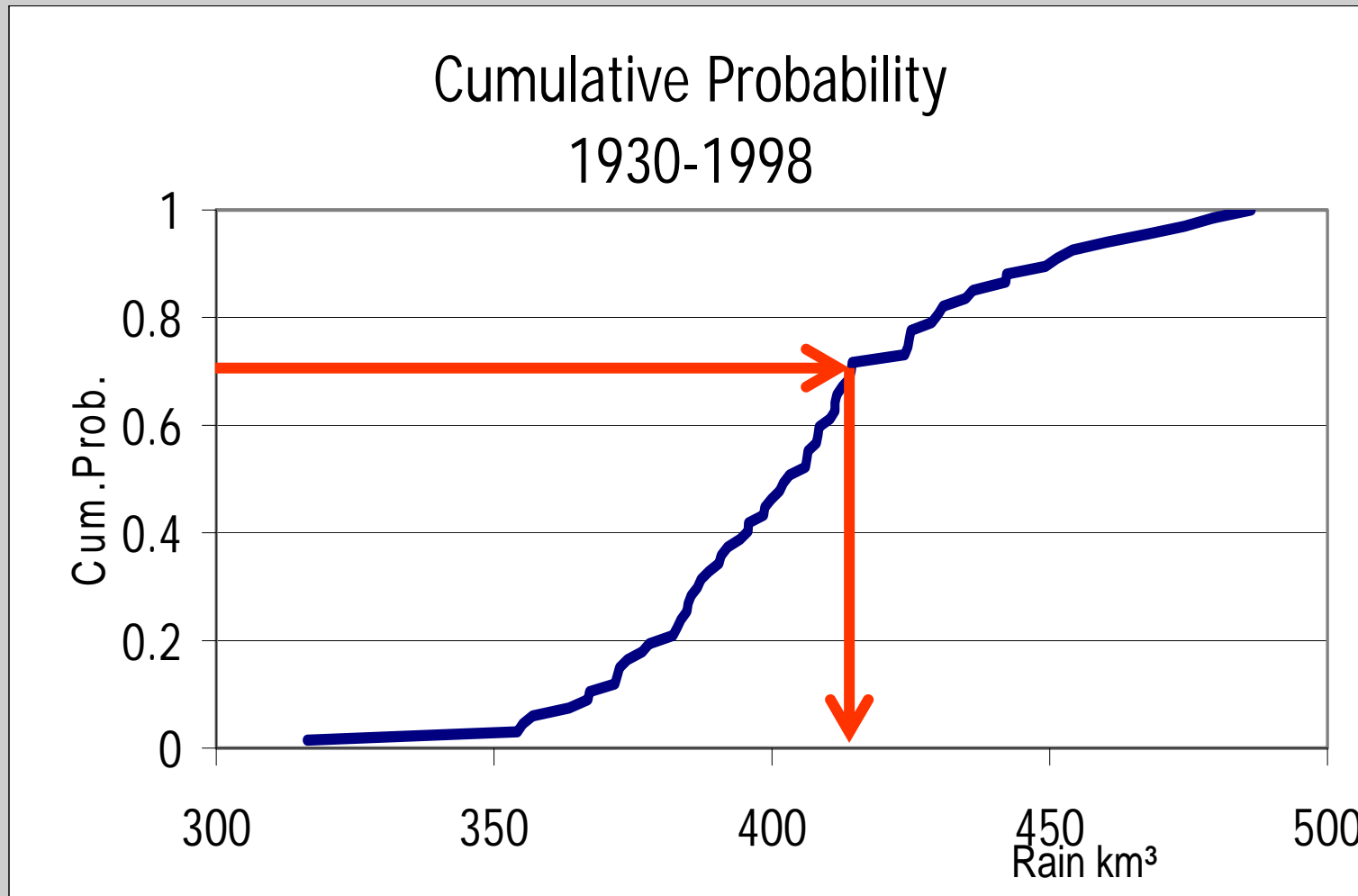




Boot strapping

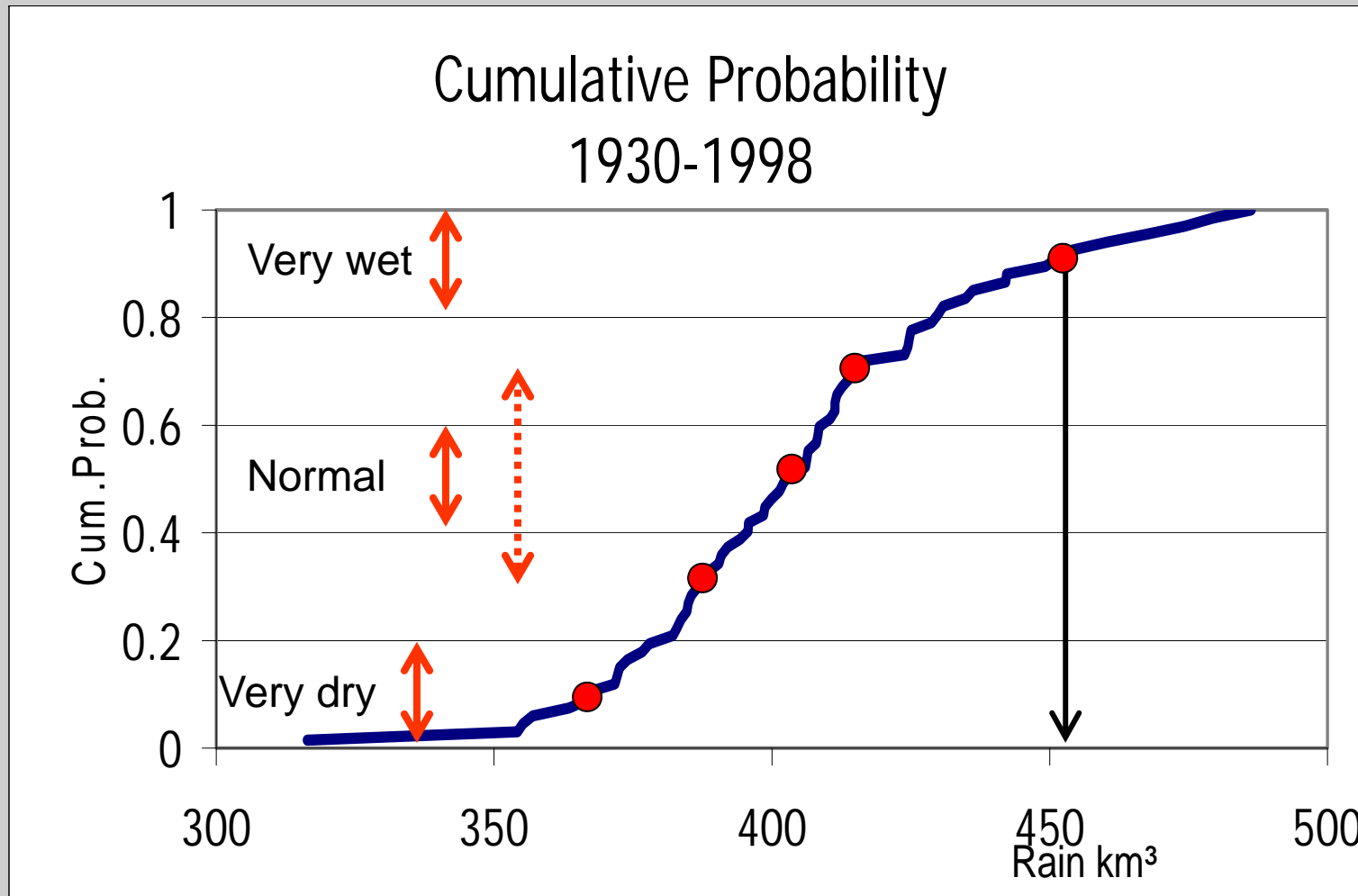


Boot strapping





Boot strapping





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Boot strapping

- Year method:
 1. Determine relevant percentiles
 2. Random number generator
 3. Random order of:
 - very wet (very cold)
 - wet (cold)
 - normal
 - dry (warm)
 - very dry (very warm)



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Boot strapping

➤ Year method:

Scenarios:

Simply increase (decrease) fraction of dry, very dry, etc.

Boot strapping

- Year method
 - Scenarios:
 - Simply increase (decrease) fraction of dry, very dry, etc

- Alternative:
 - Transform CDF

$$\hat{p}_1 \propto \mu_1 + \sigma_1 \hat{\chi}$$

$$\hat{p}_2 \propto \mu_2 + \sigma_2 \hat{\chi}$$

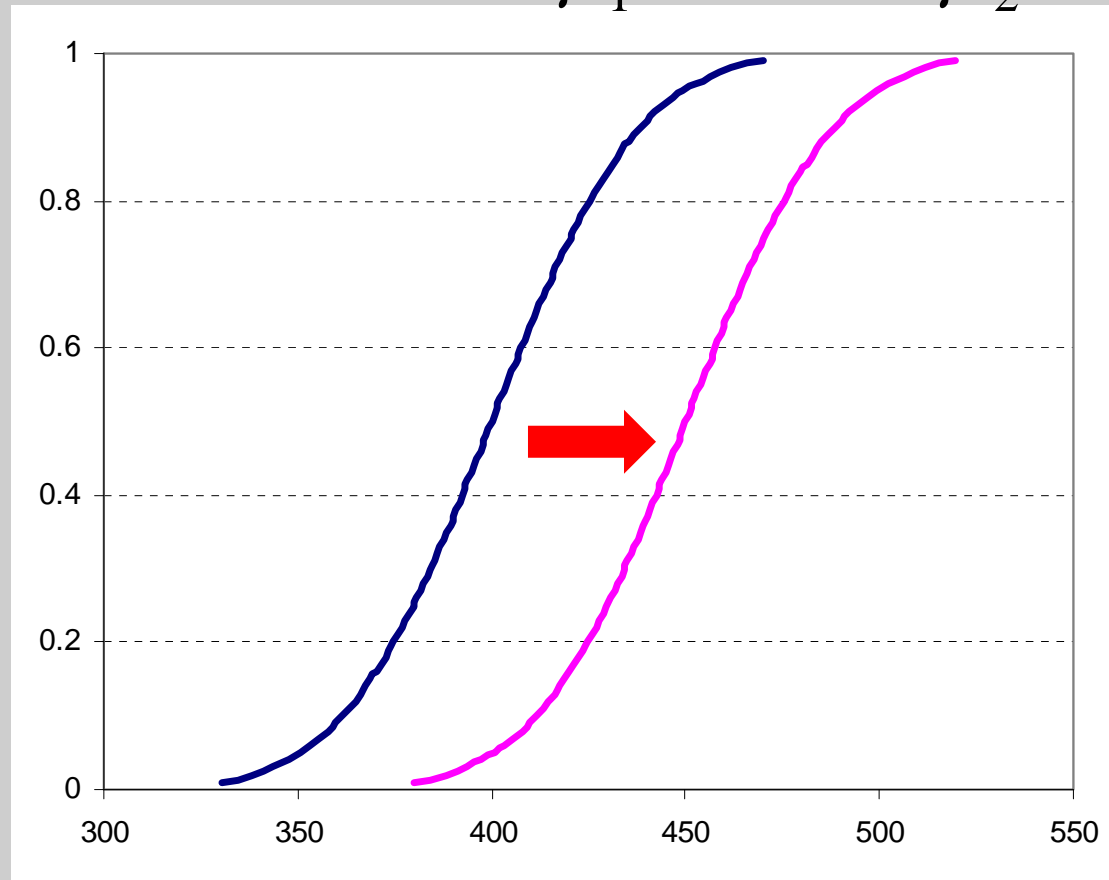
$$\hat{p}_2 \propto \mu_2 + \sigma_2 \frac{\hat{p}_1 - \mu_1}{\sigma_1}$$

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Boot strapping

➤ Transform

$$\mu_1 = 400 \quad \mu_2 = 450$$



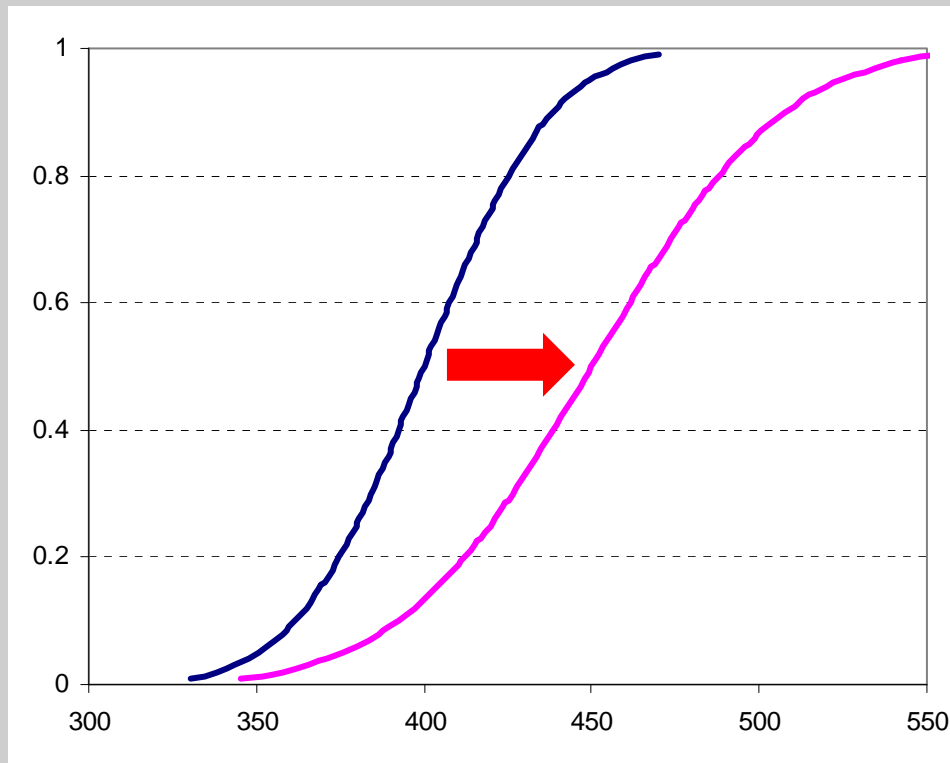
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Boot strapping

➤ Transform

$$\mu_1 = 400 \quad \mu_2 = 450$$

$$\sigma_1 = 30 \quad \sigma_2 = 45$$





Week 2: Scenarios & Tools

Sub-models:

- Water use (quantity & quality):
 - Household
 - Industry
 - Irrigation
 - Ecology
 - Hydropower
 - ...



Week 2: Scenarios & Tools

Sub-models, water use:

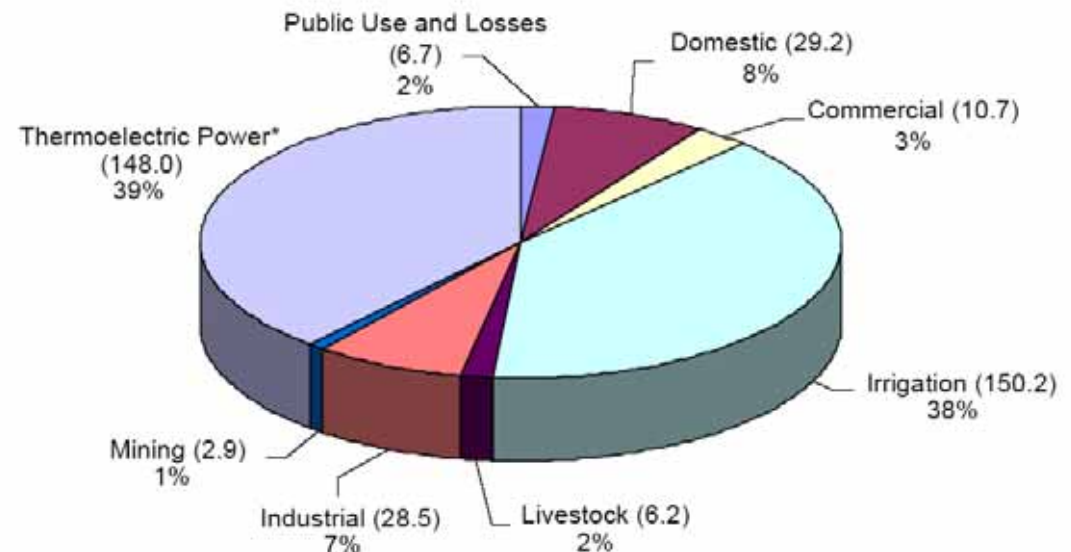
- Household:
 - Western Europe: 130 l/pd
 - Africa urban: 90 l/pd
 - Africa rural: 40 l/pd
 - Demography!

<http://esa.un.org/unpp/>

Week 2: Scenarios & Tools

Sub-models, water use:

- Industry:
 - Very specific
 - Quality
 - Heavy industry
 - Cooling



*Category includes water used in the generation of electric power with fossil-fuel, nuclear, or geothermal energy.

Source: Solley, W.B., R.R. Pierce, H.A. Perlman (1998). Estimated Use of Water in the United States in 1995. Geological Survey Circular 1200.

Water use USA, 1995

http://www.oit.doe.gov/pdfs/100903_news.pdf

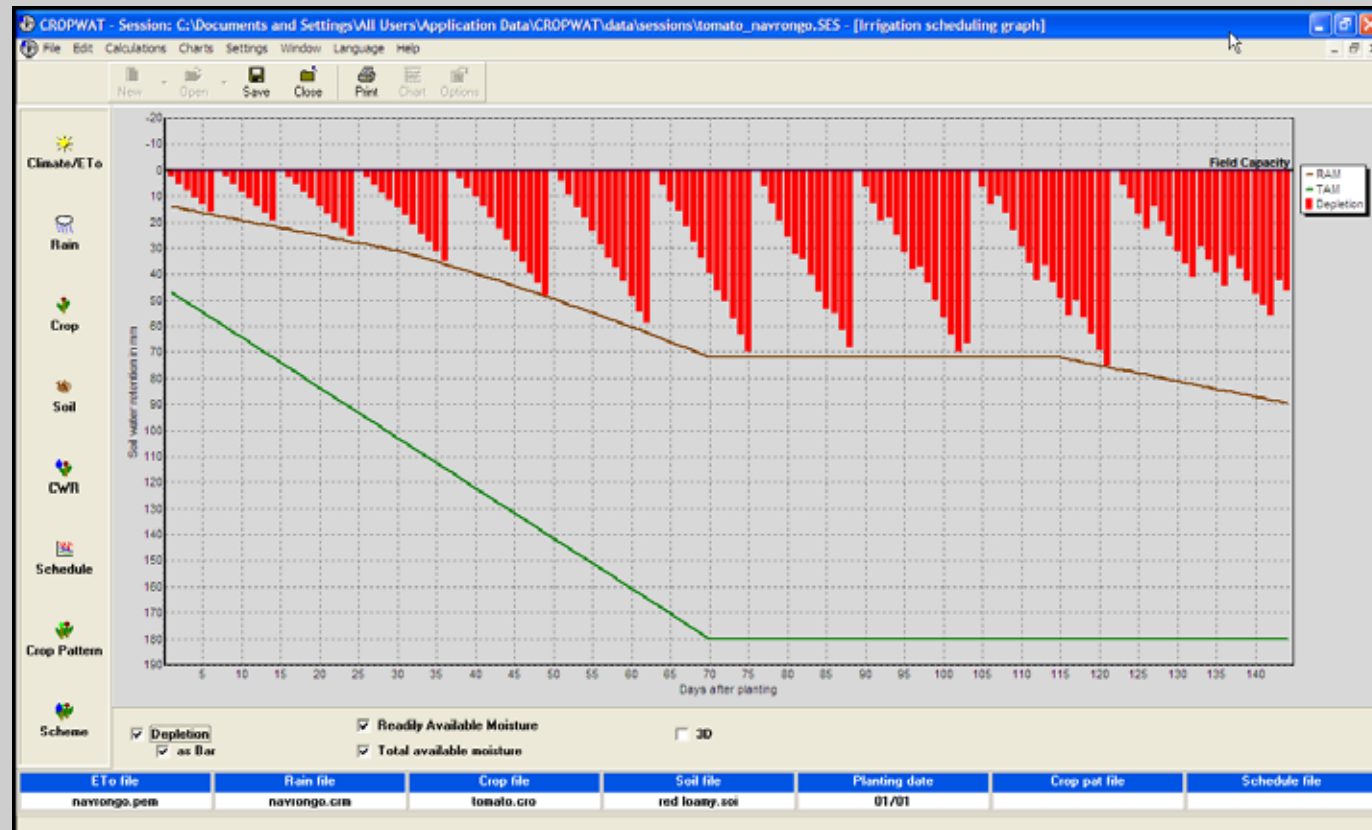


Week 2: Scenarios & Tools

Sub-models, water use:

➤ Irrigation, CropWat:

http://www.fao.org/nr/water/infores_databases_cropwat.html





Week 2: Scenarios & Tools

Sub-models, water use:

- Irrigation:
 - Crop use
 - Efficiencies (30%-60%)

- Article/Thesis Joshua Faulkner
- Thesis Ilja van Kinderen
(www.smallreservoirs.org)



Week 2: Scenarios & Tools

Sub-models, water use:

- Ecology:
 - Quantity (Minimal Streamflow Requirements)
 - Quality:
 - BOD5
 - Temperature
 - Pesticides
 - Heavy metals
 - Hormones
 - (caffeine)
 - ...



Week 2: Scenarios & Tools

Sub-models, water use:

- Ecology:
 - Quantity (Minimal Streamflow Requirements)
 - Quality:
 - BOD5
 - **Temperature**
 - Pesticides
 - Heavy metals
 - Hormones
 - (caffeine)
 - ...



Week 2: Scenarios & Tools

Sub-models, water use:

- Ecology:
 - Quantity (Minimal Streamflow Requirements)
 - Quality:
 - QUAL2K
 - WEAP...also temperature!
 - Article Martijn Westhoff, HESS



Week 2: Scenarios & Tools

Sub-models, water use:

➤ Hydropower:

➤ $E_{\text{pot}} = m \cdot h \cdot g$ (Joule)

➤ $\text{Power} = m \cdot h \cdot g / T$ (Watt)

➤ Energy: 1 kWh = 3600×10^3 Joule = € 0.25

➤ Efficiency



Week 2: Scenarios & Tools

Sub-models, water use:

- Other models?
- Questions?



Week 2: Scenarios & Tools

Discussion / Q&A:

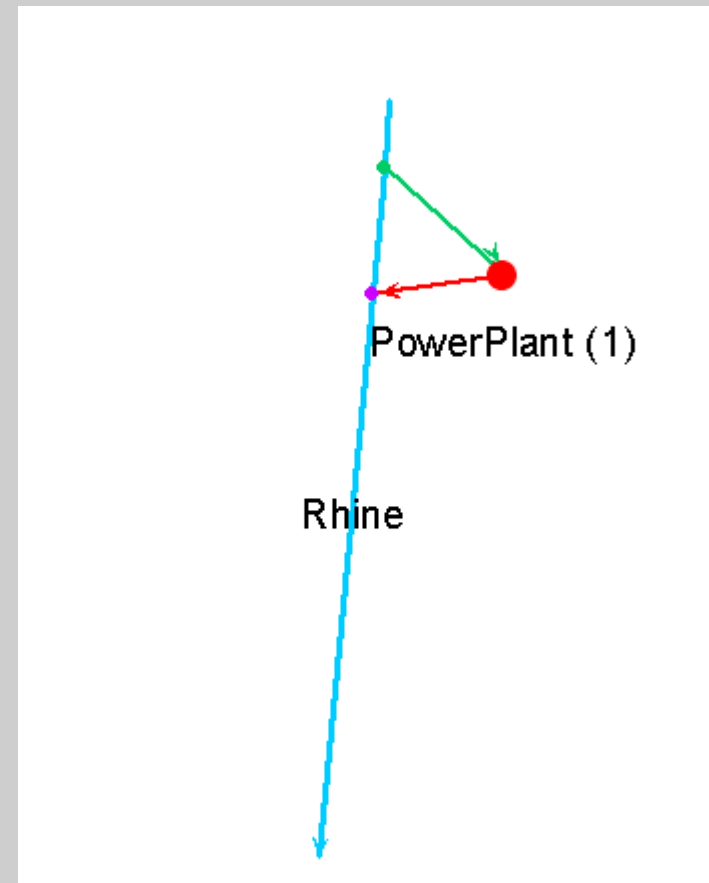
- What to do for Rhine?
- What to do for Volta?



Week 2: Scenarios & Tools

WEAP

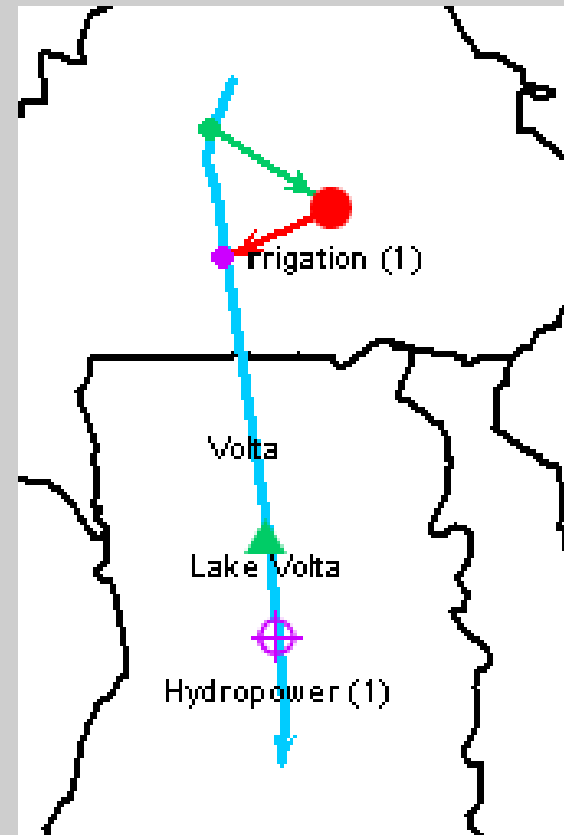
- Model development strategy
- mini-Rhine
- mini-Volta



Week 2: Scenarios & Tools

WEAP

- Model development strategy
- mini-Rhine
- mini-Volta





Week 2: Scenarios & Tools

WEAP

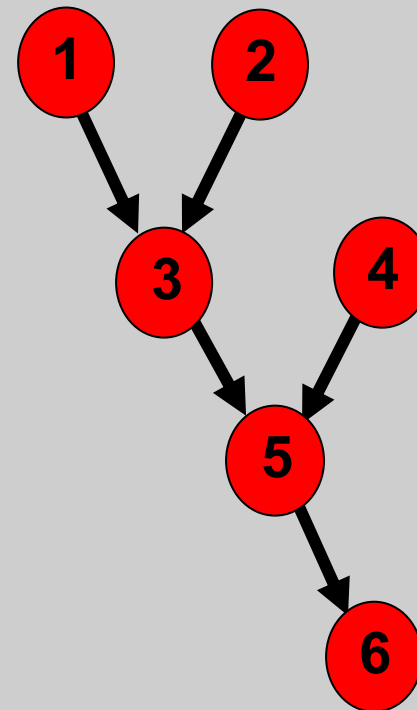
- Model development strategy
- mini-Rhine
- mini-Volta

THIS IS NOT A WEAP COURSE!



Graph Theory

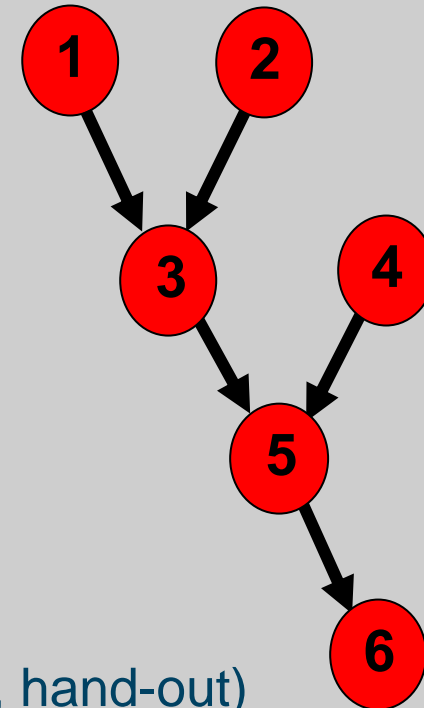
- Overview
- Exercise





Graph Theory

- Nodes & links/edges
 - Directed vs non-directed
 - Cyclic vs non-cyclic
 - Trees
 - Incidence & connectivity matrix (Excel, hand-out)



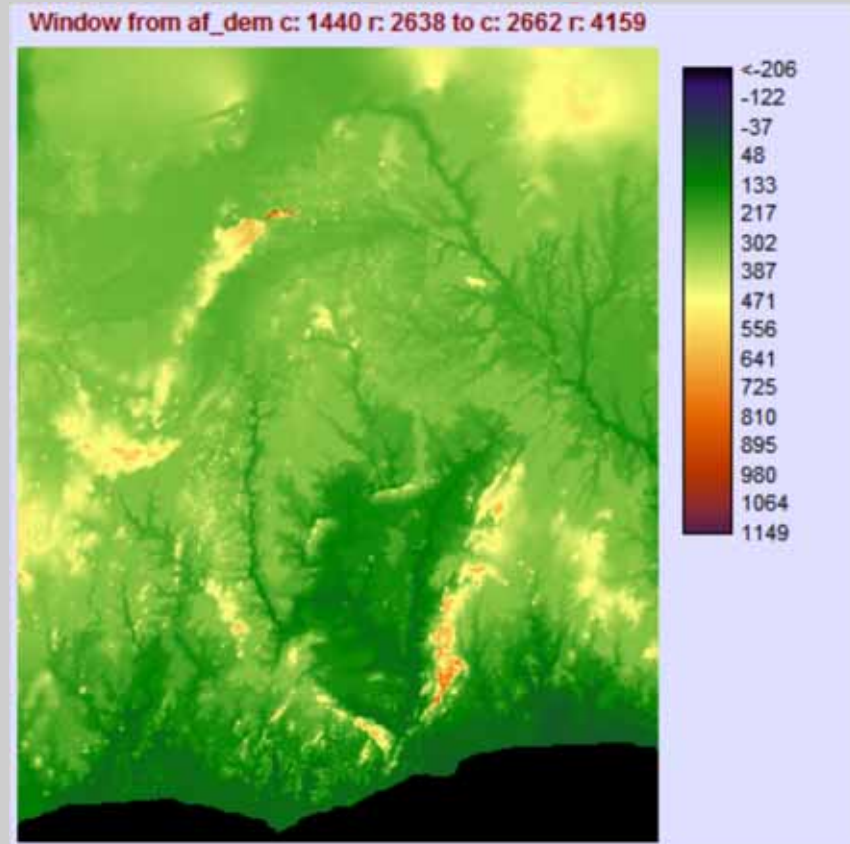


Week 2: Scenarios & Tools

Graph Theory

➤ DEM Analysis

1. DEM

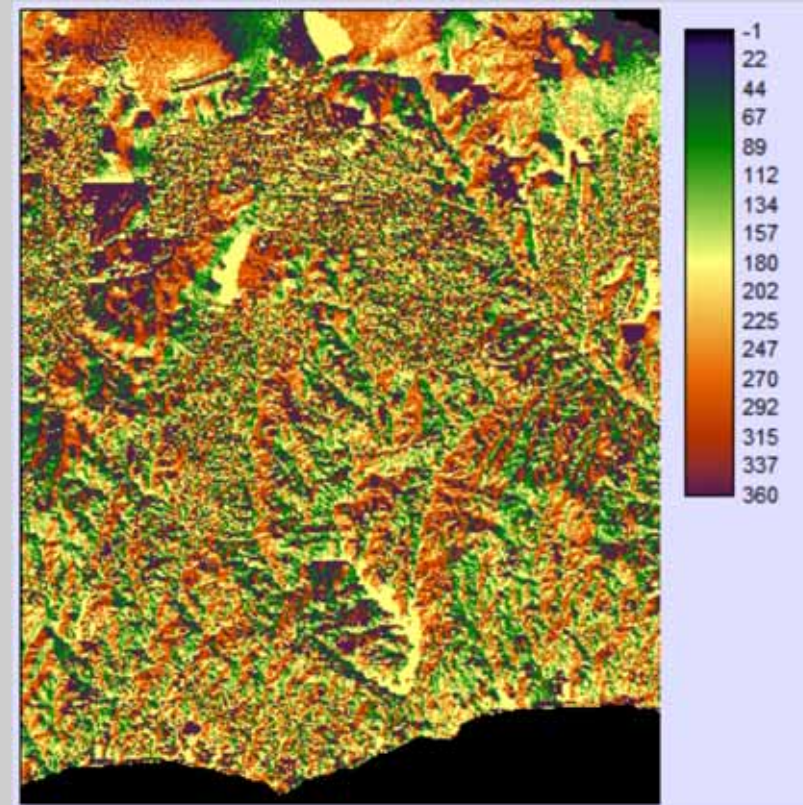




Week 2: Scenarios & Tools

Graph Theory

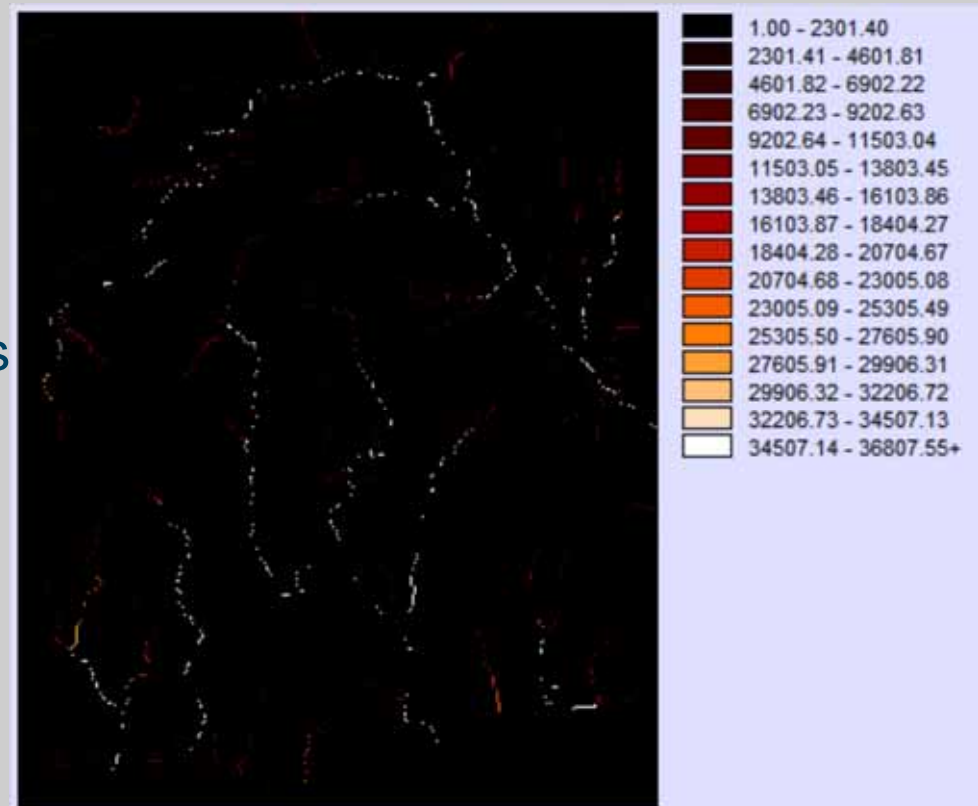
- DEM Analysis
 1. DEM
 2. Flow direction





Graph Theory

- DEM Analysis
 1. DEM
 2. Flow direction
 3. Invert/sum columns



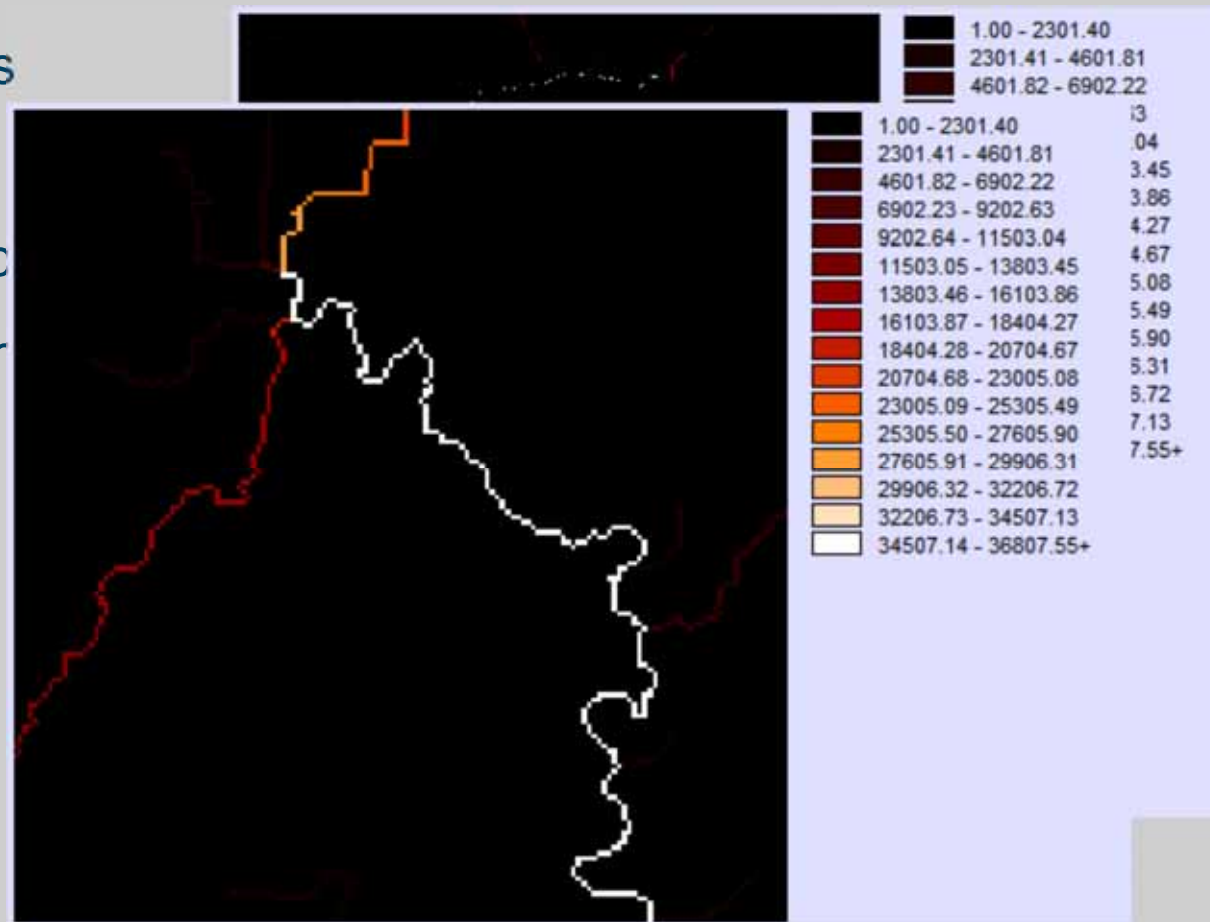


Graph Theory

► DEM Analysis

1. DEM
2. Flow direction
3. Invert/sum

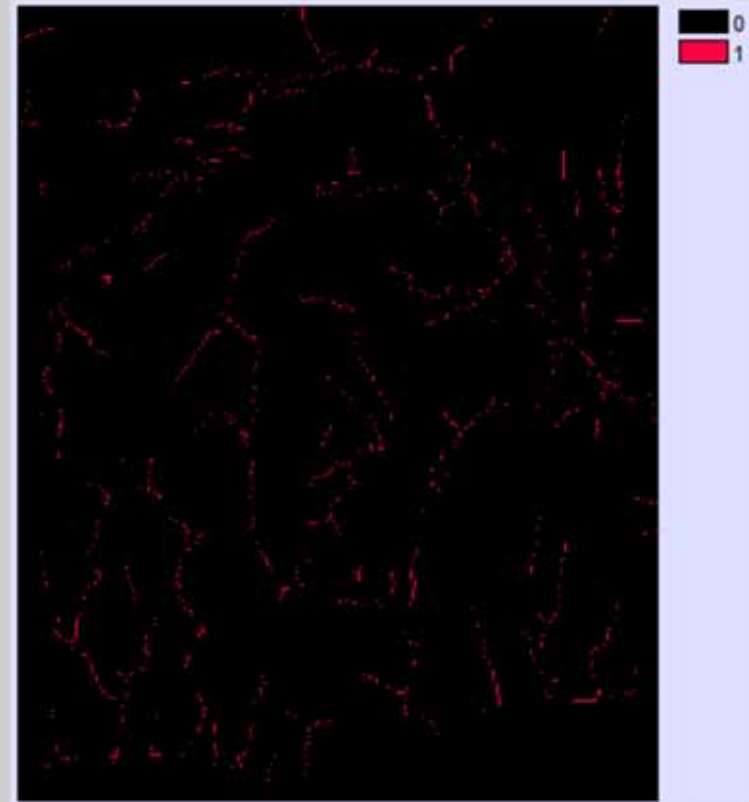
ZOOM





Graph Theory

- DEM Analysis
 1. DEM
 2. Flow direction
 3. Invert/sum columns
 4. River network

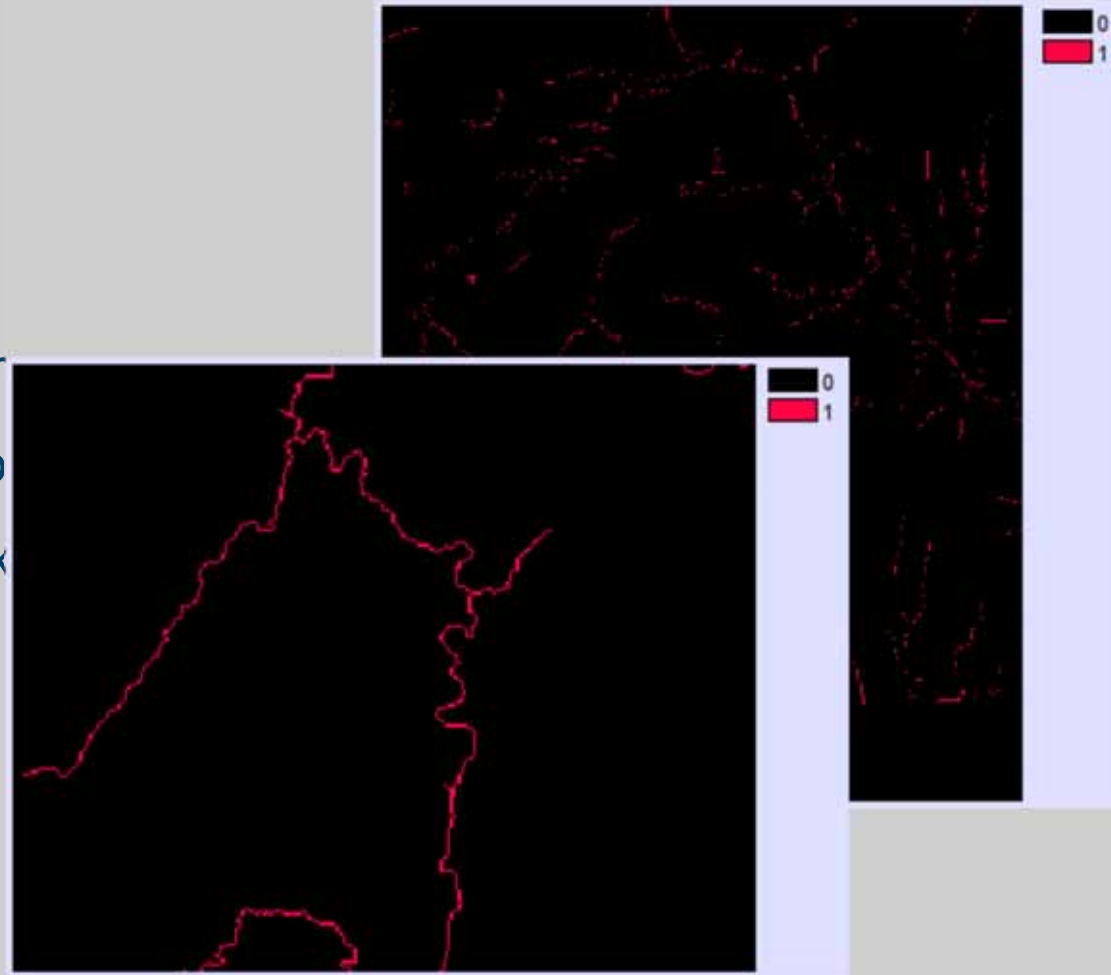




Week 2: Scenarios & Tools

Graph Theory

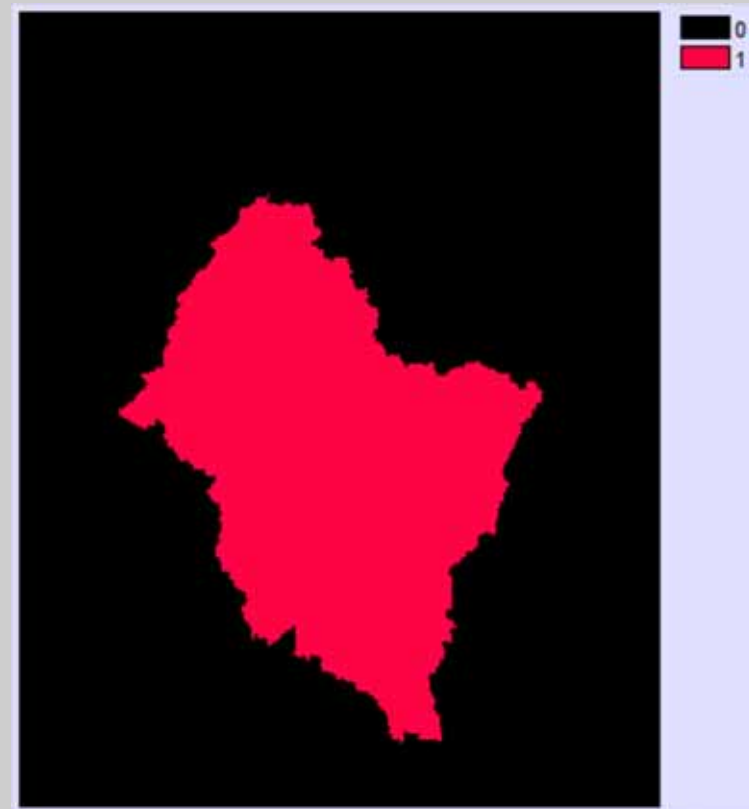
- DEM Analysis
 1. DEM
 2. Flow direction
 3. Invert/sum co
 4. River network



ZOOM

Graph Theory

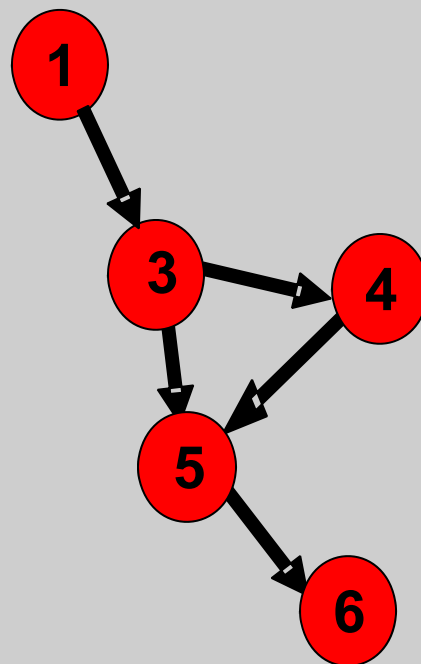
- DEM Analysis
 1. DEM
 2. Flow direction
 3. Invert/sum columns
 4. River network
 5. Watershed



Graph Theory

➤ Exercise

How does this work for a WEAP-like node network?



Use percentages of flow.