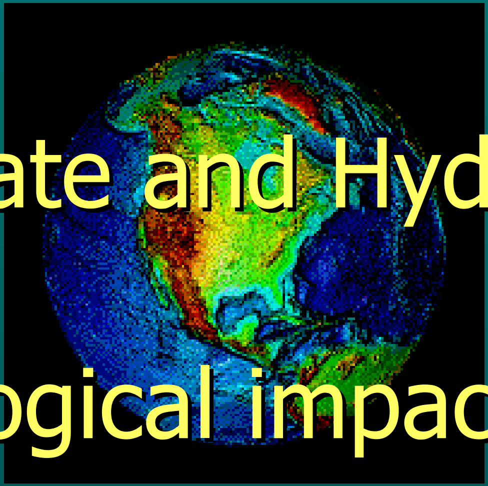
Climate and Hydrology

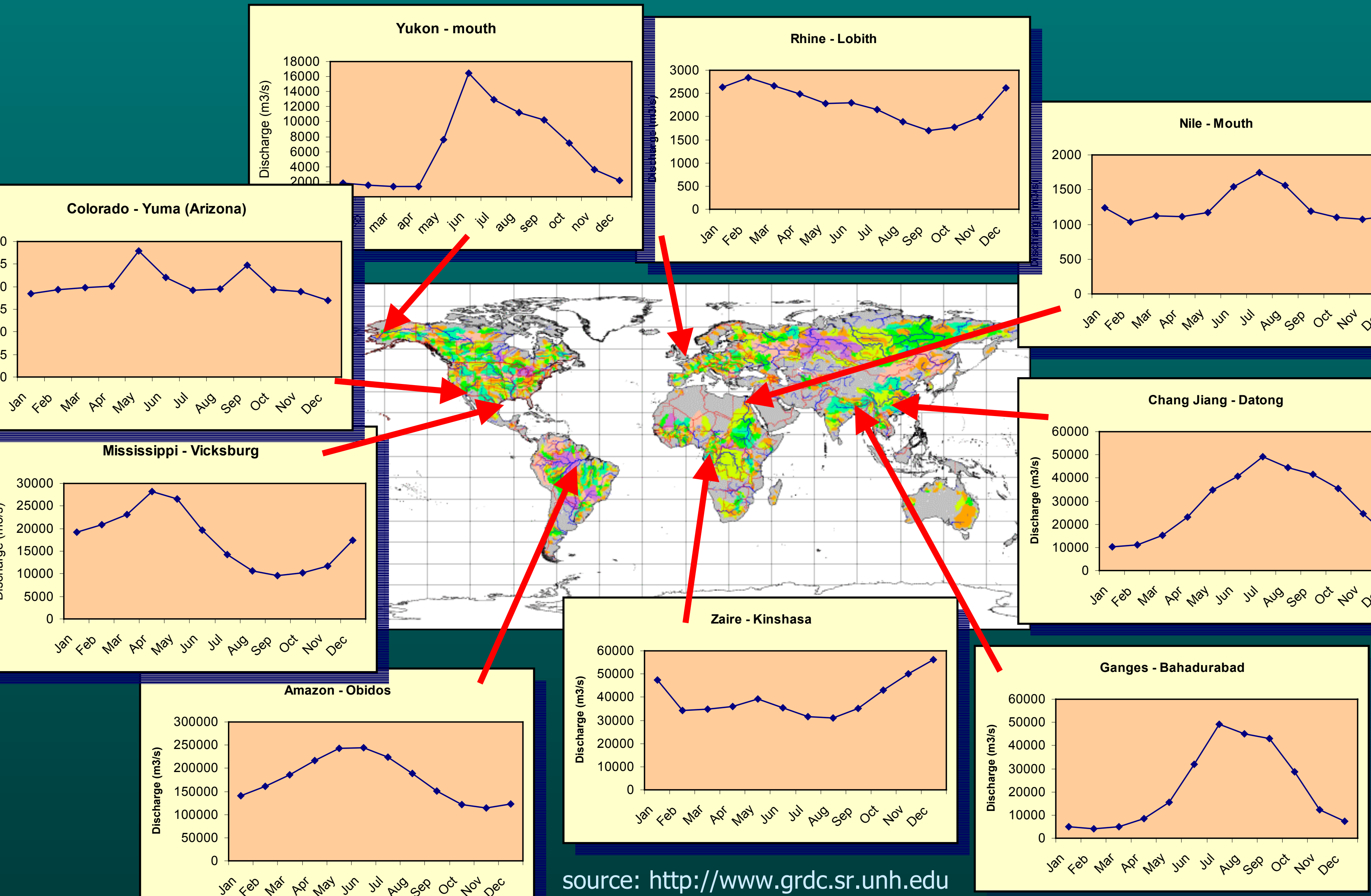


Hydrological impact studies

H. Middelkoop

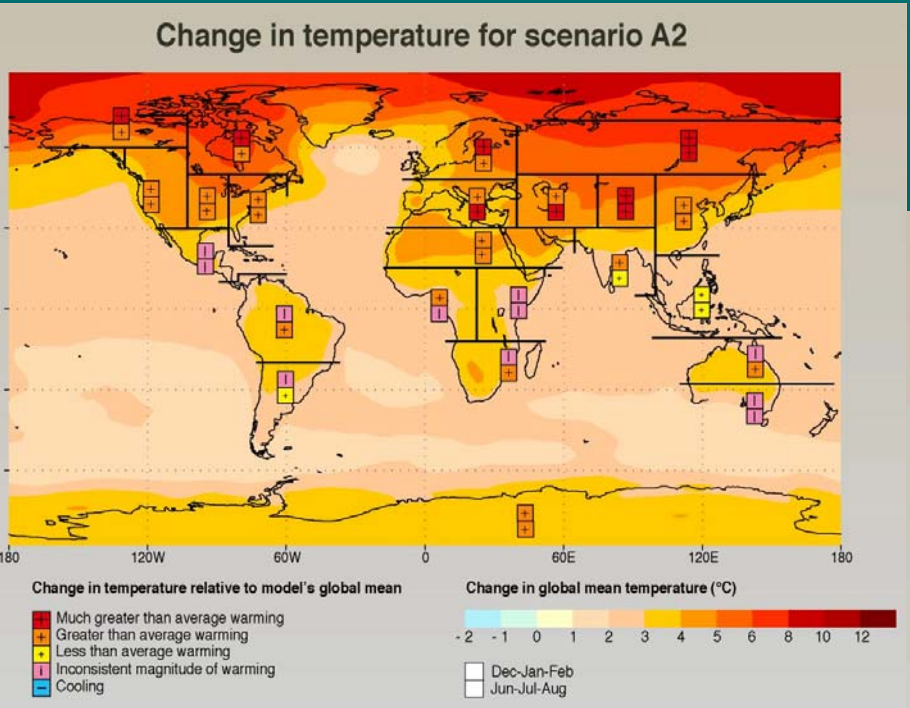
Department Physical Geography
Utrecht University
E-mail: h.middelkoop@geo.uu.nl

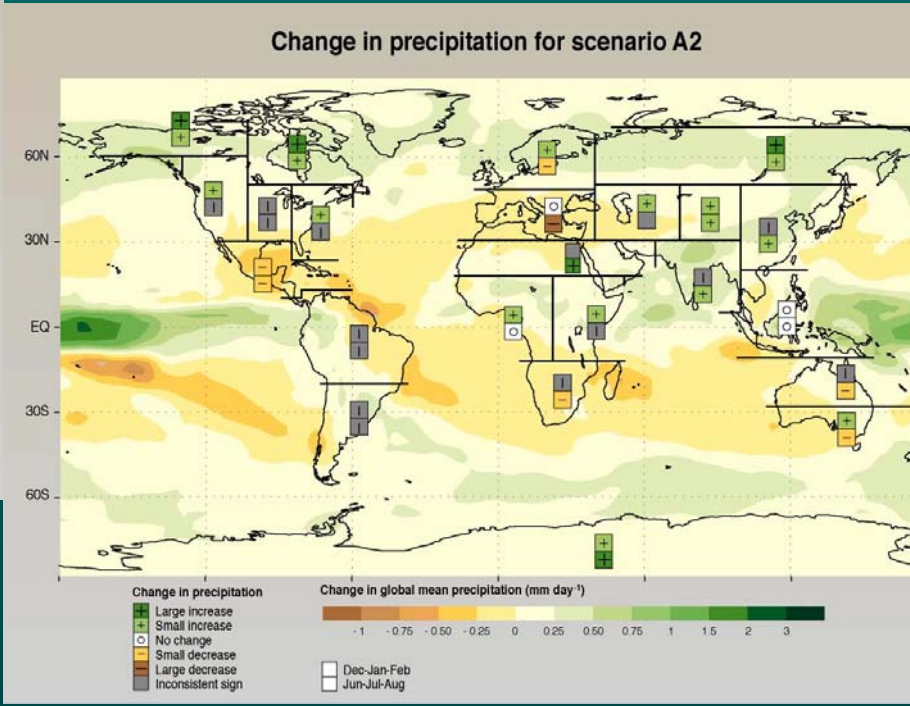
Hydrological regimes



source: http://www.grdc.sr.unh.edu

Projected climate change





IPCC SRES –A2 scenario

River functioning

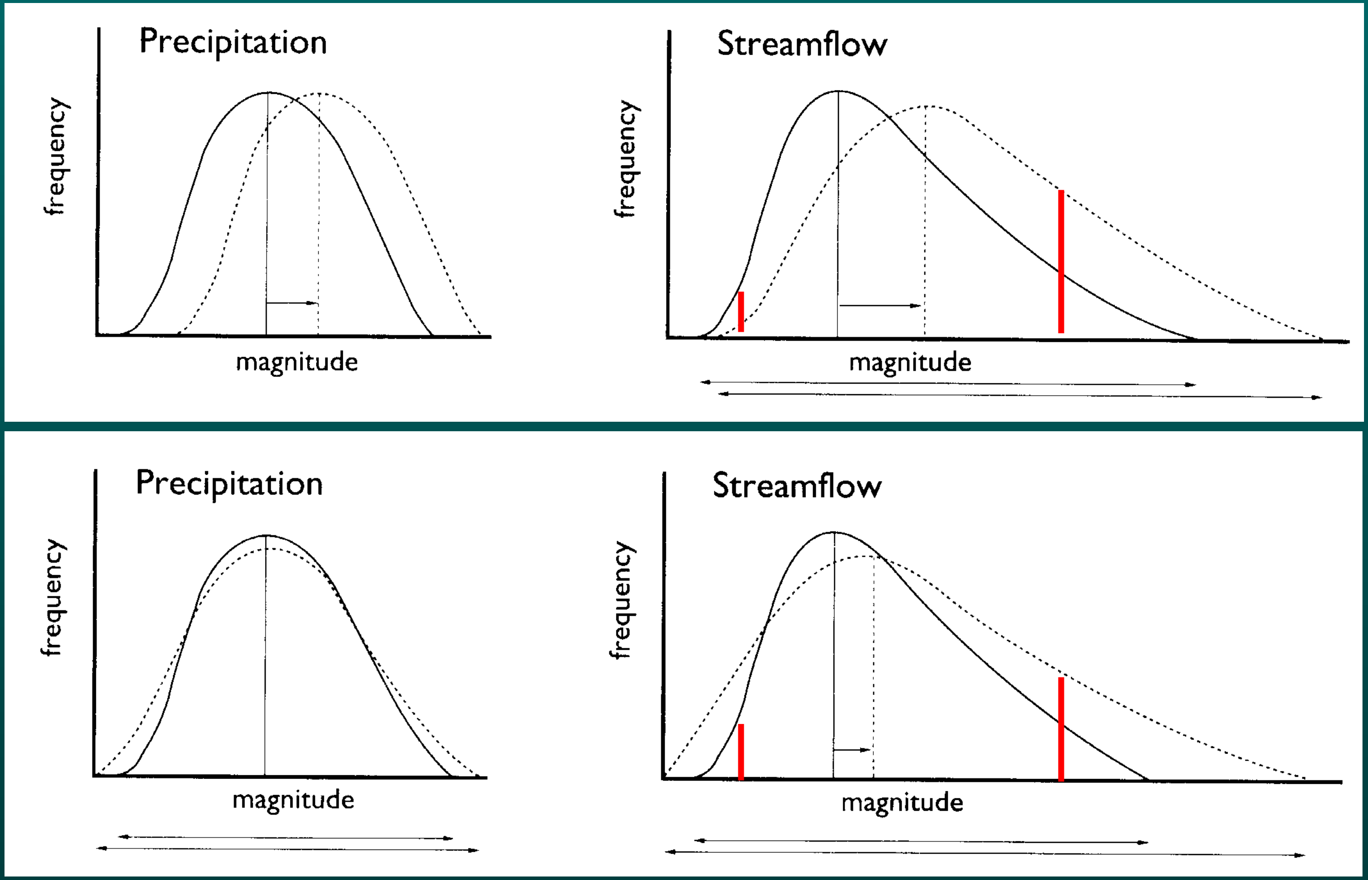
- Freshwater runoff from continents to oceans
- Transport of sediments, nutrients and pollutants
- Ecological corridors – habitats
- Socio-economic functions of rivers

- Average values
- Extremes are important

Human interests…

Non-linear responses?

- Schematic illustration of the effects of changing mean and variance of precipitation on the distribution of hydrological output

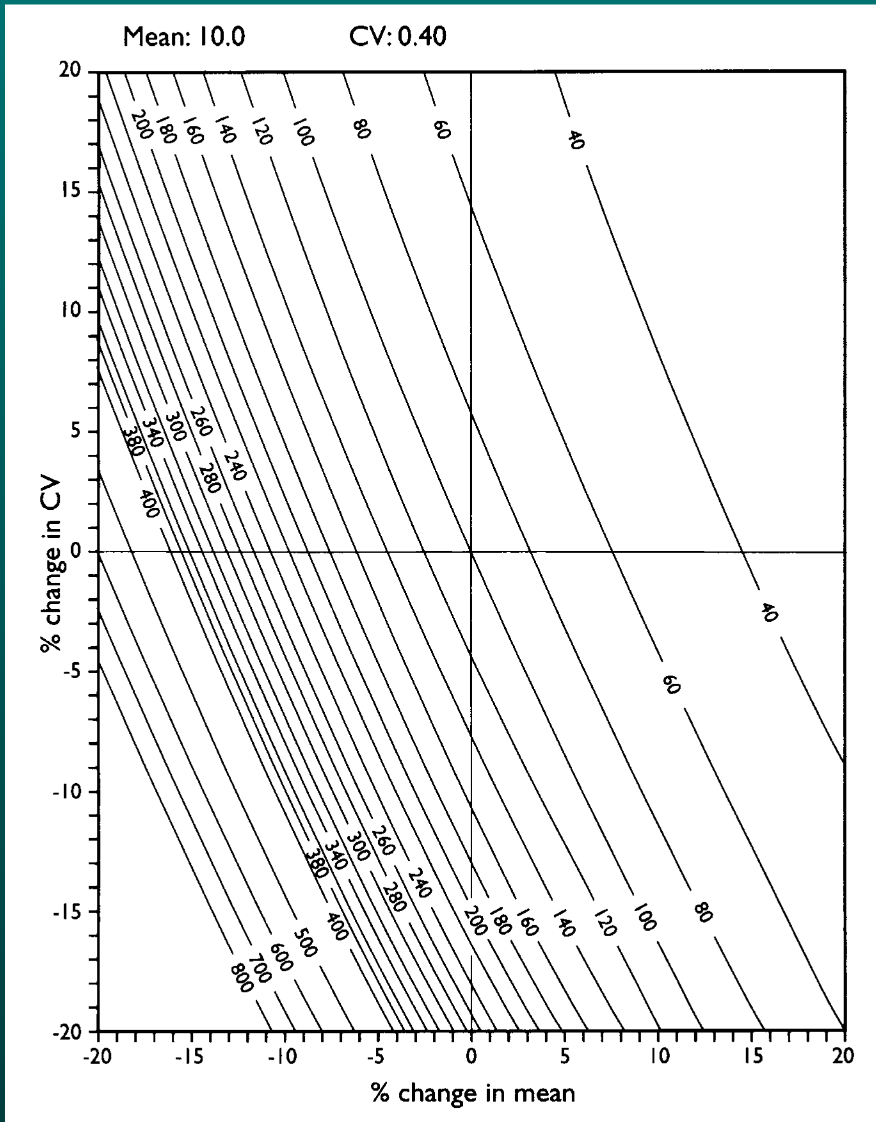


changed mean

changed variance

Arnell, 1996

Impacts on peak flows



Changes in return period of current 100-yr flood with changes in mean and coefficient of variation of discharge distribution

source: Beran and Arnell, 1996

Hydrological impact studies

- Emission scenario – global warming
- Regional / local climate change
- Hydrological model
- Reference time series
- Scenario run
- Hydrological changes
- Implications for river functioning

Water balance concept

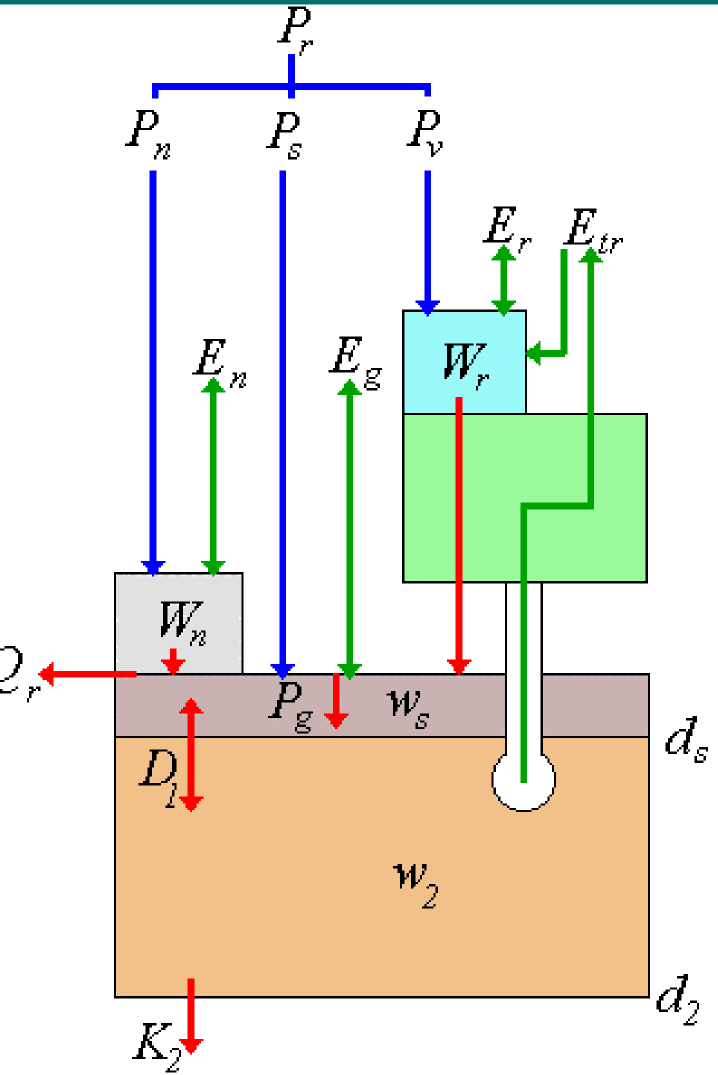
$Q = P - E \pm ?S$

where

- P = amount of precipitation
- E = amount of evapotranspiration
- ?S = change in storage

- Storages include:
  - water storage in vegetation
  - surface detention
  - storage in snow and glaciers
  - soil and groundwater storage
  - storage in lakes and channels

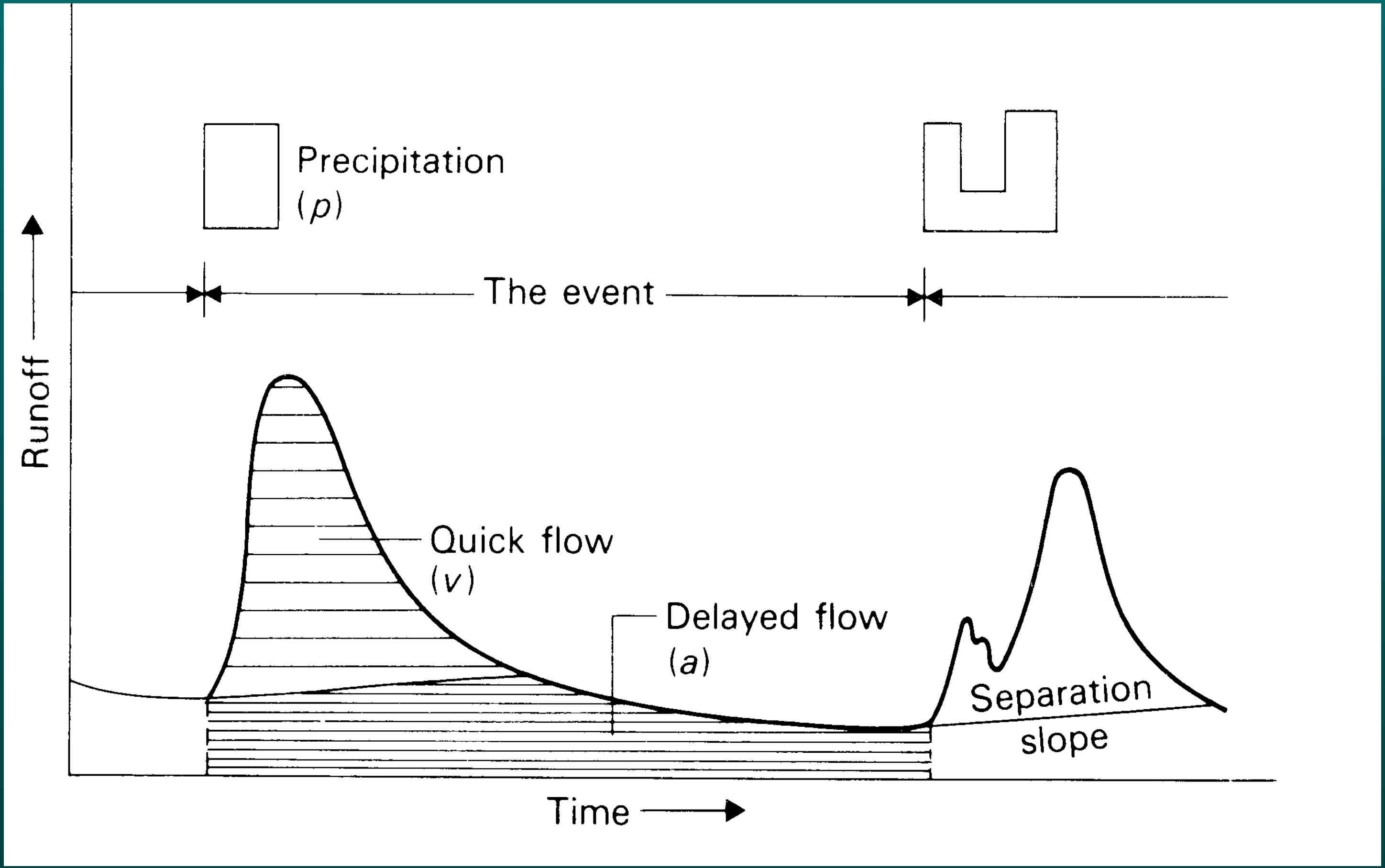
Water balance concept



Fluxes and storages

P_r	Total Precipitation (kg m^{-2} s^{-1})
P_n	Snowfall (liquid equiv.) (kg m^{-2} s^{-1})
P_s	Precipitation reaching soil (kg m^{-2} s^{-1}
P_v	Precipitation intercepted by vegetation (kg m^{-2} s
P_g	Infiltration (kg m^{-2} s^{-1})
Q_r	Surface runoff (kg m^{-2} s^{-1})
D_1	Surface/deep soil soil water diffusion (kg m^{-2} s^{-1})
K_2	Gravitational drainage (kg m^{-2} s^{-1})
E_n	Sublimation (kg m^{-2} s^{-1})
E_r	Bare-soil evaporation (kg m^{-2} s^{-1})
E_g	Evaporation from interception (kg m^{-2} s^{-1})
E_{tr}	Transpiration (kg m^{-2} s^{-1})
W_r	Canopy water store (kg m^{-2})
W_n	Snow pack SWE (Snow Water Equiv.) (kg m^{-2})
w_s	Surface soil water reservoir (m^3 m^{-3})
w_2	Bulk soil water reservoir (m^3 m^{-3})
d_1	Surface reservoir soil depth (m)
d_2	Total soil depth (m)

Water balance concept



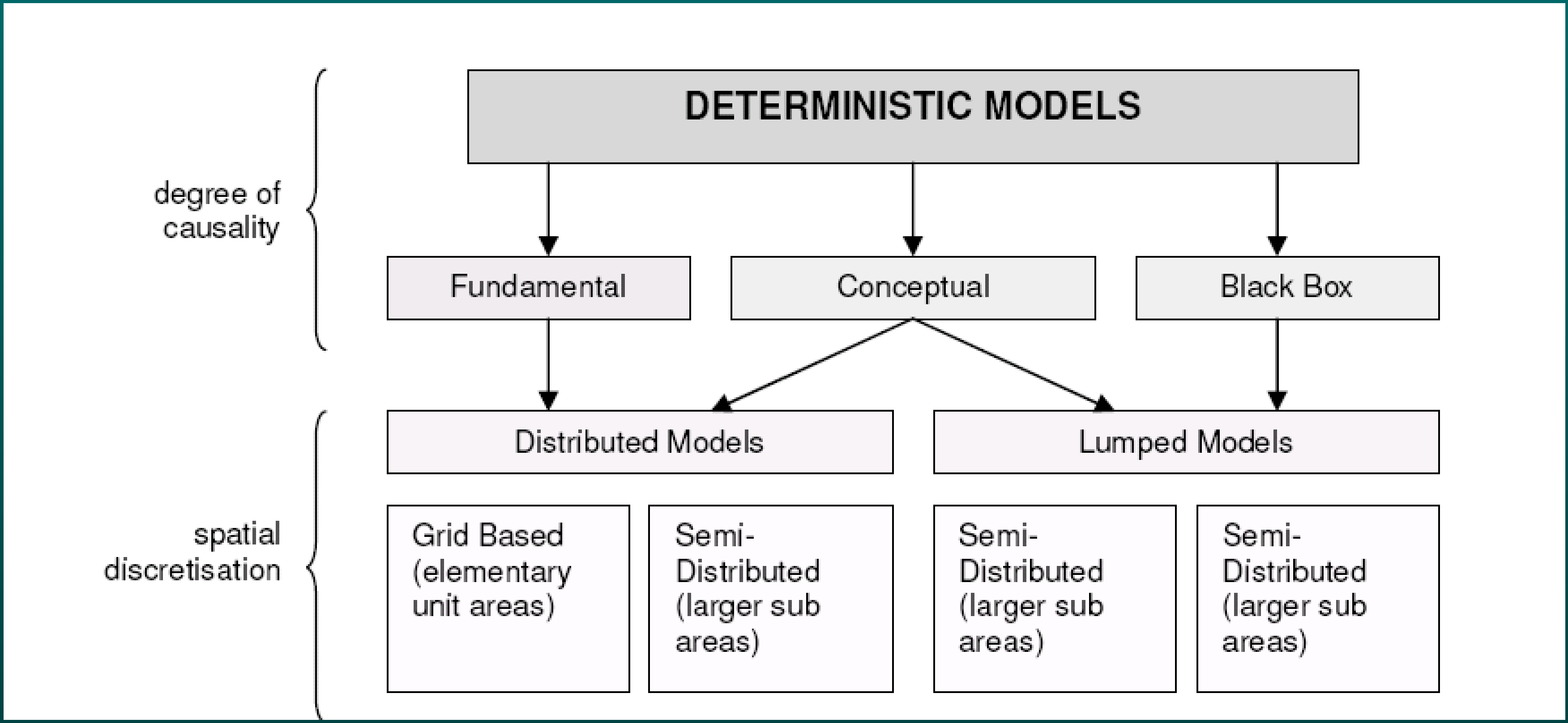
Source: Ward & Robinson, 1990

Hydrological models

- Primarily based on water balance concept
- Different approaches, depending on
  - degree of causality of physical processes implemented
  - spatial discretization
  - temporal discretization
  - spatial coverage

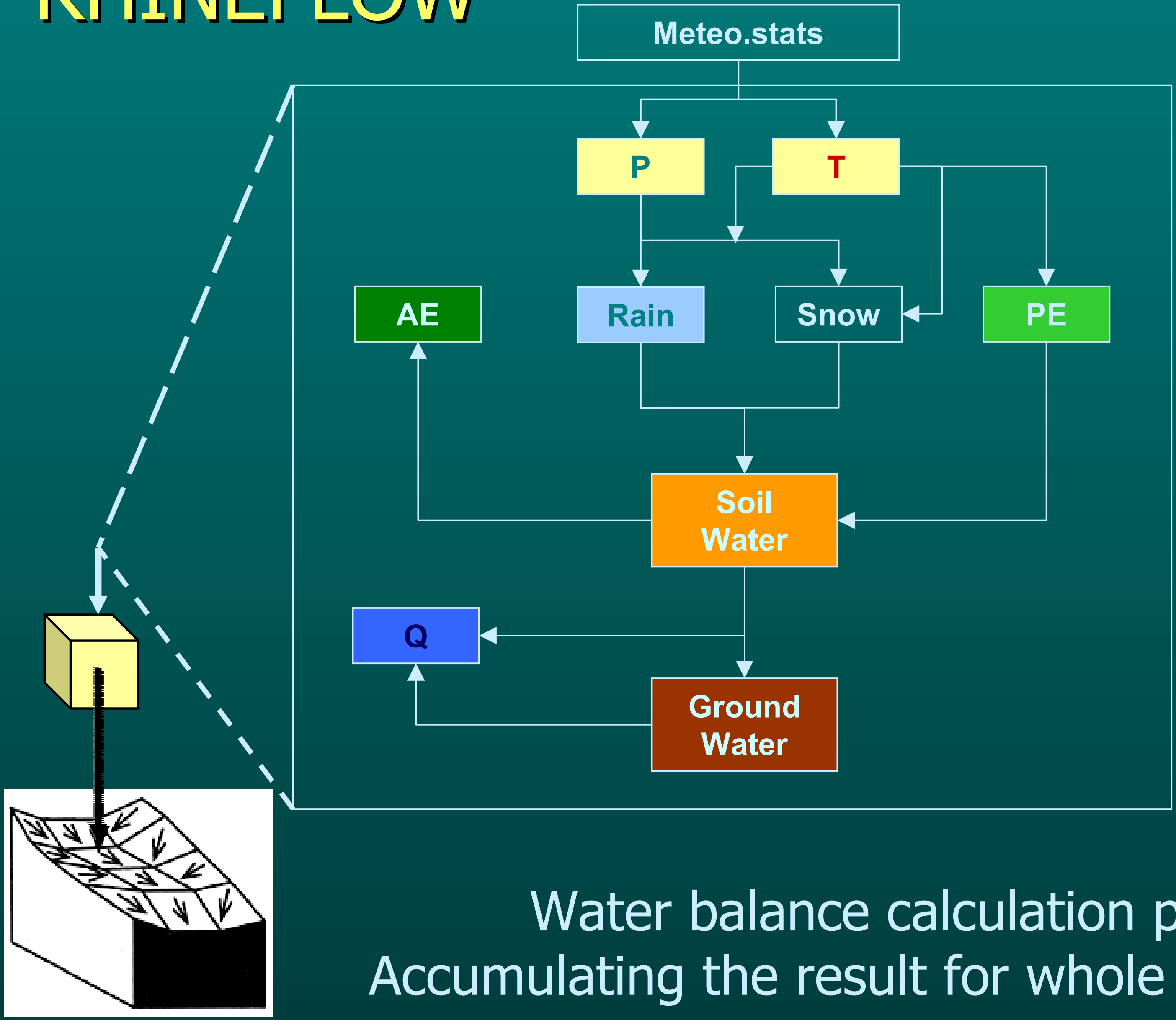
Hydrological models

- Classification of deterministic models



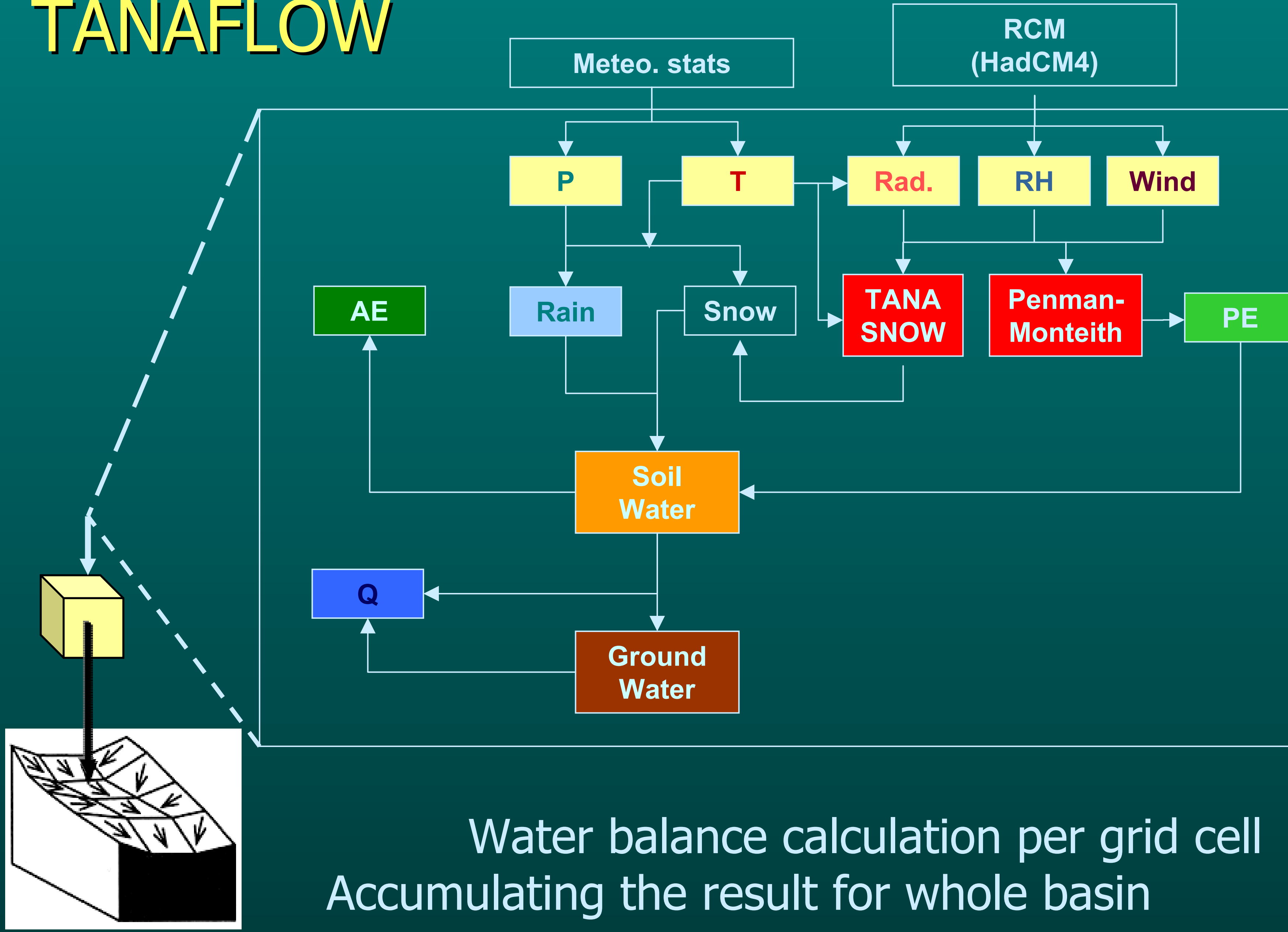
Nemec, 1993

RHINEFLOW



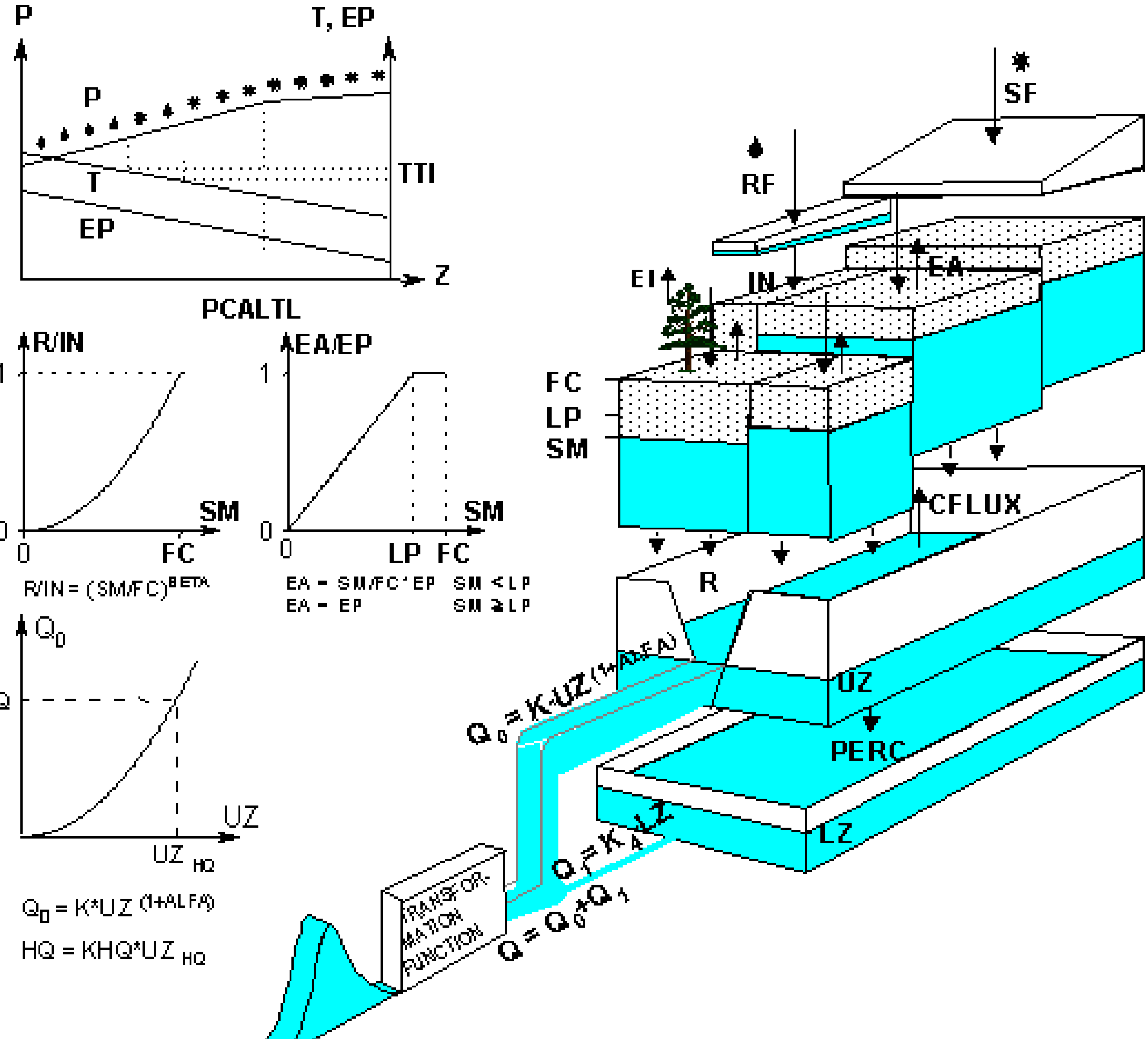
Water balance calculation per grid cell
Accumulating the result for whole basin

TANAFLOW



Water balance calculation per grid cell
Accumulating the result for whole basin

HBV model

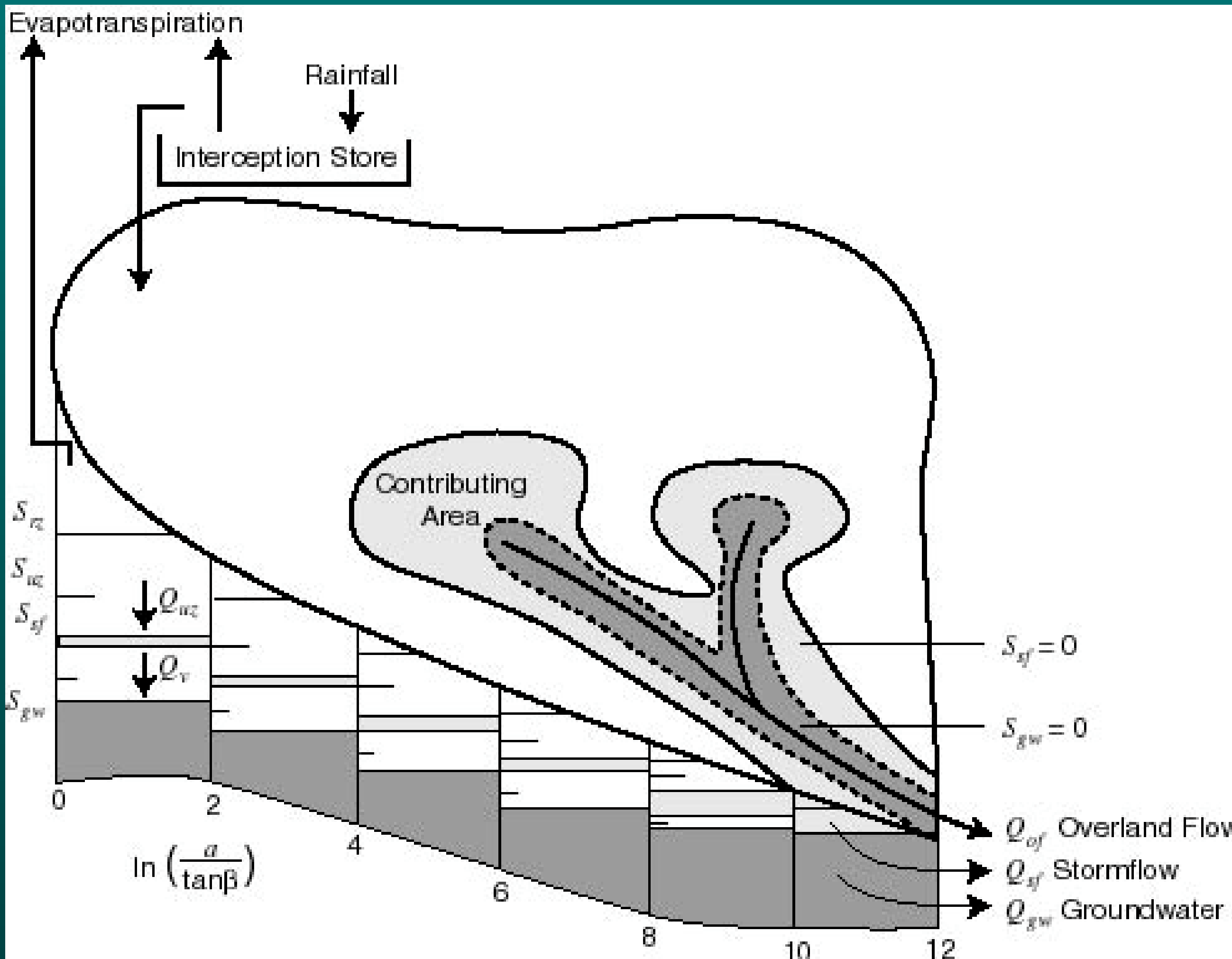


P = Precipitation
T = Temperature
SF = Snowfall
RF = Rain
Z = Elevation
PCALTL = Threshold in Lapse Rate
TTI = Threshold Temperature Interv
IN = Infiltration
EP = Potential Evaporation
EA = Actual Evaporation
EI = Interception Evaporation
SM = Soil Moisture
FC = Field Capacity
LP = Limit for potential evaporation

BETA = Soil Routine Parameter
R = Runoff
CFLUX = Capillary Flux
UZ = Upper Zone
LZ = Lower Zone
PERC = Percolation
K, K_4 = Recession Parameters
ALFA = Recession Parameter
Q_0 , Q_1 = Runoff Components
HQ = Peak Flow Level
KHQ = Recession at HQ
HQ_{UZ} = Level in UZ at HQ

Bergström, 19

TOPMODEL



Saturation and flow components based on topographic index, derived from DTM (Beven and Kirkby, 1979, and later).

TOPMODEL

Assumption 1.

Hydraulic conductivity decreasing with depth - sensitivity parameter f

$$K = K_o e^{-f z}$$

Assumption 2.

Saturated lateral flow driven by topographic gradient and controlled by depth to water table (soil moisture deficit).

$$q = \frac{K_o}{f} e^{-f z} \tan\beta \qquad Q_b = Q_o e^{-f\bar{z}} = Q_o e^{-(f/\Delta\theta)S}$$

Assumption 3.

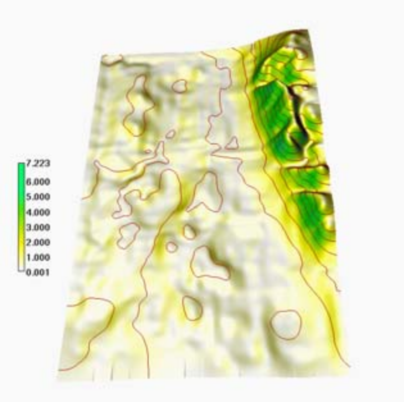
Steady state. Saturated lateral flow related to equilibrium recharge rate.

$$\Rightarrow \quad z = \bar{z} + (\lambda - \ln(a/\tan\beta))/f$$

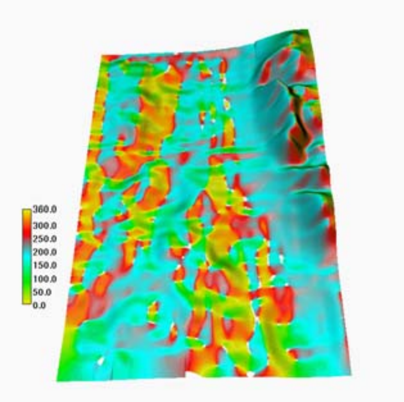
$$\lambda = \int_{\text{subbasin}} \ln(a/\tan\beta)$$

Determines depth to water table and saturation excess runoff generation when $z < 0$

TOPMODEL

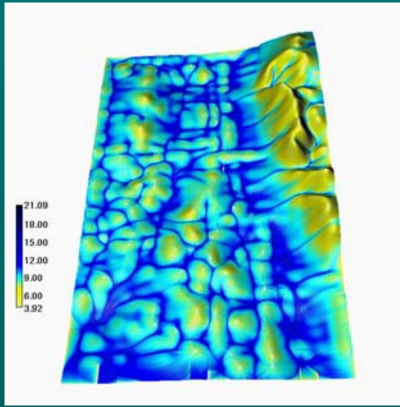


slope

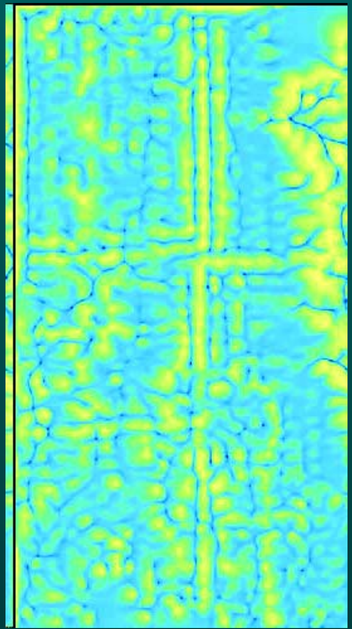


aspect

curvature



wetness index
ln(A/tan(slope)



TOPMODEL
Key-concept is wetness index, derived from DTM

1in/1hr rainfall lasting for 1 hour and water then draining for 7.5 minutes

Geographic Modeling Systems Laboratory
University of Illinois at Urbana-Champaig

Hydrological models

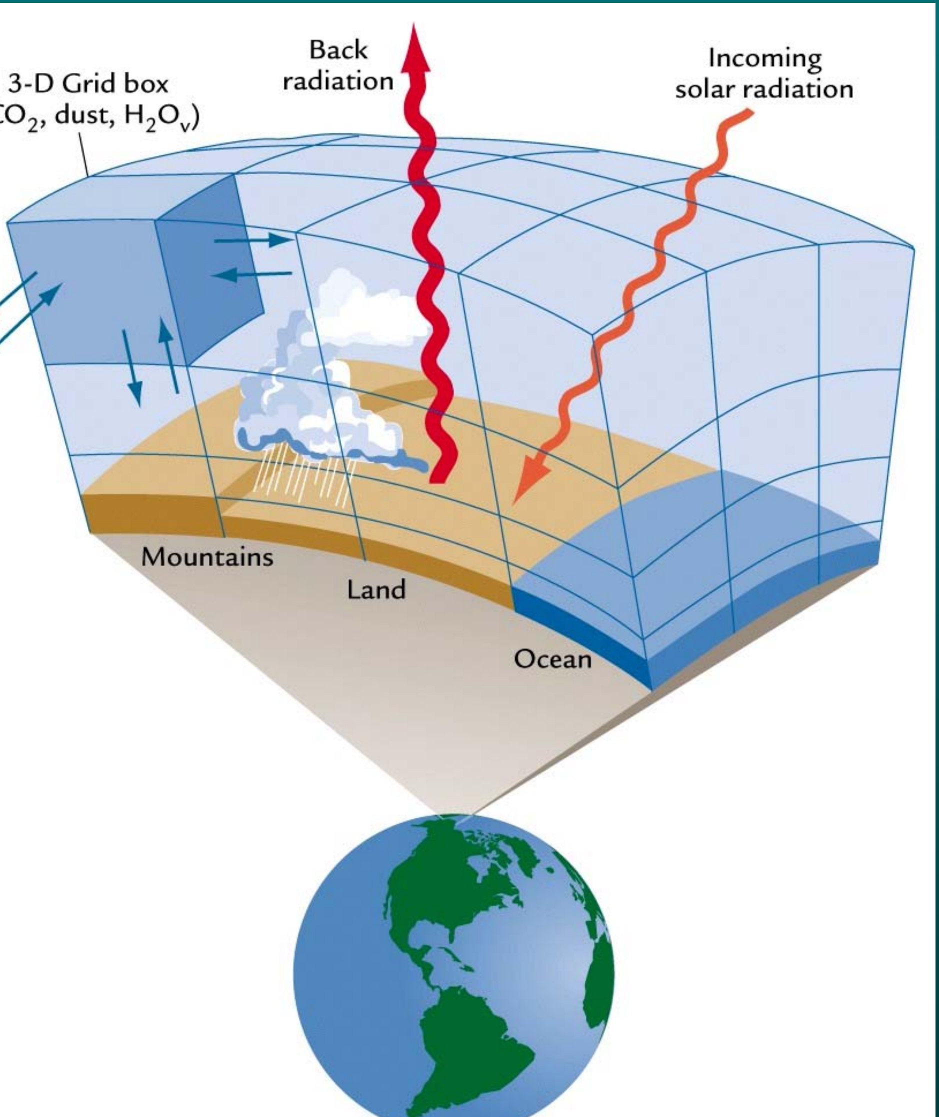
Which model type to apply in climate-impact study

- Physically-based models
  - more likely to give credible results for changed climate and land cover than empirical, black box models
  - require large number of parameters to be determined (calibration)
  - hard to implement for larger (>10000 km^2) basins
  - require high-resolution (xy and T) climate input
- Conceptual / water balance models
  - compromise between data availability and desired physical representation of processes
  - key non-linearities (e.g. snow storage) considered
  - larger areas, require less detailed climate inputs

Hydrological impact studies

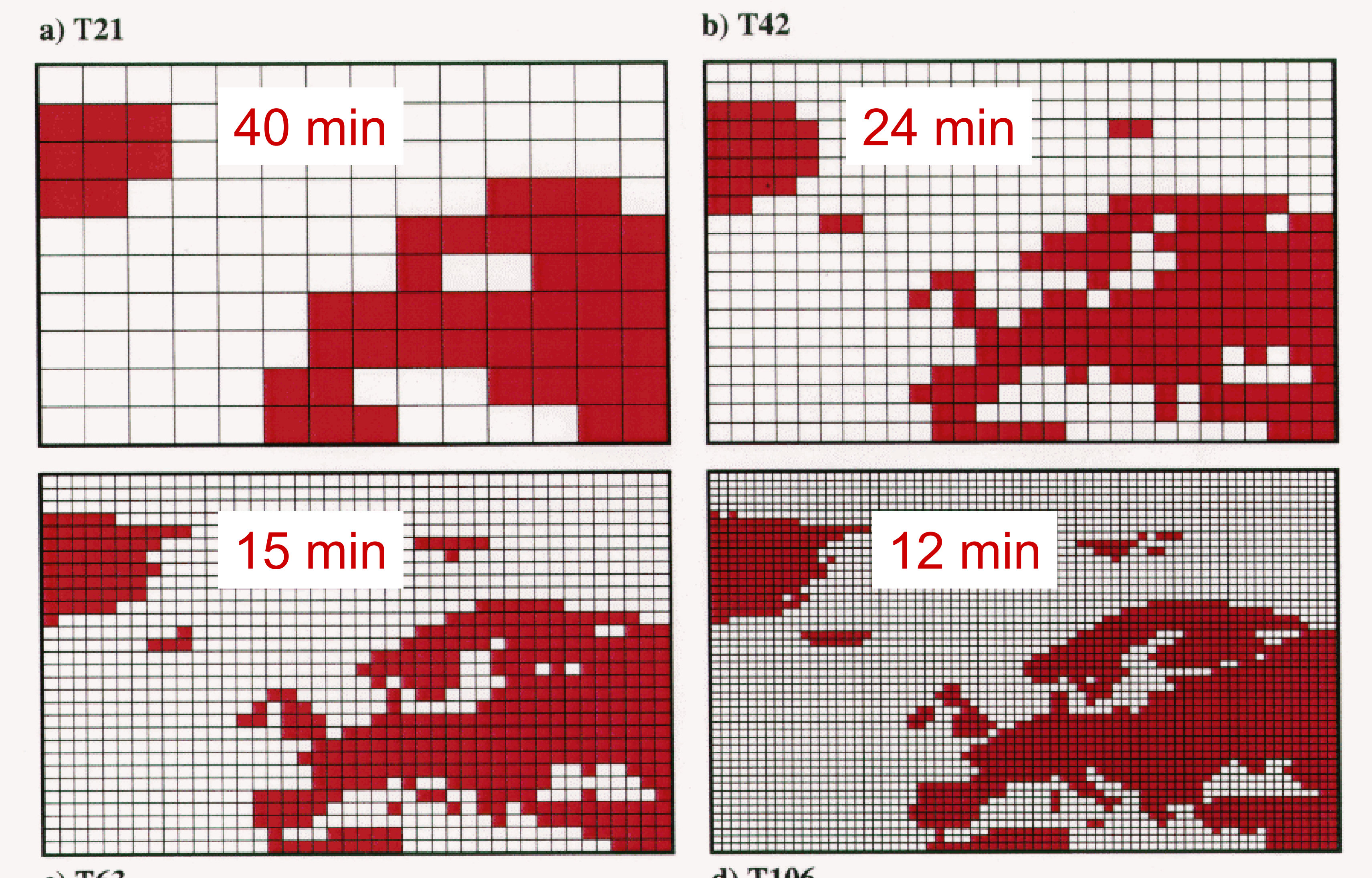
- Emission scenario – global warming
- Regional / local climate change
- Hydrological model
- Reference time series
- Scenario run
- Hydrologcal changes
- Implications for river functioning

Climate models

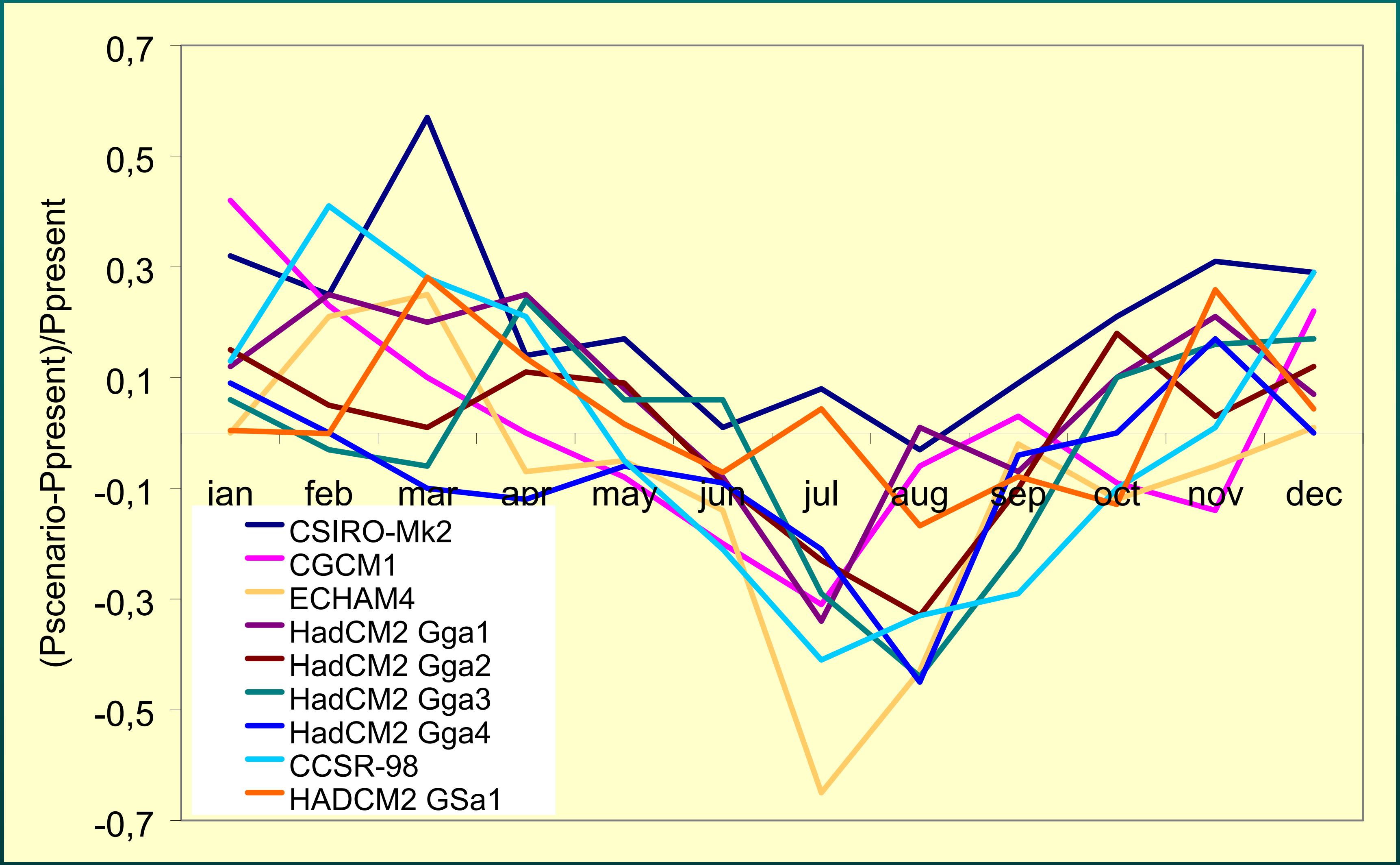


- 3-D Atmospheric General Circulation Models (AGCMs)
- Full 3D representation of atmosphere
- 20 vertical layers, horizontal resolution order 2.5 - 0.5 degree
- Physics of atmosphere processes
- Computationally intensive

Climate models - resolutions



Meuse: different GCMs - different dP



Climate inputs

- Input data of future climate to hydrological models cannot be directly obtained from GCMs
- Poor spatial resolution (2 x 3 degree lat/lon)
- Poor simulation of precipitation and precipitation extremes

GCM results - downscaling

GCM results too coarse for regional impact studies: downscaling GCM output needed

- Calculate anomalies using GCM:
  - Changes in monthly value of T (ºC) and P (%) by GCM
  - Apply anomalies to observed records in reference period
- Statistical relations between air pressure, circulation, T from GCM and precipitation (1D and 2D)
- Regional Climate Model
  - Higher-resolution model
  - Nested in global GCM
  - GCM as boundary condition for each time step

GCM results - downscaling

Using climate anomalies determined by GCM

- Obtain climate data from observation stations within drainage basin (e.g. 1960-1990)
  - spatial variability captured in meteo data
  - baseline run, used for hydrological model calibration
- Run GCM for present-day climate, determine monthly average values of climate variables
- Run GCM for changed climate (20-30 year time slice with perturbed climate), determine monthly average values of climate variables
- Determine for each month per year differences between monthly average results of both GCM runs
- Apply the obtained anomalies to the observed time series of climate

GCM results - downscaling

Calculation of T and P anomalies:

$T_{sc}(t) = T_{obs}(t) + (T_{GCM\text{-}sc} - T_{GCM\text{-}ref})$

with:

$T_{sc}(t)$ = scenario time series to be used as input for hydrological model,

$T_{obs}(t)$ = baseline observed climate series,

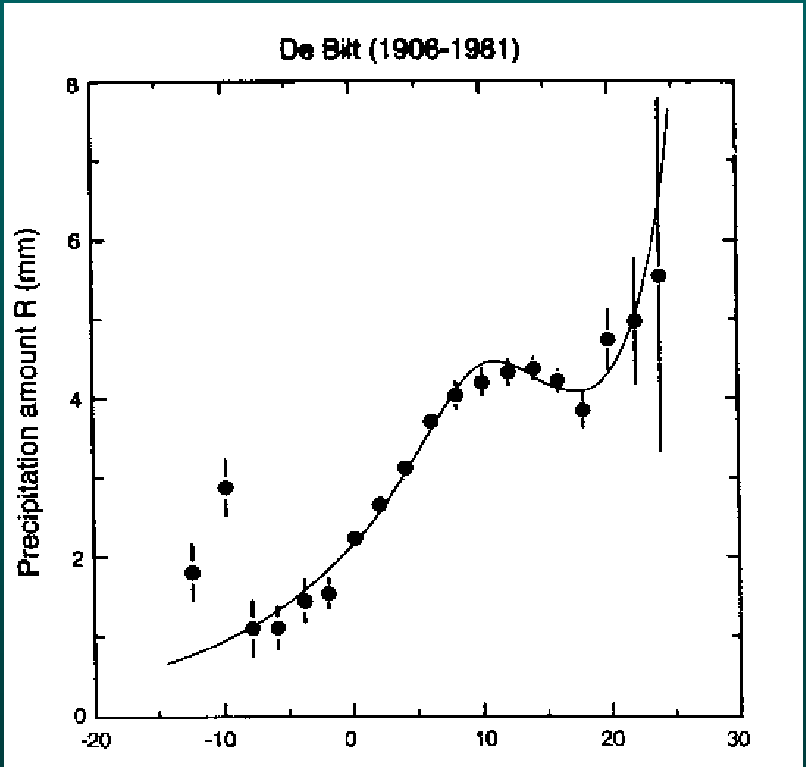
$T_{GCM\text{-}sc}$ = average climate values for changed climate, calculated with GCM,

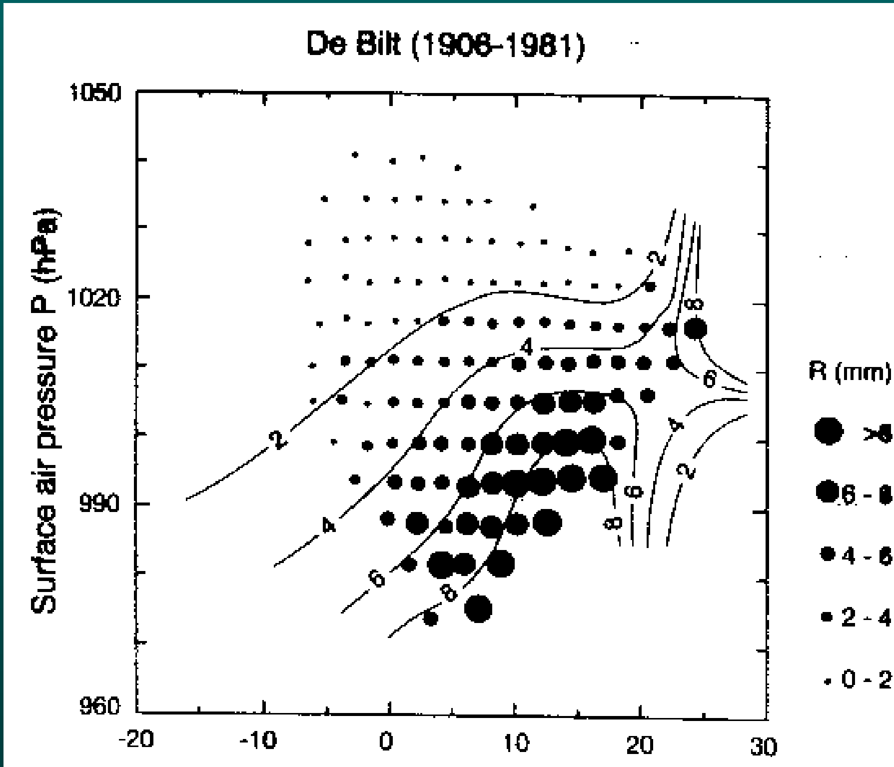
$T_{GCM\text{-}ref}$ = average climate values for the baseline climate, calculated wit GCM.

$P_{sc}(t) = P_{obs}(t) \times (P_{GCM\text{-}sc} / P_{GCM\text{-}ref})$

Statistical downscaling GCM results

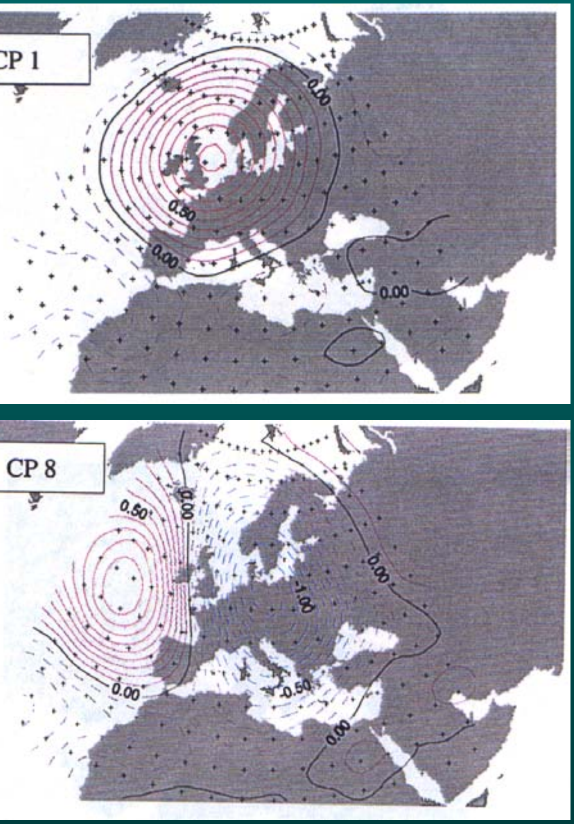
- KNMI method: empirical relations between
  - Air pressure, temperature (observed / GCM) and
  - precipitation (at 1 station)

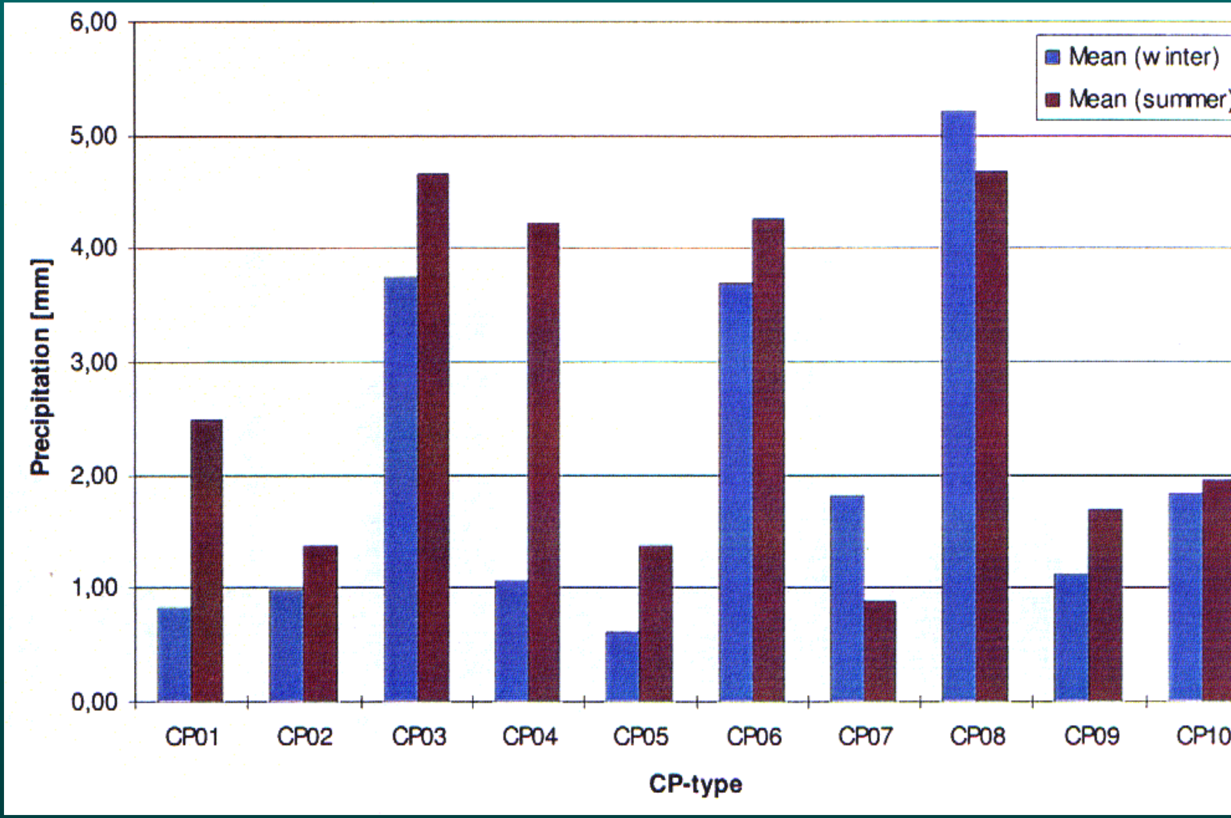




Statistical downscaling GCM results

- Empirical relations between atmospheric circulation patterns and precipitation



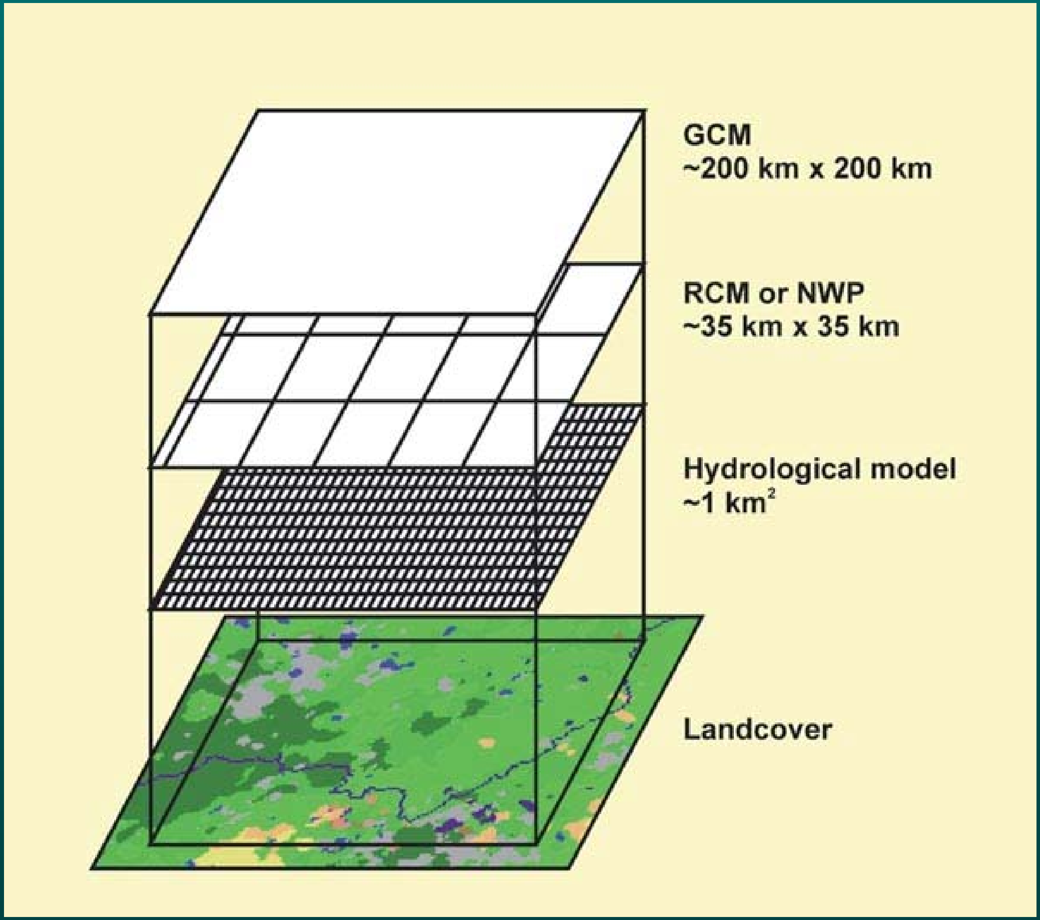


Comparison downscaling

Scenario technique	Strengths	Weaknesses
Climate anomalies	Station-scale scenarios Computationally straightforward and quick to apply Local climate change scenario is directly related to changes in the regional climate model output	Depends on realism of the climate model providing the change factors Temporal structure is unchanged for future climate scenarios Step changes in scaling at the monthly interface Restricted to time-slice scenarios
Statistical downscaling	Station-scale scenarios Ensembles of climate scenarios permit uncertainty analyses Delivers transient climate change scenarios at daily time-scale Allows exploration of temporal sequencing of meteorological events	Depends on realism of the climate model providing the forcing Requires high quality observations and climate model output Predictor-predictand relationships are not always stationary Choice of predictor variables and transfer function affects results

source: Diaz-Nieto & Wilby, 2005

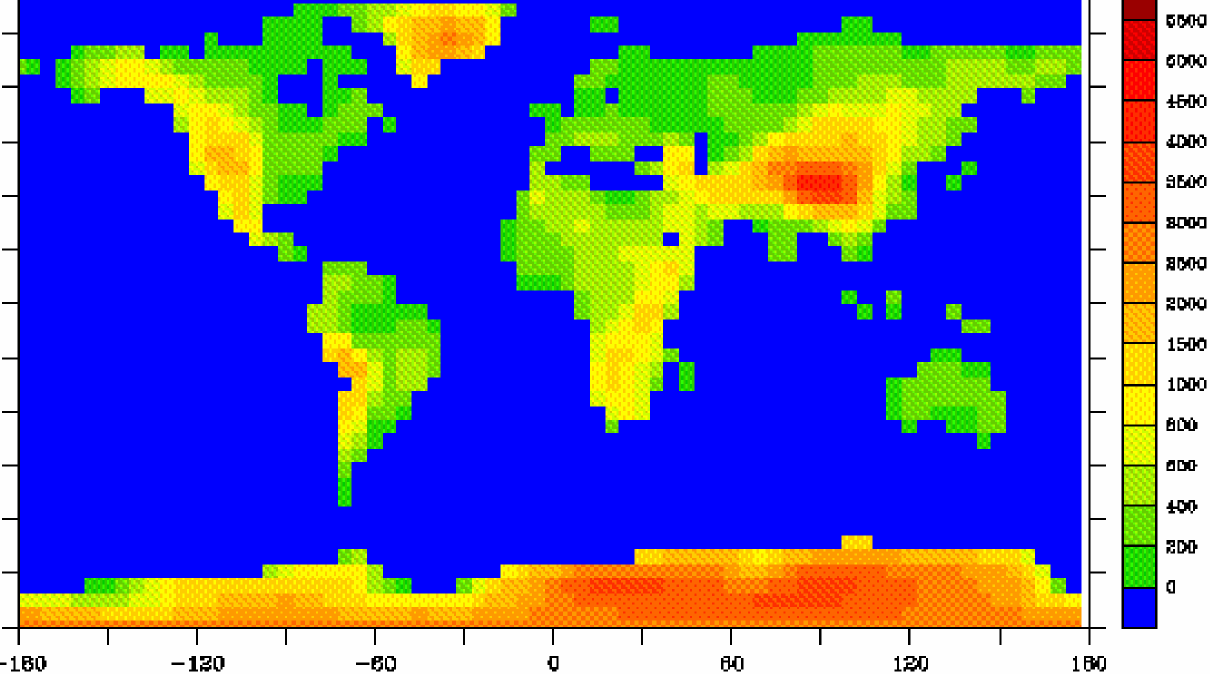
Different spatial resolutions - RCM



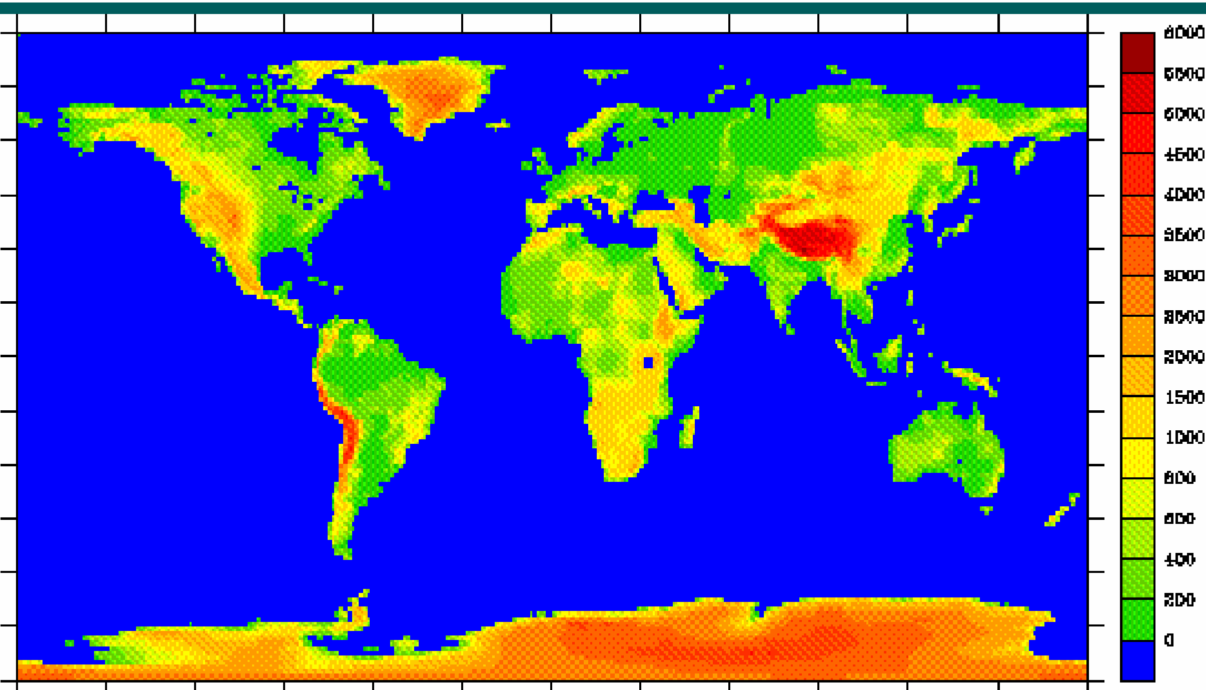
Regional climate models may bridge the gap in spatial resolution between GCMs and hydrological models

RCMs are run nested within a global GCM, providing regional climate detail

Orography

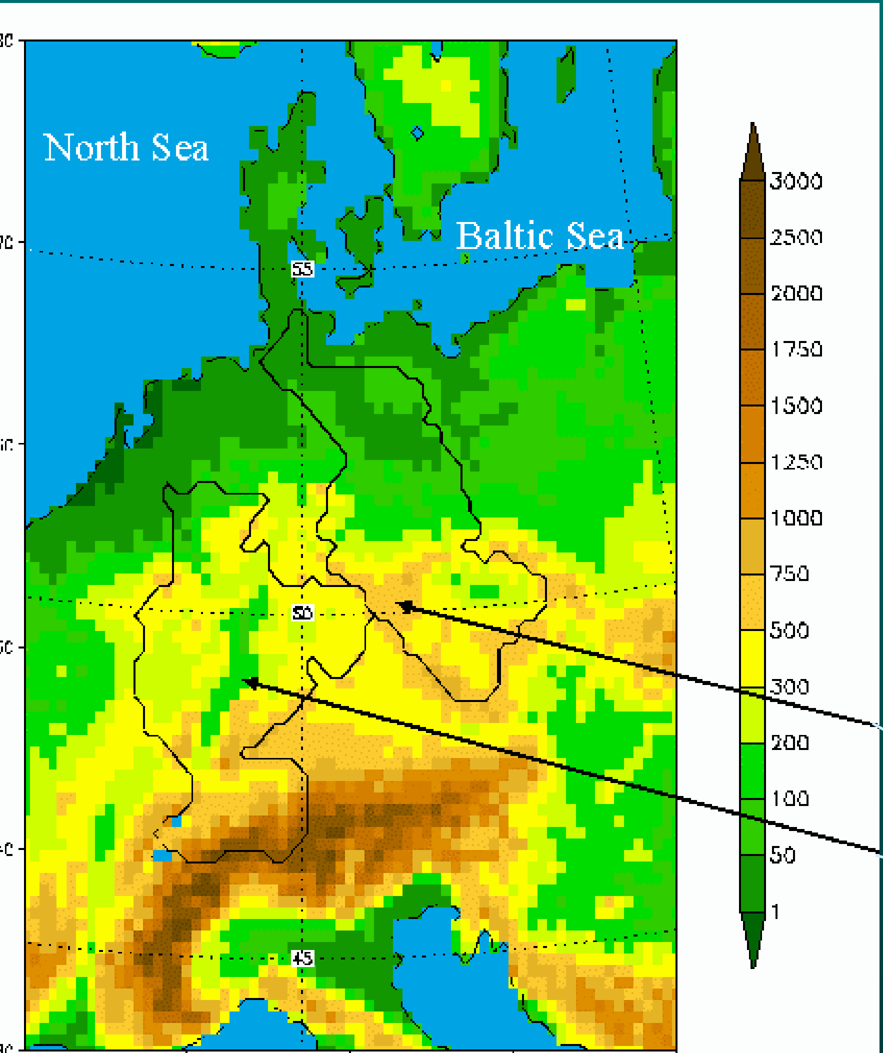


Low resolution GCM



High resolution GCM

Regional Climate Model (RCM)



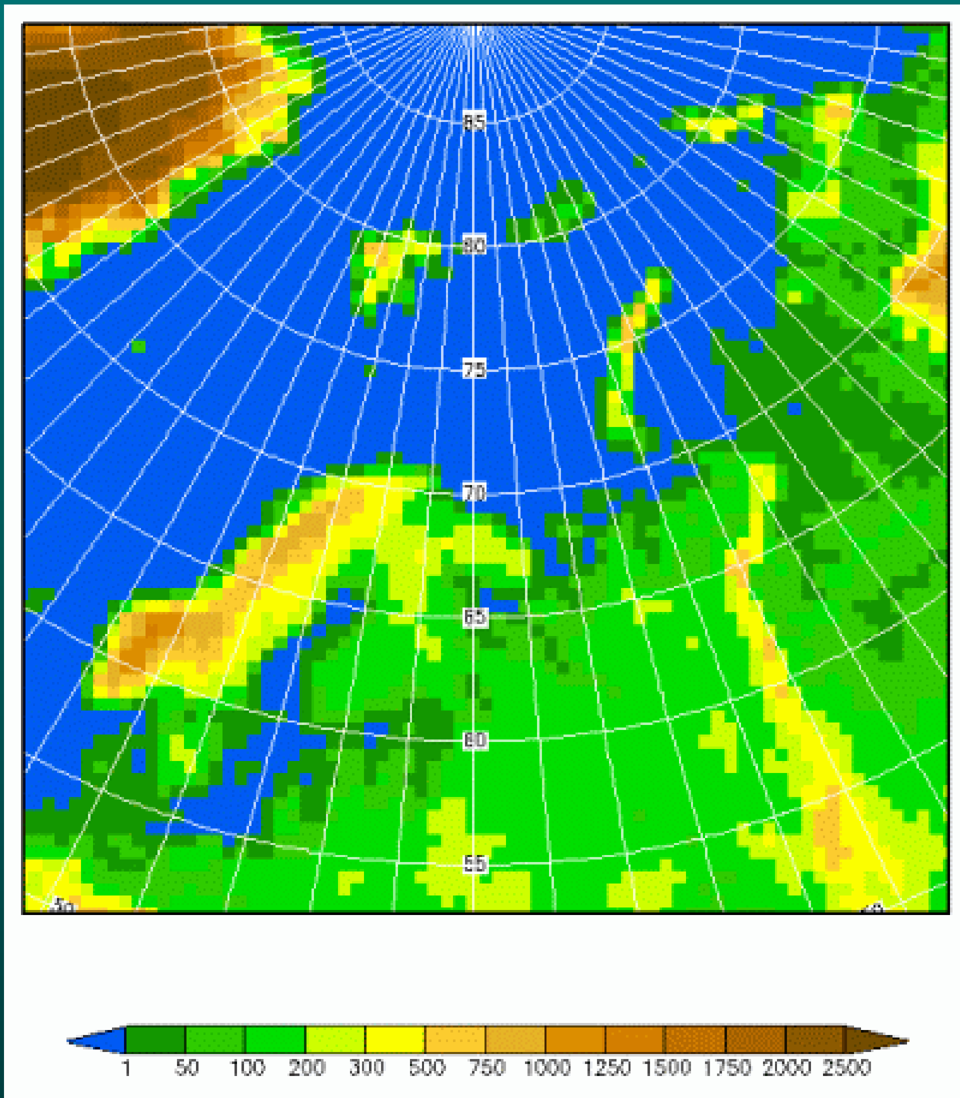
Example: REMO

- Horizontal resolution: 1/6° (appr. 18 km)
- Vertical resolution: 19 levels
- Time step: 2 minutes
- Integration time: 10-30 yr
- Initialization and forcing at the lateral boundaries with GCM

Elbe basin
Rhine basin

Max-Planck-Institut für Meteorologie

Regional Climate Model (RCM)



REMO model region
½ degree resolution

Regional Climate Model (RCM)

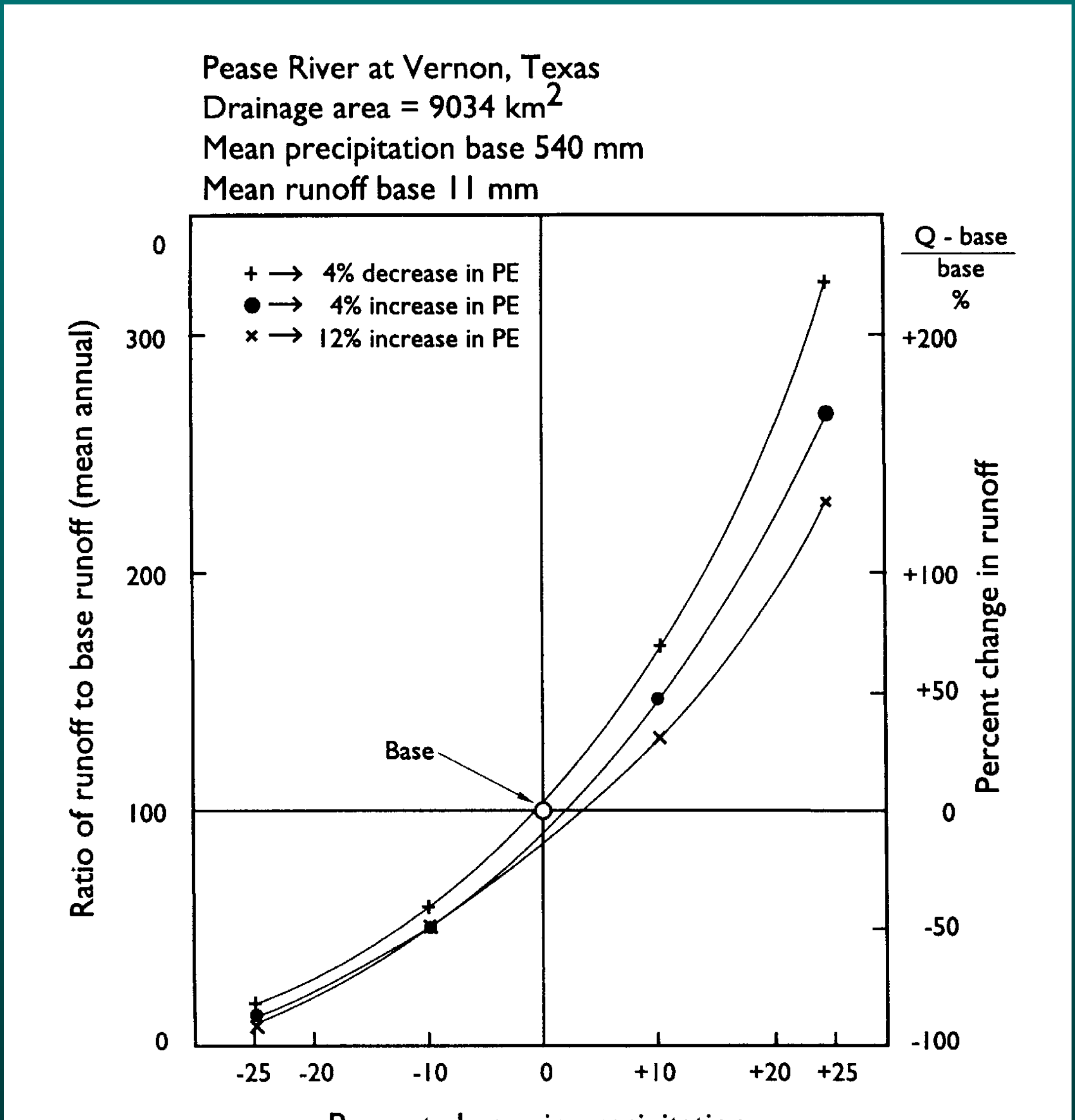
Regional Climate Model

- Nested in GCM
- Spatial resolution finer than 50 x 50 km
- Land surface and regional climate
  - relief, lakes, vegetation, snow
- Realistic daily variability of T, simulation of P much better than GCM but remains difficult
- Computationally demanding
- Validation data needed (mountain areas)

Hydrological impact studies

- Sensitivity analyses using hydrological models
- Climate scenario studies
  - Directly from GCM
  - Directly from RCM
  - Linking climate model to hydrological model

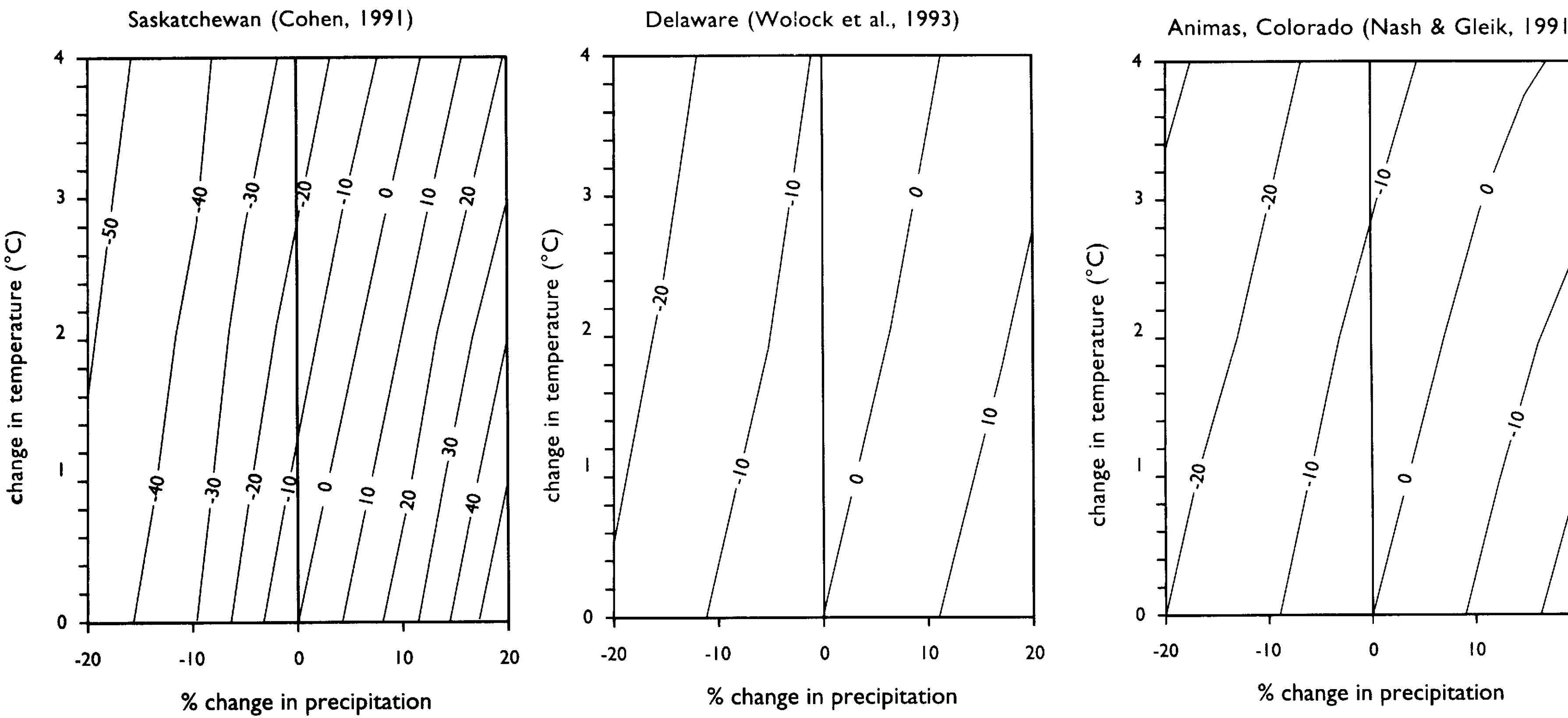
Sensitivity analyses



Analysing runoff changes in response to varying P and/or T using a hydrological model

source: Arnell, 1996

Sensitivity analyses



Sensitivity of annual runoff to changes in P and T

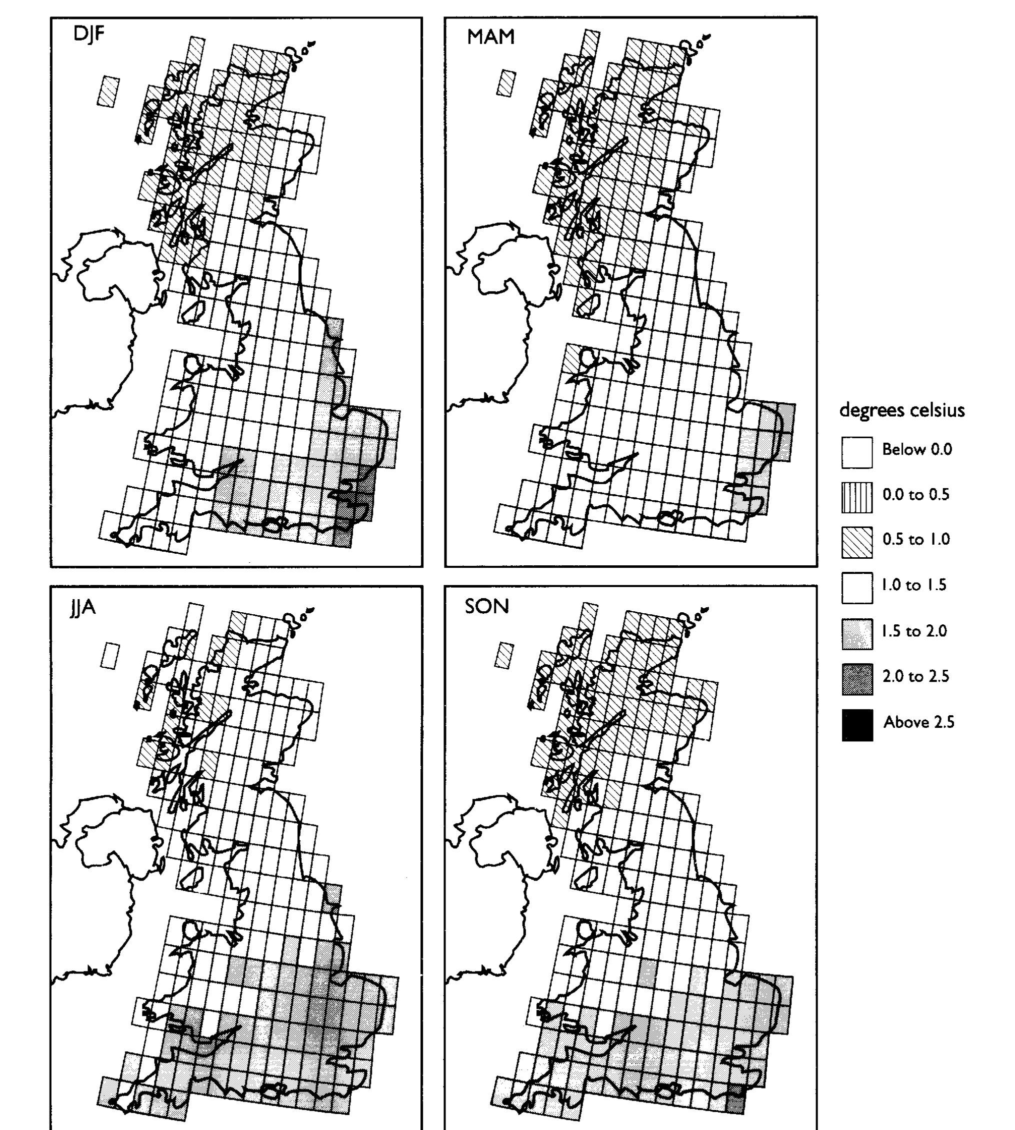
source: Arnell, 199

Sensitivity analyses

General conclusions from sensitivity studies

- annual runoff volume is more sensitive to changes in precipitation than to changes in runoff
- a given percentage change in precipitation results in a greater increase in runoff
- this amplification increases with decreasing proportion of precipitation going to runoff:
  - changes in P-E will be larger than changes in P, with increasing amplification as E approaches P
  - arid catchments show greater sensitivity
- changes in annual runoff depend on seasonality of P
  - larger winter P results in larger Q increase than larger summer P

Water balances from GCM output

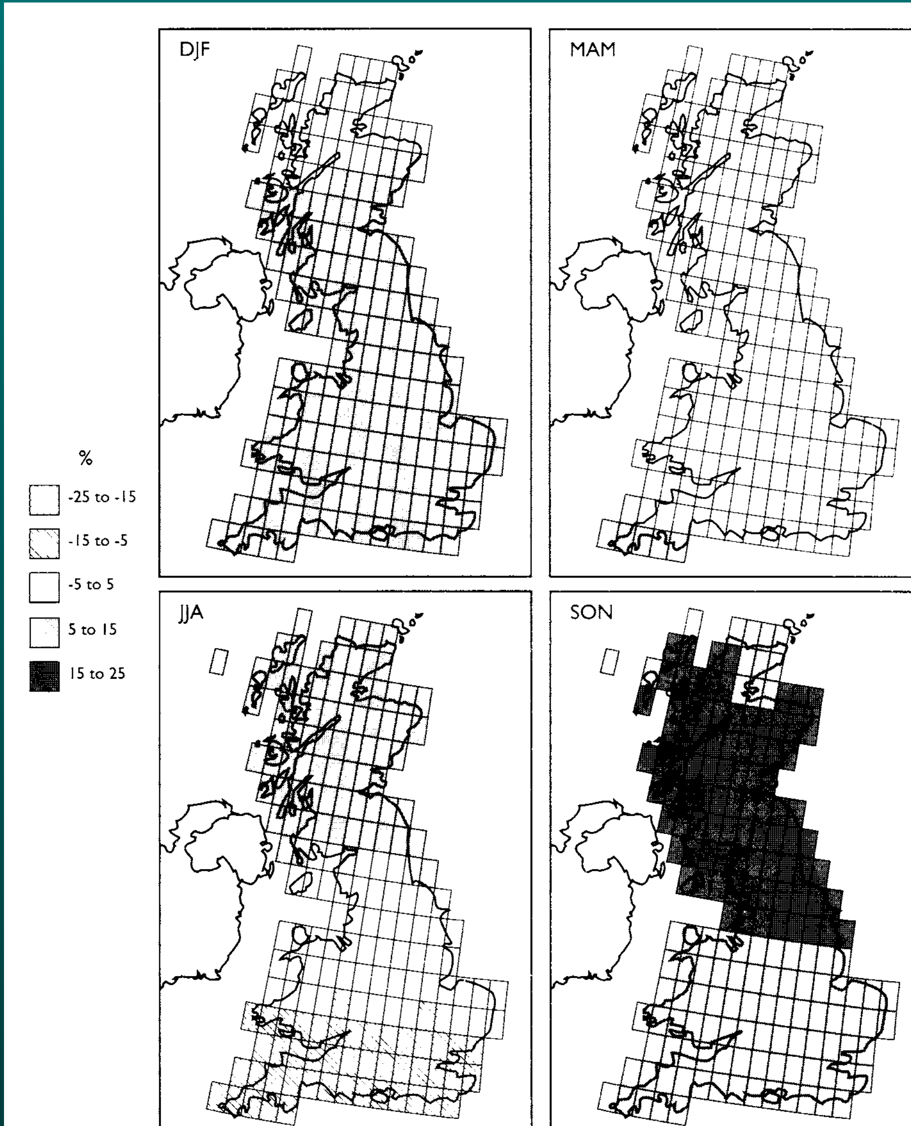


Changes in seasonal temperature, 2050
GCM results interpolated to 0.5 x 0.5 degree grid

source: Arnell, 199

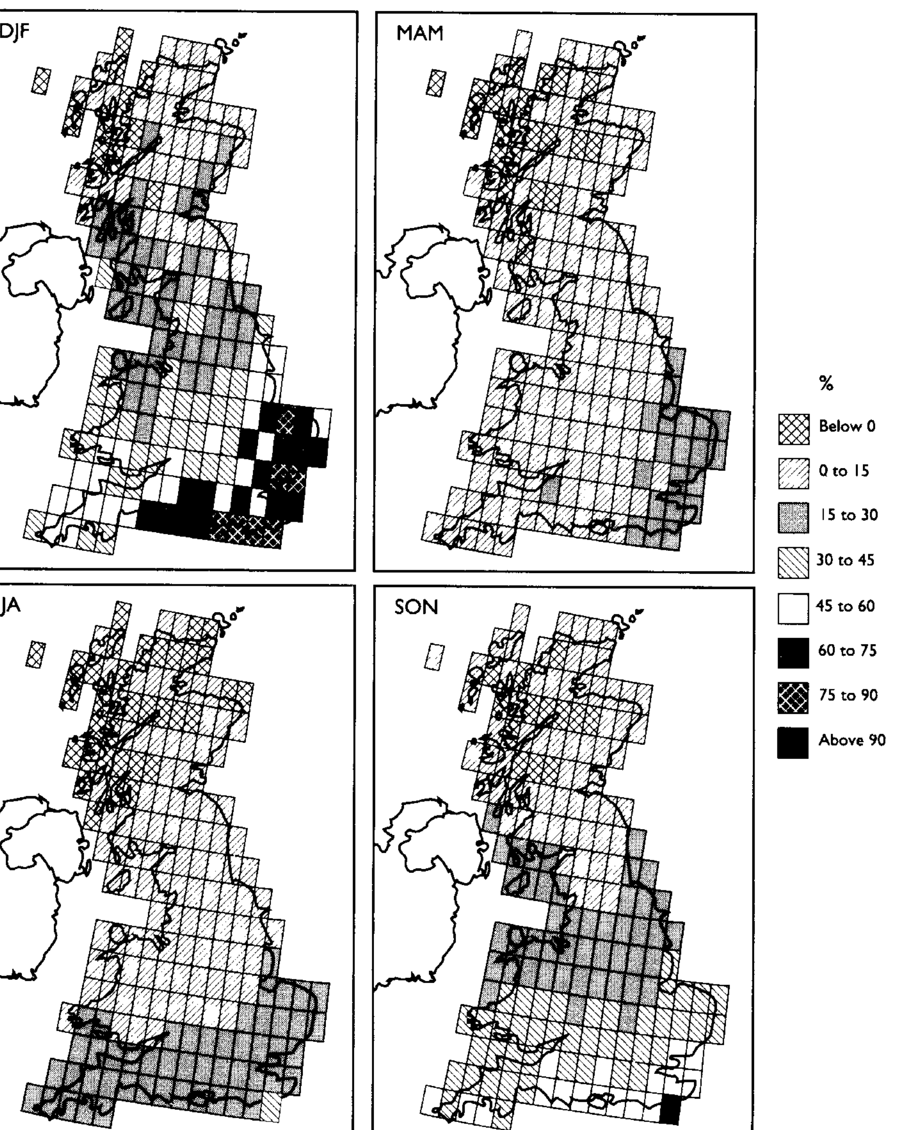
Water balances from GCM output

Changes in seasonal precipitation, 2050
GCM results interpolated to 0.5 x 0.5 degree grid



source: Arnell, 1996

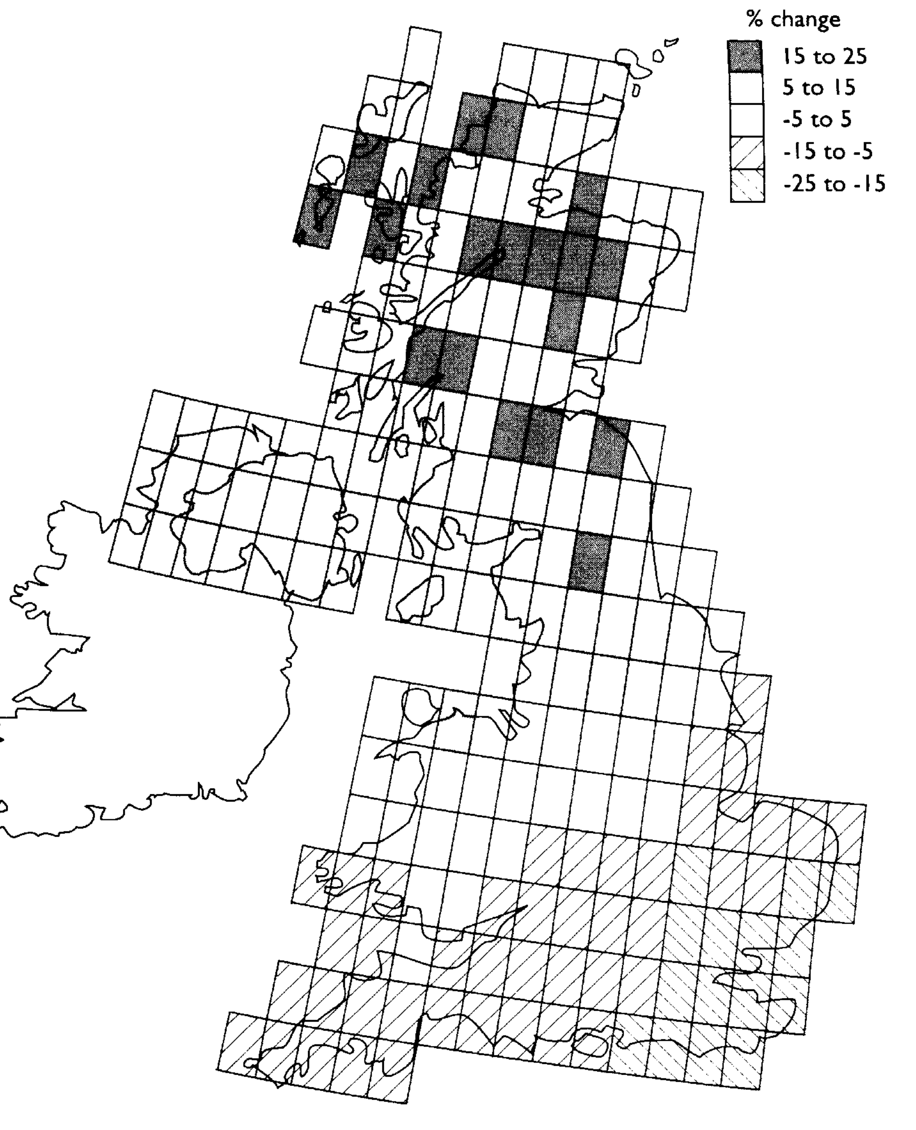
Water balances from GCM output



Changes in seasonal potential evaporation, 2050 GCM results interpolated to 0.5 x 0.5 degree grid

source: Arnell, 199

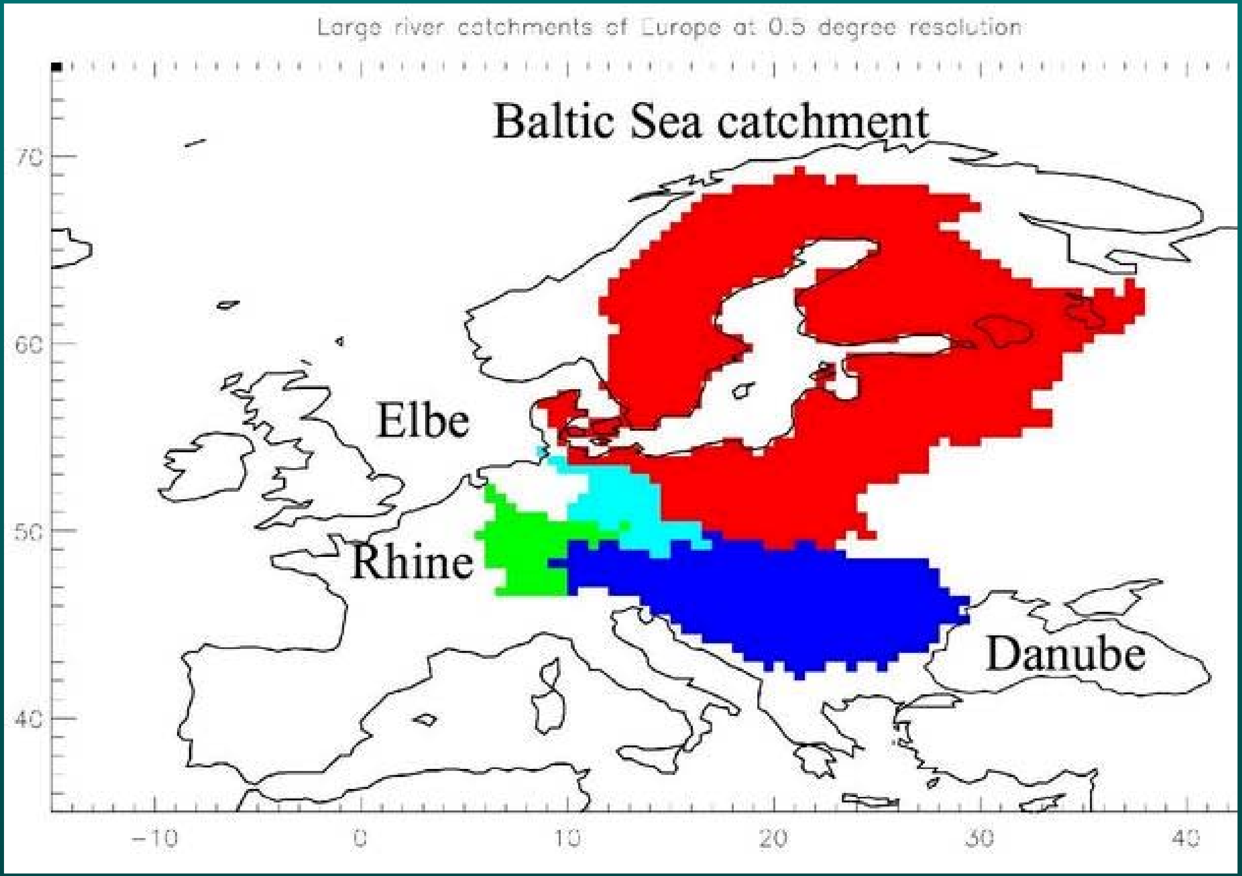
Water balances from GCM output



Changes in average annual runoff, 2050

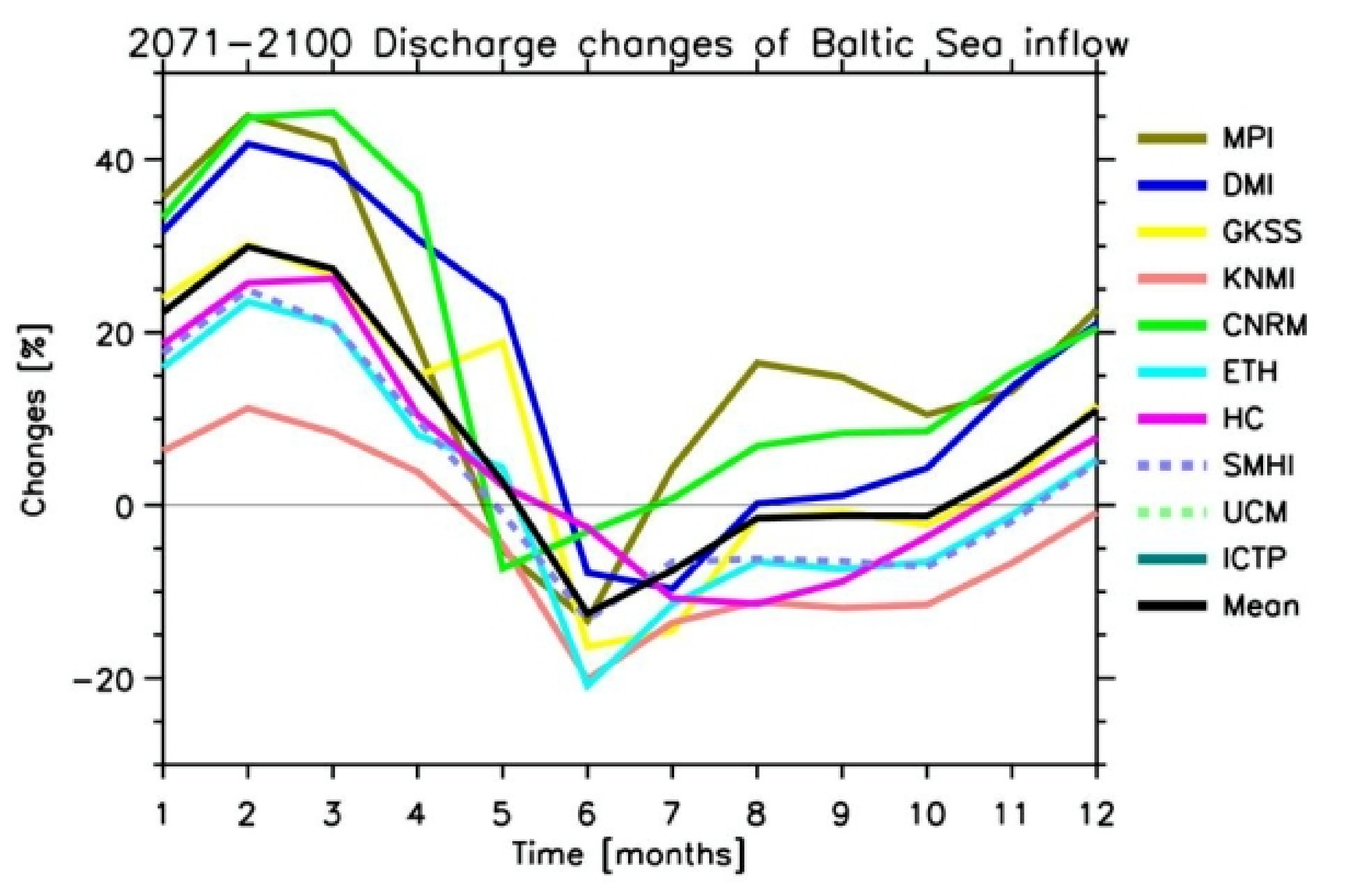
source: Arnell, 199

PRUCENCE RCM comparison

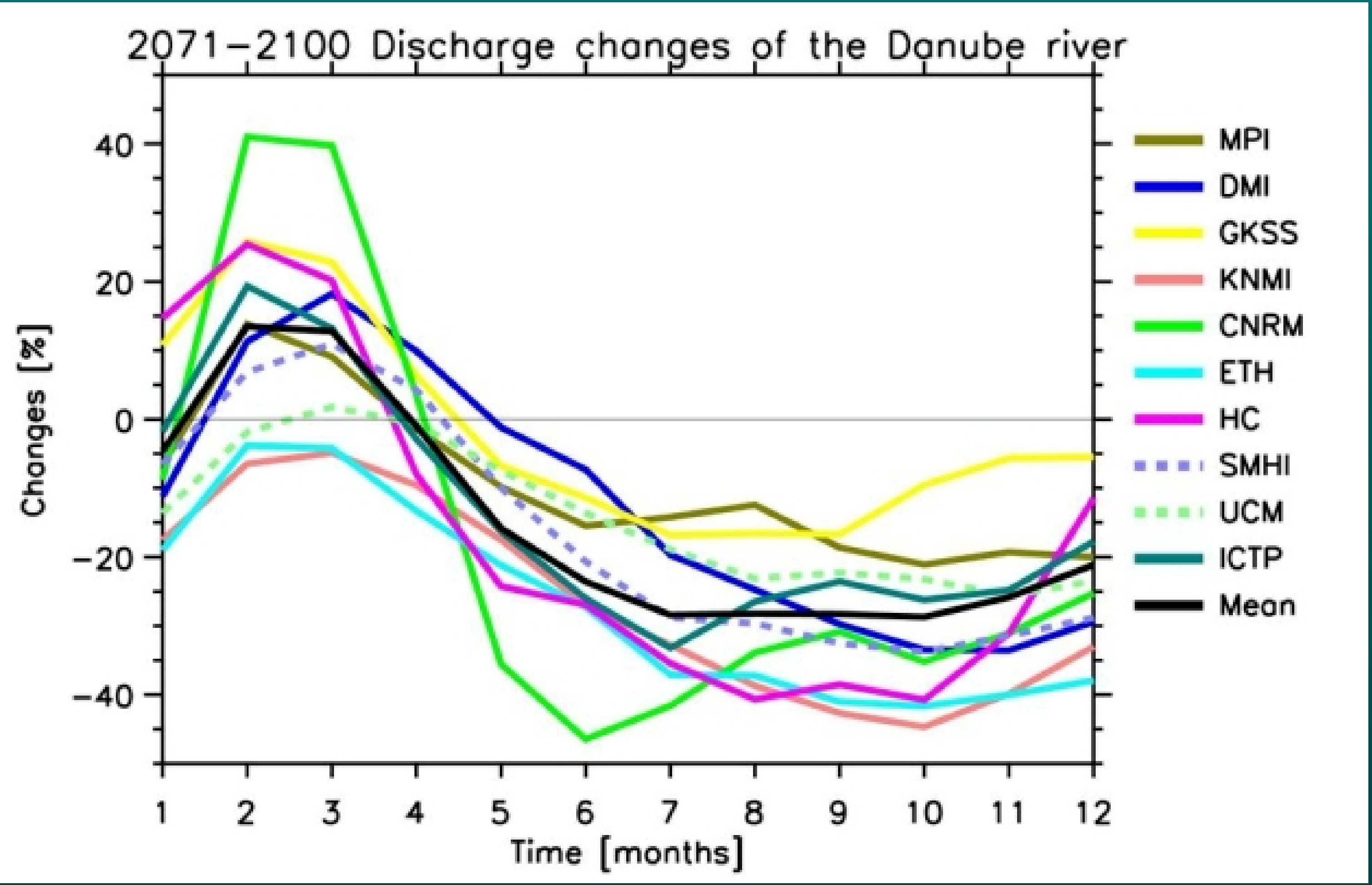


Comparison of RCMs, driven by HadCM3 GCM, IPCC A2 scenario, projection 2071-2100

PRUCENCE RCM comparison



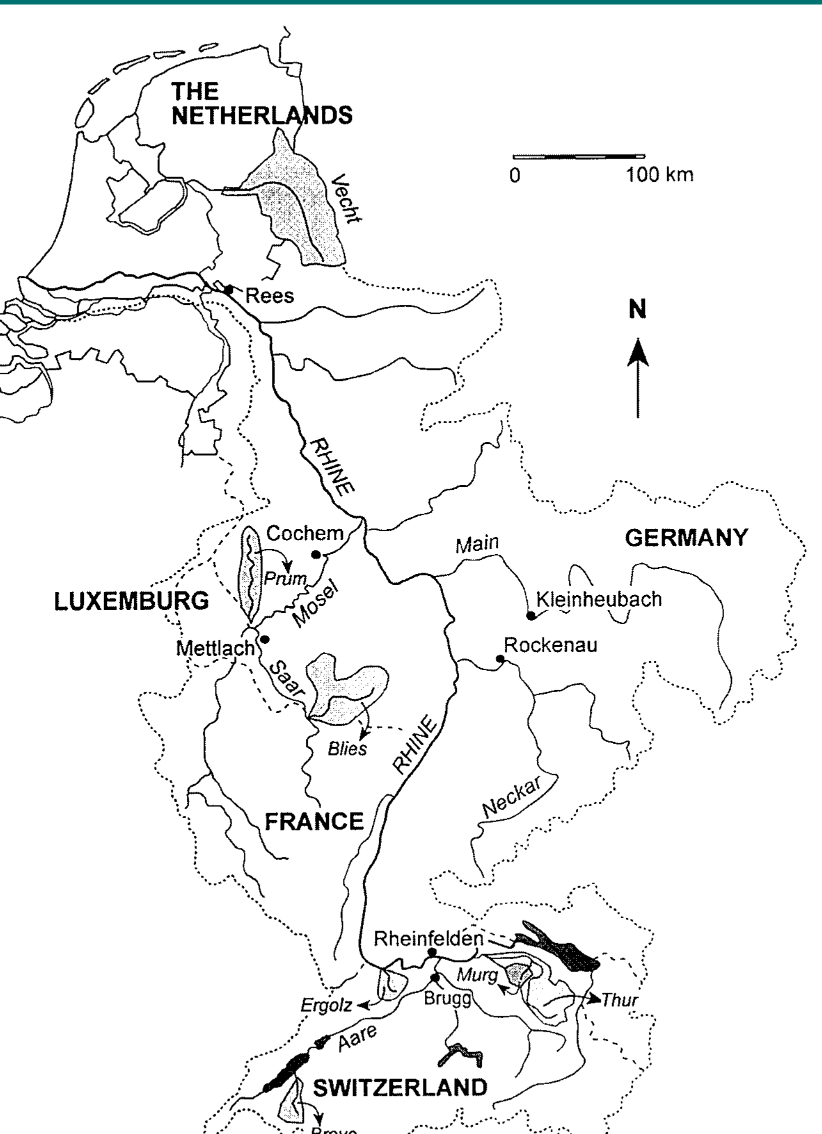
PRUCENCE RCM comparison

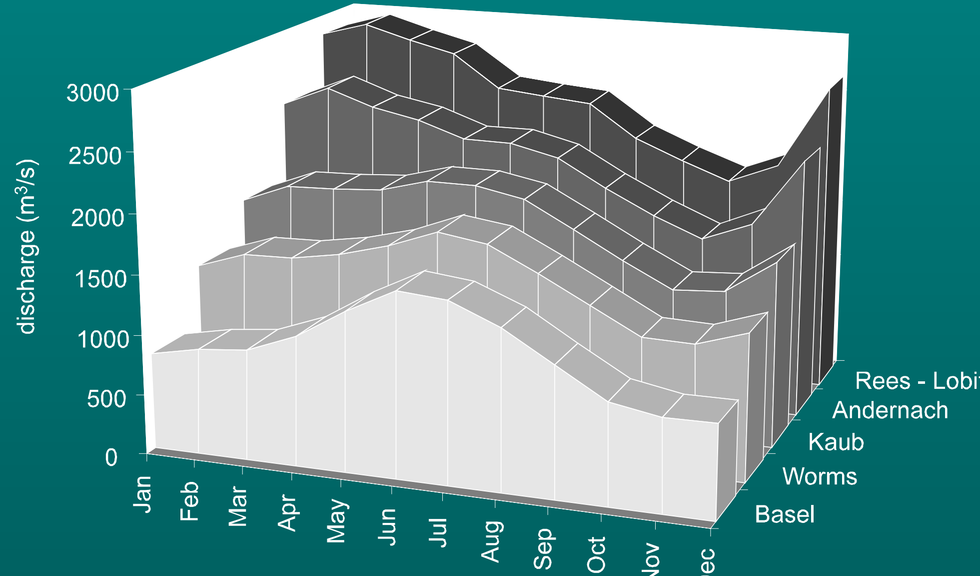


PRUCENCE RCM comparison

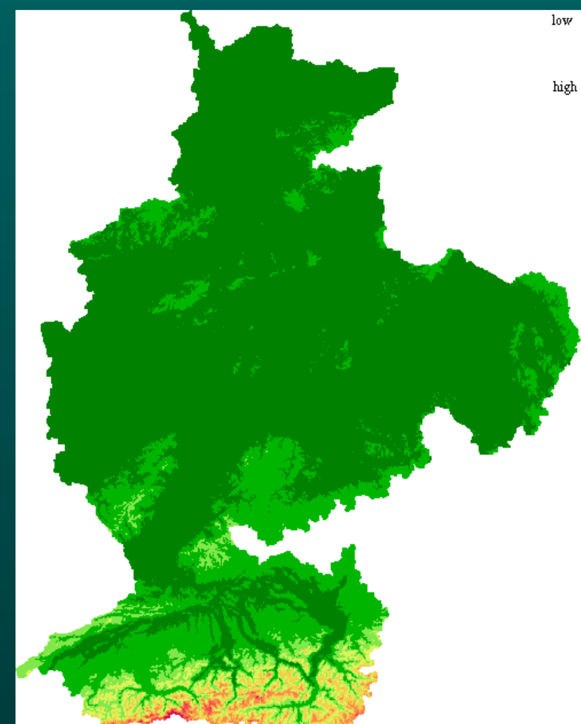
- Validation results: multi-model ensemble mean is closer to the observations than each of the models
- Scenario simulations predict a gradient in the climate change signal over Northern and Central Europe
- Common features: future warming and a general increase of evapotranspiration
- Northern parts: warming will enhance the hydrological cycle leading to an increased discharge (Baltic Sea inflow)
- Central parts: large summer warming, reducing summer discharge (Danube river)

Rhine basin study





source: CHR/KHR,1976

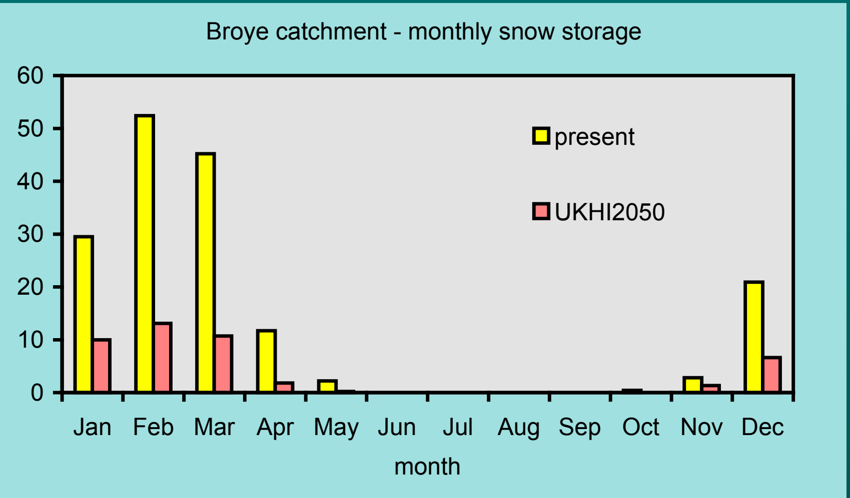


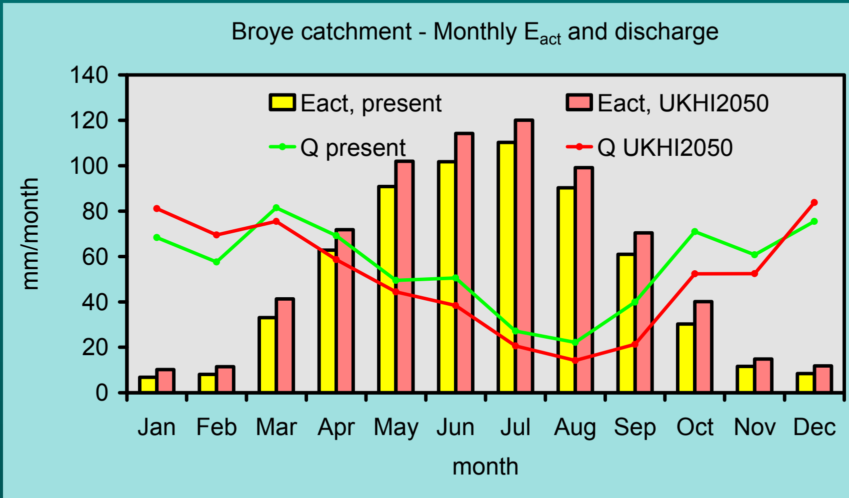
Rhine basin study - snow

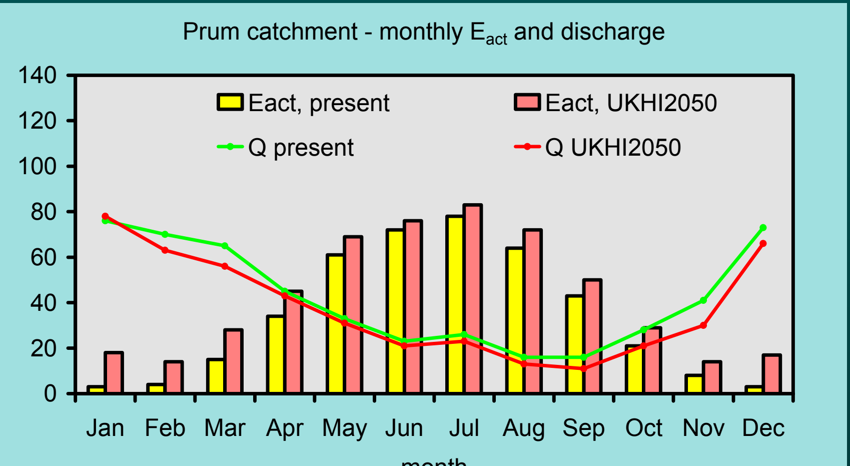
- Climate change scenarios
- 2 GCM simulations
- Projection year 2050
- Used as input for hydrological models (perturbation of baseline climate)

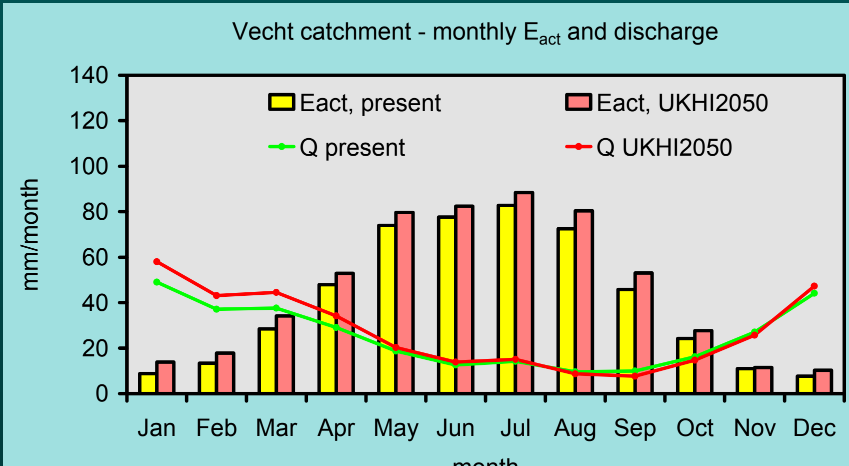
		Alpine area			Central Germany			Lowland		
		Y	W	S	Y	W	S	Y	W	S
UKHI	dT(ºC)	2.2	2.3	2.0	2.1	2.4	1.9	2.0	2.3	1.6
	dP(%)	1.8	8.6	-5.1	5.4	12.6	-1.9	11.0	17.7	4.5
XCCC	dT(ºC)	1.6	1.6	1.7	1.3	1.2	1.3	1.0	1.0	1.0
	dP(%)	4.9	9.5	-3.0	4.5	11.0	-2.0	4.8	10.1	-0.4

Rhine basin study

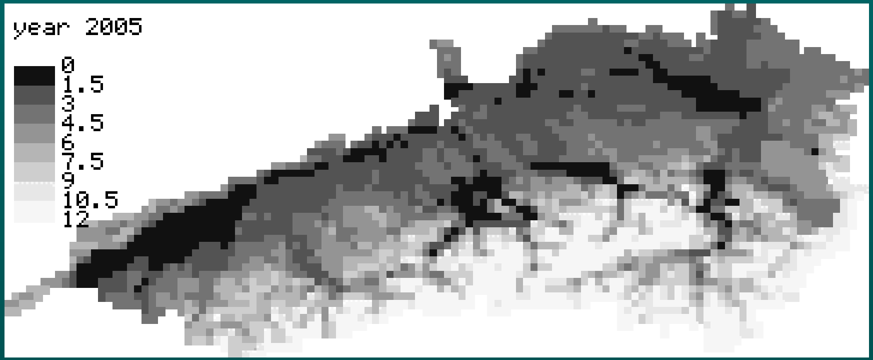


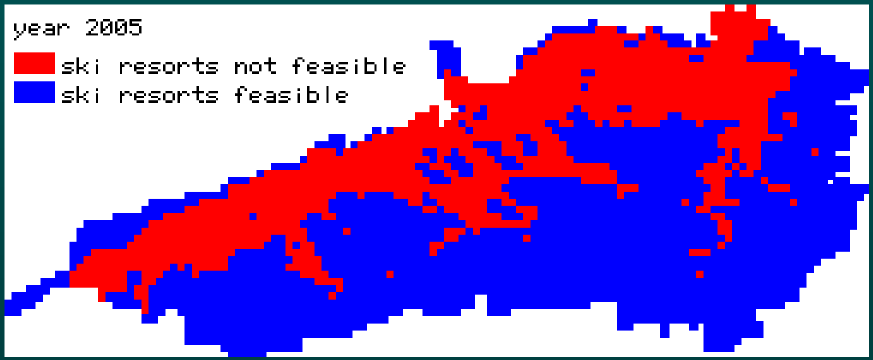




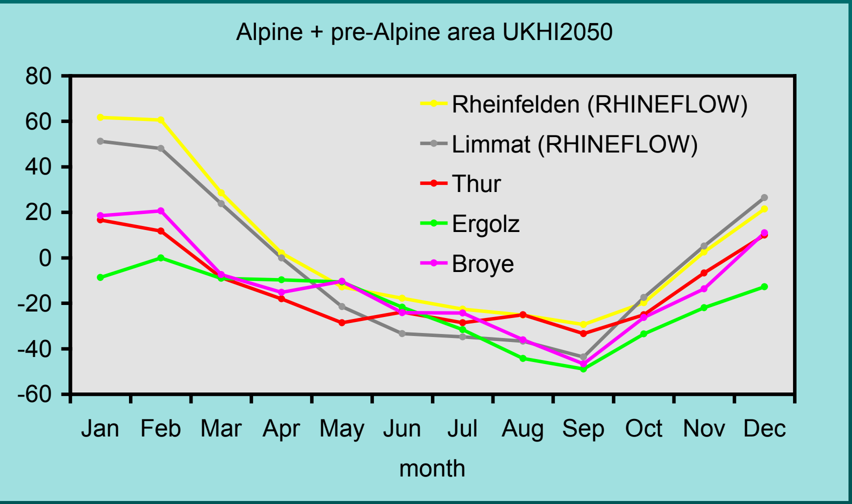


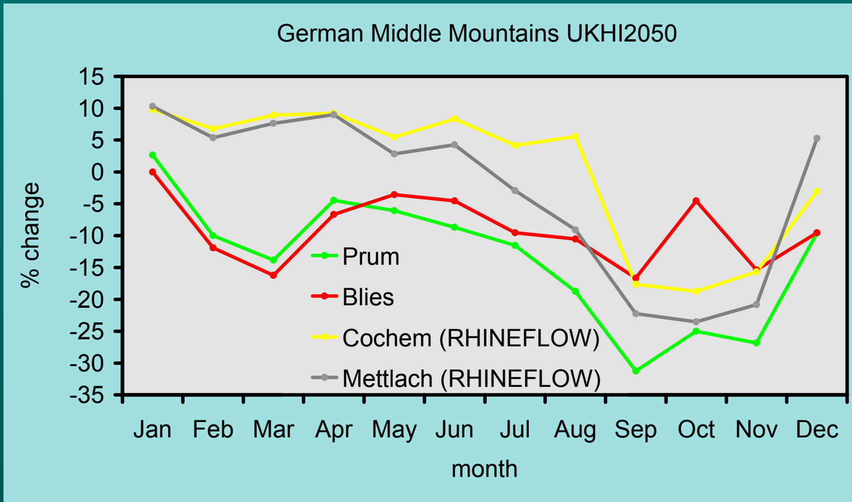
Rhine basin study - snow

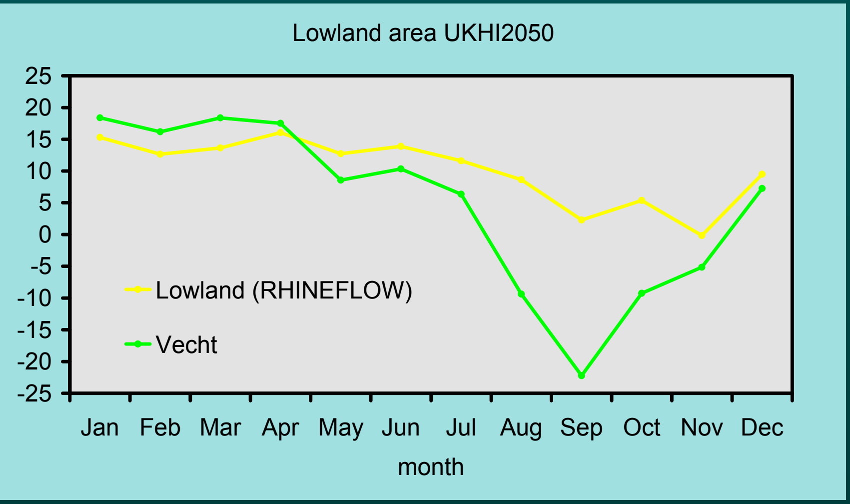




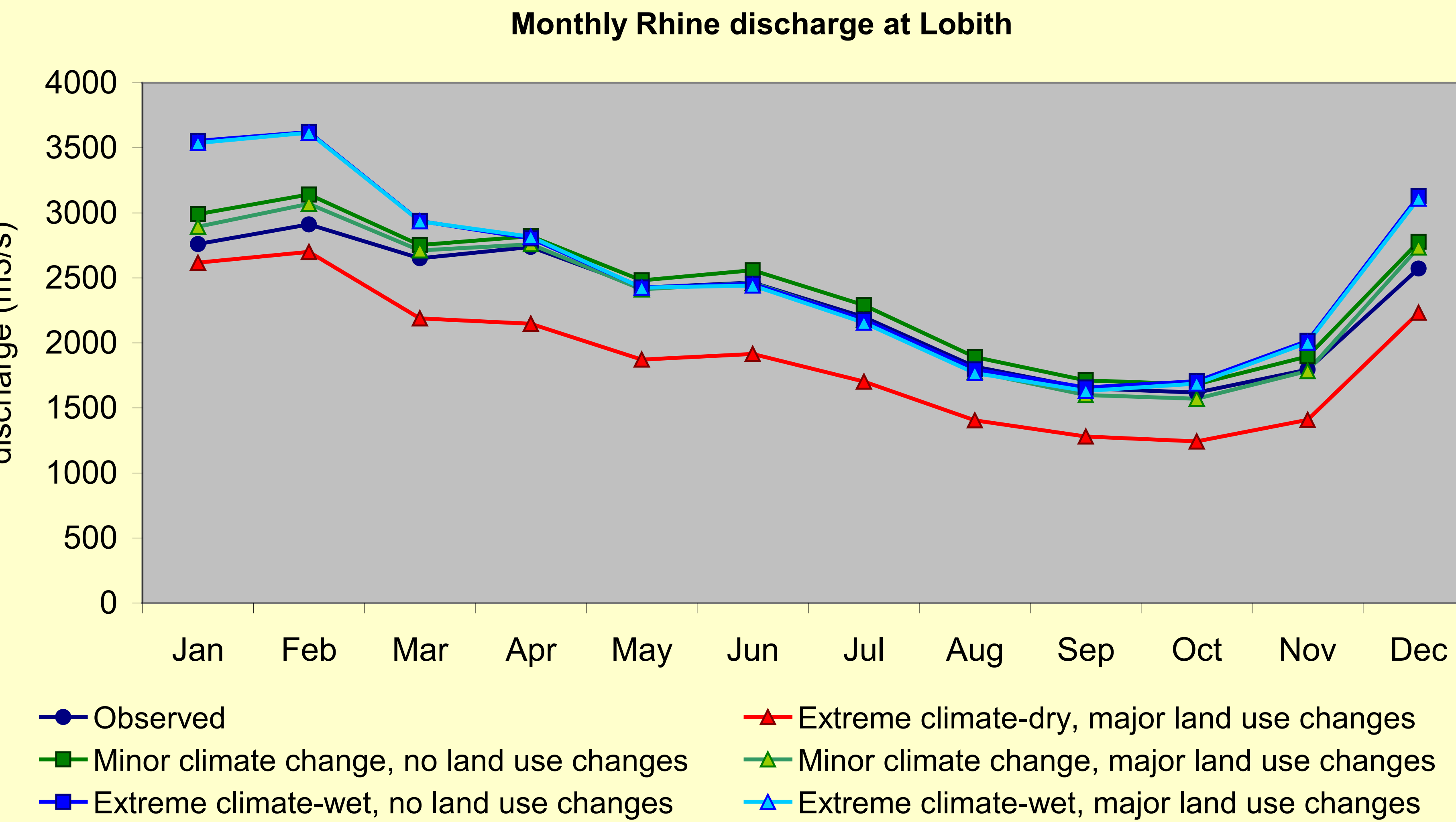
Rhine basin study



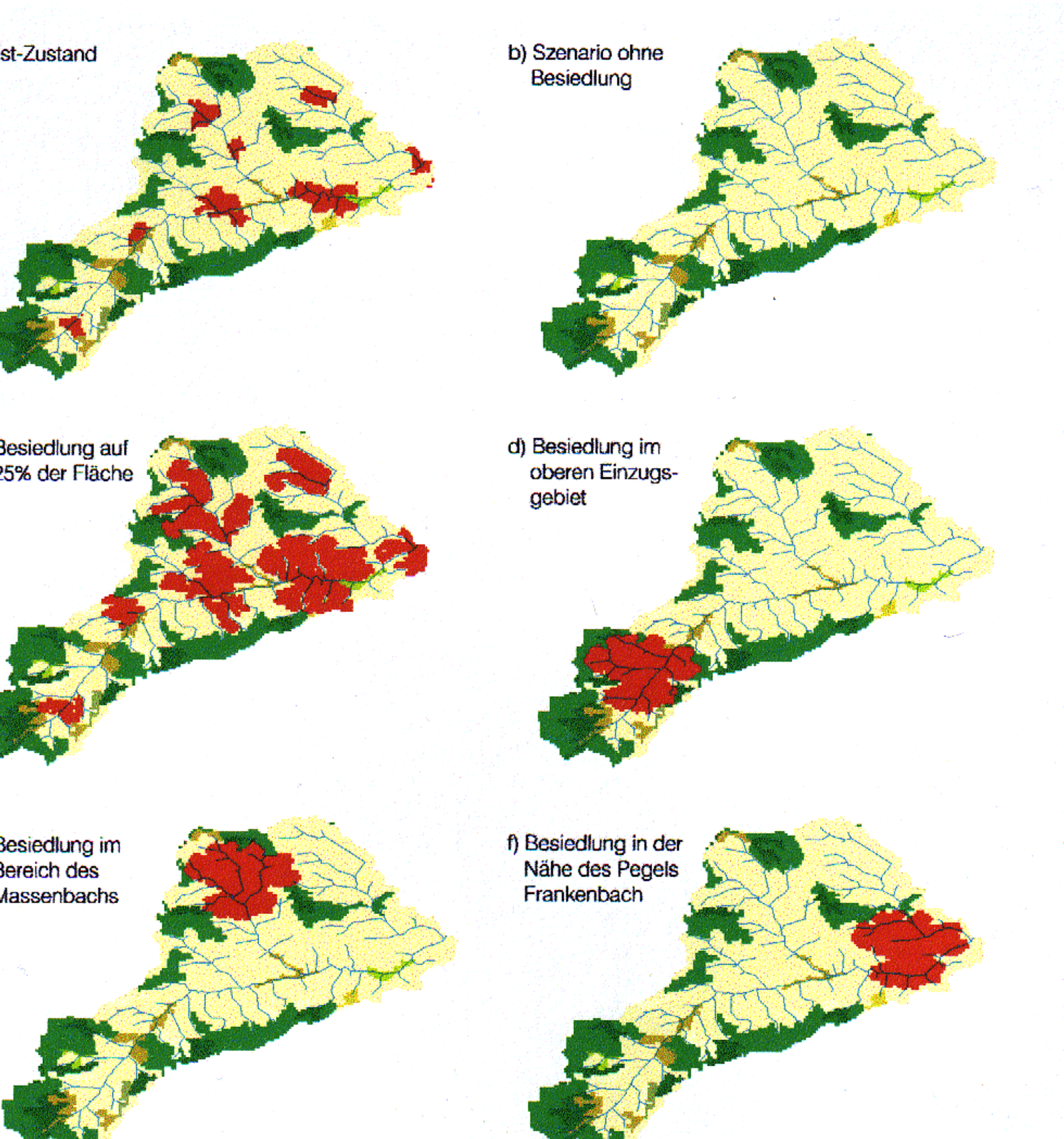




Land use and climate change



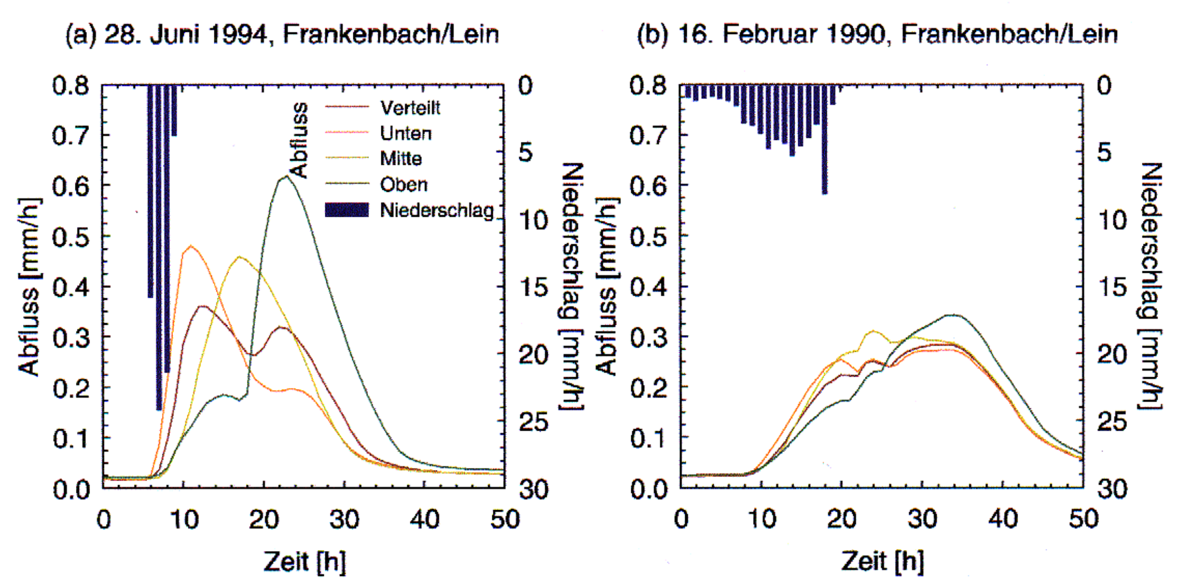
Land use change



- Example: small catchment within the Rhine basin: Lein catchment
- Land use scenarios for hydrological sensitivity analysis

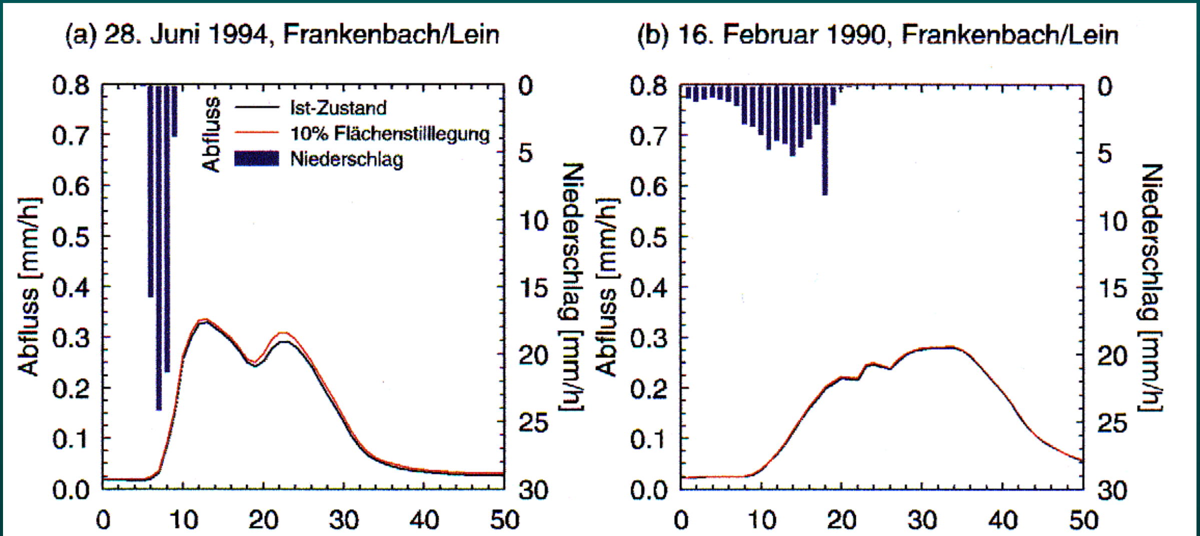
Bron: Fritsch & Niehoff, 2002

Land use and peak flows



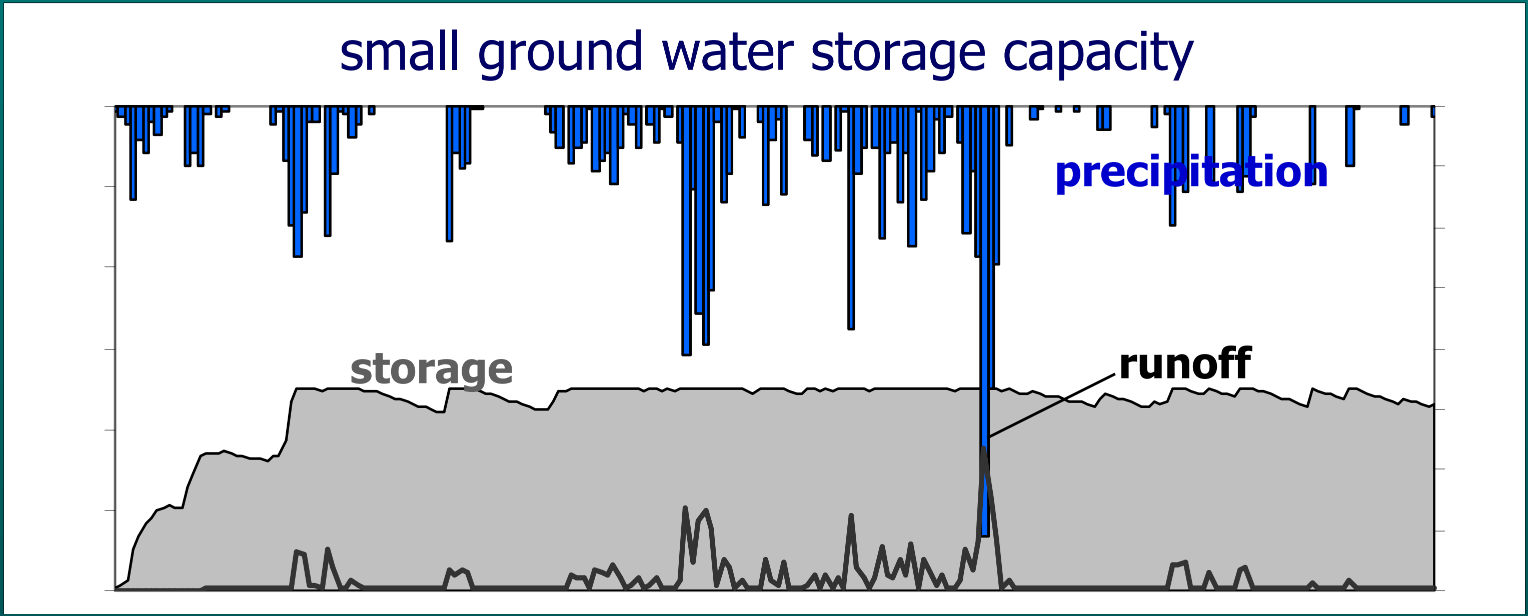
Effect of land use changes on peak flows

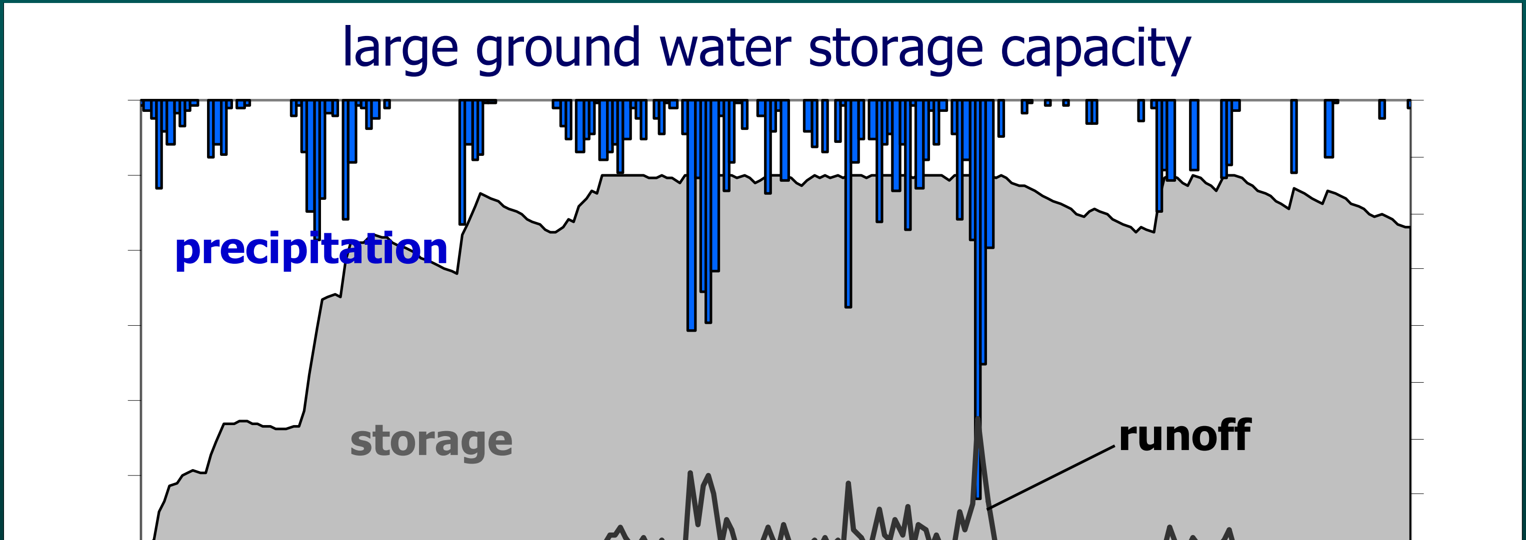
9% increase of urban area (= reduction upstream detention)



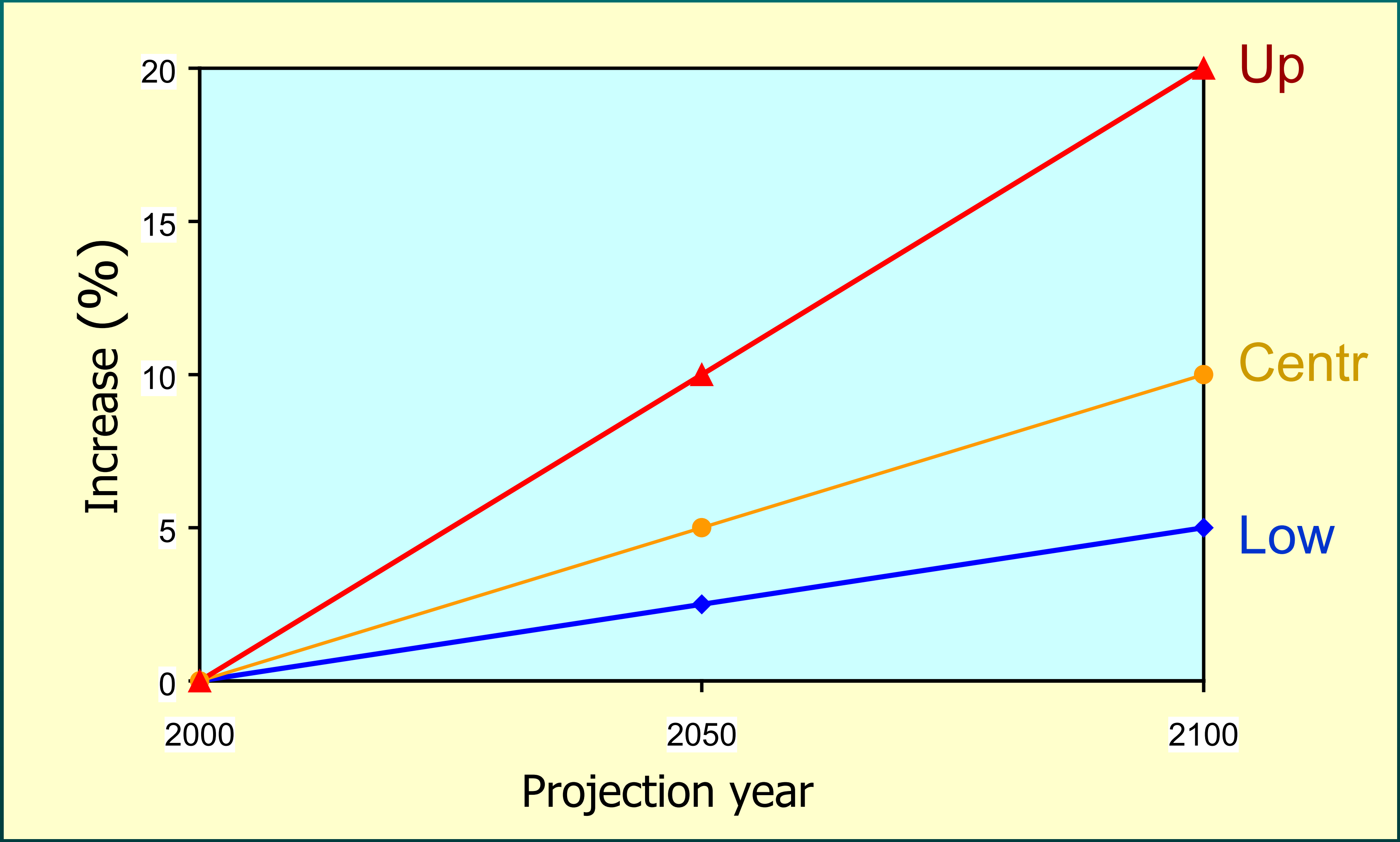
10% agriculture area replaced by nature areas

Land use and peak flows



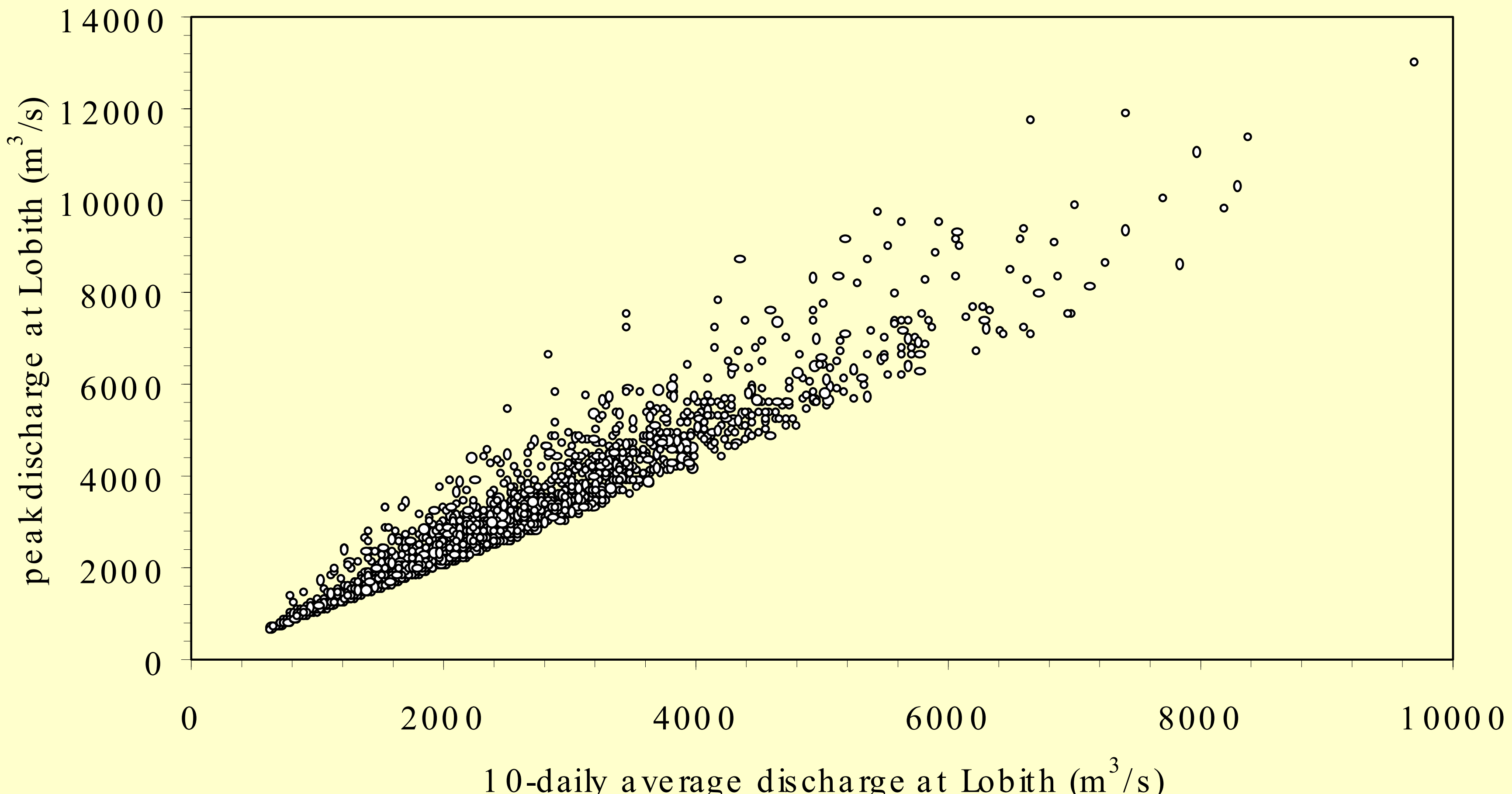


Scenarios for sensitivity analysis



Changes in peak flows

Relation between 10-daily discharges and peak discharges 1901-1995



Implications for water management in the Netherlands - Rivers

- Safety: changes in peak flows
- Statistical extrapolation to changes in design discharge

Projection year	Current (m^3/s)	Lower estimate (m^3/s)	Central estimate (m^3/s)	Upper estimate (m^3/s)
2000	16,000			
2050		16,250	16,500	17,500
2100		16,500	17,500	20,000

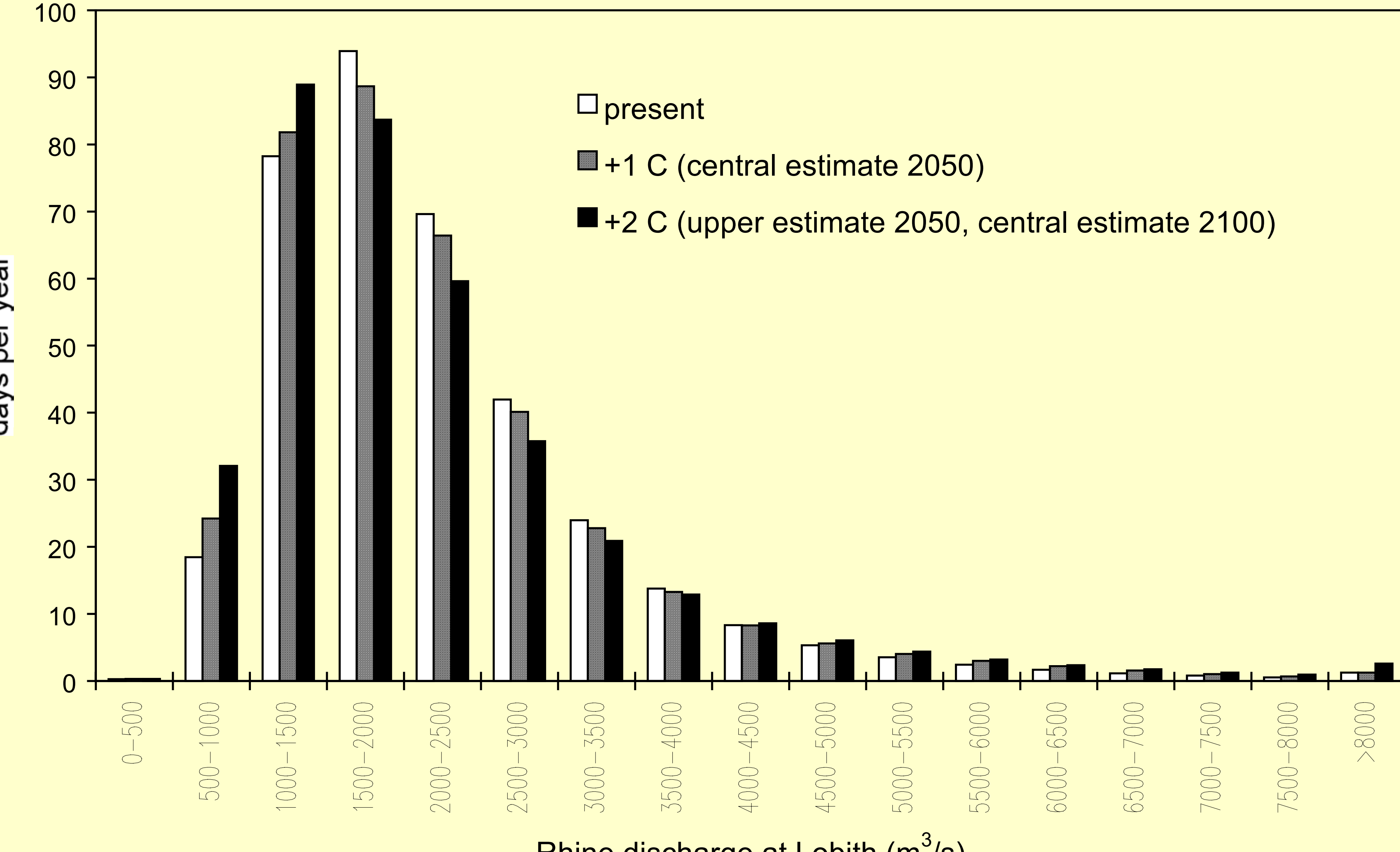
Inland navigation Rotterdam - Basel

Inland navigation on the Rhine:

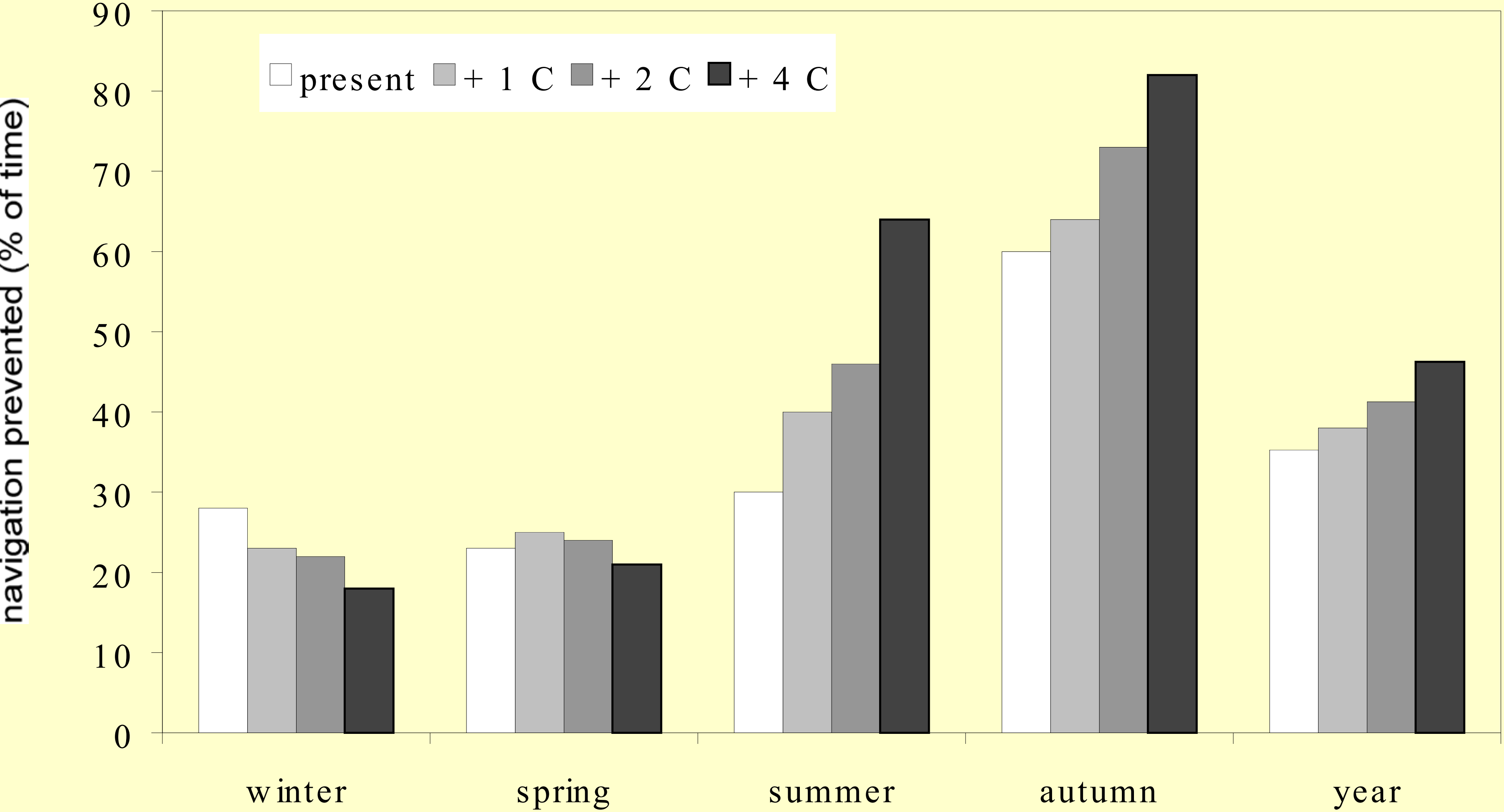
Low river flow = shallow water depth in river channel:

- less cargo
- increased cost
- reduced reliability

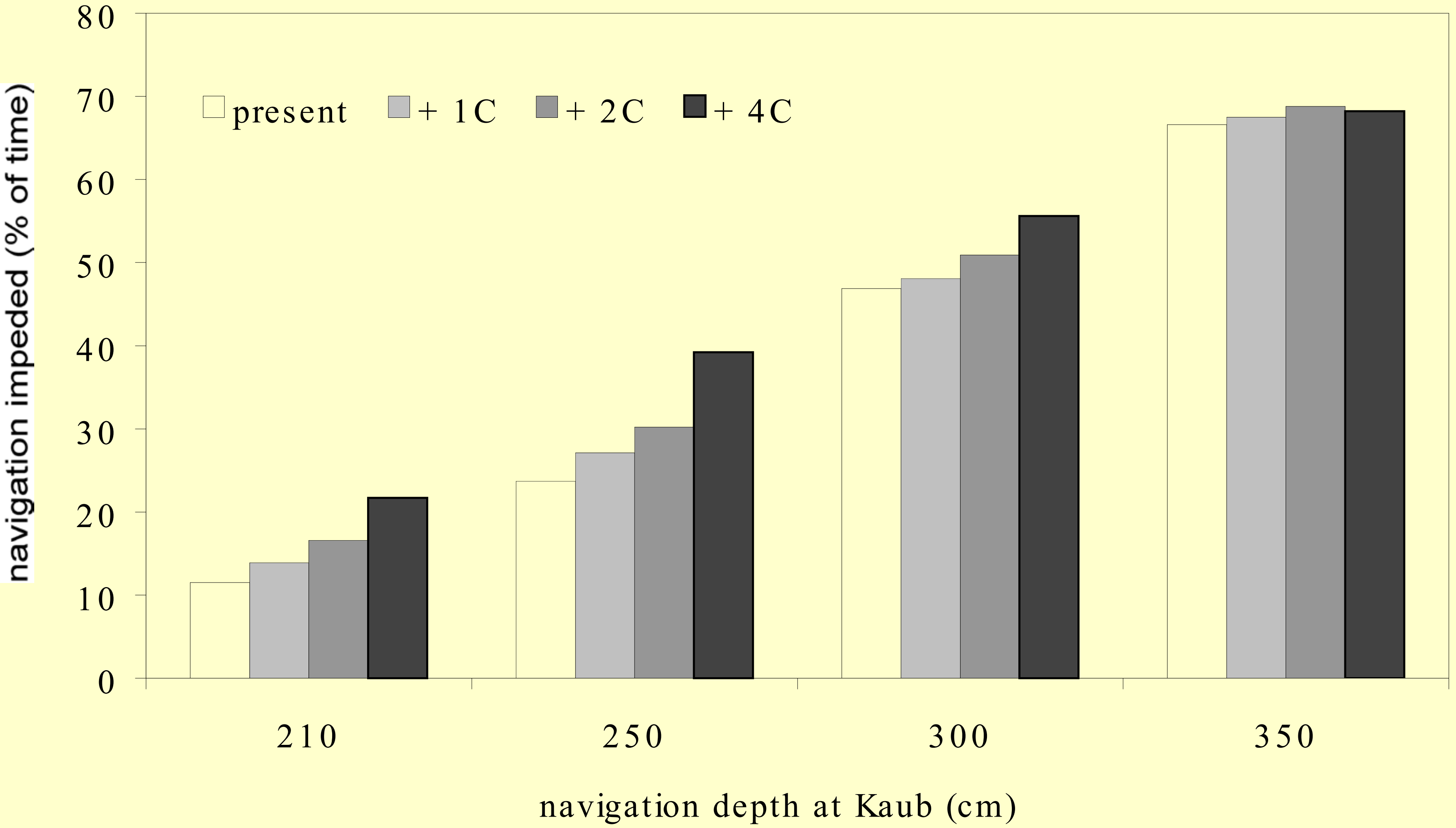
Implications for inland navigation



Hindered navigation at Kaub



Hindered navigation at Kaub



Conclusions Rhine basin

- Climate change more important than land use change
- Annual average discharge changes little
- Winter flow increases due to
  - higher winter precipitation
  - reduced snow storage in Alps
- Summer flow decreases
  - intensified evapotranspiration
  - less snow melt from Alps
- Increase of peak flows: 5 – 10% by 2100
  - flood risk increases: design Q from 16,000 m^3s^{-1} to 18,000 m^3s^{-1} ?
- Less water available in summer, when demand is largest:
  - water management W-Netherlands
  - agriculture, drinking water, navigation

Hydrological impacts - Subarctics

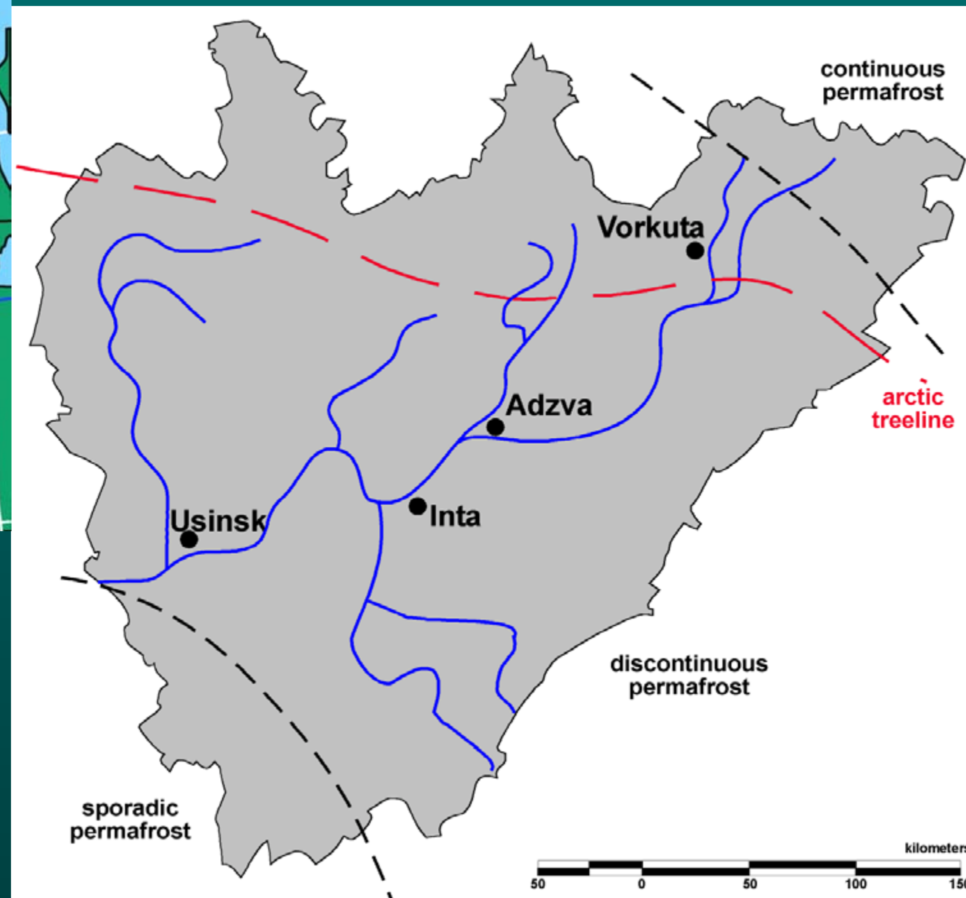
- Modelling studies by Dankers and Van der Linden
- EU-projects on climate impacts on sub-arctic regions
- Tana river – N-Finland
- Usa river – NW Siberia

Table 1 Catchment characteristics and runoff regimes.

Data	Tana River	Usa River
Catchment size	16 000 km^2	93 000 km^2
Hydrograph character	Subarctic nival river regime	Subarctic nival river regime
Mean annual discharge	166 m^3/sec, highly variable	1091 m^3/sec, highly variable
Snowmelt peak runoff	1500–3000 m^3/sec	6000–15 000 m^3/sec
Mean annual air temperature	−0.5 to −3°C	−3 to −7°C
Mean annual precipitation	340–460 mm	400–800 mm
Permafrost (predominantly)	Sporadic to discontinuous	Discontinuous to continuous

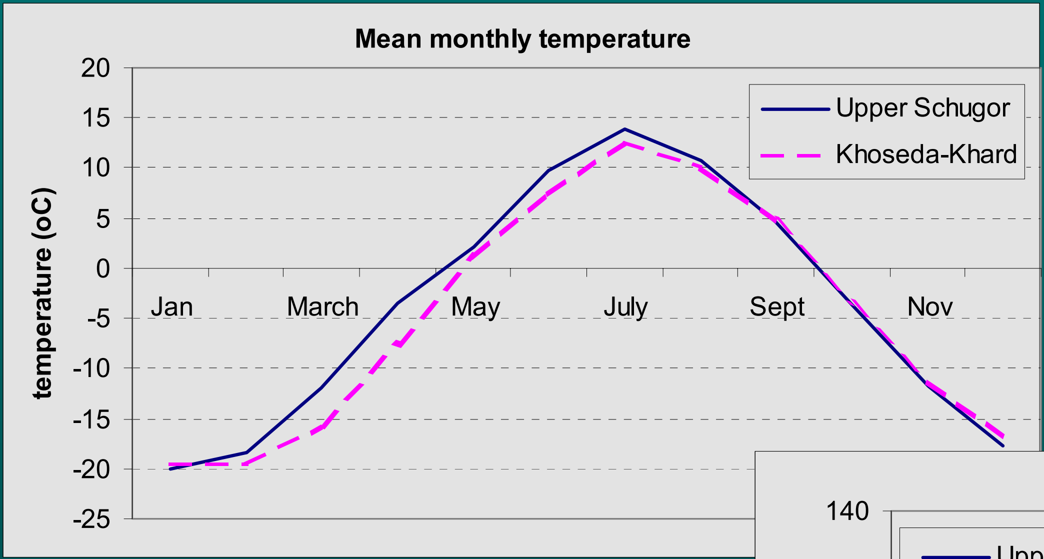
Koster et al., 2005

Hydrological impacts - Usa basin



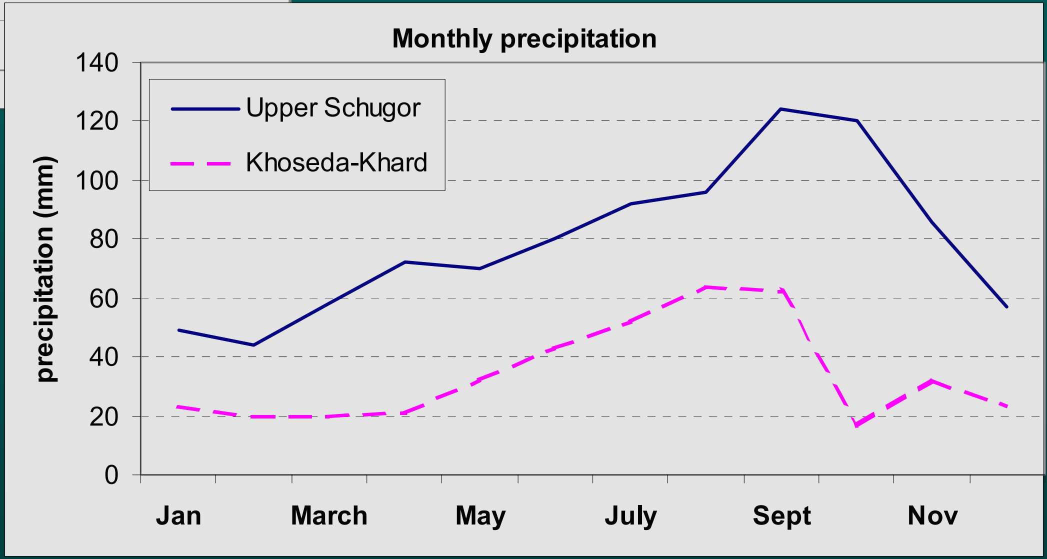
Sandra van der Linden, 200

Hydro-meteorological characteristics 1

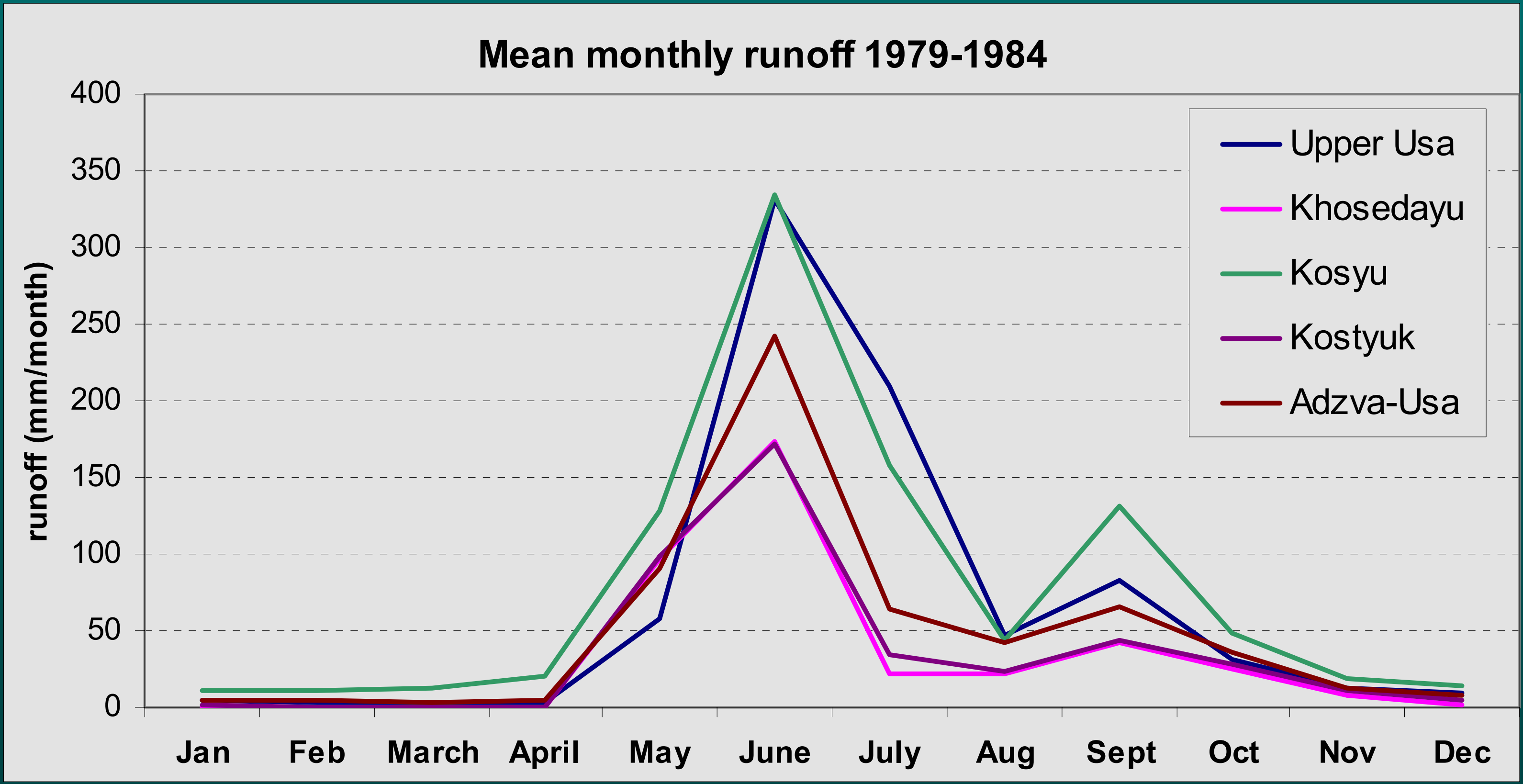


temperature

precipitation

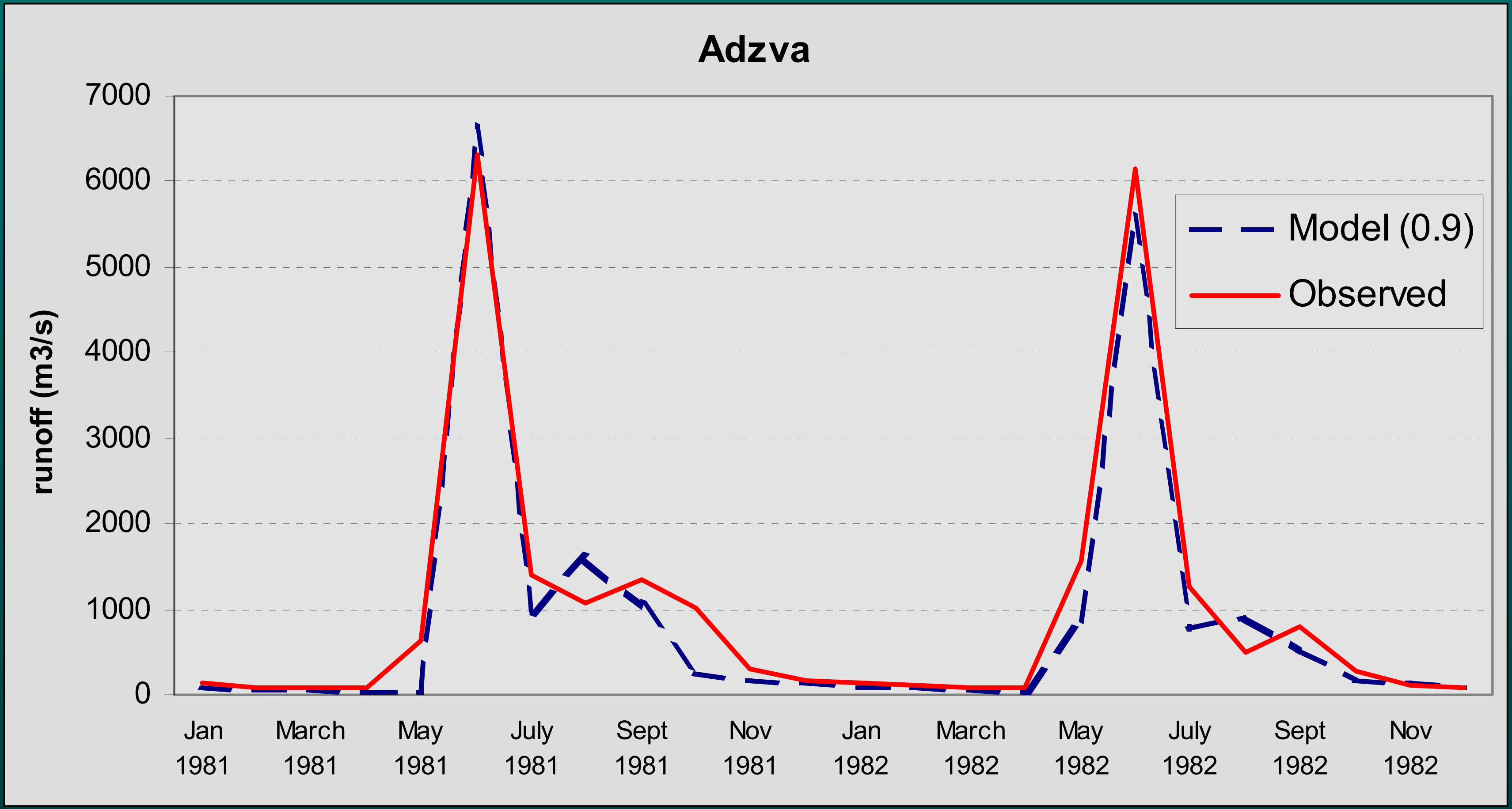


Hydro-meteorological characteristics 2



runoff

Model performance

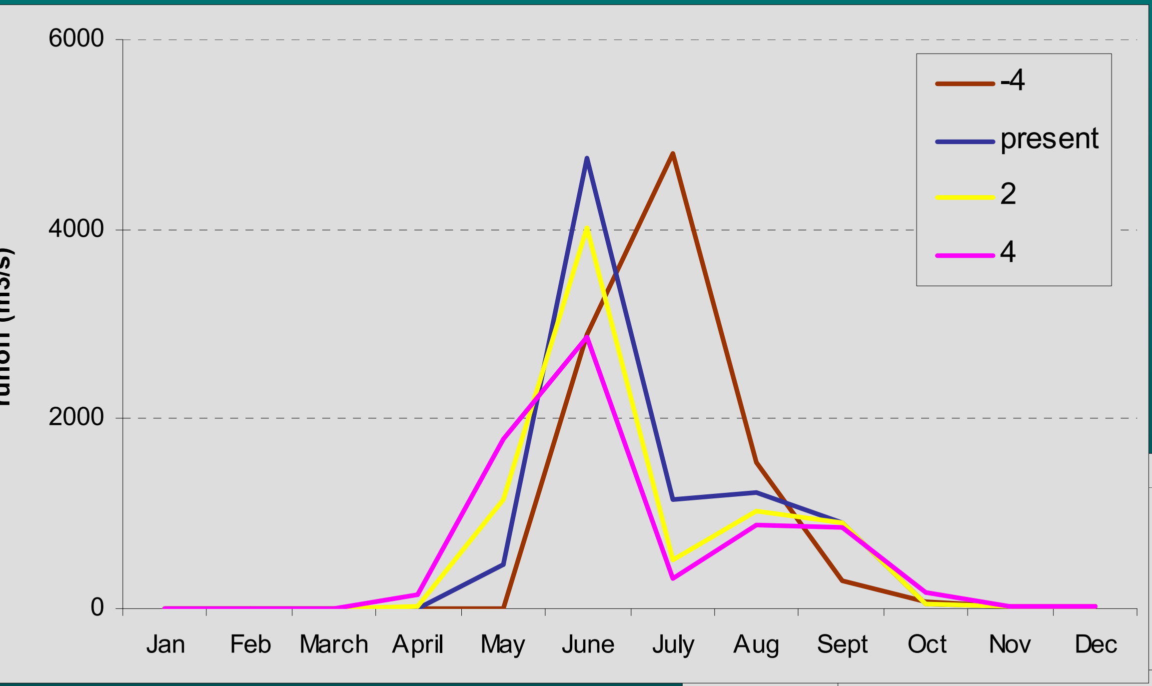


Model application

Sensitivity analyses

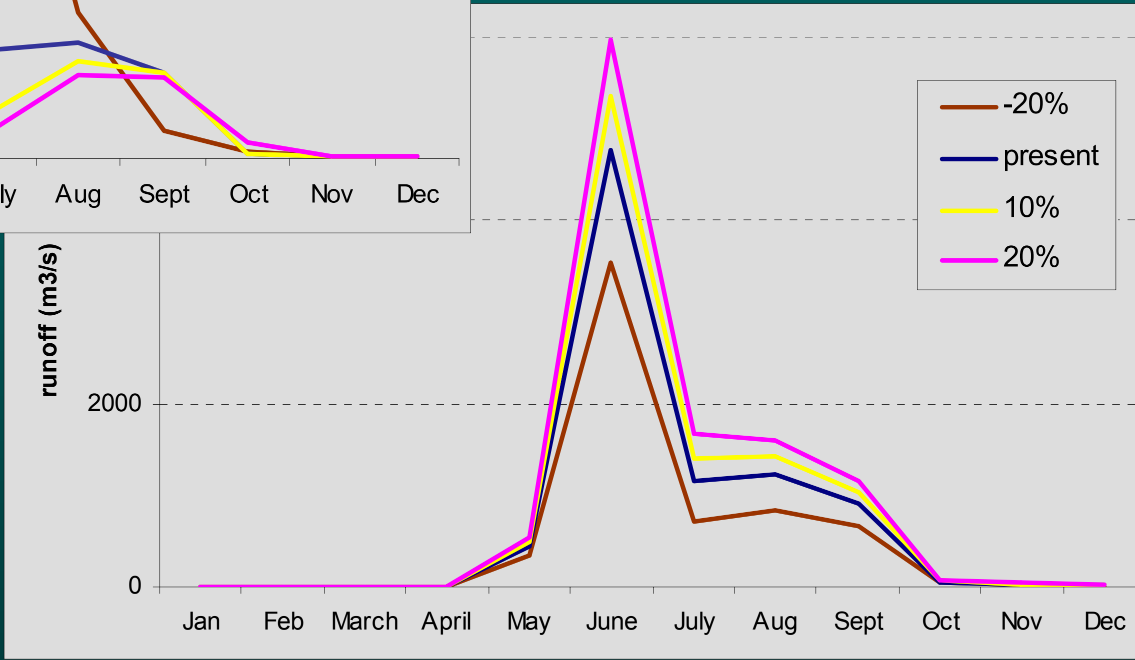
- changes in
  - temperature
  - precipitation
  - vegetation - evaporation
  - permafrost - separation direct runoff / groundwater
- Climate scenarios HadCM2 S750 experiment
- GHG concentrations stabilized in 2200 at 750 ppm, projected to the years
  - 2080 (incl. permafrost change)
  - 2230 - ‘equilibrium’ (incl. permafrost + veg. change)

Sensitivity analyses Usa



Temperature change

Precipitation change



Usa - Adzva station

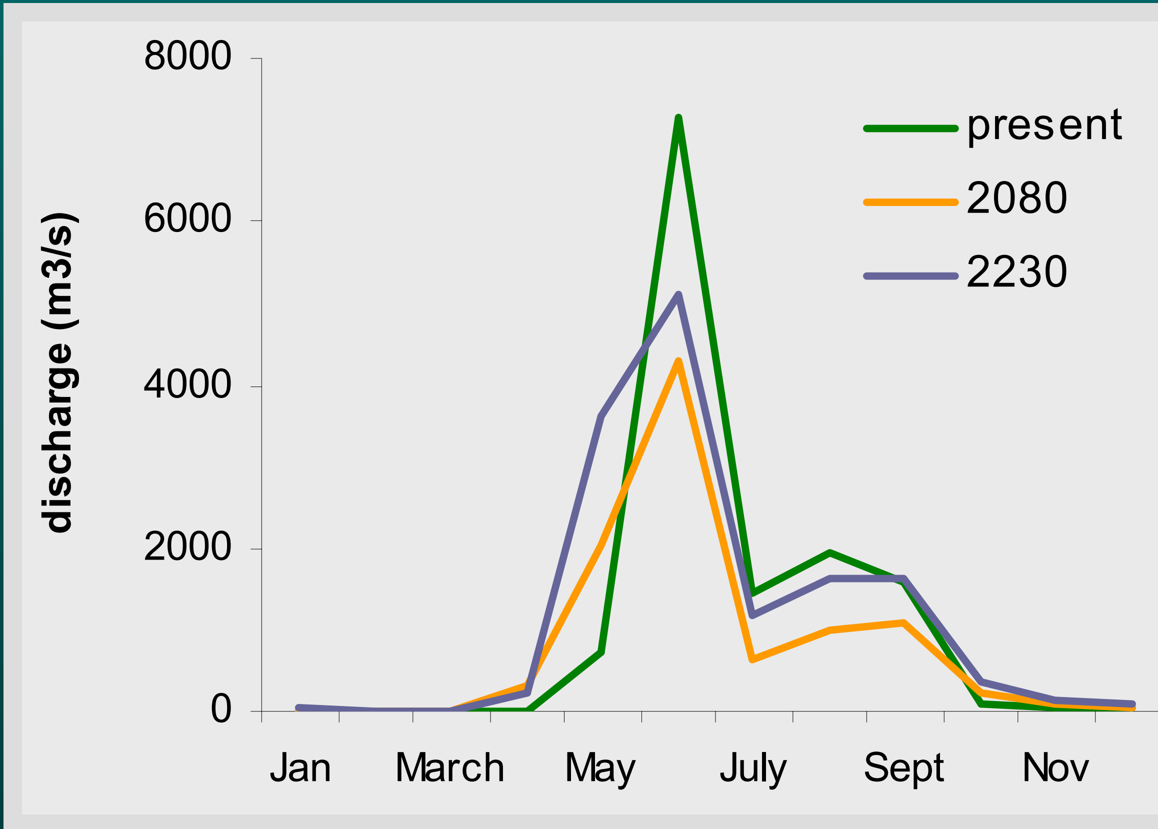
Climate change scenarios

- Direct climate parameters
- Snow melt
- Permafrost: separ. coeff.
- Vegetation change: ΔE

Scenario 2080:
- $\Delta P = + 10\%$
- $\Delta T = + 2.8°C$
- separ. coeff. * 3

Scenario 2230:
- $\Delta P = + 23\%$
- $\Delta T = + 4.1°C$
- separ. coeff. * 3
- $\Delta E = + 20\%$

Usa



Usa basin conclusions

- Impacts of climate larger than effects of vegetation and permafrost changes
  - dP = annual discharge volume, snow volume
  - dT = snow volume, timing and magnitude of peak Q, E
- 2080 scenario:
  - 20% *decrease* of annual Q due to intensified E
  - 20% *decrease* of snow volume - lower peak, earlier snowmelt
- 2230 scenario:
  - 10% *increase* of annual Q due to higher P
  - 10% *increase* of snow volume - lower peak, earlier snowmelt
- Counterbalancing mechanisms: simple extrapolation of model results not possible

Climate impacts - Tana basin

Rutger Dankers, 200

Scenario analyses Tana basin

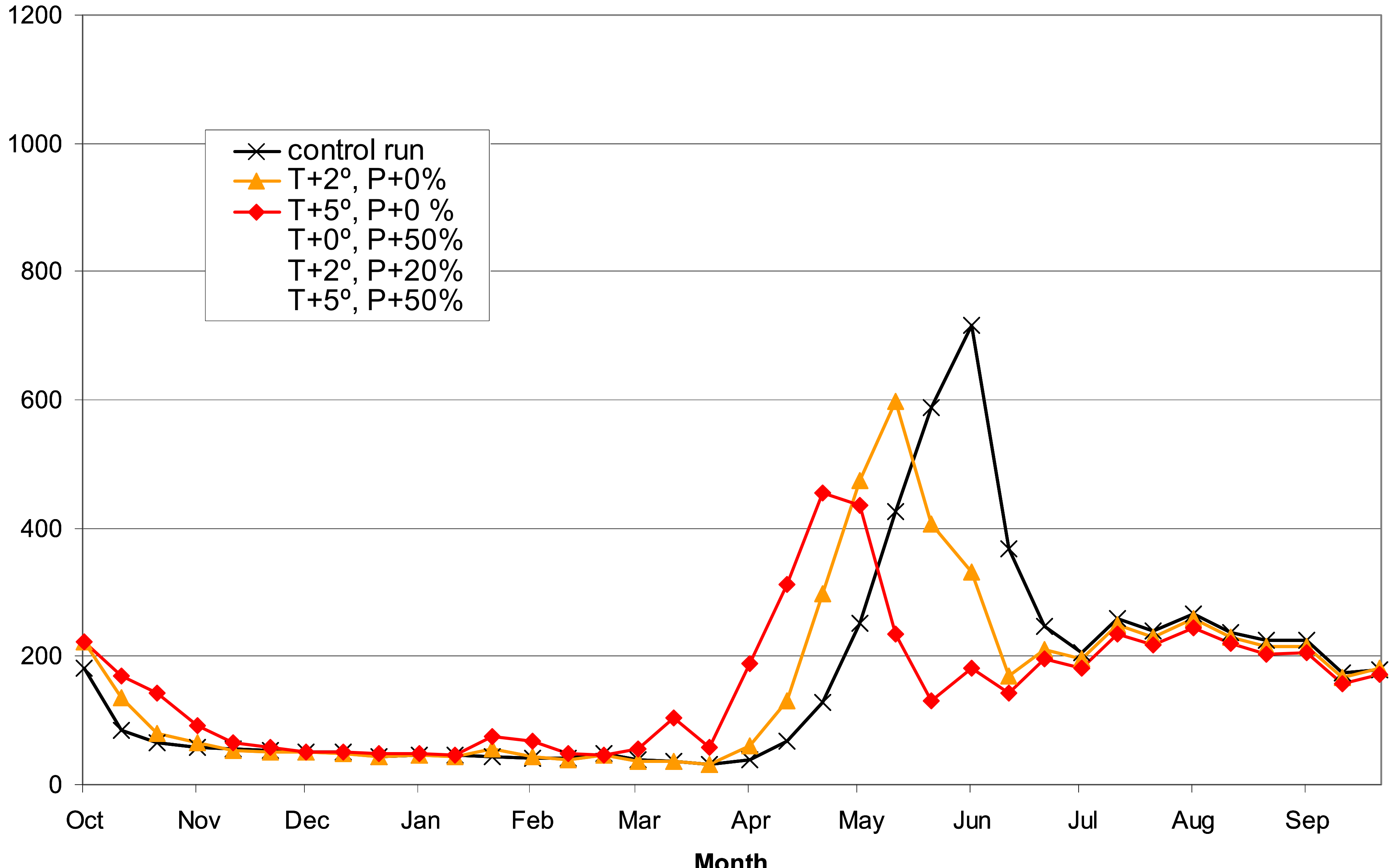
Sensitivity analyses

- changes in
  - temperature
  - precipitation

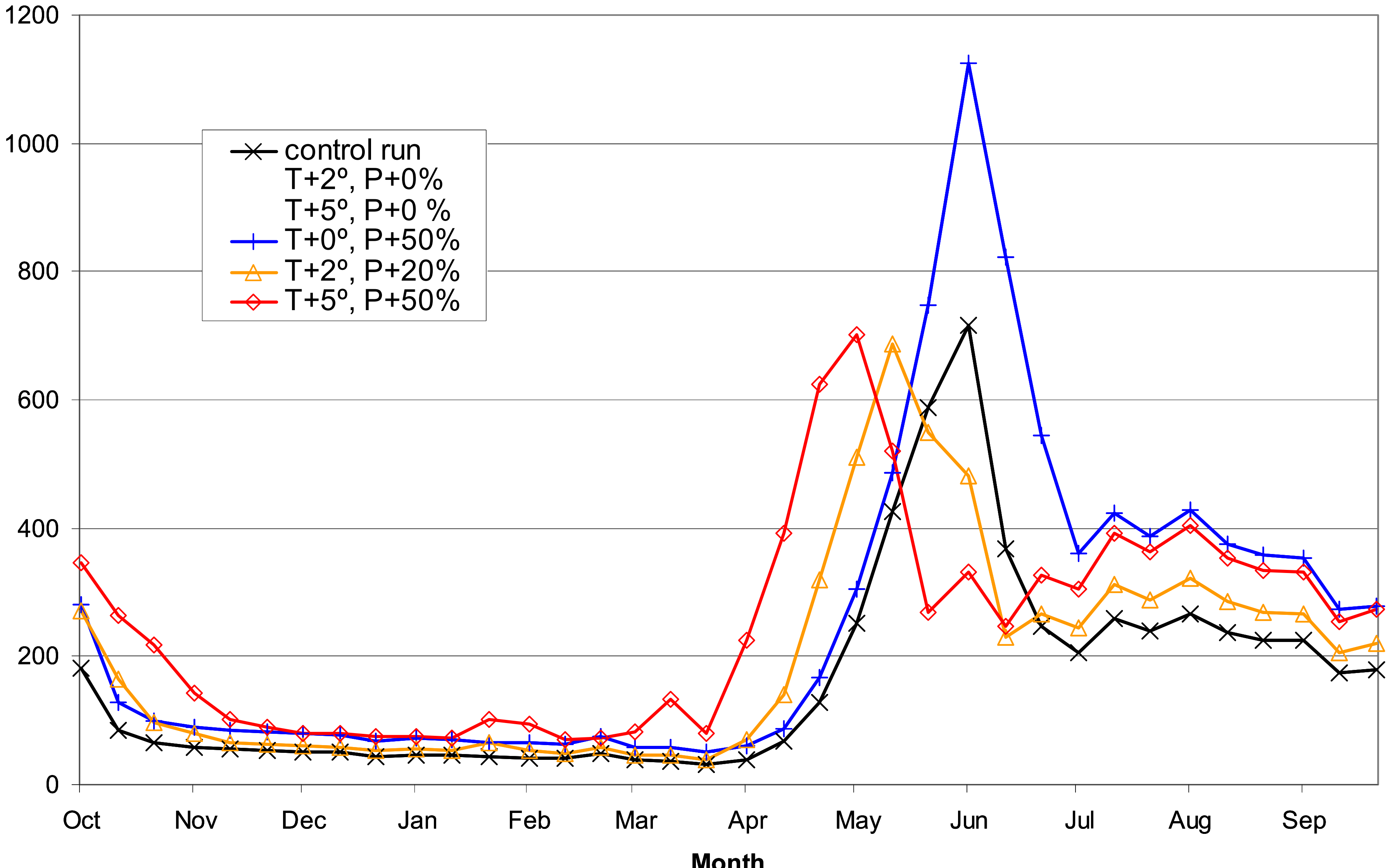
Climate change scenario

- ECHAM/OPYC GCM with SRES A2 scenario
- downscaling using HIRHAM RCM
- projection period 2070-2100

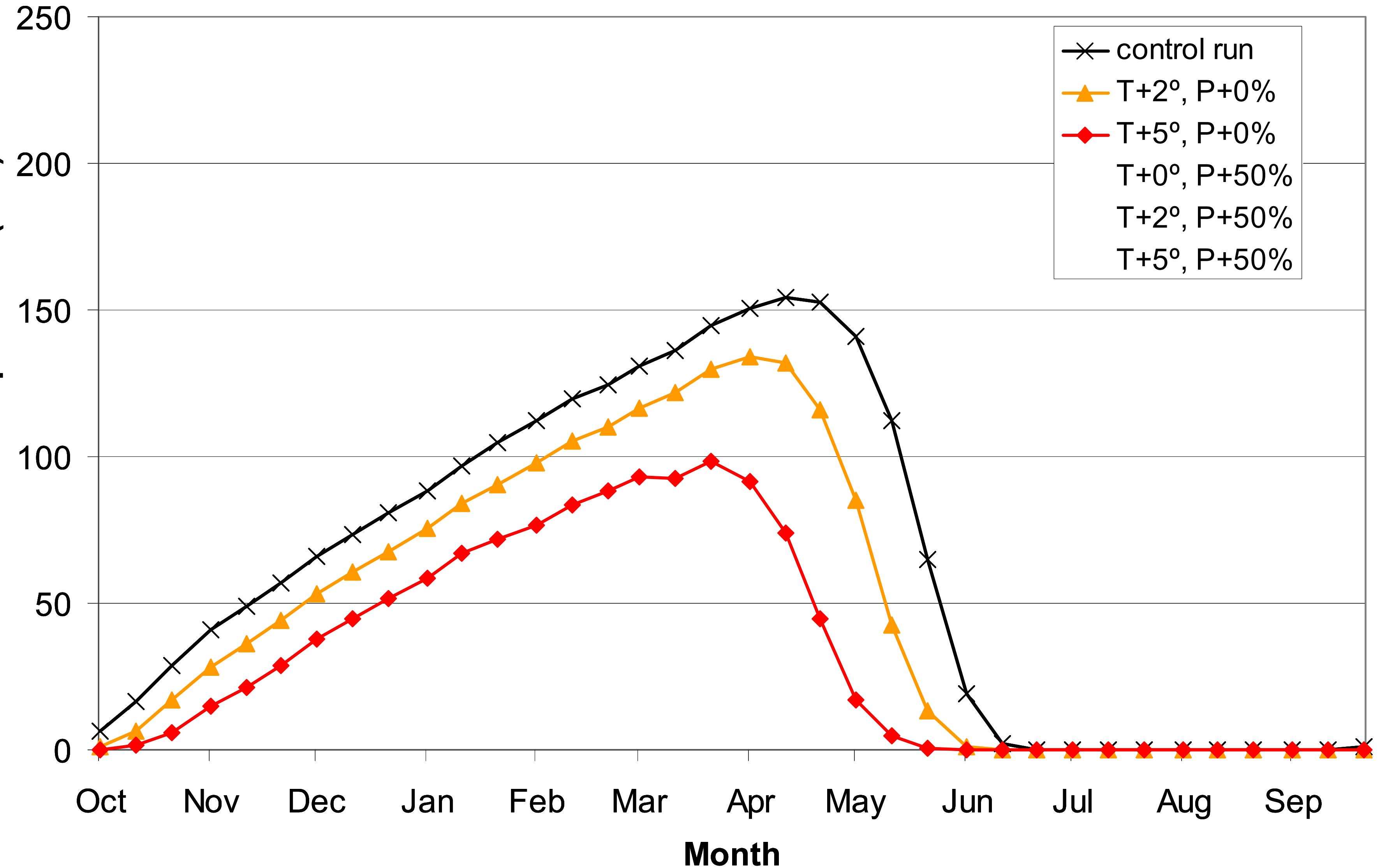
Sensitivity analyses Tana basin



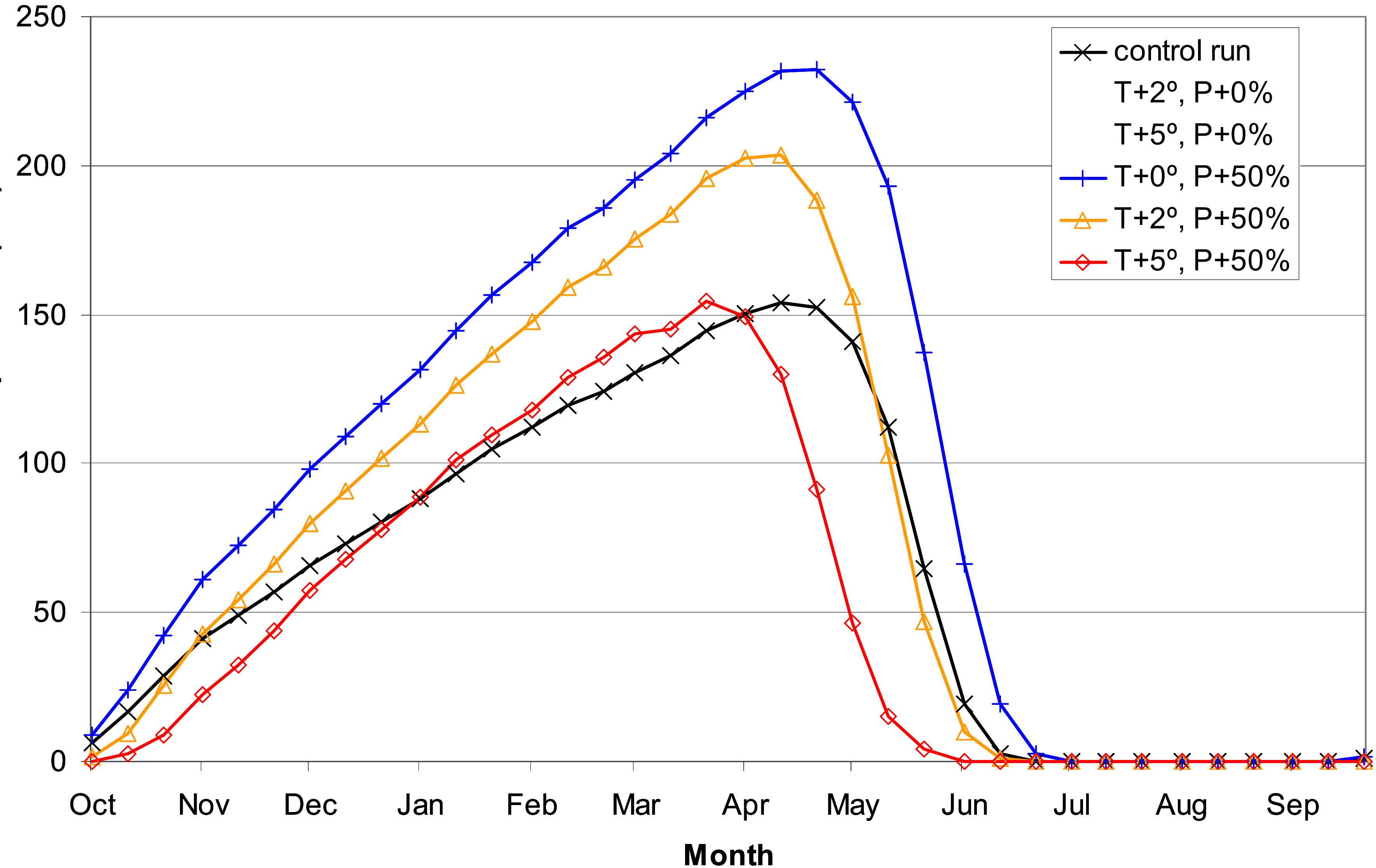
Sensitivity analyses Tana basin



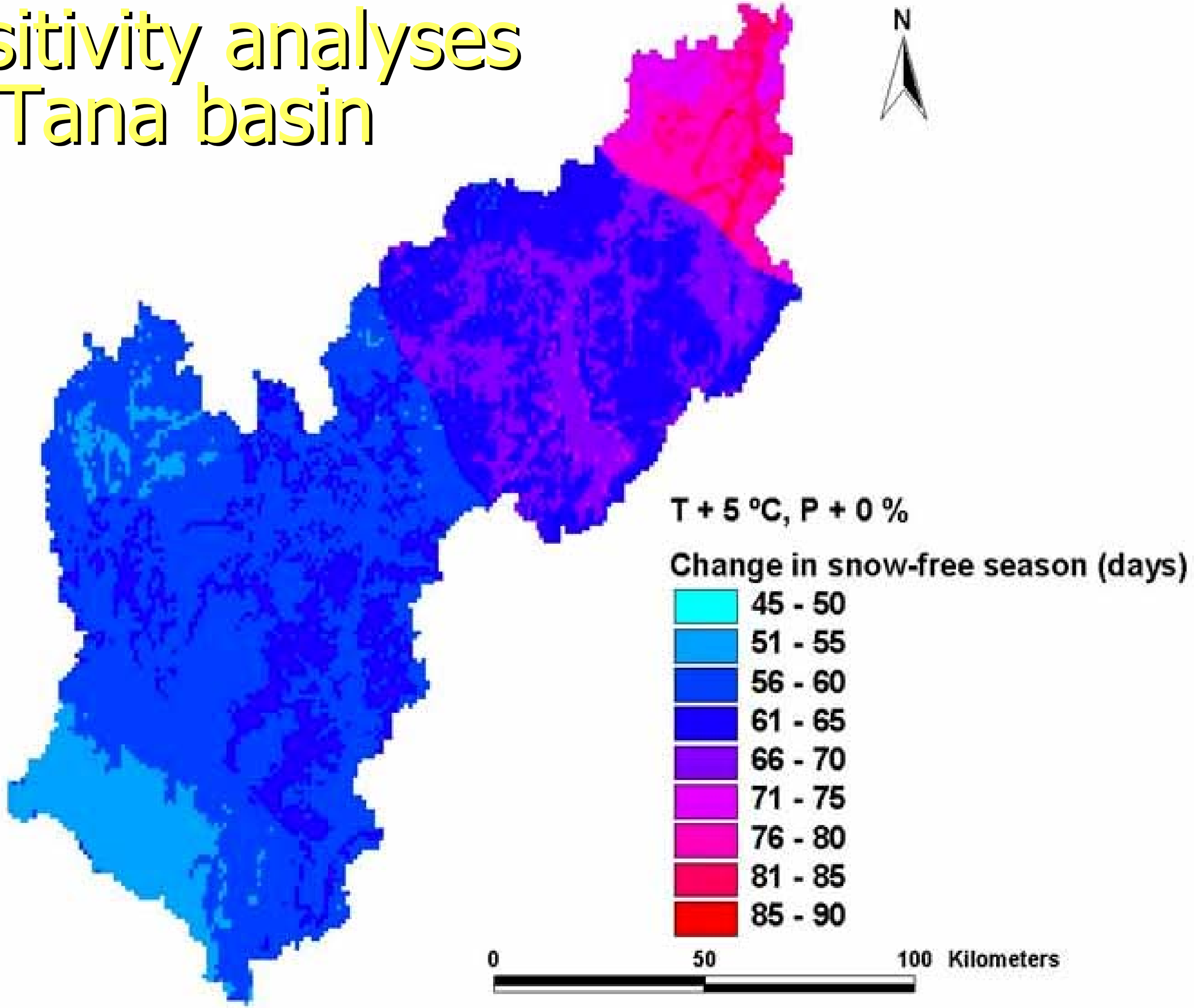
Sensitivity analyses Tana basin



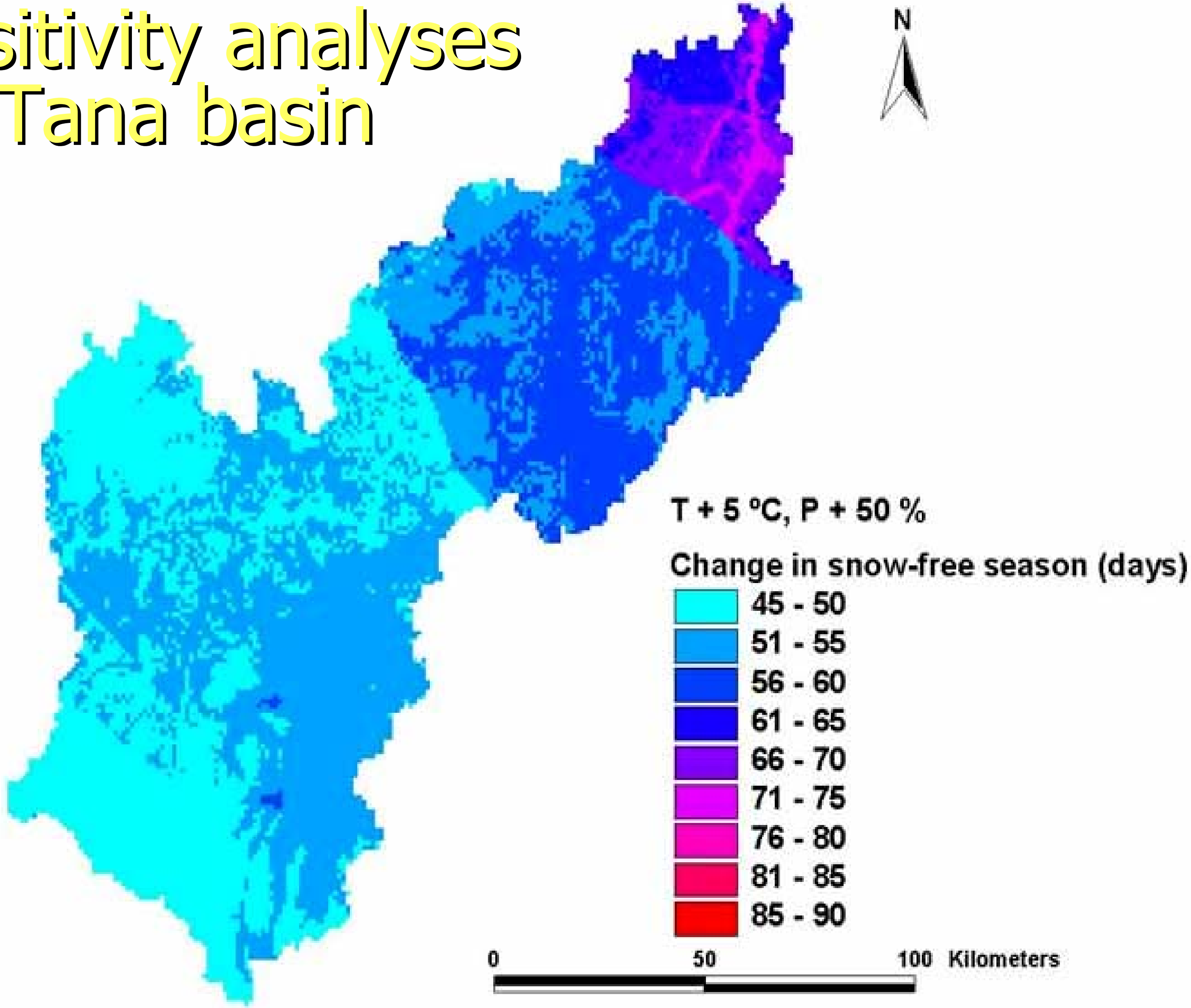
Sensitivity analyses Tana basin



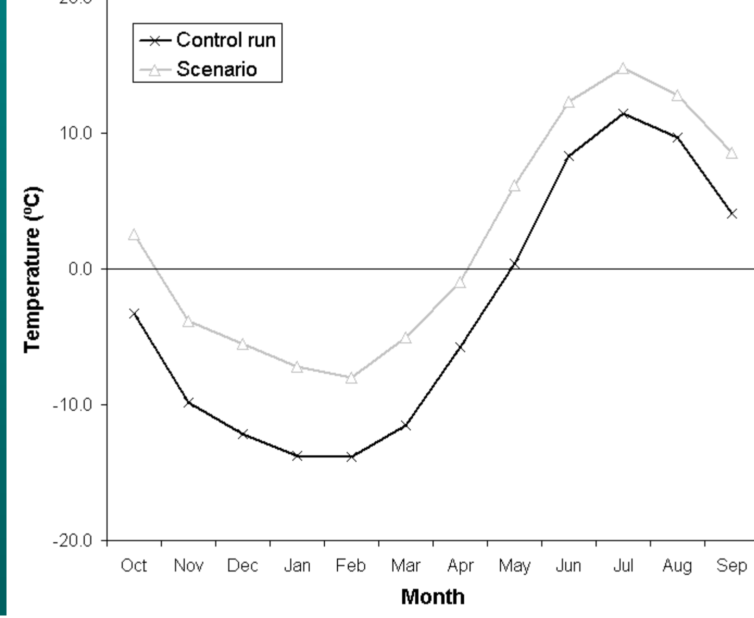
Sensitivity analyses
Tana basin

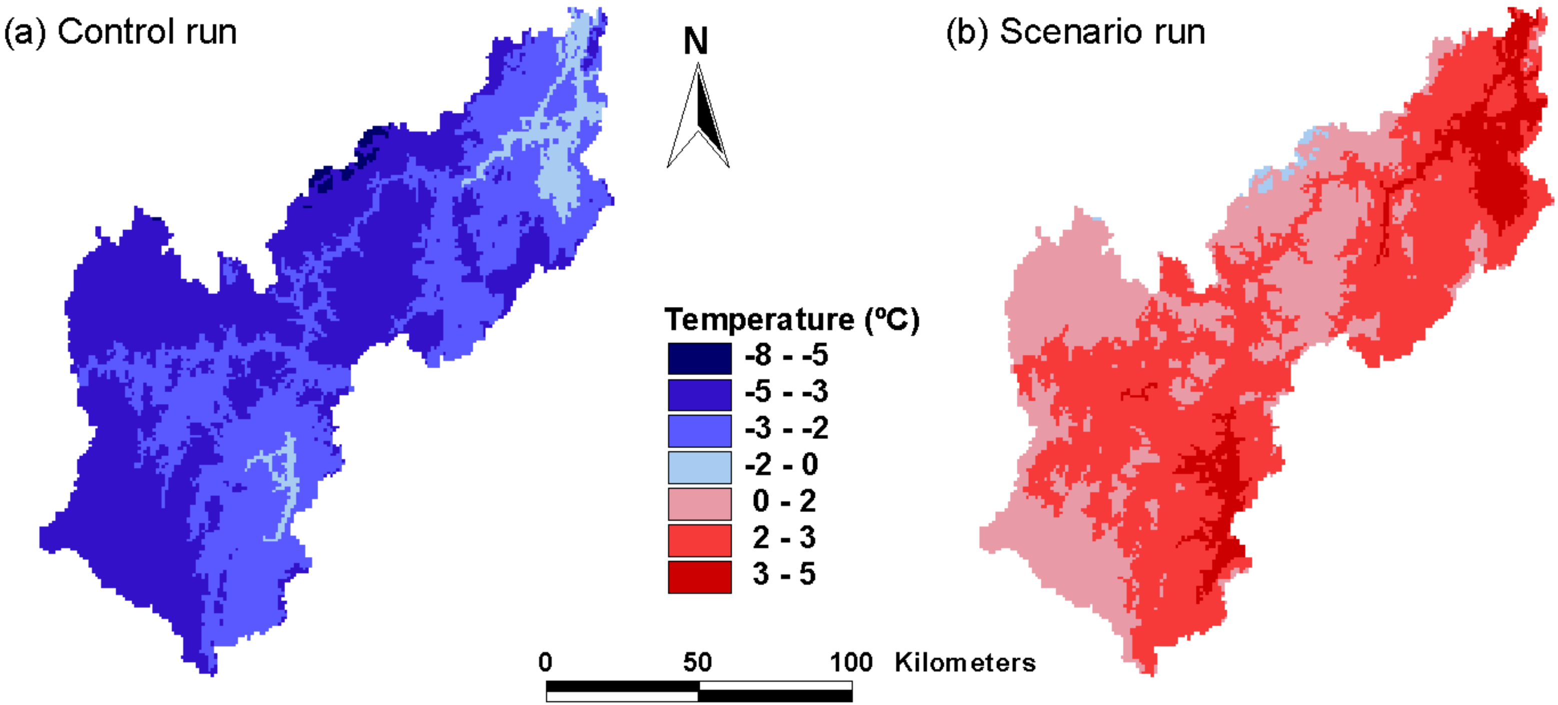


Sensitivity analyses Tana basin

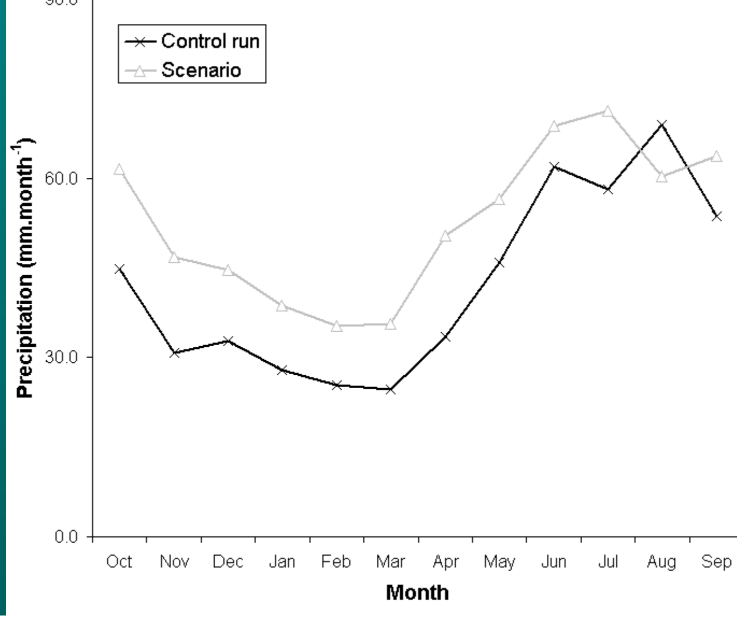


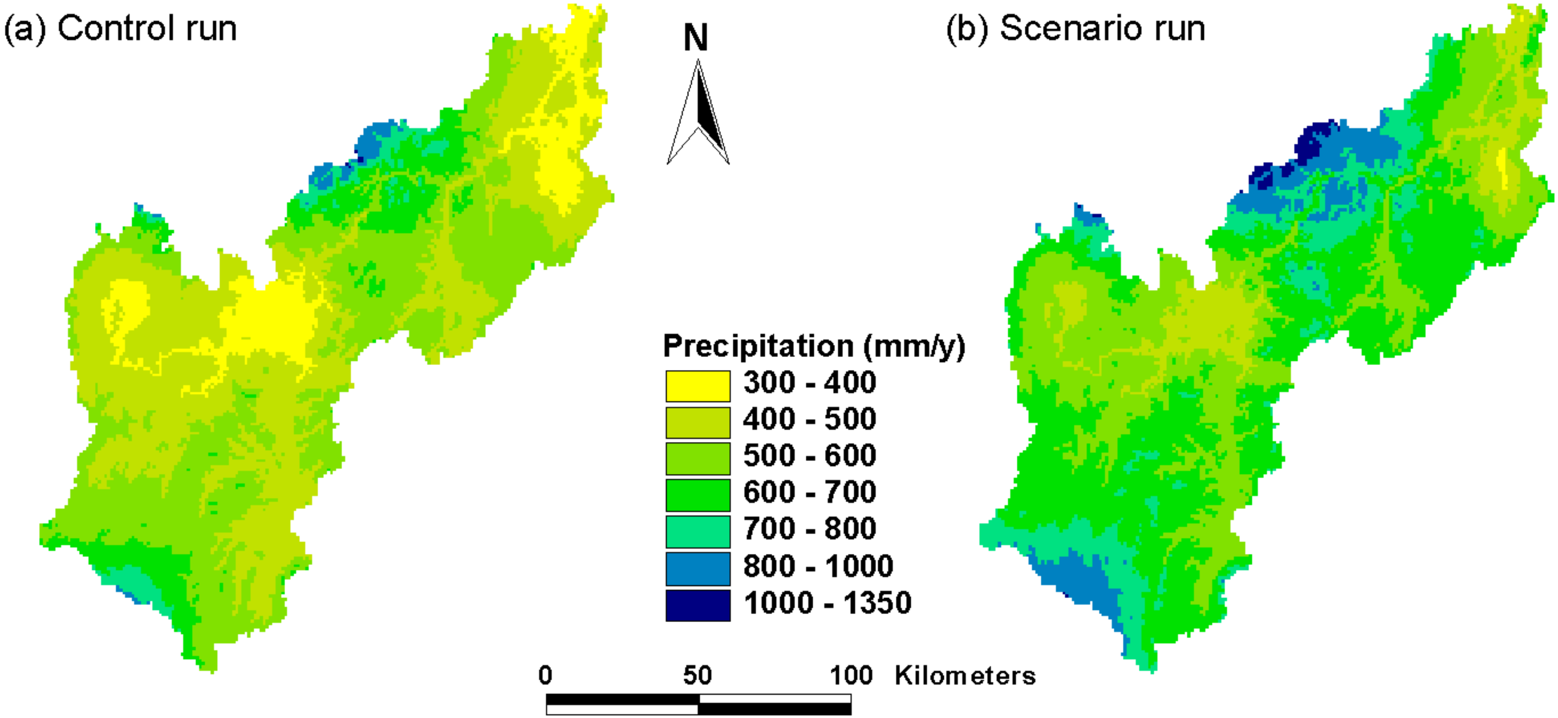
Climate scenario - dT



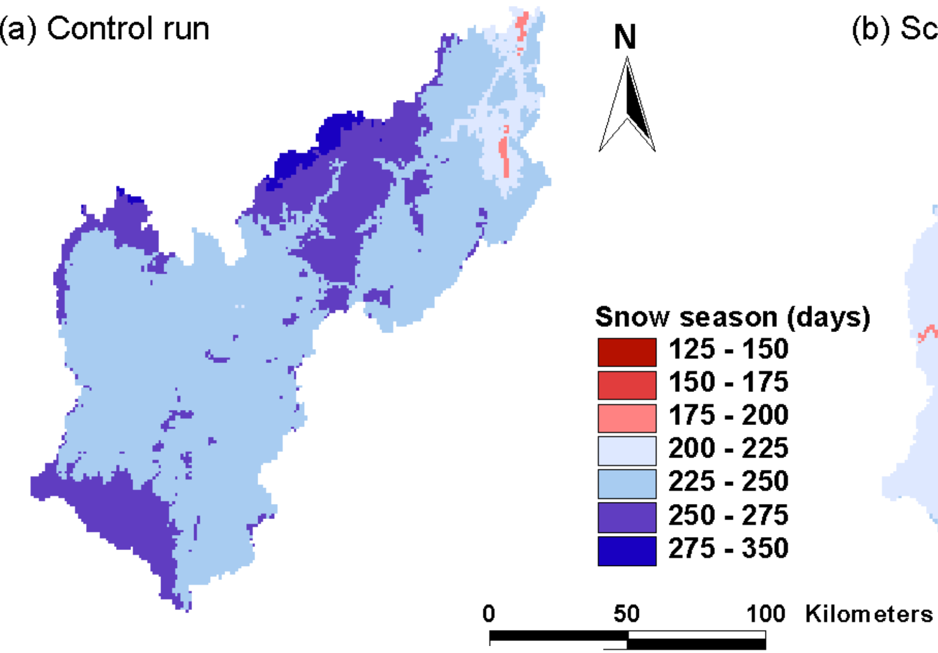


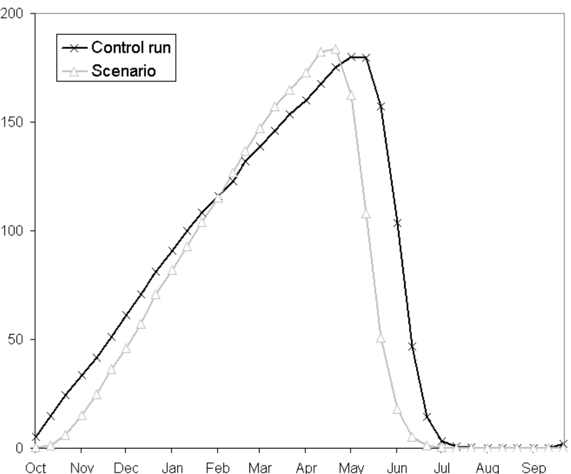
Climate scenario - dP

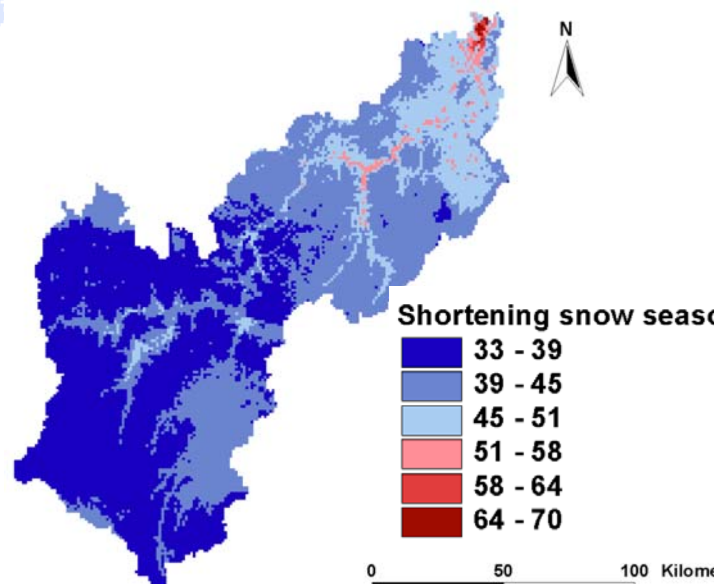




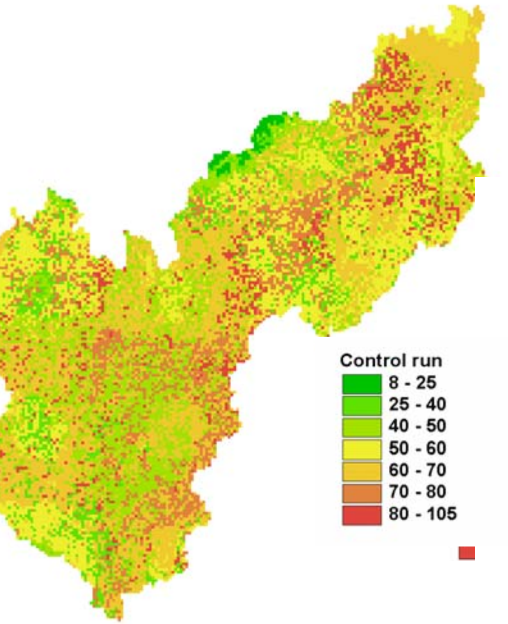
Climate scenario - Snow cover period

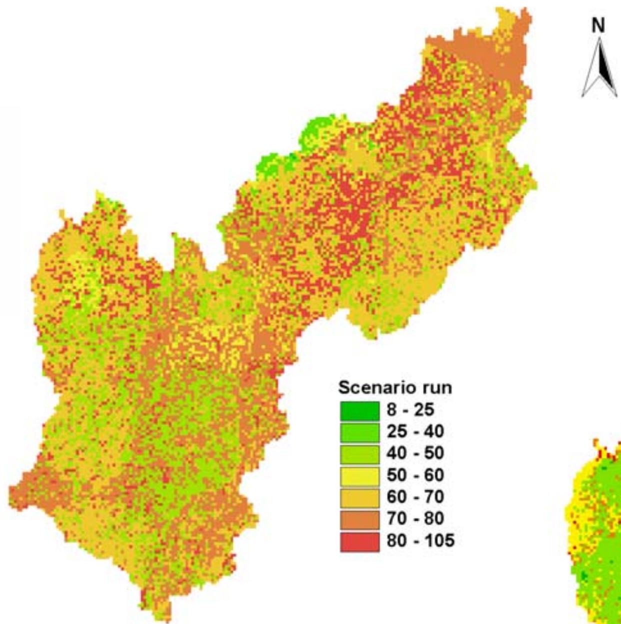


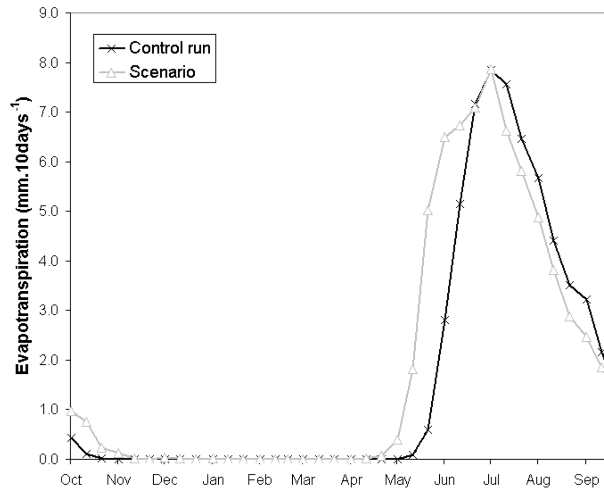


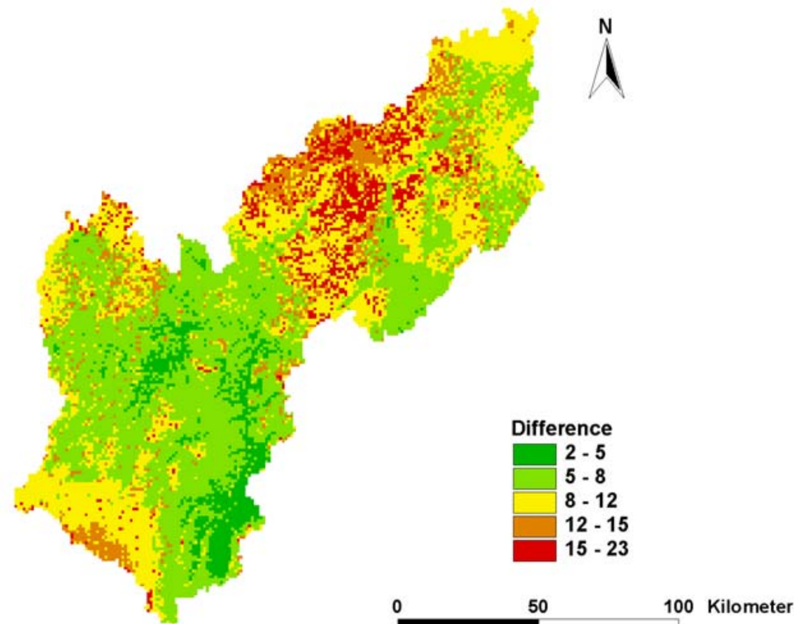


Climate scenario - Evapotranspiration



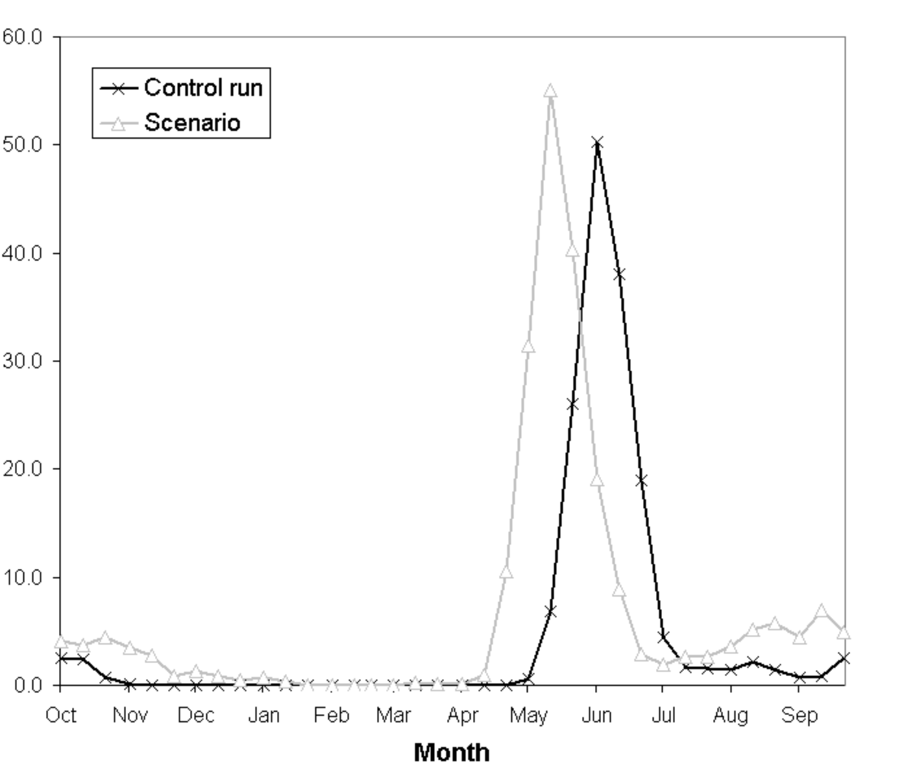


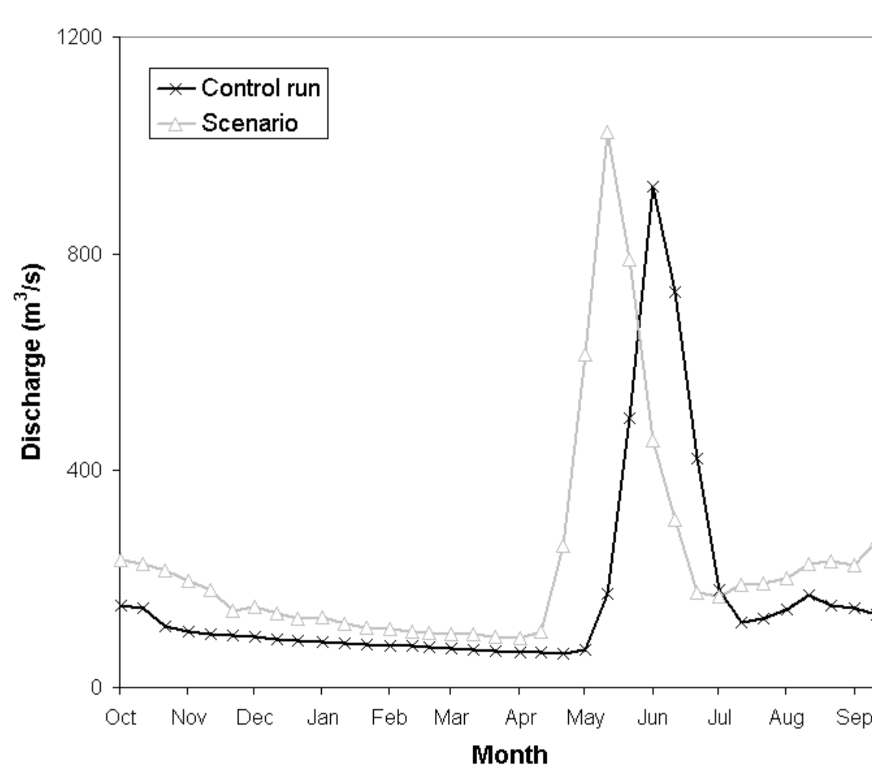




Evapotranspiration (mm)

Climate scenario - Snowmelt and Runoff

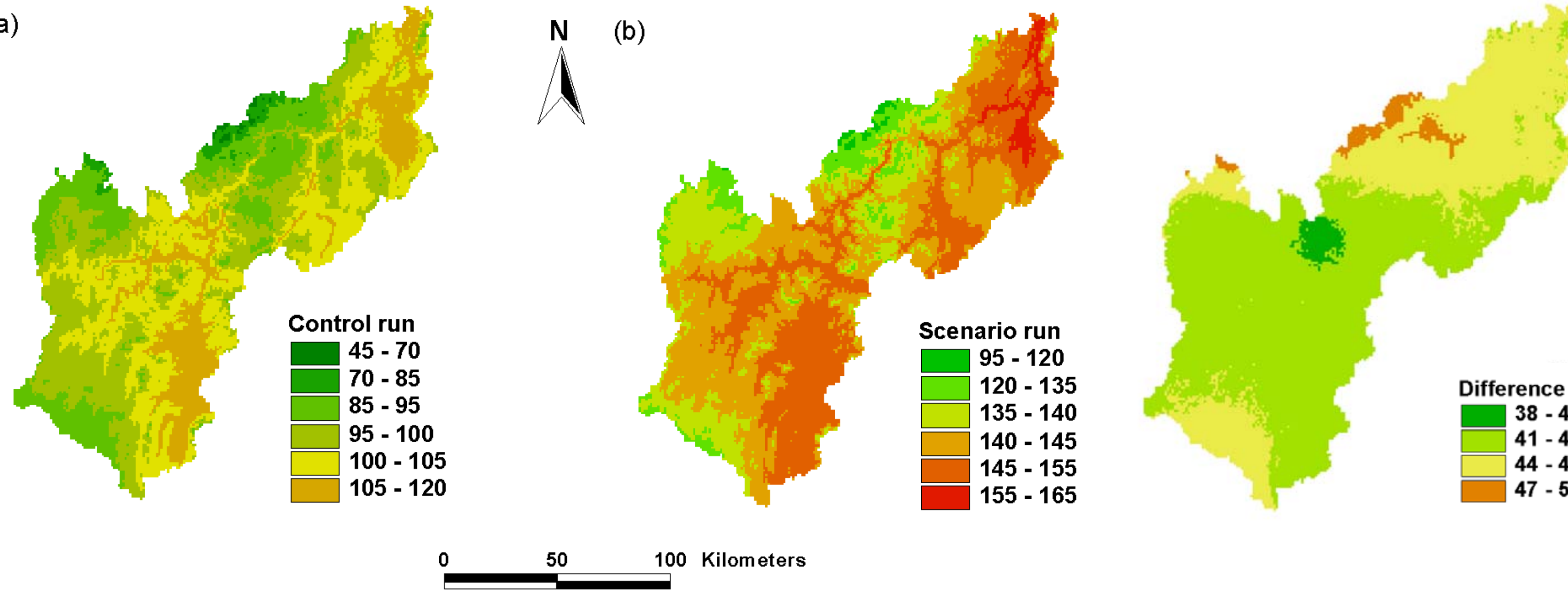




Snowmelt (mm/10d)

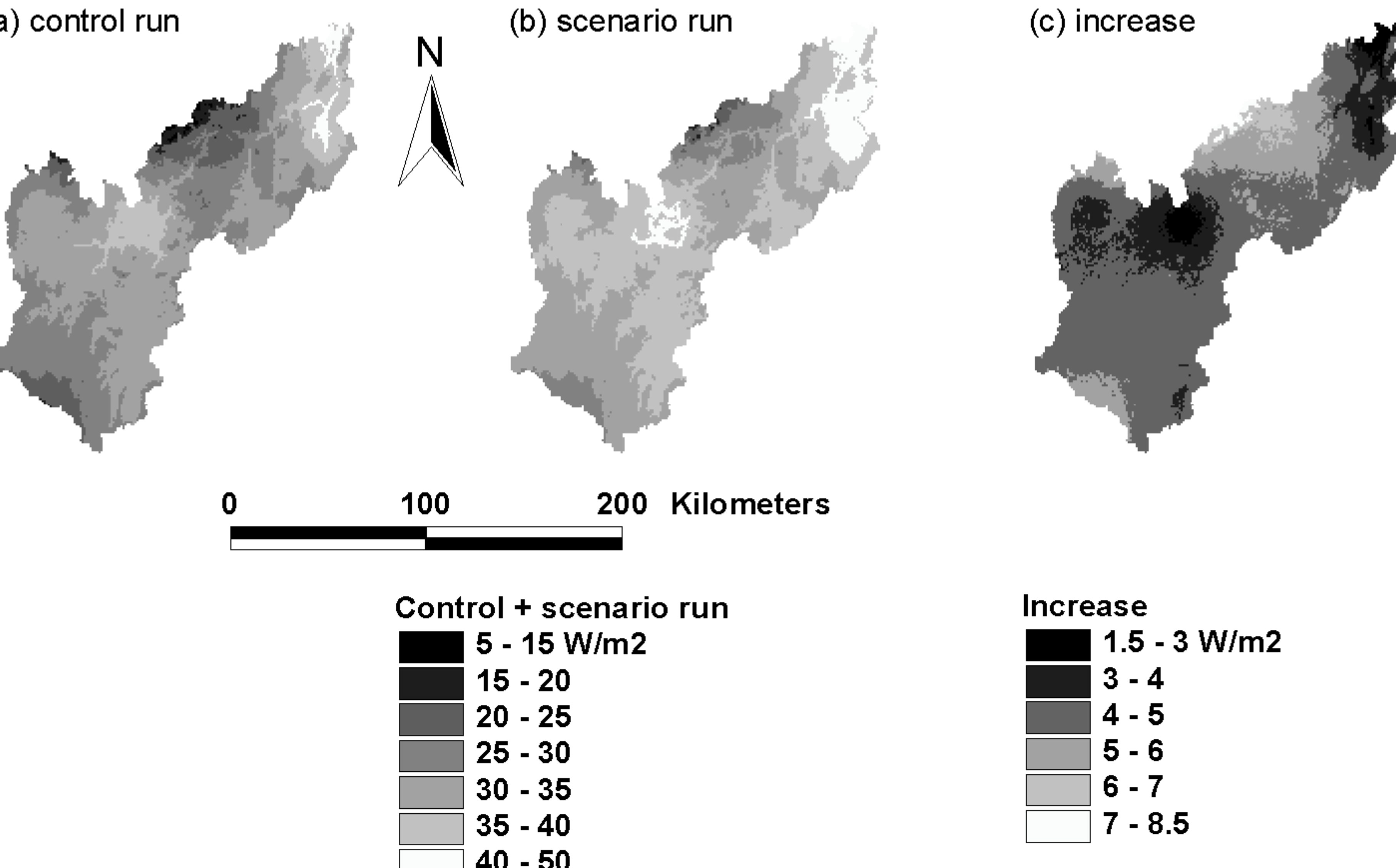
Total runoff (m^3/s)

Climate scenario - Growing season



Length of growing season (days)

Climate scenario - Average radiation



Hydrological impacts - water balance

able 2 Water balance of the Tana and Usa river basins in the control and scenario runs. All quantities are annual verages over 30 years and expressed in mm/year. The observed discharge is the discharge measured at Polmak Norway) in the period 1961–1990 for the Tana River, and at Makarikha (Russia) in the period 1941–1970 for the Usa iver. Makarikha drains only 71% of the entire Usa Basin, which explains the difference between observed and imulated river discharge (here normalized by drainage area).

	Tana			Usa		
	Control	Scenario	% change	Control	Scenario	% change
recipitation	508	634	+25	600	768	+28
ublimation	90	63	−30	N/A	N/A	N/A
vapotranspiration	59	63	+7	154	210	+36
ischarge, observed	368			503		
ischarge, simulated	361	502	+39	443	554	+25

Koster et al., 2005

Hydrological impacts - water balance

- Increase in total runoff
- Earlier snow-melt
  - Peak flow shifts 1 - 2 weeks earlier in spring
  - Magnitude of snow melt peak depends on P and T
- Large winter flow, larger base flow
- Higher summer storm peaks
- Increased evapotranspiration
- Trends non-linear, due to combined effects of precipitation, snowmelt, permafrost melting

Hydrological impacts - conclusions

Sub-arctic rivers

- Drastic effects on annual cycle of river flow
- Mostly due to less stable winter conditions
- Largest changes in snowmelt-dominated catchments
  - Snow integrates differences over many months
- Implications for
  - ecology - growing season and radiation
  - water fluxes to Arctic Ocean - timing and magnitude
  - changes in albedo, permafrost
  - local water users

Hydrological impacts - uncertainties

- Climate change scenarios
  - emissions
  - GCM output
- Downscaling variables (T, P)
- Role of evapotranspiration, present and future
- Role of groundwater – wetlands – frozen ground
- Feed-back effects
  - vegetation
  - snow - albedo
  - large-scale runoff