Training Institute on Adaptive Water–Energy Management in the Arid Americas

Climate change/variability, water and energy, and adaptation

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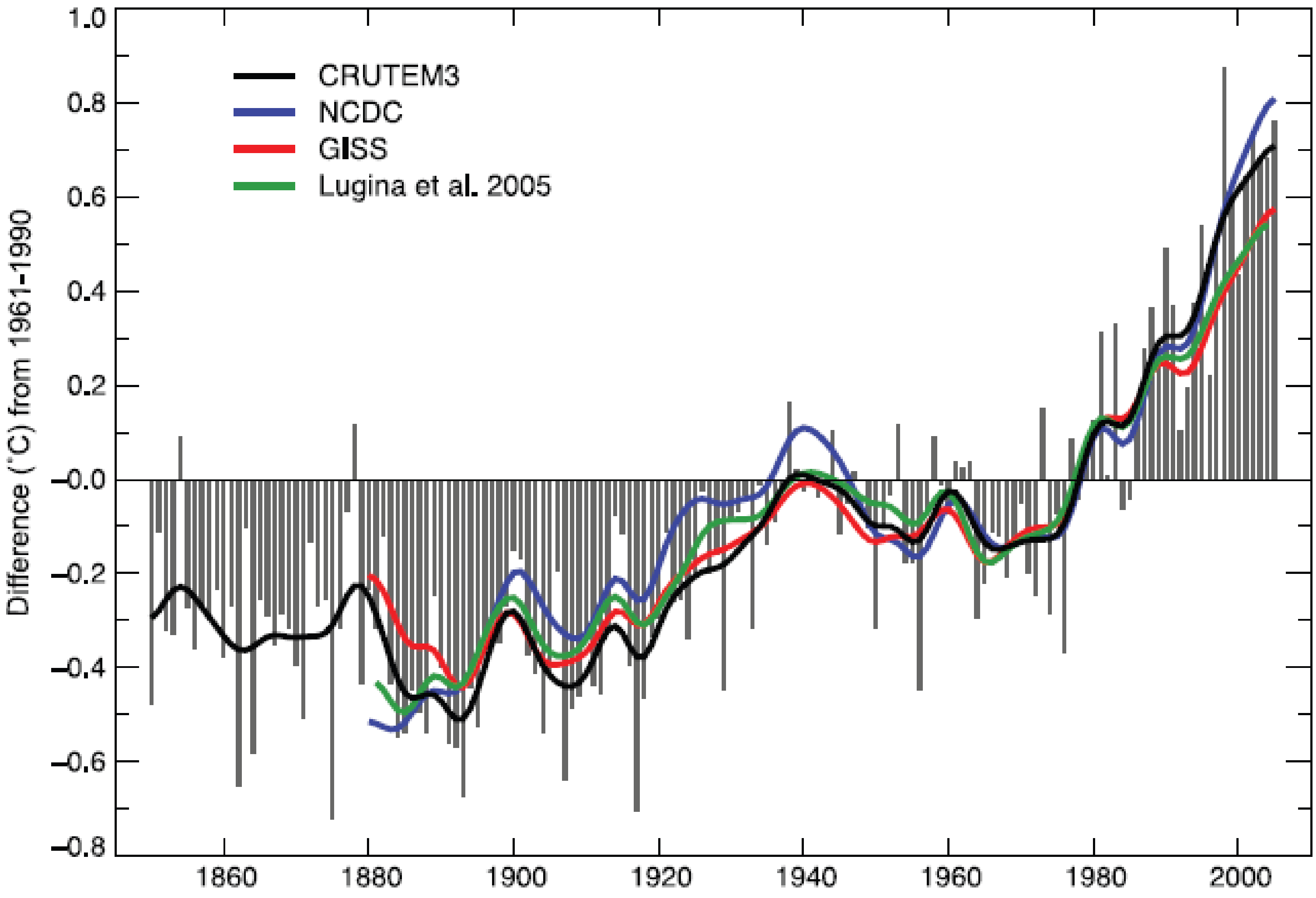
Topics

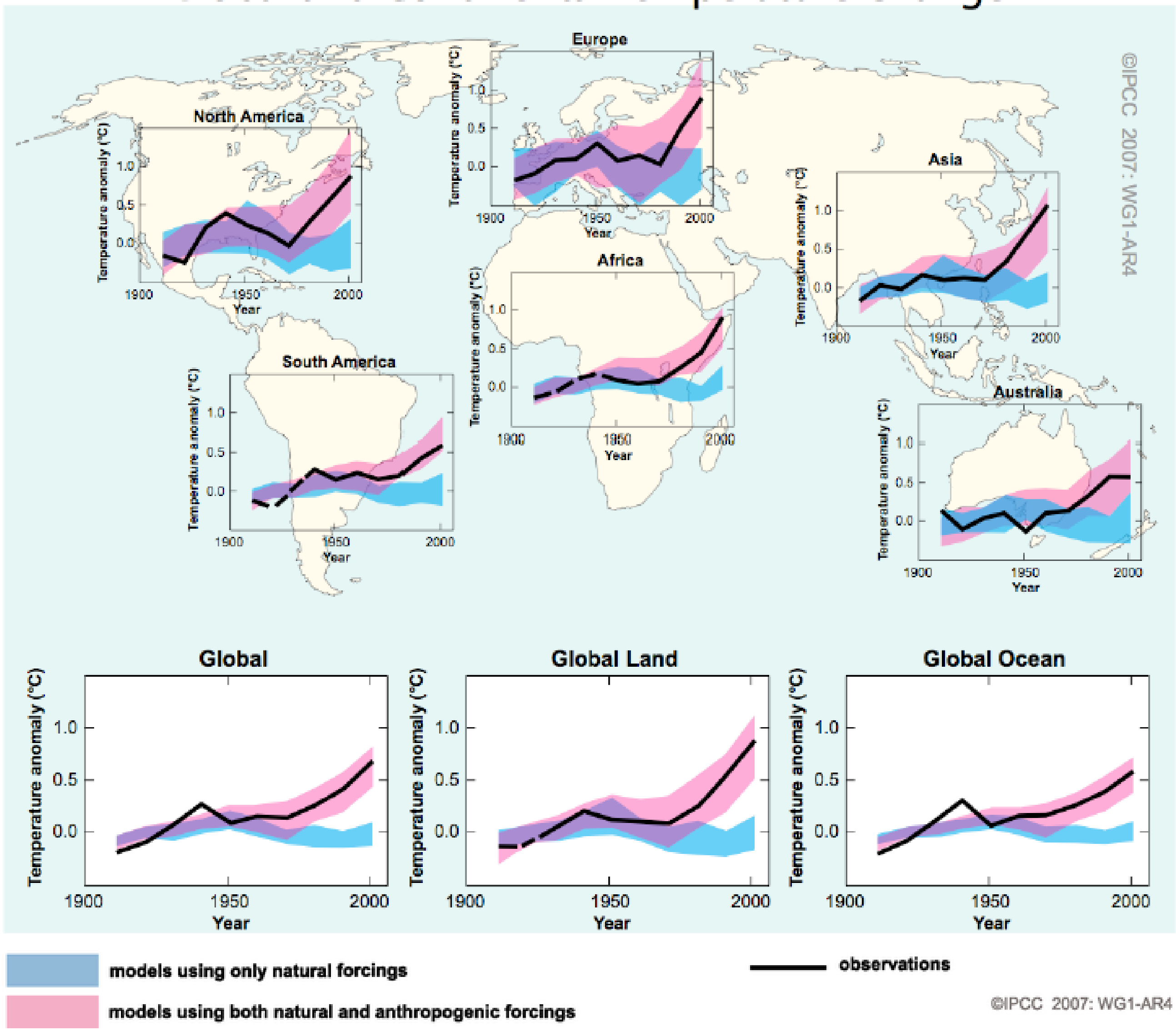
- IPCC Scenarios and Global Circulation Models
- Bias Correction
- Water Balance Simulation
- Hydrological Model
- Simulation and Optimization
- Exercise

IPCC Scenarios and Global Circulation Models

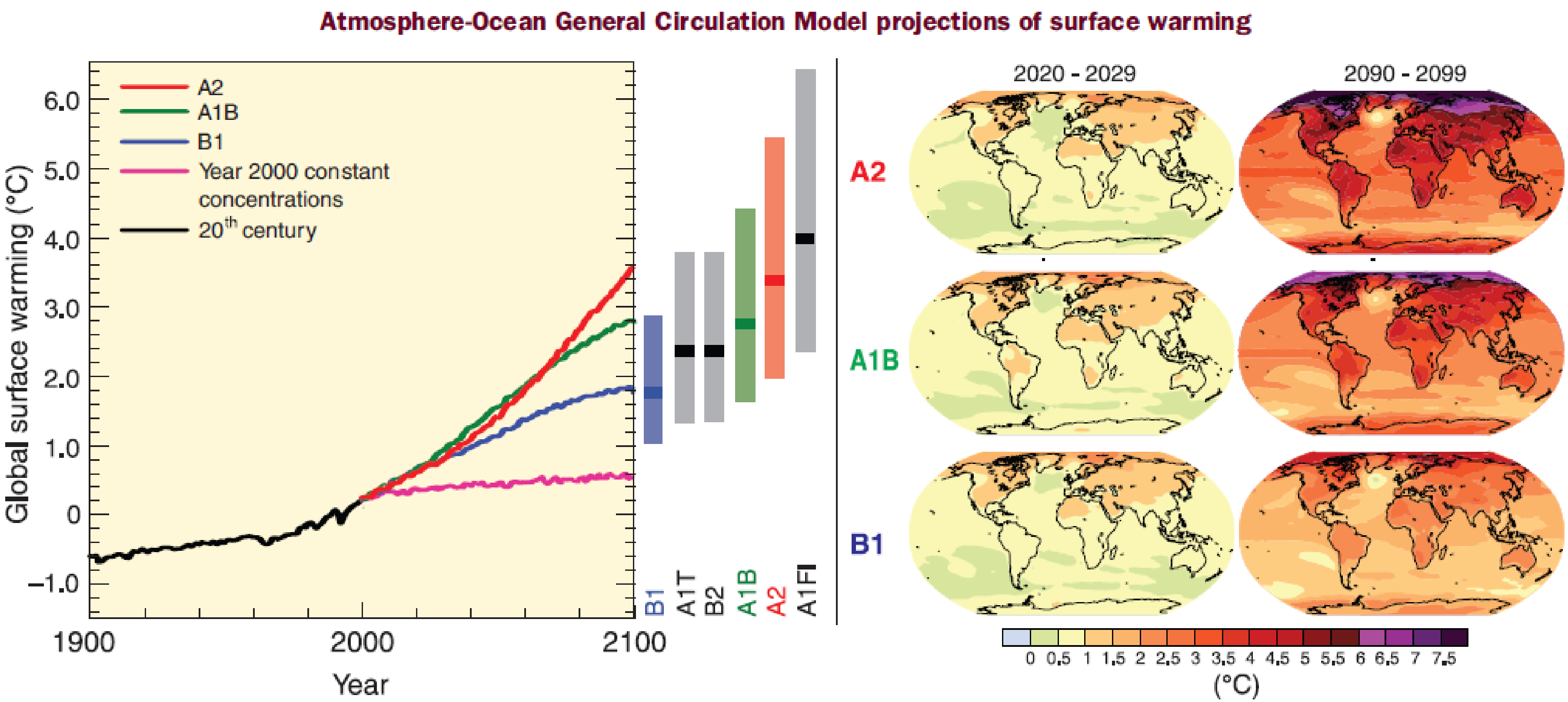


Annual anomalies of global land-surface air temperature (°C), 1850 to 2005, relative to the 1961 to 1990 mean

Global and Continental Temperature Change

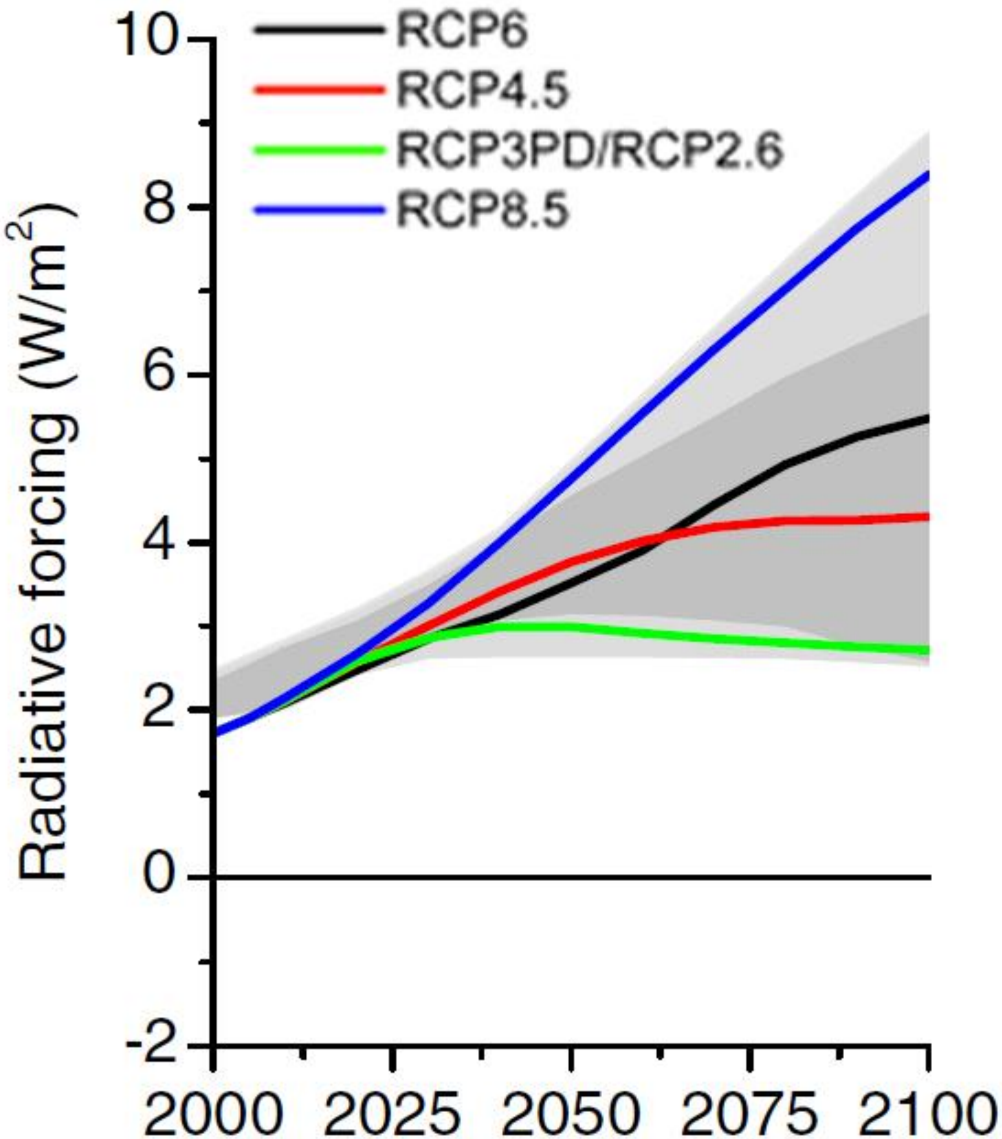


AR4–SRES Scenarios



AR5-RCP

Four RCPs were selected and defined by their total radiative forcing (cumulative measure of human emissions of GHGs from all sources expressed in **Watts per square meter**) pathway and level by 2100. The RCPs were chosen to represent a broad range of climate outcomes, based on a literature review, and are neither forecasts nor policy recommendations.

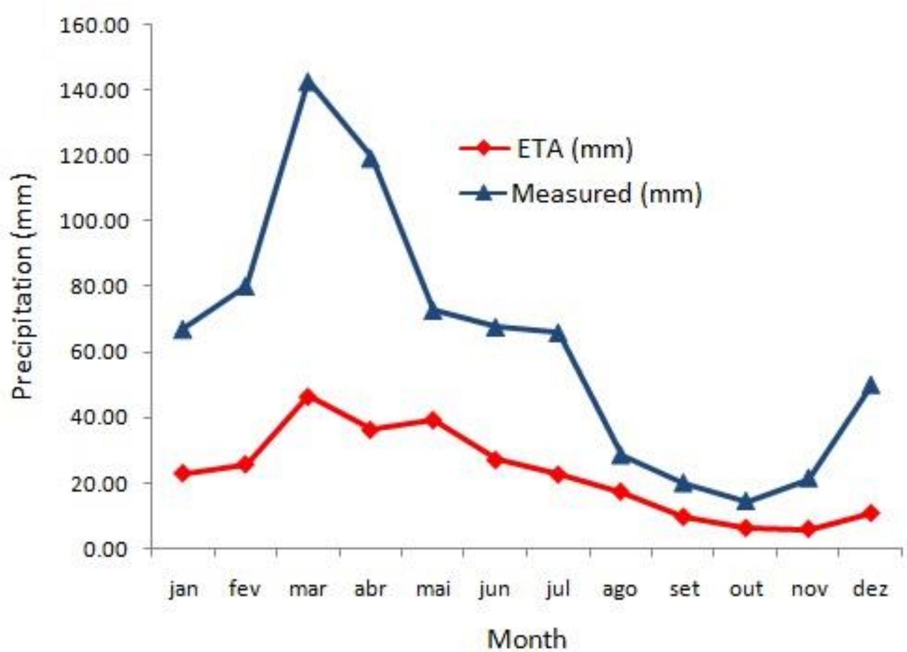


Bias Correction

Bias correction

Eta CCS precipitation underestimate

Correction with cumulative density function (CDF)



Bias correction

Correction with cumulative density function (CDF)

1. For each grid point and for each month (January-December), it is necessary to compute the cumulative frequency of the model and observed rainfall;
2. The second step is to determine the frequency of the rainfall model, and then replace the raw value with the amount of rainfall observed associated with the matching cumulative frequency;

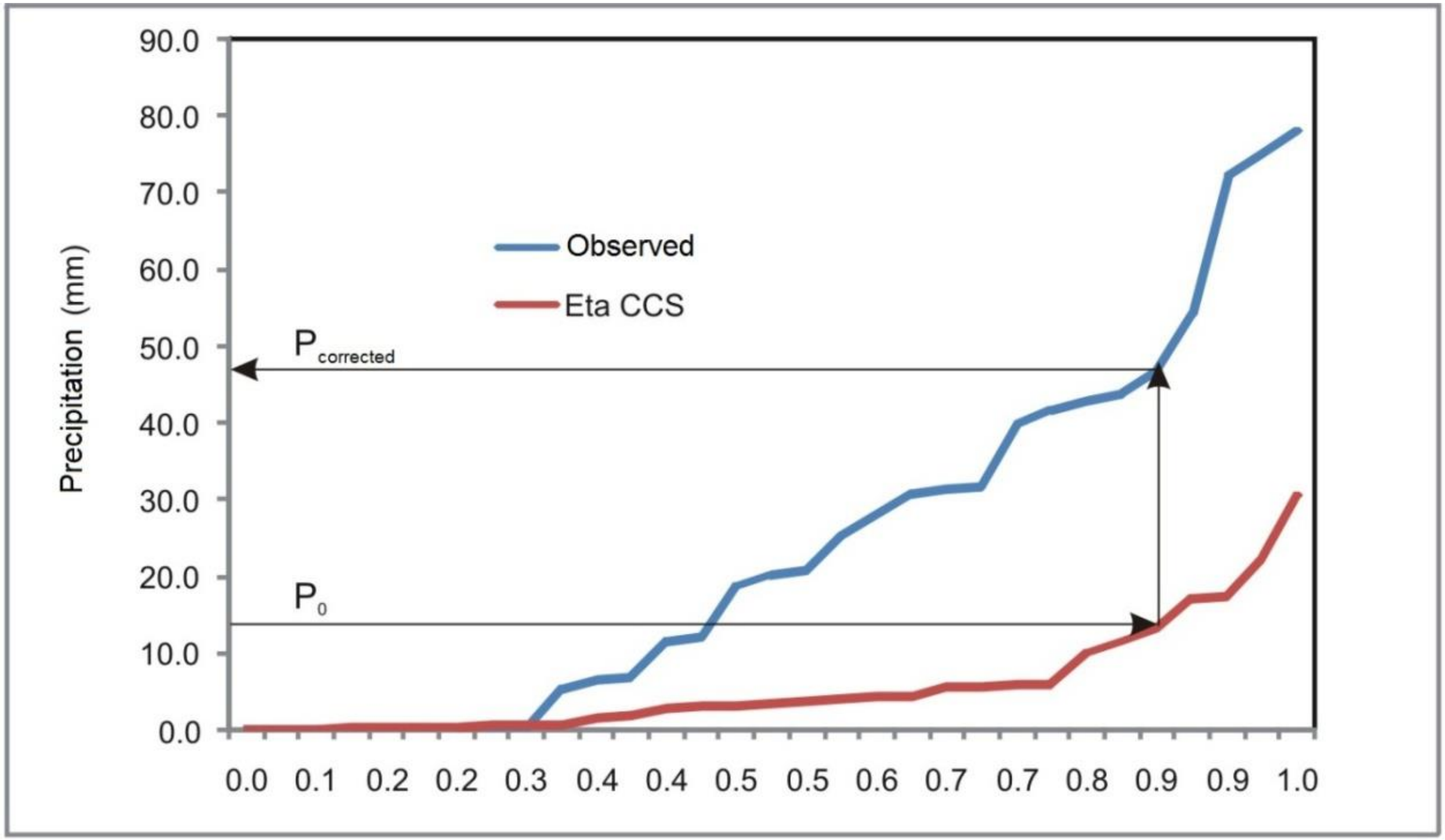
Year	P (mm)	Order	P (mm)	F (%)	Year	P (mm)	Order	P (mm)	F (%)
1960	27.5	1	12.97	3.23	1976	27.51	17	33.27	54.84
1961	77.68	2	13.59	6.45	1977	19.83	18	34.32	58.06
1962	21.47	3	13.82	9.68	1978	15.66	19	35.71	61.29
1963	13.99	4	13.99	12.90	1979	113.98	20	36.46	64.52
1964	70.78	5	15.66	16.13	1980	18.04	21	38.76	67.74
1965	16.67	6	16.63	19.35	1981	33.27	22	70.78	70.97
1966	16.63	7	16.65	22.58	1982	35.71	23	77.68	74.19
1967	12.97	8	16.67	25.81	1983	16.65	24	100.61	77.42
1968	133.39	9	16.87	29.03	1984	134	25	112.54	80.65
1969	194.41	10	18.04	32.26	1985	18.79	26	113.98	83.87
1970	100.61	11	18.79	35.48	1986	36.46	27	117.98	87.10
1971	29.27	12	19.83	38.71	1987	34.32	28	133.39	90.32
1972	117.98	13	21.47	41.94	1988	13.82	29	134	93.55
1973	270.72	14	27.5	45.16	1989	13.59	30	194.41	96.77
1974	16.87	15	27.51	48.39	1990	112.54	31	270.72	100.00
1975	38.76	16	29.27	51.61					

$$F = \frac{m}{n}$$

m= order

n= number of years

Bias correction



Bias correction

Correction with cumulative density function (CDF)

3. In the case of simulations of the future, instead of directly using CDF corresponding to the observed rainfall, the method first identifies the future rainfall value in the CDF of the model in the present time;
4. The correction is made matching the quantile found in the CDF of the model to the same value in the CDF of the observed rainfall.

Bias correction

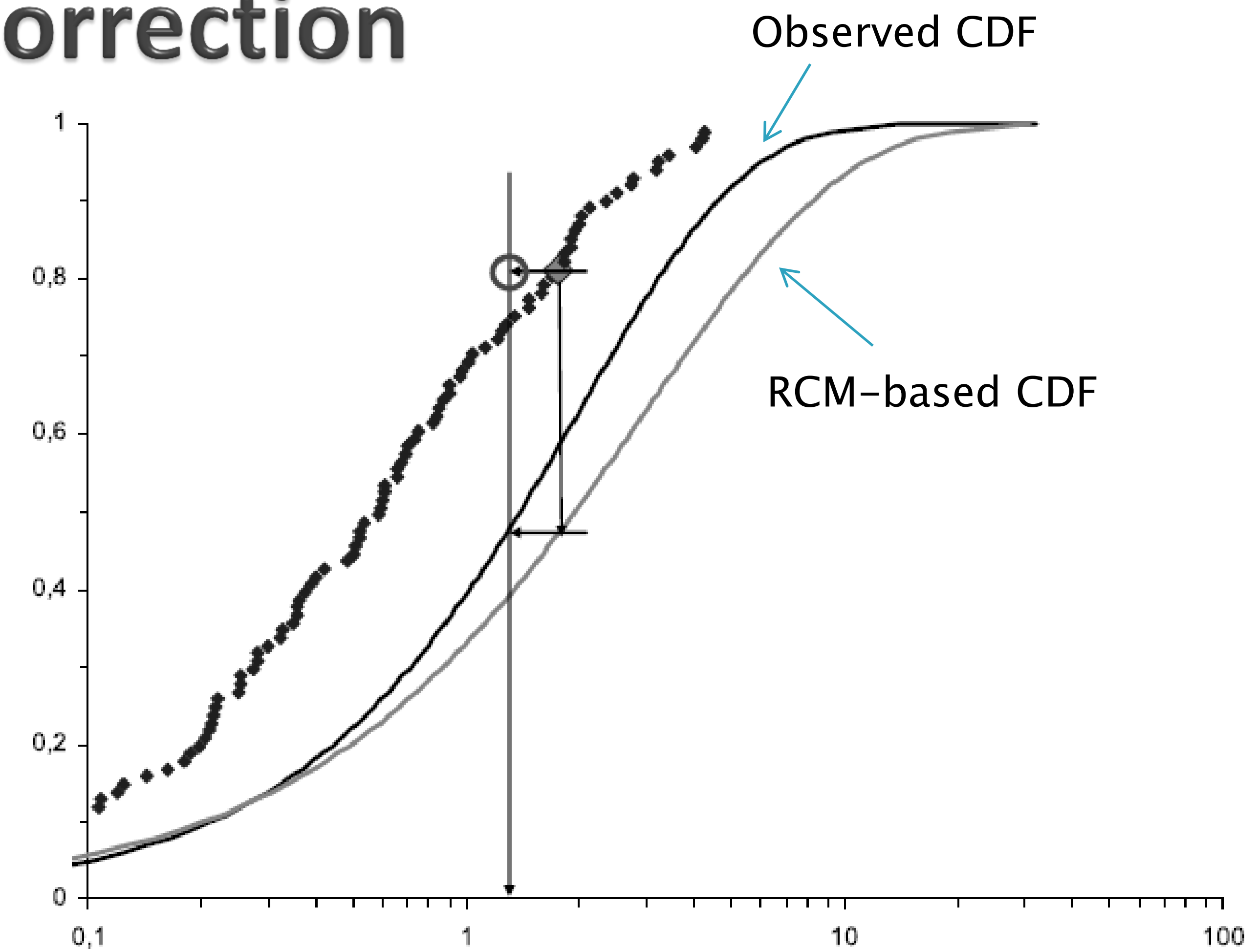


Figure 11. A sketch of the double quantile-quantile transform relating a given RCM future fdf to the observed cdf through the corresponding RCM cdf; the latter would be obtained from the observation period (see equation (2)). The vertical axes show cumulative probabilities, and horizontal axes are in millimeters. The sources are as follows: black line, observed cdf; gray line, RCM-based cdf (observation period); black diamonds, RCM future fdf. The RCM future point (large gray diamond) is matched with the same value on the observed RCM cdf, shifted at the same quantile level to the observed cdf and back to the same quantile level at the future value to give the point in the circle, in the process preserving the rank of the shifted value.

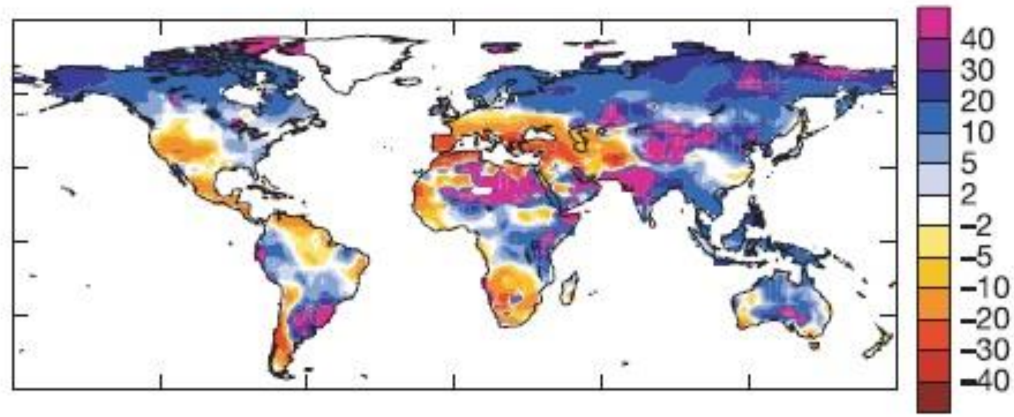
Water Balance Simulation

How to estimate the impact?

Use of Global Circulation Models (GCM)

~100-300 km resolution

Budget P – E



Use of Hydrological Models

Input precipitation and air temperature from GCM

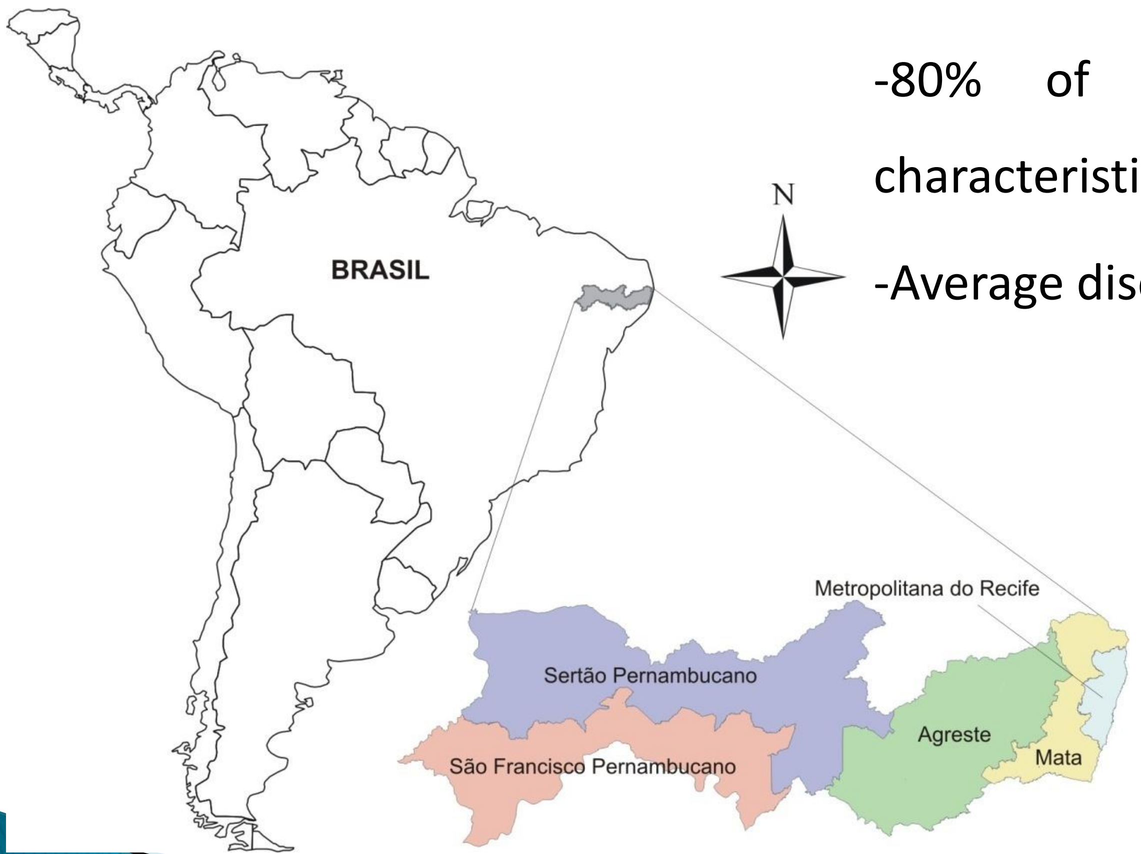
Better spatial resolution

Water balance simulation

Objective

To estimate the impact of climate on surface runoff, evapotranspiration and soil moisture in the territory of Pernambuco State-Brazil.

Area Under Study



-99,123.00 km^2 in area;

-80% of the area with semiarid characteristics (precipitation 400-800 mm)

-Average discharge: 263 m^3/s

Thornthwaite-Mather Method

Determine the water regime of a site using

-Water capacity of the soil

-Precipitation

-Potential Evapotranspiration

Water Capacity of the Soil - W_C

<u>Dunne and Willmott (1996)</u>

Global distribution of plant-extractable water capacity of soil

0.5° x 0.5° spatial resolution

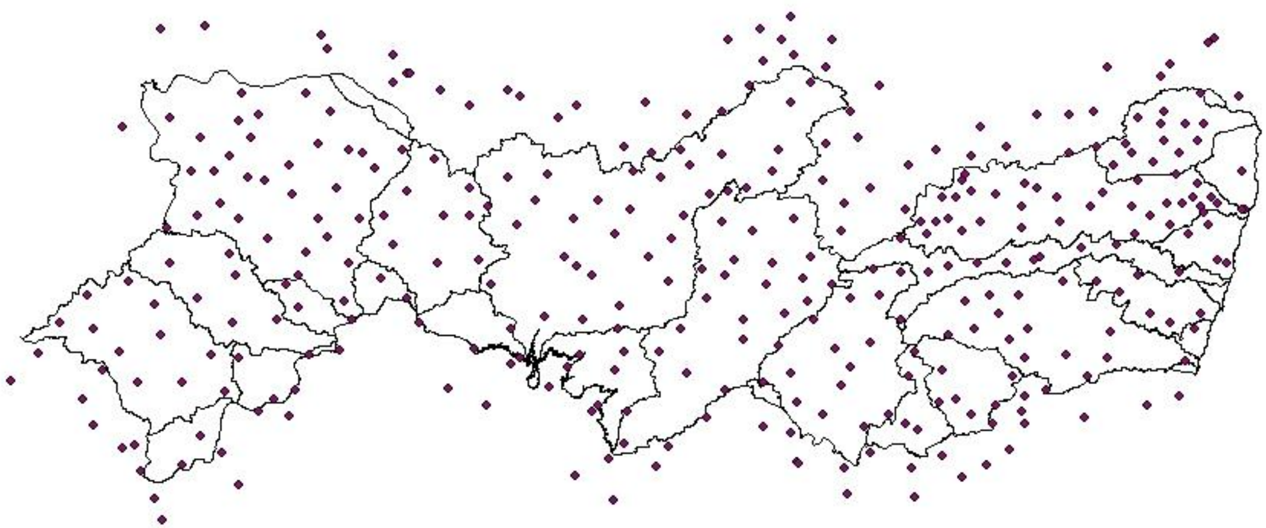
Precipitation - P

National Water Agency

348 rain-gauges

Monthly time step

Inverse distance weighted



Potential evapotranspiration - PET

Hargreaves method

Air temperature (°C) and relative humidity (%)

$$PET = F \cdot 0{,}158 \cdot (100 - UR)^{0{,}5} \cdot (32 + 1{,}8 \cdot T)$$

PET is potential evapotranspiration (mm/month)

F is the potential evapotranspiration factor (mm/month)

Thornthwaite-Mather Method

Surface runoff, water deficit, actual evapotranspiration and soil moisture at each time step.

$$W_{t+1} = W_t \cdot e^{\frac{P_{t+1} - ETP_{t+1}}{W_C}} \text{, se } P - ETP < 0$$

The actual evapotranspiration (ET) and water deficit (DEF) are given by:

$ET_{t+1} = P_{t+1} - (W_{t+1} - W_t)$

$DEF_{t+1} = ETP_{t+1} - ETR_{t+1}$, if $ETR_{t+1} < ETP_{t+1}$

$DEF_{t+1} = 0$, if $ETR_{t+1} = ETP_{t+1}$

Thornthwaite-Mather Method

When $P - ETP \geq 0$, W, ET and DEF are:

$$W_{t+1} = W_t + P_{t+1} - ETP_{t+1}$$

$$ETR_{t+1} = ETP_{t+1}$$

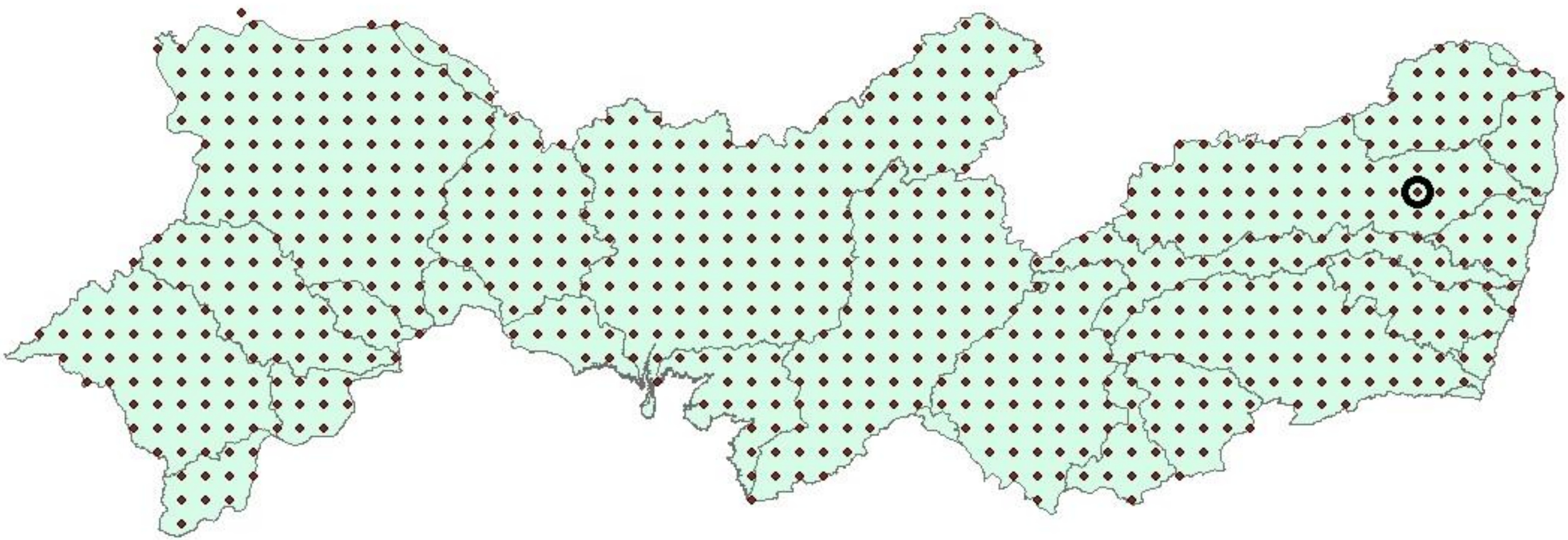
$$DEF_{t+1} = 0$$

The surface runoff (RO) is calculated by

$$RO_{t+1} = W_{t+1} - W_C, \text{ when } W_{t+1} > W_C$$

$$RO_{t+1} = 0, \text{ when } W_{t+1} \leq W_C$$

Thornthwaite-Mather Method



$W_c = 98$ mm

Regional climate model

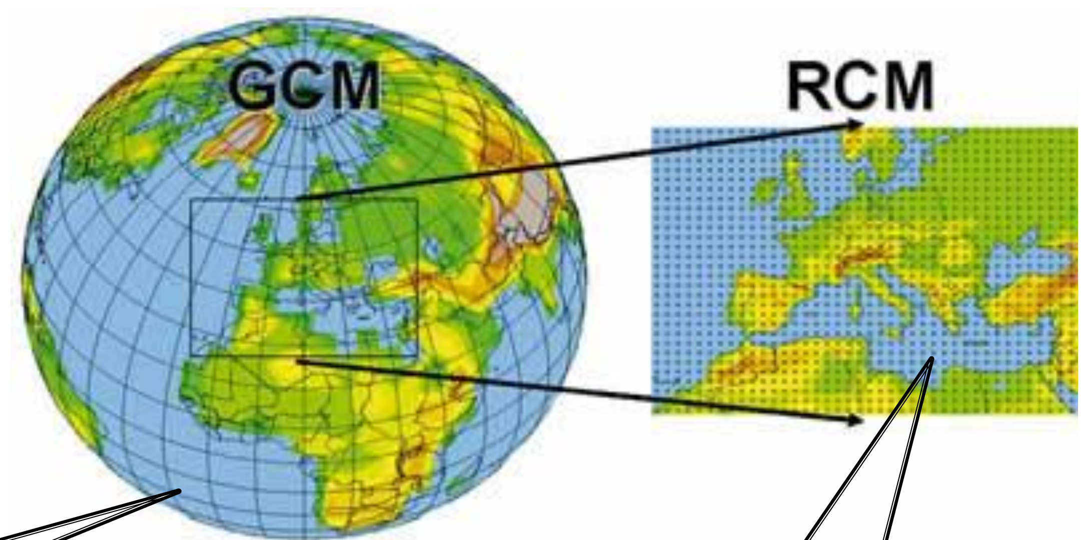
GCM → HadAM3P (UK Met Office Hadley Centre)

RCM → Eta CCS (50 km resolution)

IPCC scenarios A2 and B2

Baseline 1960-1990

Future 2070-2100

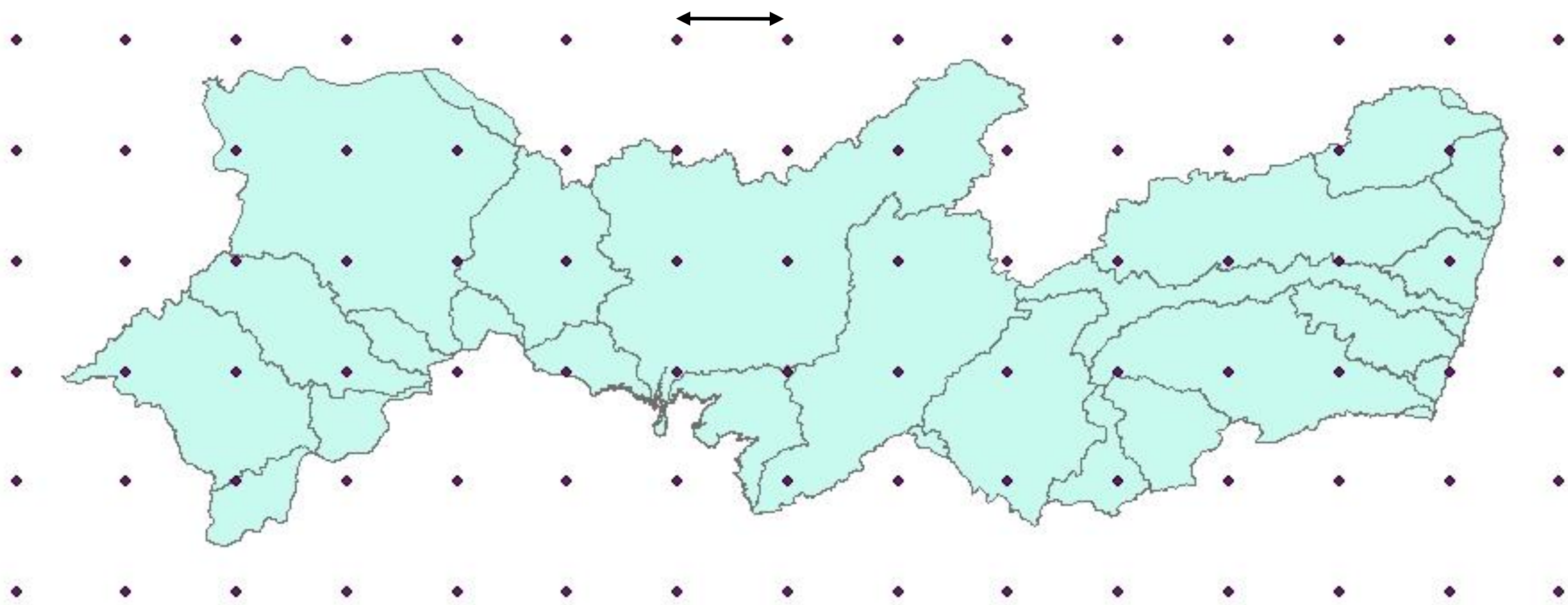


100 km – 300 km

20 km – 50 km

Regional climate model

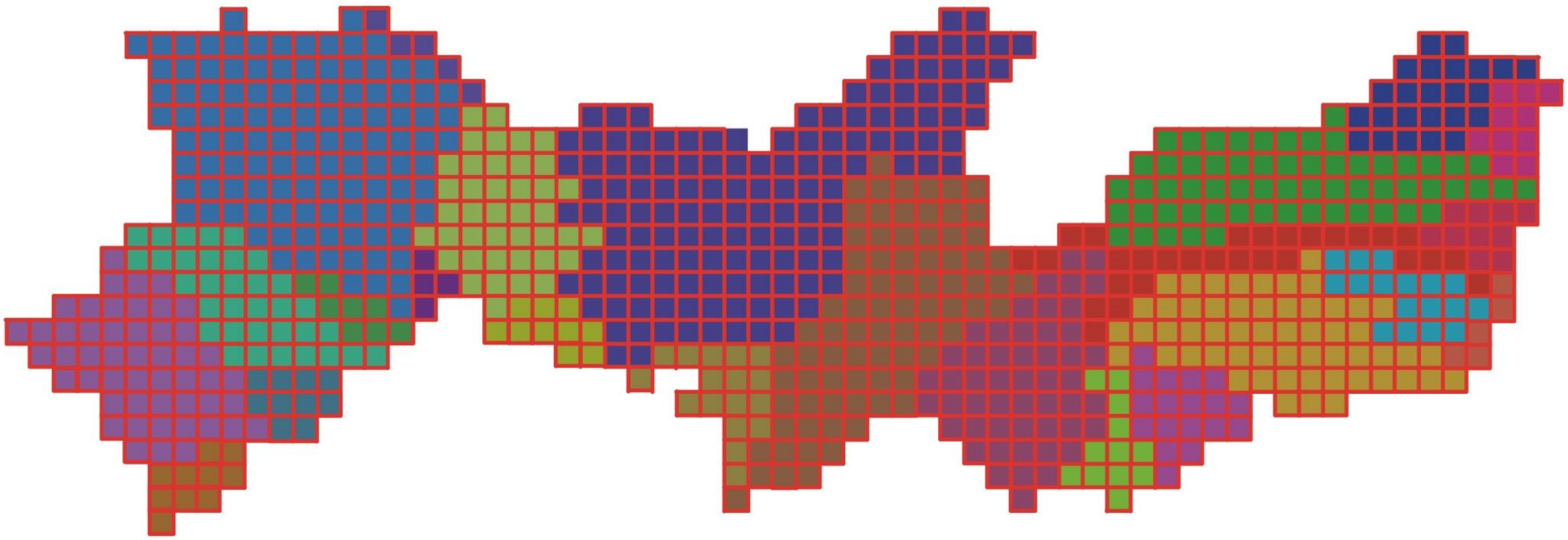
Spatial resolution: 50 km



Water balance

Spatial resolution: 0.1° x 0.1° (about 10 km)

Application of Thornthwaite-Mather method in each cell

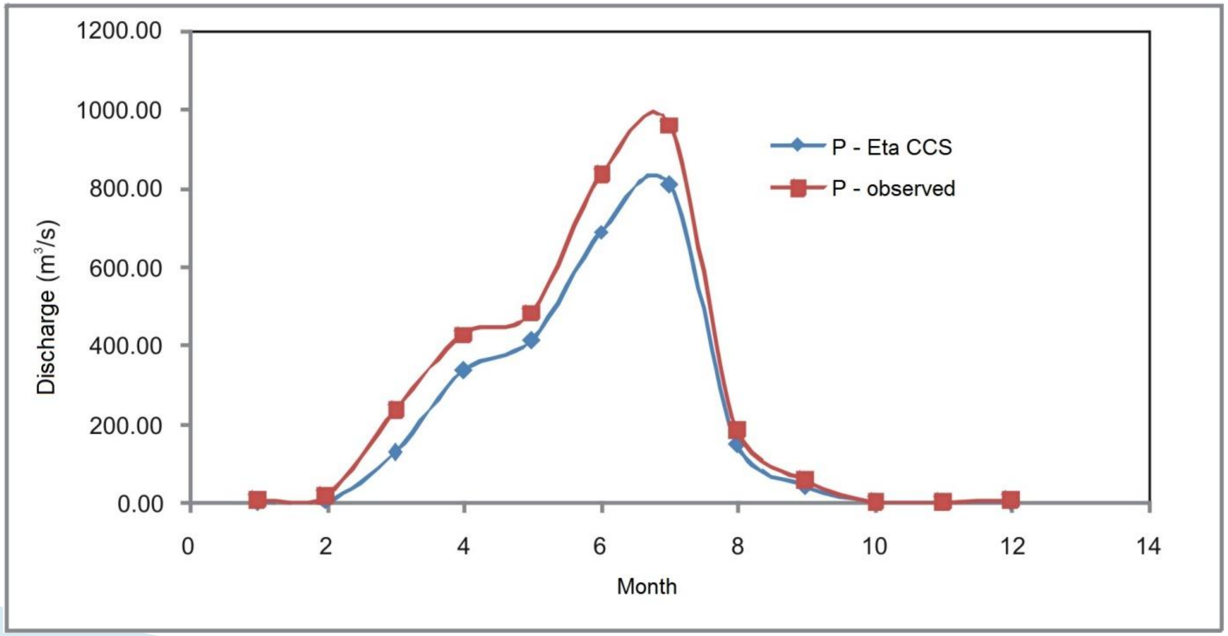


Water balance

Discharge simulated by water resources master plan of Pernambuco: **263.54 m³/s**

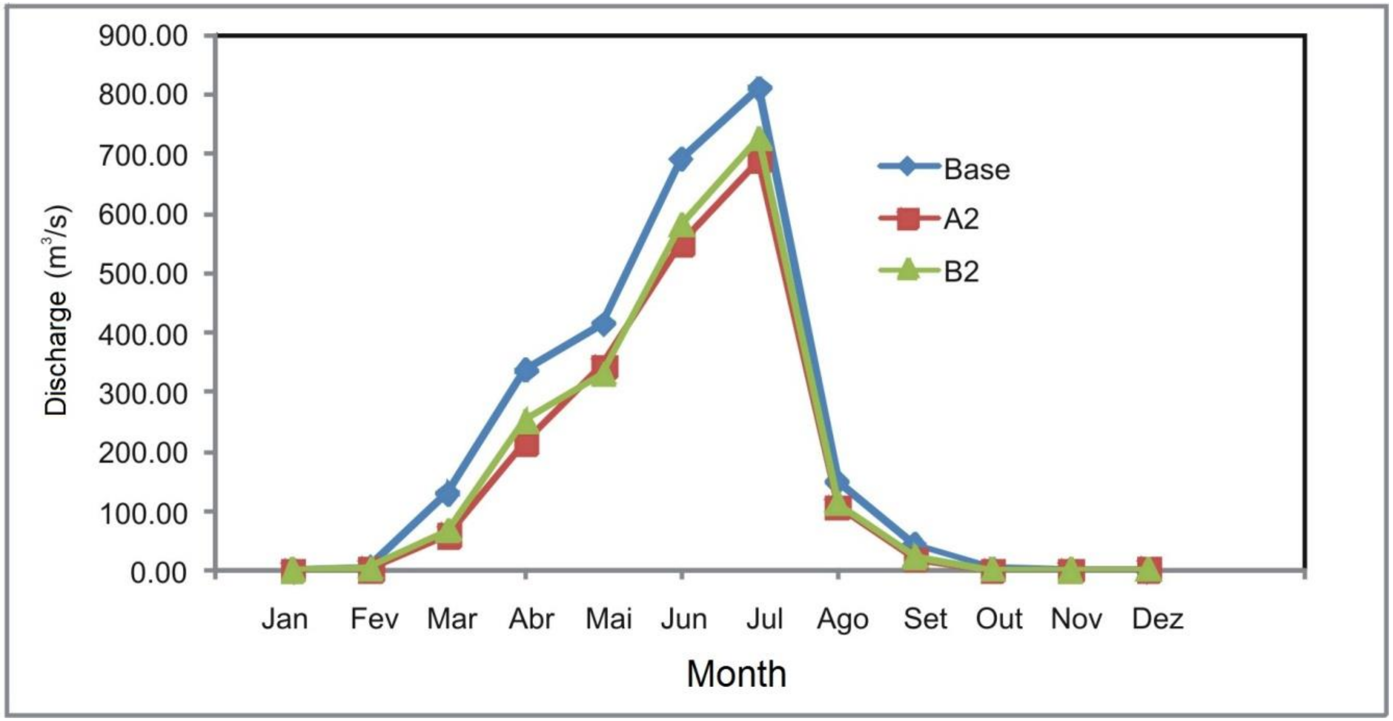
Discharge simulated with observed precipitation: **267.78 m³/s**

Discharge simulated with Eta CCS precipitation: **213.86 m³/s**



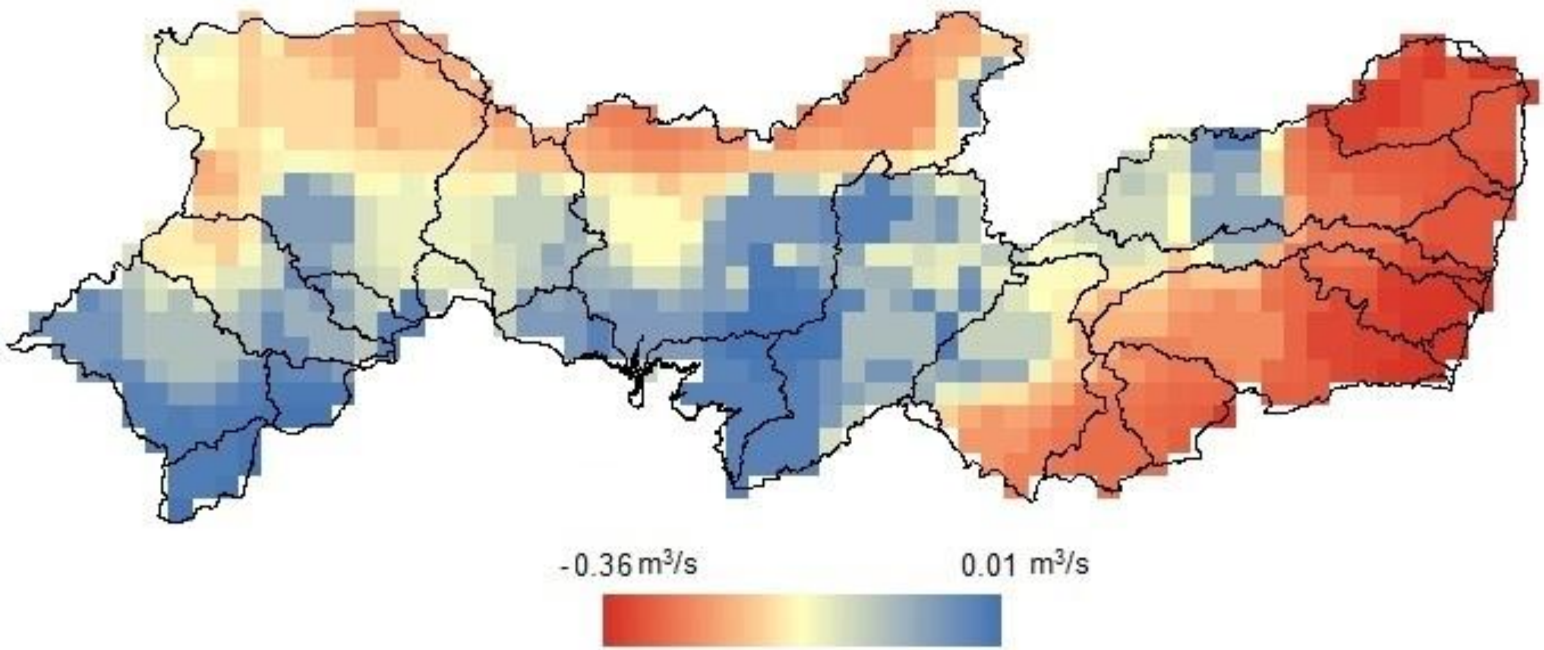
Results

Discharge in the baseline (1960-1990) and scenarios A2 and B2 (2070-2100)



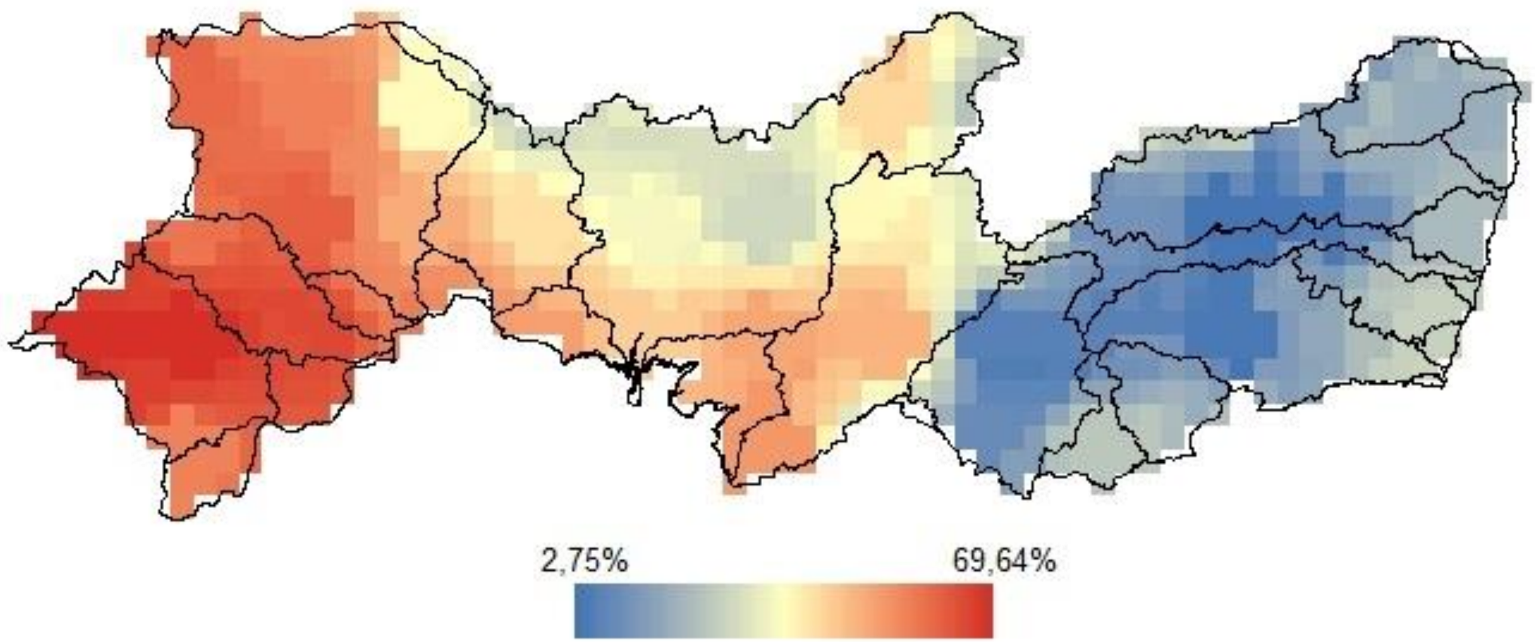
Results

Difference in the **surface runoff** between scenario A2 and baseline in m^3/s (negative values representing reduction of the runoff).



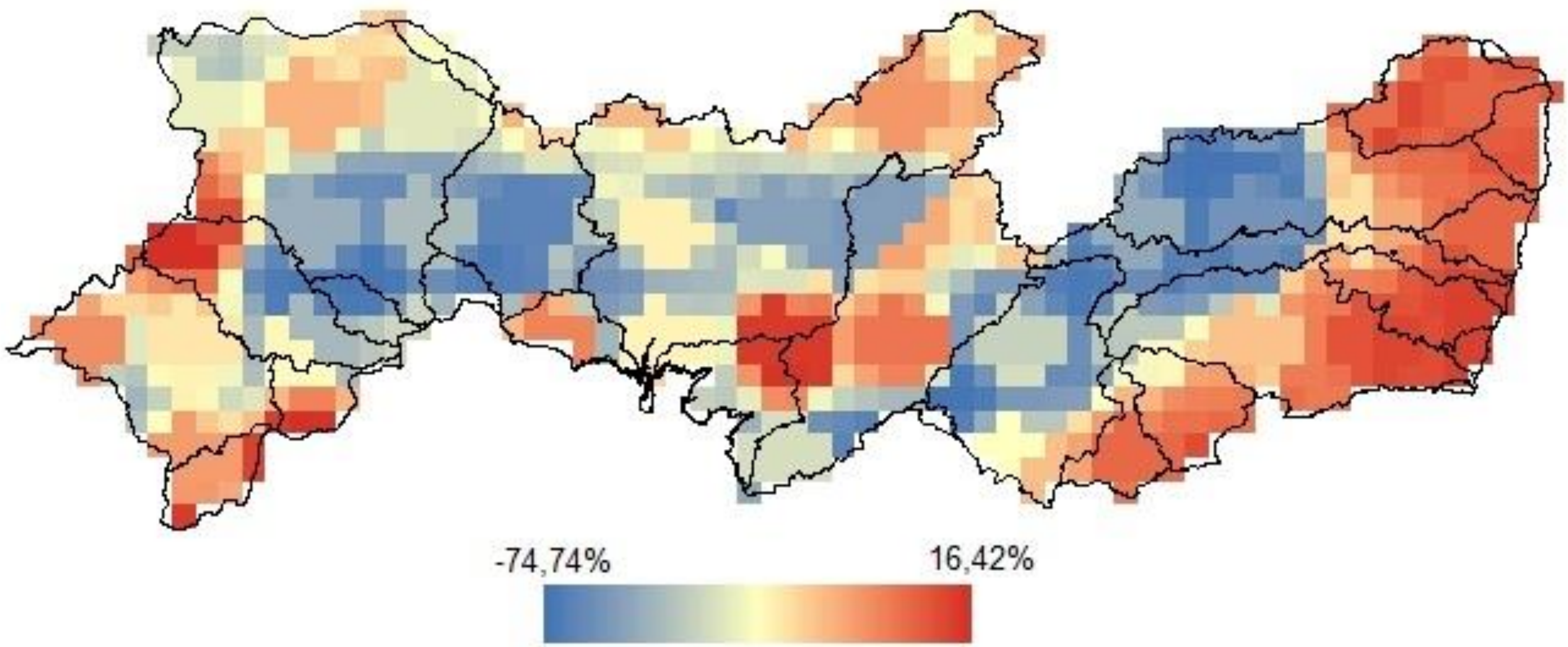
Results

Difference in the actual **evapotranspiration** between scenario A2 and baseline expressed as a percentage.



Results

Difference in the **soil moisture** between scenario A2 and baseline expressed as a percentage.



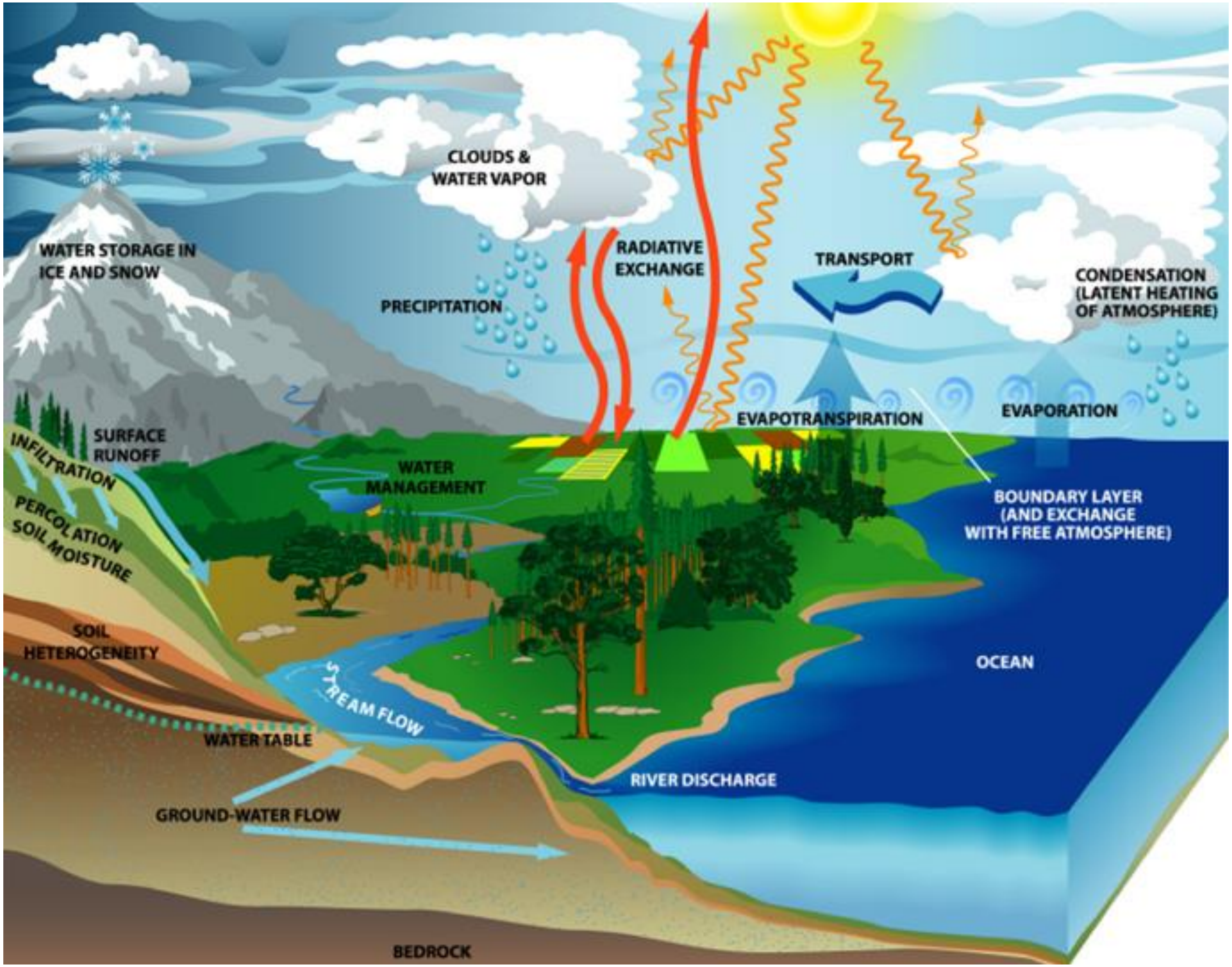
Results

- Results in agreement with Milly (2005): surface runoff reduction of 20%
- And disagreement with UK Met Office (2005) and Salati et al. (2008)
- Thornthwaithe-Mather is an alternative to complex hydrological models

Hydrological Model

Concept

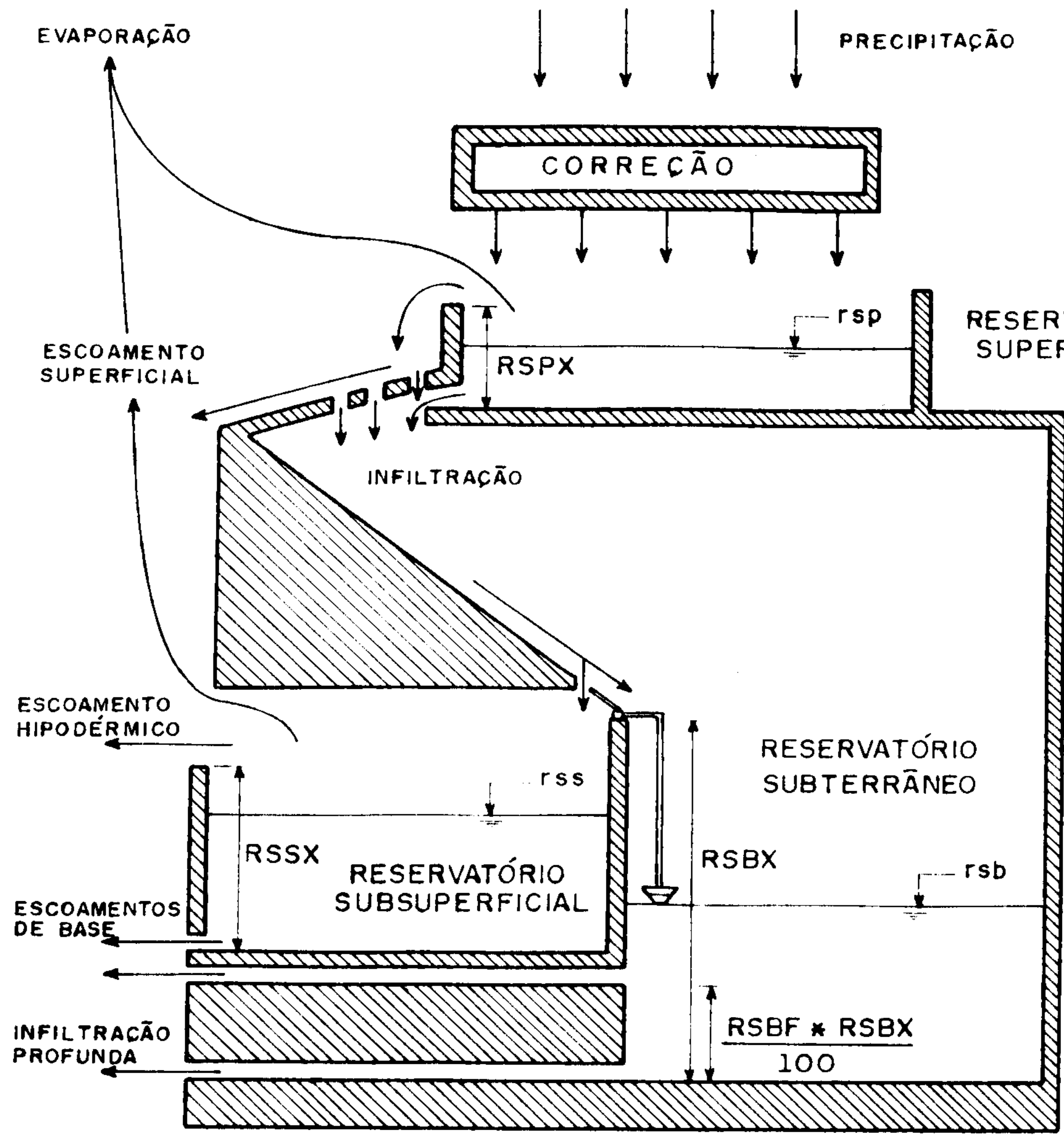
Rainfall-runoff models represent the part of hydrological cycle between the rainfall and the streamflow. They simulate the spatial distribution of rainfall, loses by interception, evaporation, depression in the soil, flow into the soil by the infiltration, percolation and groundwater, surface flow, interflow and the flow in the river.


CLOUDS &
WATER VAPOR
WATER STORAGE IN
ICE AND SNOW
RADIATIVE
EXCHANGE
TRANSPORT
CONDENSATION
(LATENT HEATING
OF ATMOSPHERE)
PRECIPITATION
EVAPOTRANSPIRATION
EVAPORATION
SURFACE
RUNOFF
INFILTRATION
WATER
MANAGEMENT
PERCOLATION
SOIL MOISTURE
BOUNDARY LAYER
(AND EXCHANGE
WITH FREE ATMOSPHERE)
SOIL
HETEROGENEITY
OCEAN
STREAM FLOW
WATER TABLE
RIVER DISCHARGE
GROUND-WATER FLOW
BEDROCK

MODHAC Model

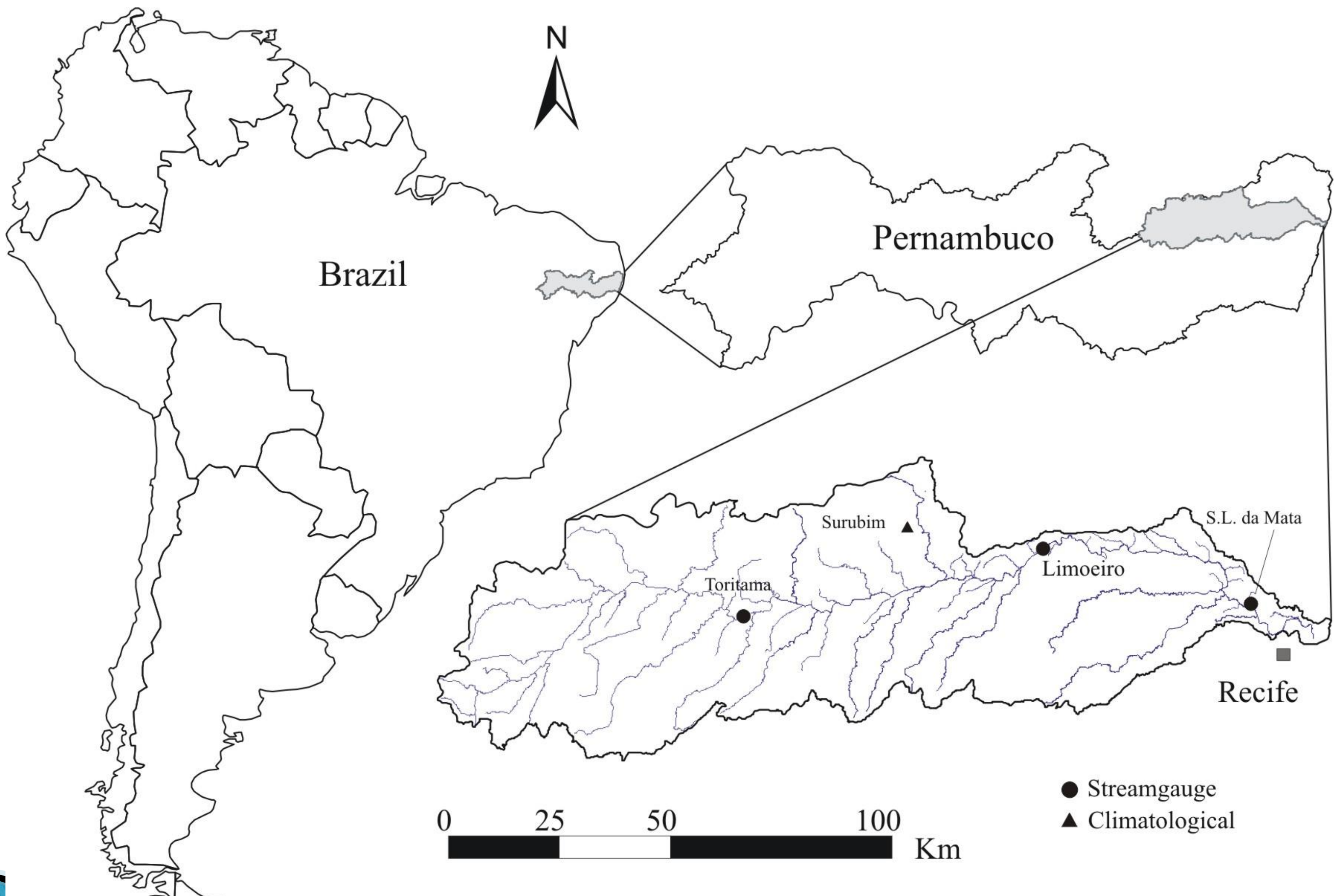
- Deterministic, conceptual, lumped
- Daily and monthly time step
- Input data
  - Precipitation
  - Observed streamflow
  - Potential evapotranspiration
- Output: streamflow at the mouth of the basin

MODHAC Model

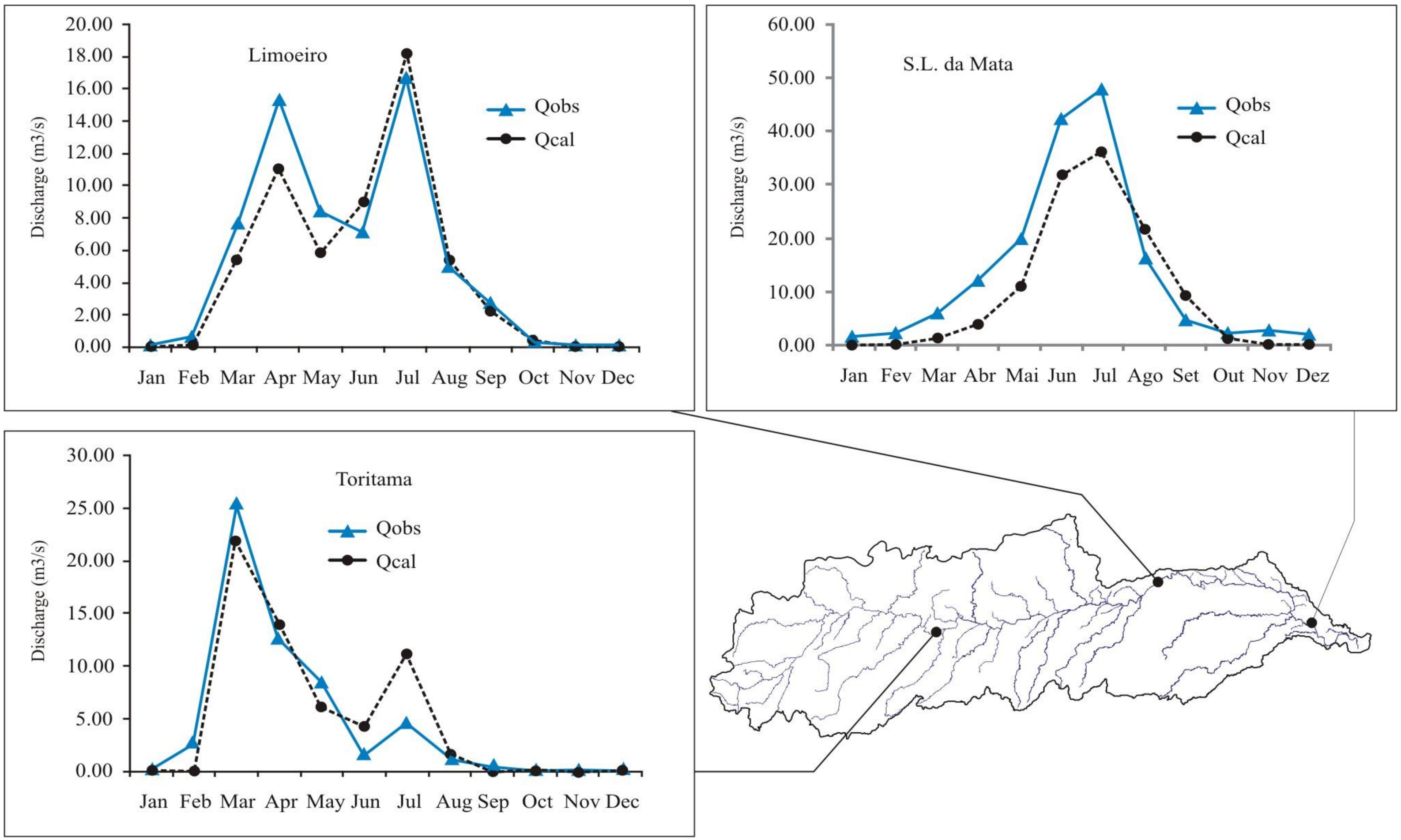


Parameter	Description	Value	Mínimum	Máximum
RSPX (mm)	capacidade máxima do reservatório superficial	43,47	0	60
RSSX (mm)	capacidade máxima do reservatório sub-superficial	199,7	20	300
RSBX (mm)	capacidade máxima do reservatório subterrâneo	6,15	0	300
RSBY	Efetivos no ajuste da curva de recessão do hidrograma	0	0	100
IMAX (mm)	permeabilidade do solo (infiltração máxima)	121,4	20	100
IMIN (mm)	infiltração mínima	0,1278	0	10
IDEC	coeficiente de infiltração	0,1387	0	1
ASP	Expoente da lei de esvaziamento do reservatório superficial	0,4399	0	1
ASS	Expoente da lei de esvaziamento do reservatório sub-superficial	0,0262	0	1
ASBX	Expoente da lei de esvaziamento do reservatório subterrâneo	1	0,001	0,1
ASBY	Efetivos no ajuste da curva de recessão do hidrograma	1	0	1
PRED	correção da precipitação	999,9	0	0
CEVA	parâmetro da lei de evapotranspiração do solo	0,7	0	1
CHET	fração da evapotranspiração potencial (evaporação direta da chuva)	0,85	0	1

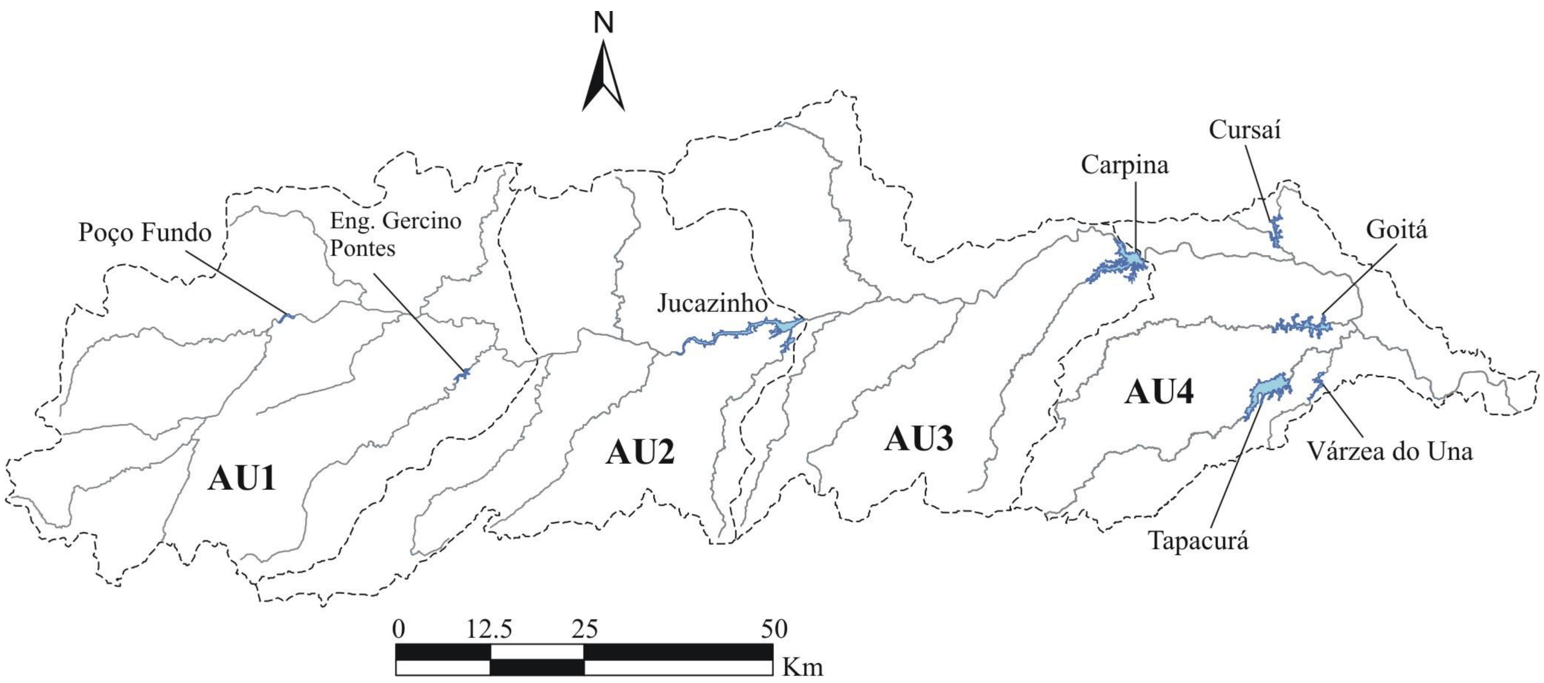
Application



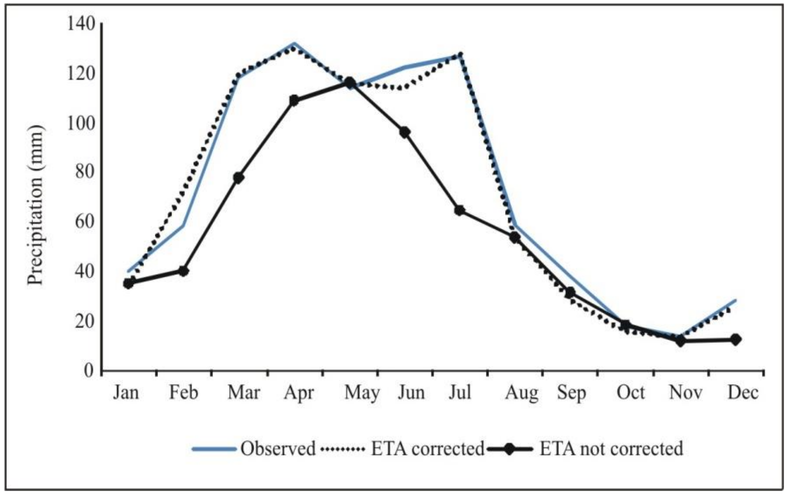
Calibration



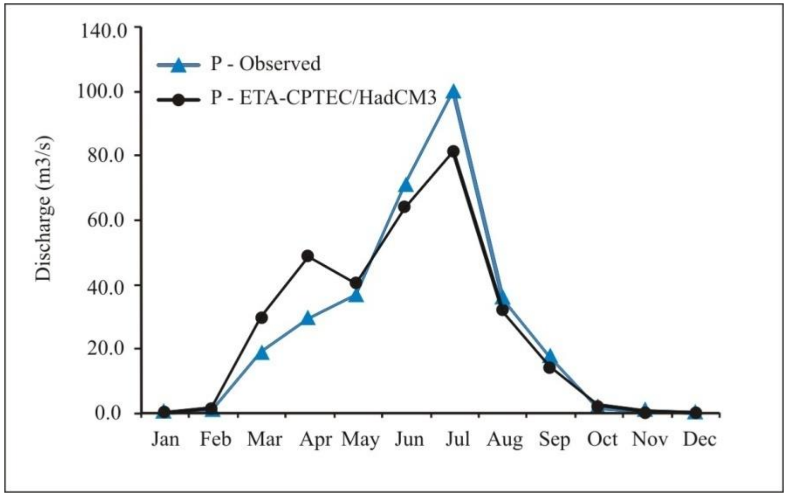
Simulation


N
Poço Fundo
Eng. Gercino Pontes
Jucazinho
Carpina
Cursaí
Goitá
Várzea do Una
Tapacurá
AU1
AU2
AU3
AU4
0
12.5
25
50
Km

Simulation

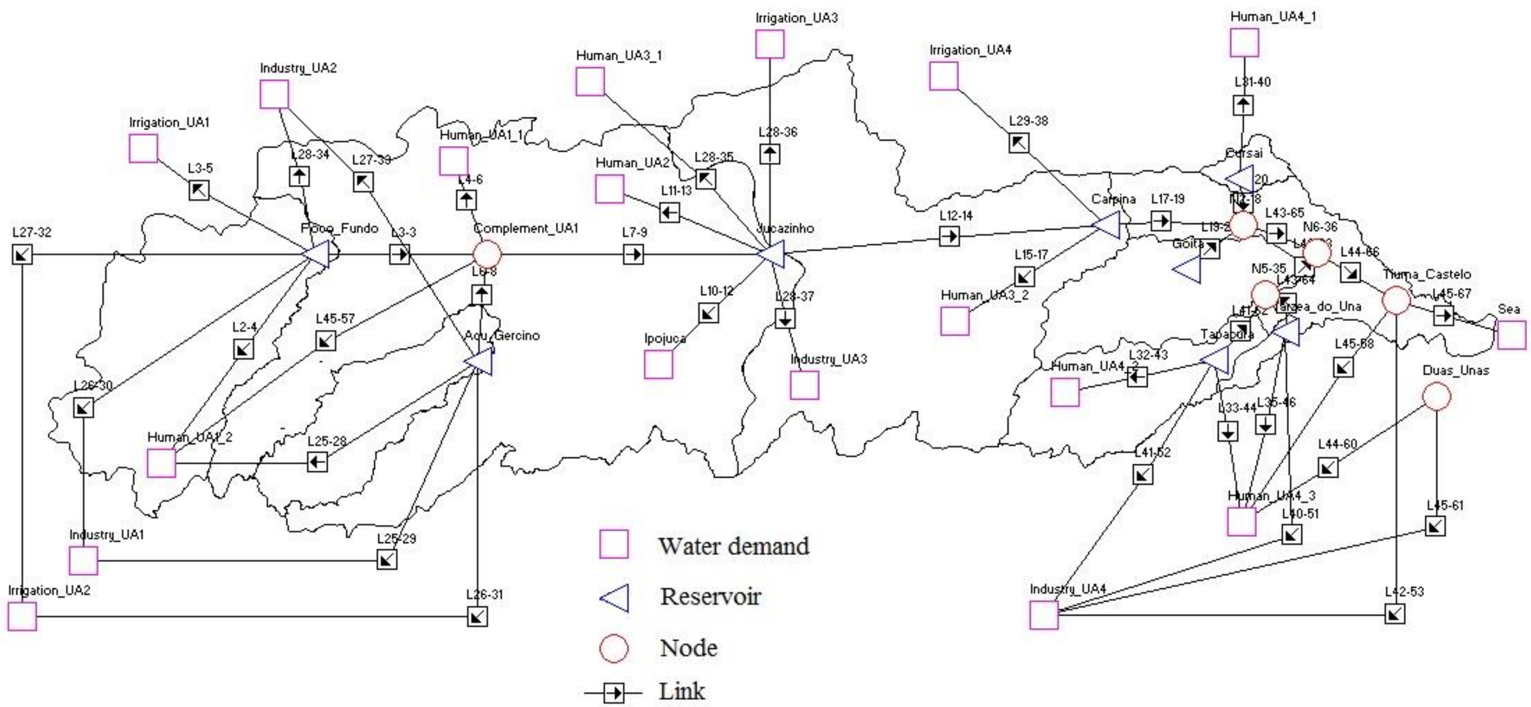


Mean precipitation in the Capibaribe river basin

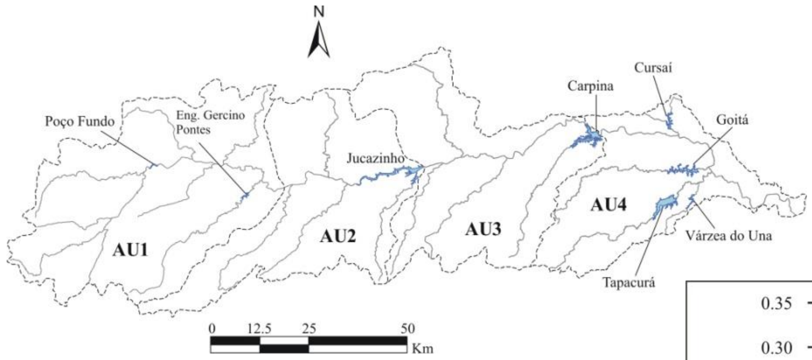


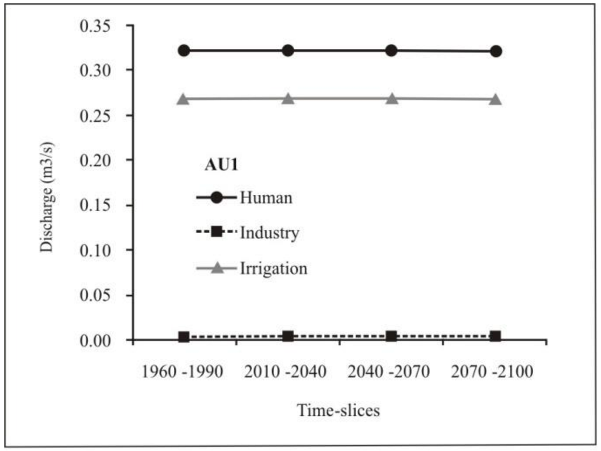
Streamflow at the outlet section of Capibaribe river calculated with MODHAC

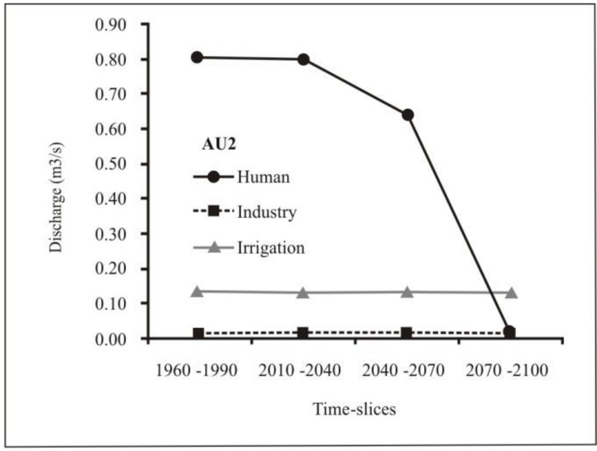
Network Flow Model

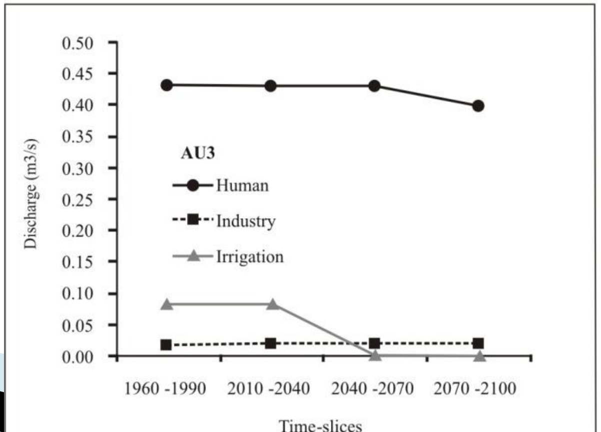


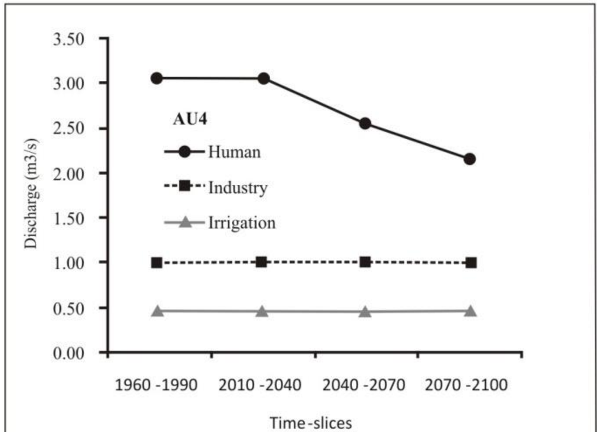
Network Flow Model











Simulation and Optimization

System analysis techniques in water resources

Simulate real-world and optimize the decision processes that play a role on this reality.

Simulation

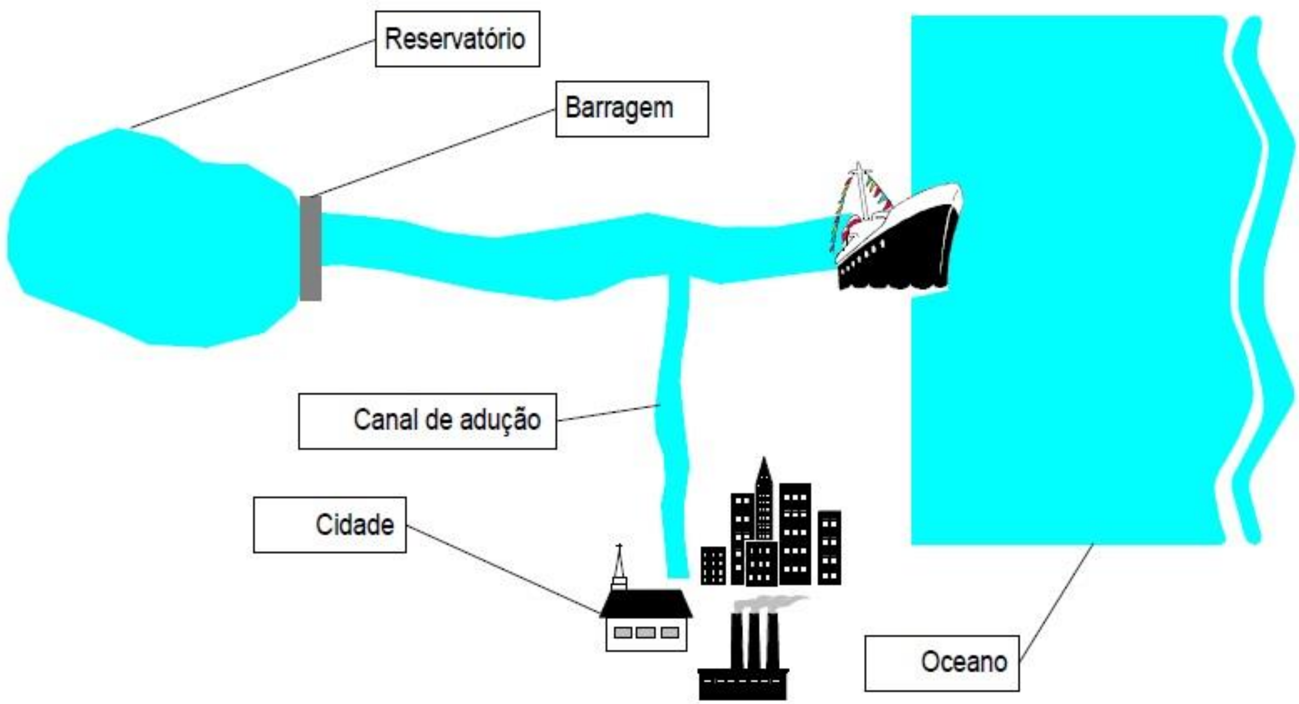
Modelling techniques used to represent the behavior of a system.

Optimization

Decision process according to a valuation stablished by the Objective-Function.

Simulation

Reservoir yield that supplies water for one city.



Representação esquemática de um sistema de recursos hídricos

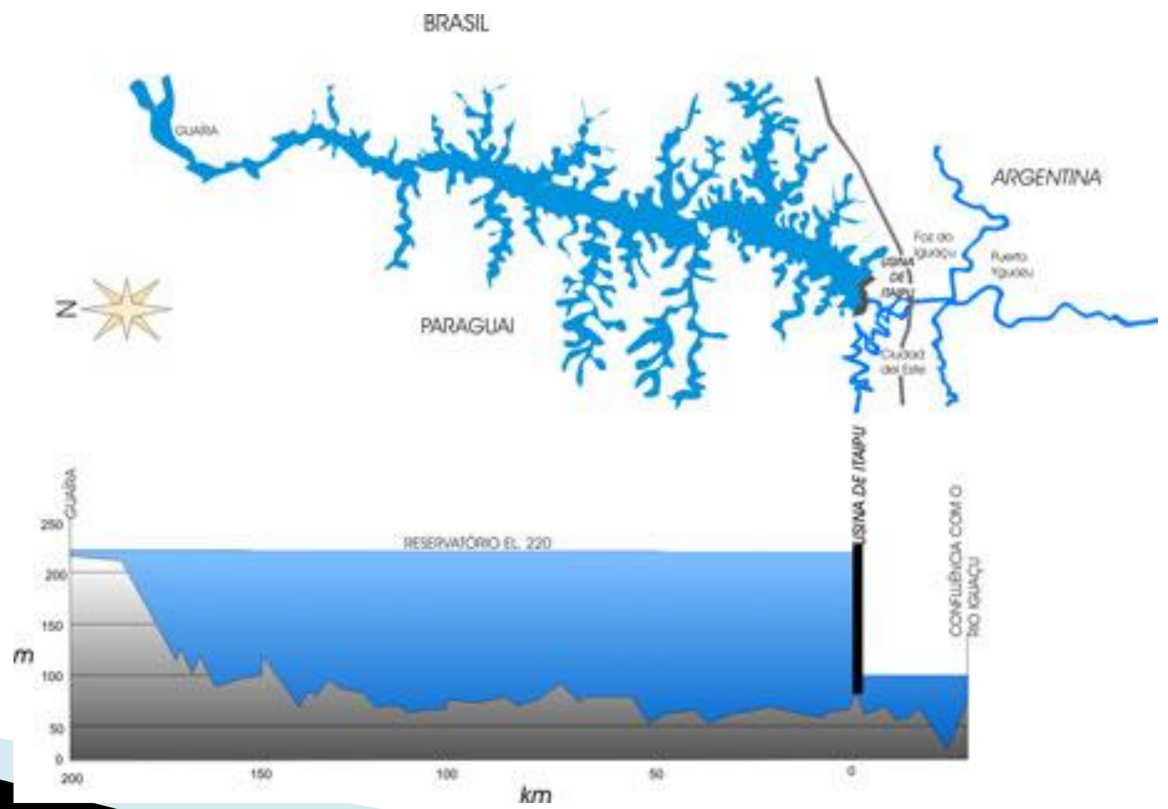
OPTIMIZATION:

Achieve the optimum (maximum or minimum) of a process.

Optimization

Use of mathematical techniques to:

-Design reservoir capacity



Optimization

Use of mathematical techniques to:

-Design canals

Optimization

Use of mathematical techniques to:

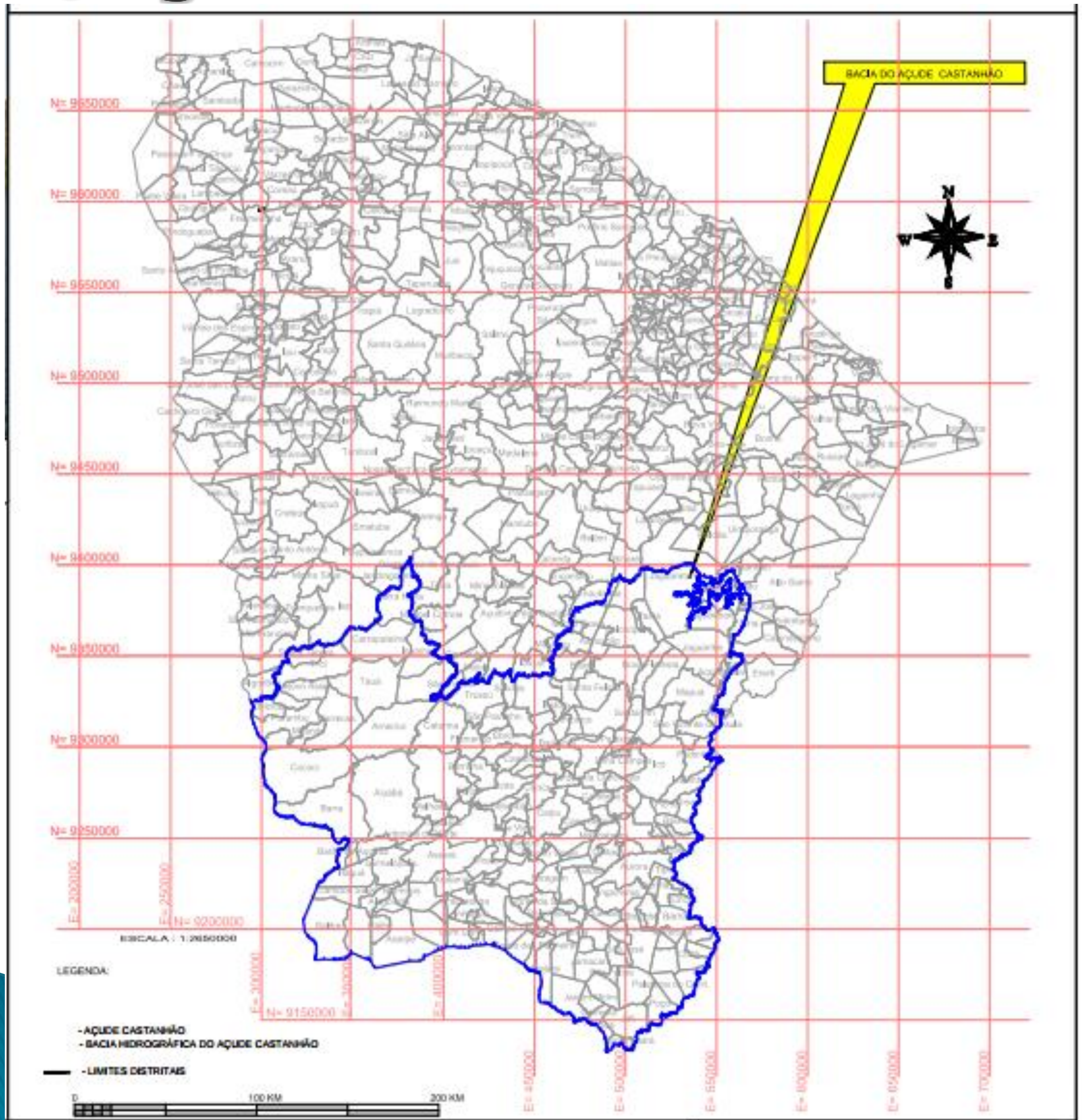
-Water alocation for several uses

Optimization

- Decision Variables
- Objective Functions
- Constraints
- State Variables

Exercise

Jaguaribe River–Castanhão reservoir

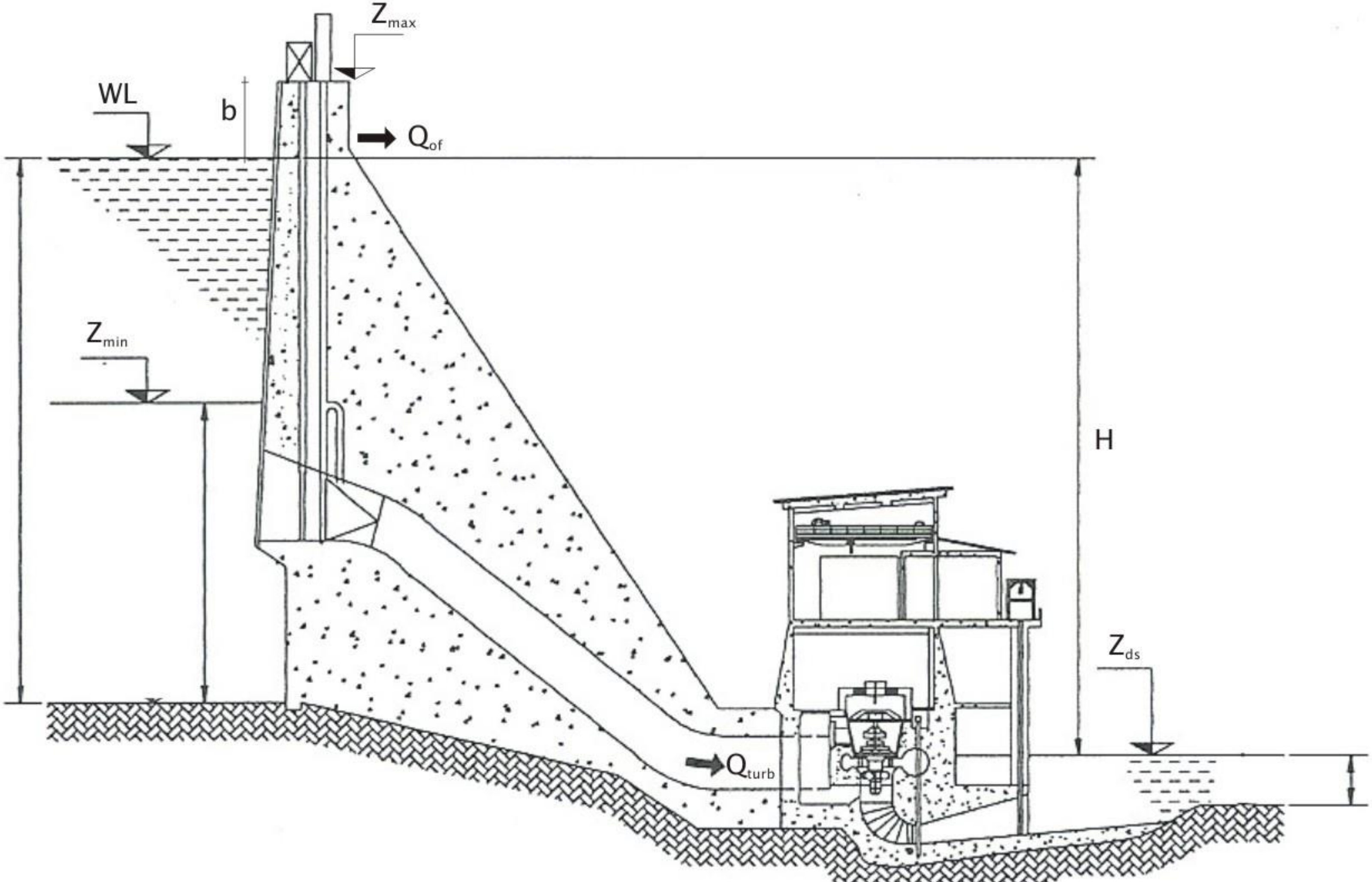


Ceará State in Northeast

Drainage area: 45,450 km^2

Capacity: 6.7 billion m^3

Multiple Use Reservoir



Multiple Use Reservoir

Decision Variables

- Maximum level of the dam: Z_{max}
- Discharge for power generation: Q_{turb}
- Discharge for irrigation: Q_{irrig}

Multiple Use Reservoir

State Variables

- Operational water level: $Z = Z_{max} - b$
- Storage: $S = a_s.Z^3 + b_s.Z^2 + c_s.Z + d_s$
- Yield discharge: $Q_{yie}=a_y.(Z-Z_0)^3+b_y.(Z-Z_0)^2+c_y.(Z-Z_0)+d_y$
- Overflow discharge: $Q_{of} = a_o.e^{bo.(Z-Z0)}$
- Total discharge: $Q_{tot} = Q_{turb} + Q_{irrig}$
- Maximum inundated area: $A = a_a.Z^2 + b_a.Z + c_a$

Multiple Use Reservoir

State Variables

- Volume for irrigation per year: $V_{irrig} = Q_{irrig}.86400.365$
- Water head for power generation: $H = Z - Z_{ds}$
- Discharge returned to the river: $Q_{ds} = Q_{turb} + Q_{of}$
- Discharge supplied in the n hours of irrigation:

  $Q_n = Q_{irrig}.24/n$
- Area that can be irrigated with Q_n: $A_{irrig} = Q_{irrig}.1000/q_{irrig}$

Multiple Use Reservoir

Benefit-Cost

1. <u>Capital costs</u>

- Expropriated area: $A_e = a_e.Z_{max}^2 + b_e.Z_{max} + c_e$
- Total cost of expropriation: $C_e = CU_e . A_e$
- Costs of execution: $C_{ex} = a_3.(Z-Z_1)^{b3}$
- Total capital cost: $C_c = C_e + C_{ex}$
- Capital recovery factor: $R = \dfrac{i \cdot (i+1)^n}{(1+i)^n - 1}$
- Annual amortization cost: $C_a = R.C_c$

Multiple Use Reservoir

Benefit-Cost

2. <u>Irrigation</u>

- Operational cost: $C_{irrig} = A_{irrig}.Cu_{irrig}$
- Price of selling of the production:

  $B_{irrig} = k_1.V_{irrig} + k_2.\ln(0.01+0.3.V_{irrig})$
- Profit of irrigação: $Prof_{irrig} = B_{irrig} - C_{irrig}$

Multiple Use Reservoir

Benefit-Cost

3. <u>Energy</u>

- Energy generated: $E(kwh) = 85935.6 \times Q_{turb} \times H \times \eta$
- Benefit of energy: $Be = E \times 0.40$

Multiple Use Reservoir

Benefit-Cost

4. Navigation

- Benefit of navigation: $B_n = a_4 . Q_{ds}^{b4}$

Multiple Use Reservoir

Constraints

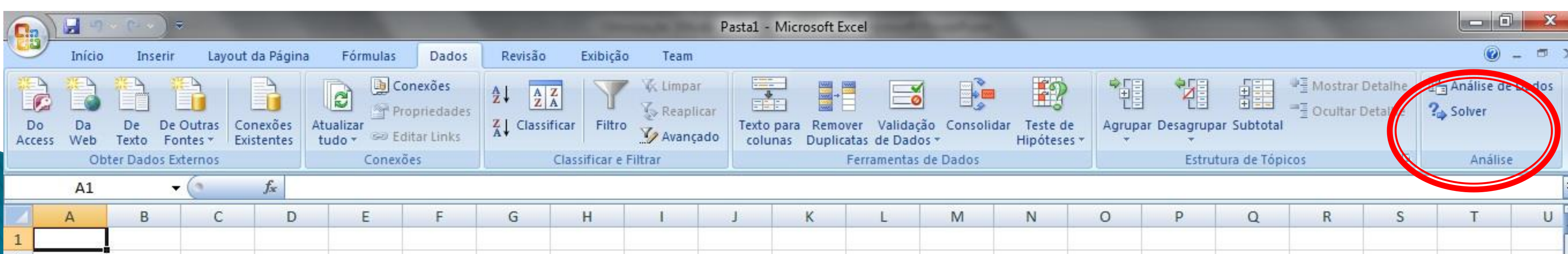
1. $Z_{max} \geq 0$
2. $Q_{turb} \geq 0$
3. $Q_{irrig} \geq 0$
4. $Z_{max} \leq$ Maximum level possible
5. $Z_{max} \geq$ Minimum level possible
6. $A_{irrig} \leq A_{max,irrig}$
7. $Q_{ds} \geq Q_{min}$
8. $Q_{tot} \leq Q_{yie}$
9. $H \geq H_{min}$

Solver

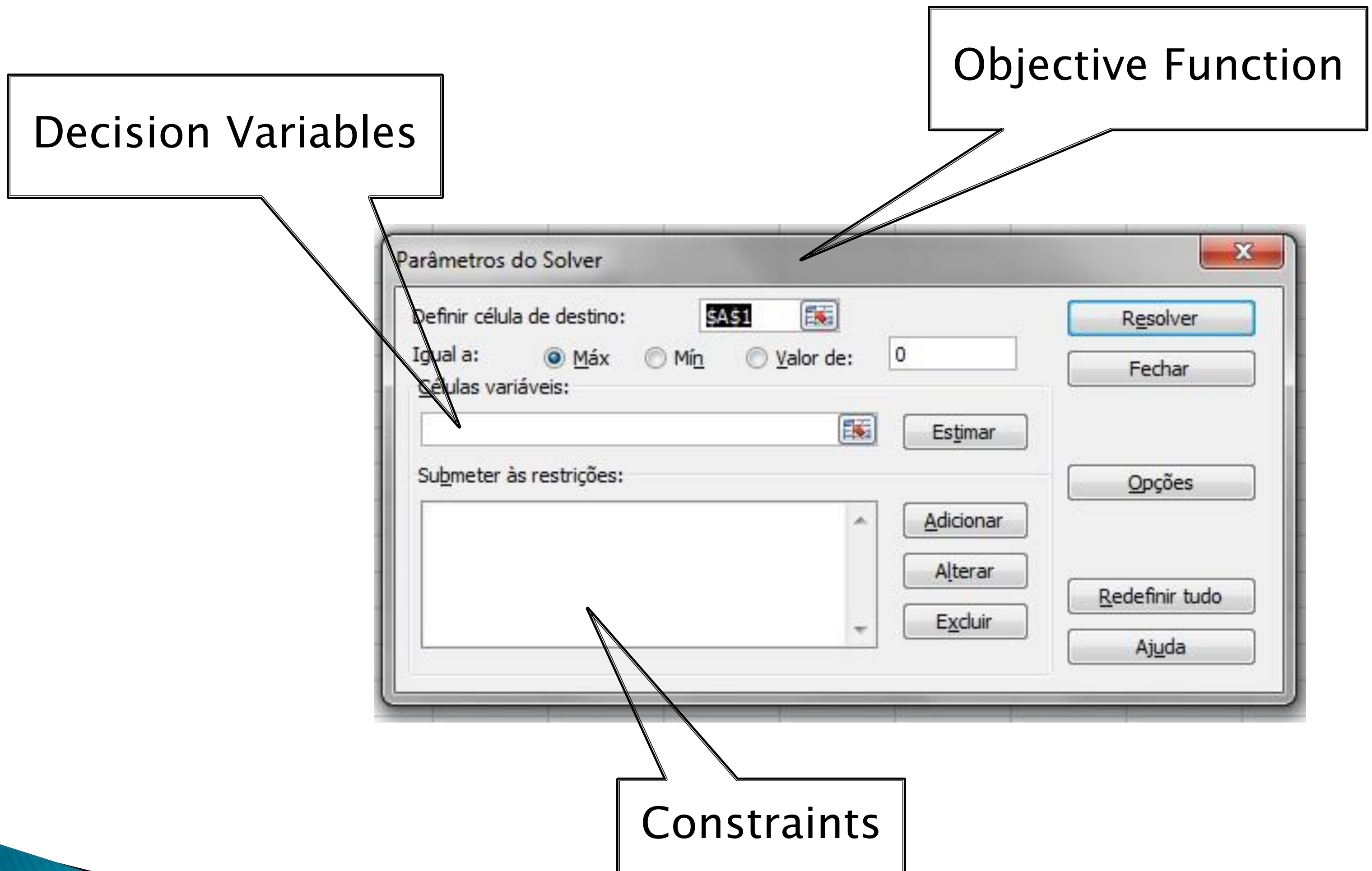
Microsoft Office 2007

Click in “Buton Office”  and, after, “Excel Options”. Select “Supplement” and click in the buton “Go ...”. Select the Solver clicking in the box;

Solver is accessed in menu “Data”.



Solver


Objective Function
Decision Variables
Parâmetros do Solver
Definir célula de destino:
A1
Igual a:
Máx
Mín
Valor de:
0
Células variáveis:
Estimar
Submeter às restrições:
Adicionar
Alterar
Excluir
Resolver
Fechar
Opções
Redefinir tudo
Ajuda
Constraints

Summary

- Downscaling: dynamic and statistic
- Bias correction
- Hydrological model
- Simulation/Optimization tools
- Simulate IPPC scenarios
- Evaluate adaptation actions

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Thank you!

Gracias!

Obrigado!

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