SWAT 2015
PULA / SARDINIA / ITALY

Climate Change effects in a medium-sized Mediterranean basin using the tRIBS hydrologic model

M. Piras(1), G. Mascaro(1,2), R. Deidda(1), E. R. Vivoni(2)

(1) CINFAI, University of Cagliari, Italy
(2) Arizona State University, USA

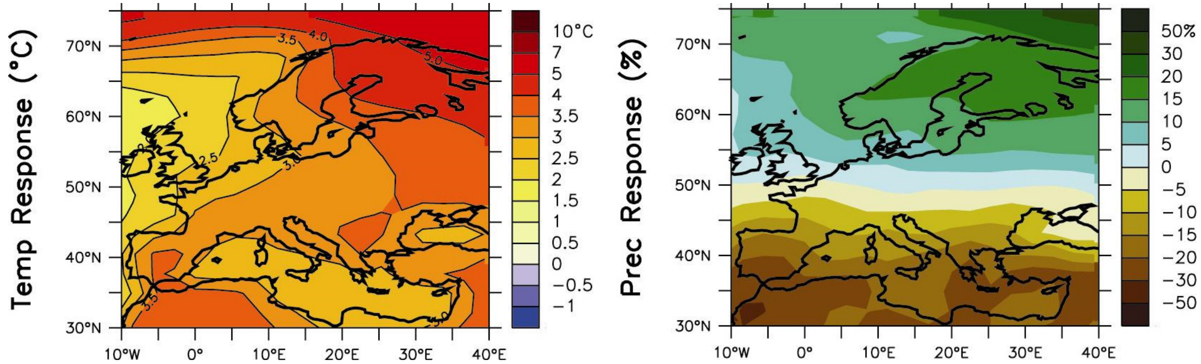
Pula, June 24th 2015

Motivations

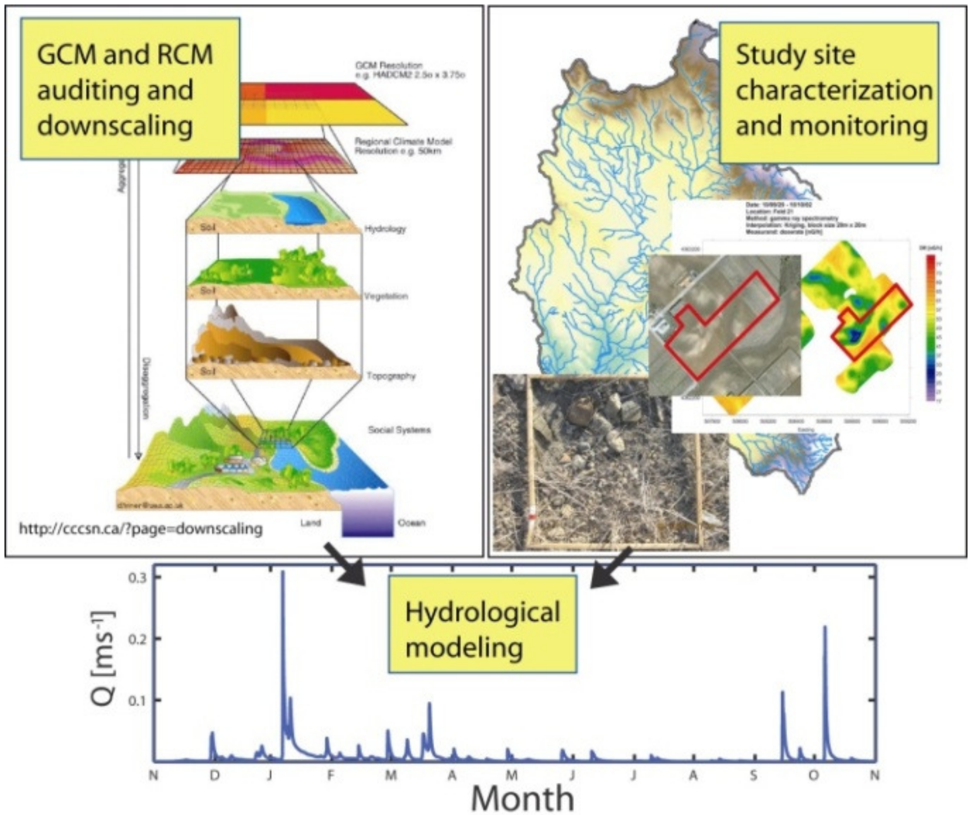
- The **Mediterranean basin** is expected to be at risk under **climate change** (CC), in particular water resources. CC projections suggest increasing frequency of extremes.

- The local impacts on hydrological cycle and water resources due to CC may be evaluated by coupling **global and regional climate models** with **distributed hydrological models**.

- **Downscaling techniques** can be used to bridge the scale mismatch between climate and hydrological models.



MMD-A1B simulations. Annual mean. IPCC 2007



Objective and methods

Develop a modeling approach which allows evaluating local hydrological impacts of climate change in a study site in Sardinia, Italy.

1. *Use different future climate scenarios as driving inputs of hydrological simulations in the future period 2041-2070.*

2. *Apply a hydrological model (tRIBS) to simulate land-surface water and energy fluxes at high spatial and temporal resolution.*

3. *Compare results with simulations of other hydrologic models and characterize uncertainty using multi-model ensemble techniques*

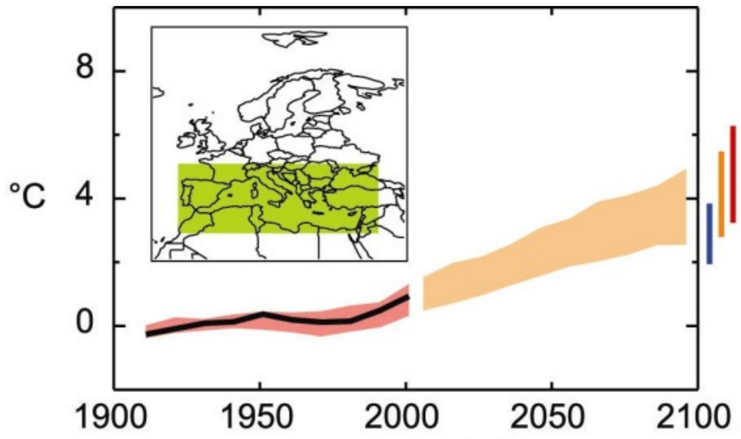
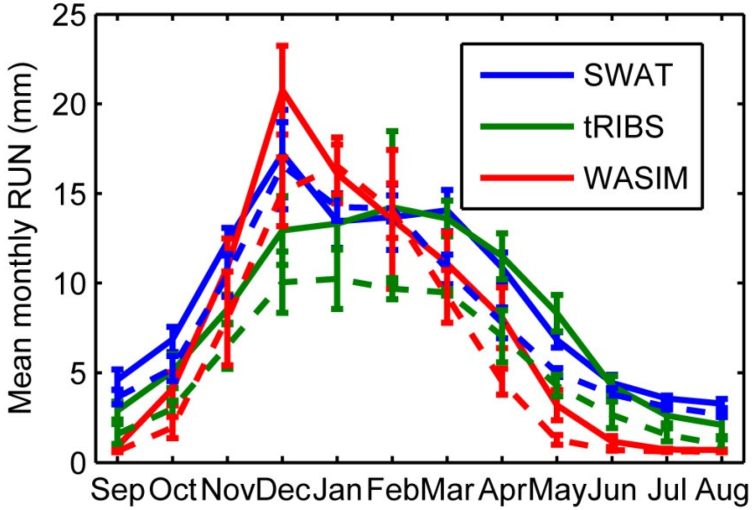


Fig. 11.4. IPCC Report on Regional Climate Projections



<u>Provide high resolution spatio-temporal information which can be used to support management water resources at local scale.</u>

Outline

- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

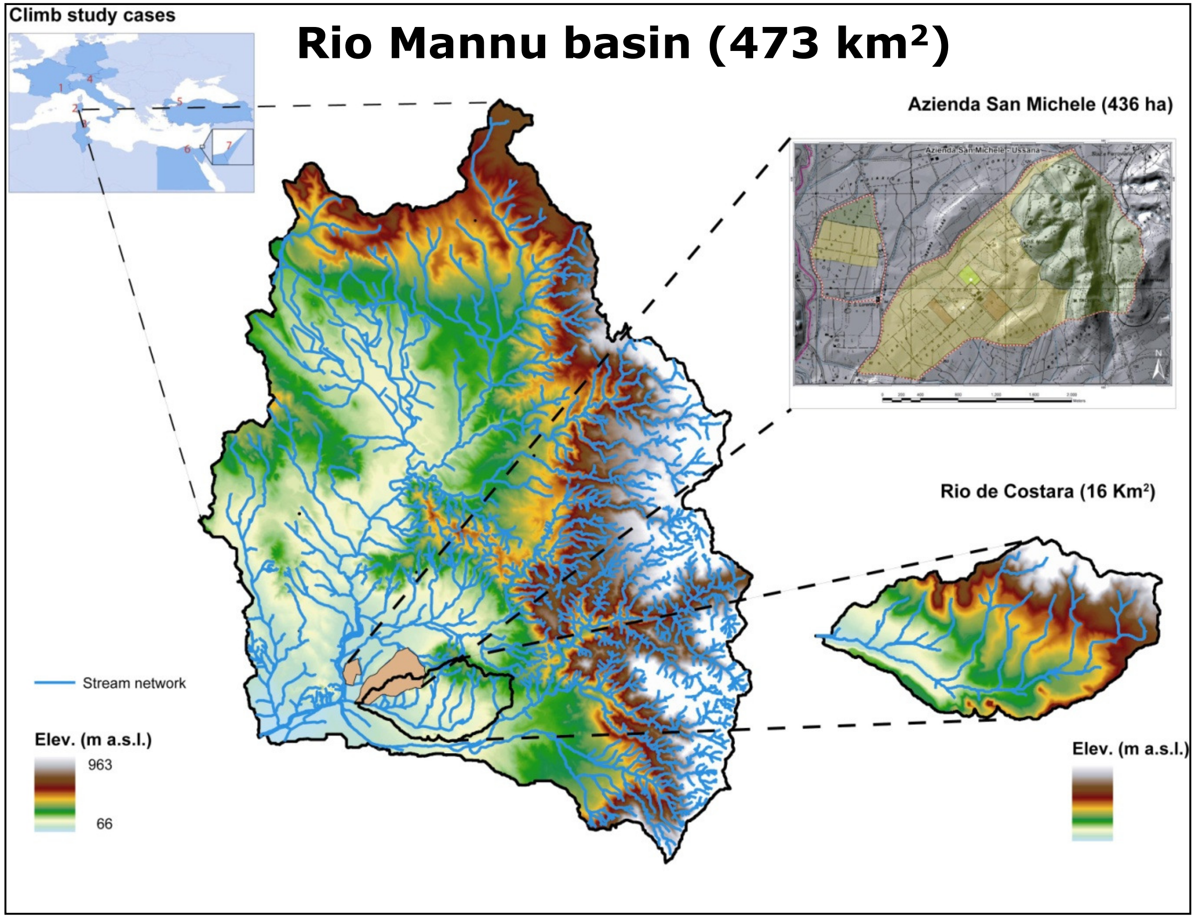
Outline

- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

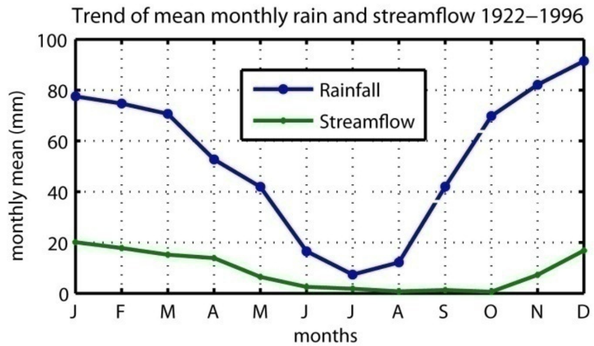
Case study

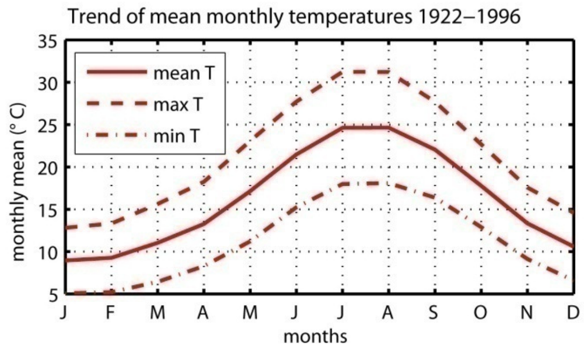
The case study is the Rio Mannu (RM) basin, Sardinia, Italy

Study case location and terrain (*Mascaro et al. 2013*)



Average intra-annual variability of precipitation, streamflow and temperature

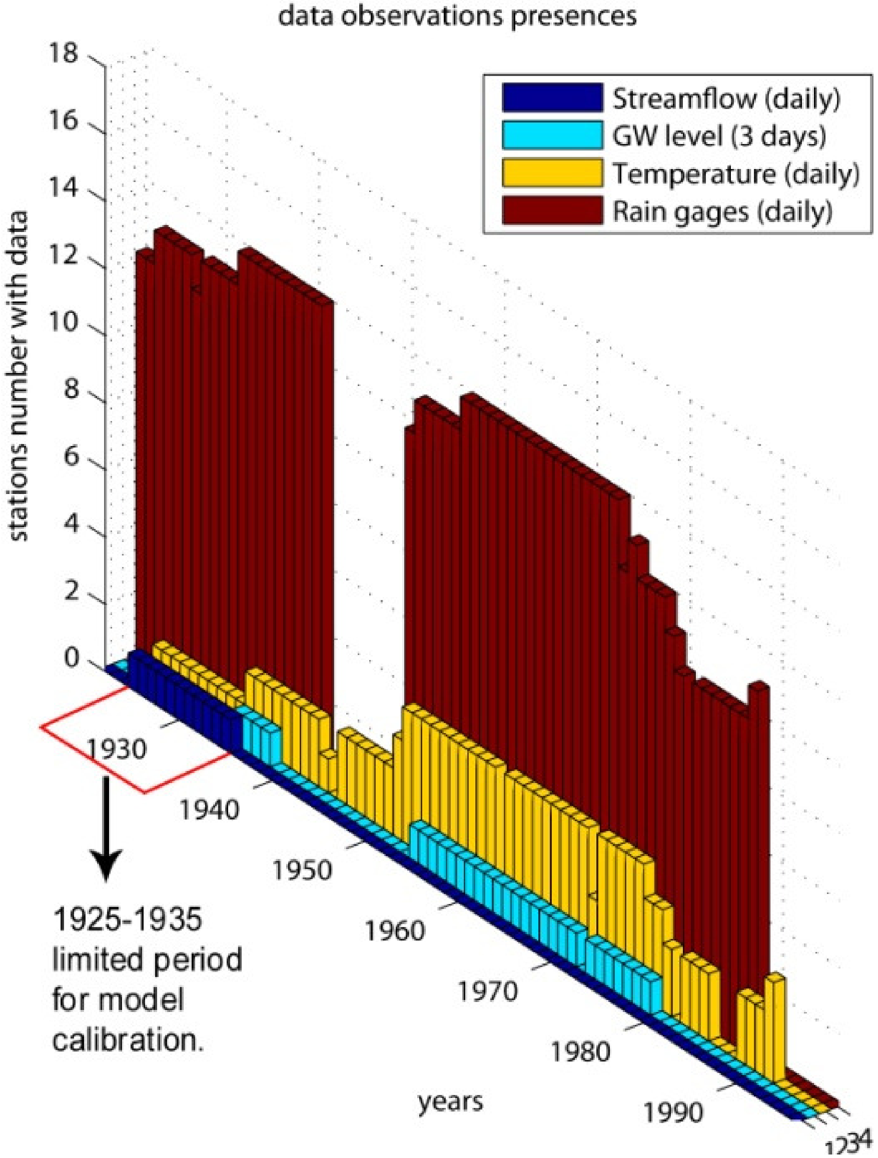




Rio Mannu physiographic properties (from 10-m DEM)			
H_{min}	H_{max}	H_{mean}	s
[m]	[m]	[m]	[%]
66	963	296	17.3

Case study

Limited data availability and uncertainty



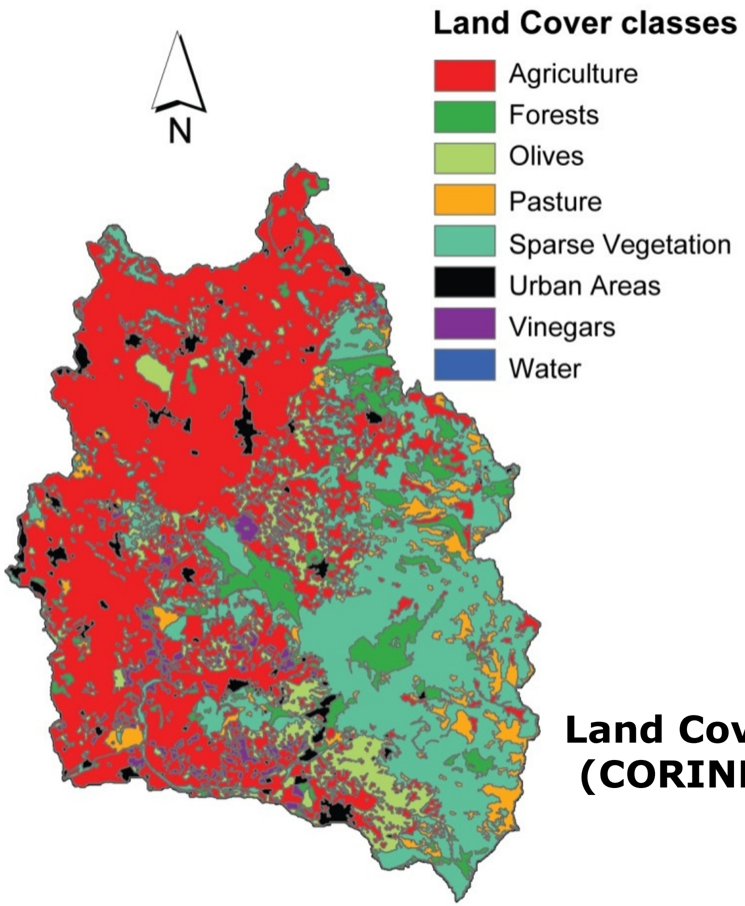
- Streamflow measurements covering only eleven years (1925-1935)
- 12 rain gages working at the same time.
- One station with minimum and maximum temperatures.

↓

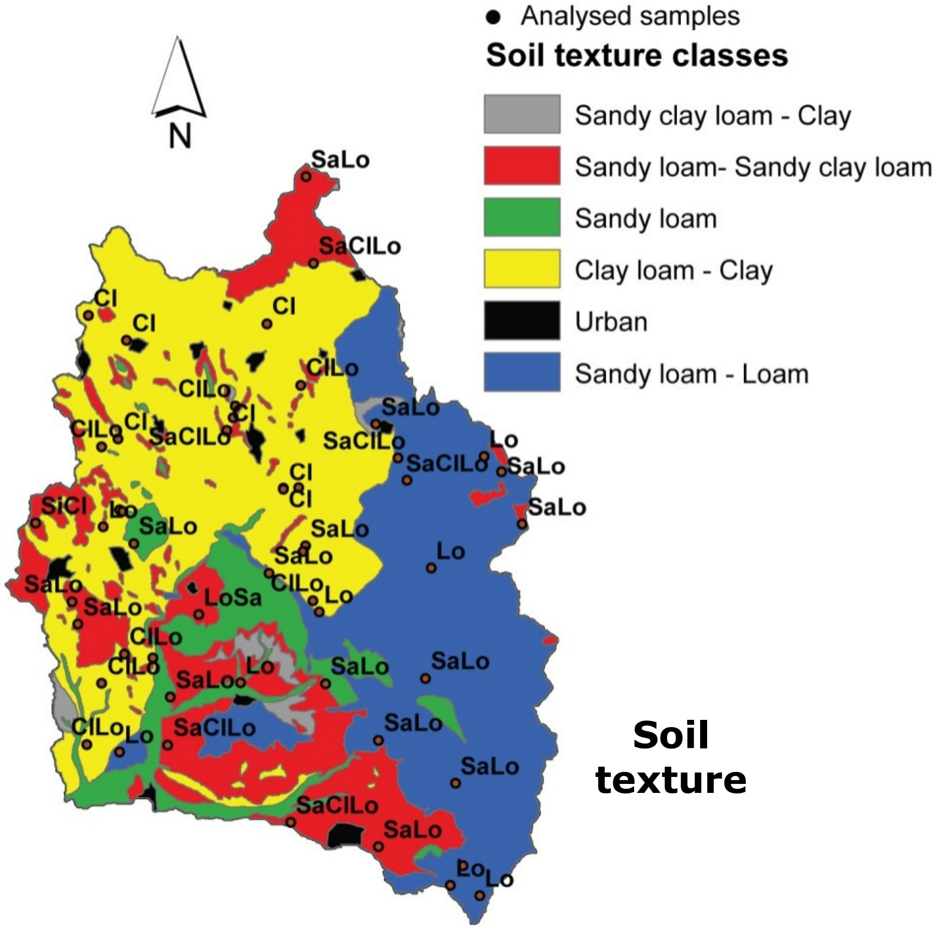
- *Limited data availability for hydrological model calibration.*
- *Limited period for model calibration, constrained by the presence of streamflow data.*
- *Uncertainties in streamflow data published from Italian technical reports (Annali Idrologici).*
- *Daily resolution too coarse for hydrologic simulations.*

Case study

Field campaigns to characterize the RM basin properties.



Land Cover (CORINE)



Soil texture

Outline

- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

tRIBS overview

TIN based real time Integrated basin Simulator (**tRIBS**) is a fully-distributed model of coupled hydrologic processes.

Model history

• Originally developed at MIT by Prof. Rafael Bras' research group.

• Heritage of RIBS (*Garrote and Bras*, 1995) and CHILD (*Tucker et al.*, 2001) models:

L. Garrote, R.L. Bras / Journal of Hydrology 167 (1995) 279–306

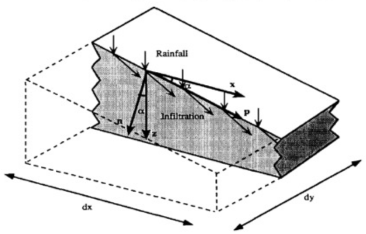


Fig. 1. Coordinate systems used for infiltration analysis on a grid element.

Garrote and Bras (1995)

L. Garrote, R.L. Bras / Journal of Hydrology 167 (1995) 279–306

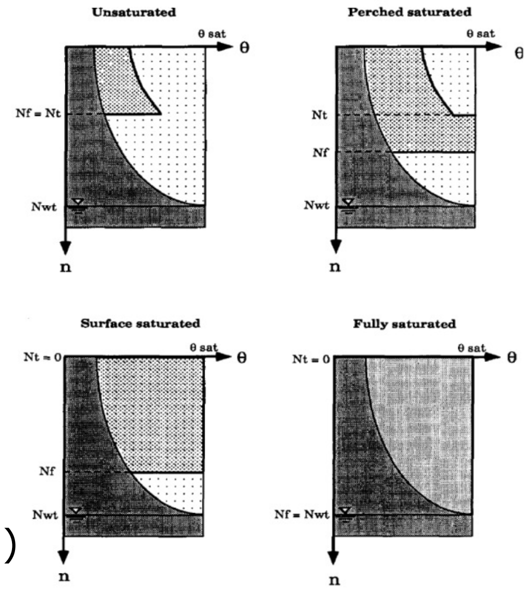


Fig. 4. Four runoff-generation states for a soil column.

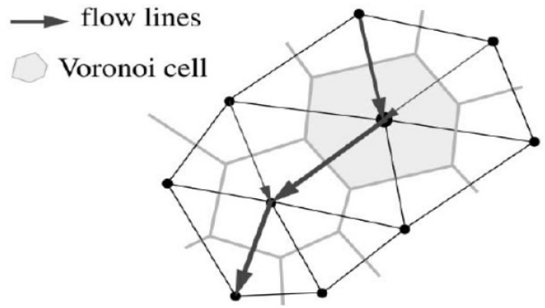


Fig. 5. Illustration of steepest-descent flow routing in TIN framework.

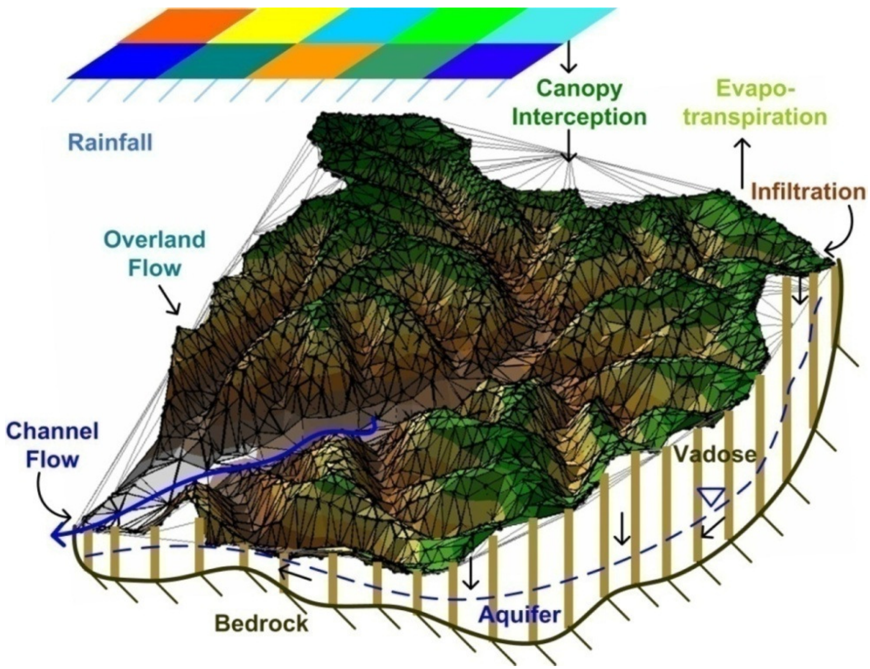
Tucker et al. (2001)

• Model description in *Ivanov et al.* (2004a).

tRIBS overview

tRIBS represents the terrain through TINs and models the different hydrologic processes:

Schematisation of hydrological processes represented in tRIBS model (*Ivanov et al. 2004a, 2004b*).



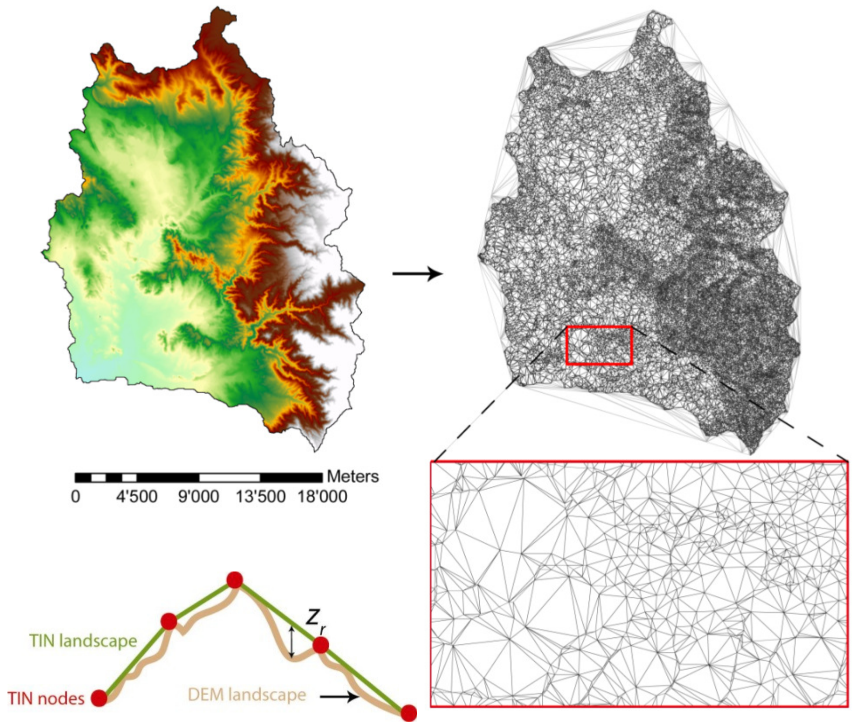
- Interception *(Rutter et al. 1972)*, evaporation and transpiration *(Wigmosta et al., 1994; Deardorff, 1978)*.
- Solar radiation and energy balance *(Lin, 1980; Hu and Islam, 1995)*.
- Infiltration in heterogeneous and anisotropic soils *(Cabral et al., 1992; Beven, 1982,1984)*.
- Soil humidity redistribution *(Morel-Seytoux et al. 1974; Neuman 1976)*. Coupled vadose and saturated zones with dynamic water table.
- Topography-driven lateral fluxes in vadose and groundwater *(Smith et al., 1993; Childs et al., 1969)*.
- Four runoff generation mechanisms.
- Hydrologic and hydraulic routing.

tRIBS overview

Topographic representation via Triangulated Irregular Networks (TINs)

DEM 10-m resolution.

TIN with z_r = 3 m.



Advantages:

- Significant reduction of computational nodes as compared to grid-based models *(Vivoni et al., 2004 and 2005)*.
- Multiple resolution domains.
- Preservation of linear features such as stream networks and terrain breaklines.

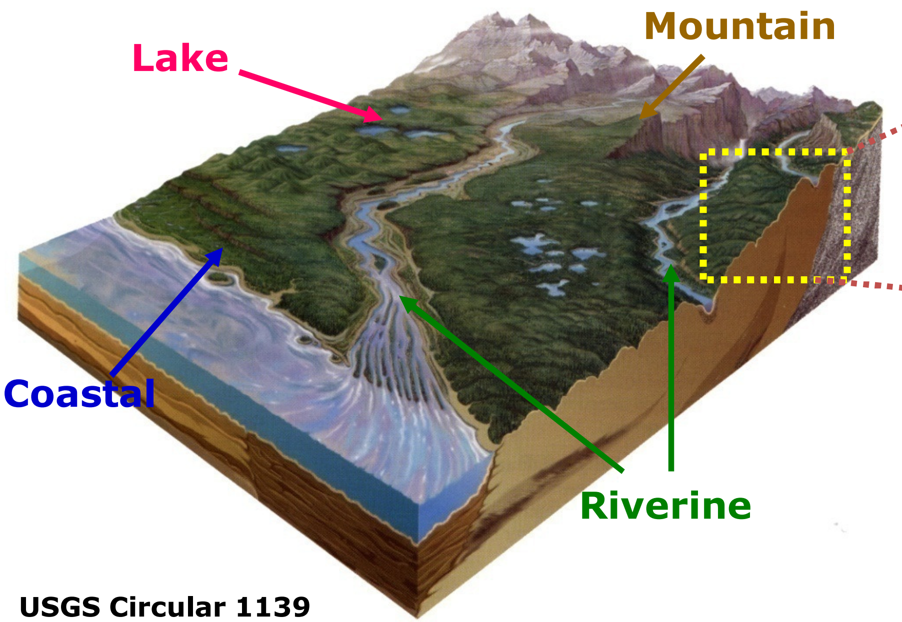
Parameters used to quantify spatial aggregation from DEM to TIN:

$d = \frac{n_t}{n_g}$ Horizontal point density.

z_r Vertical tolerance.

Hydrologic Processes

Unsaturated-Saturated dynamics

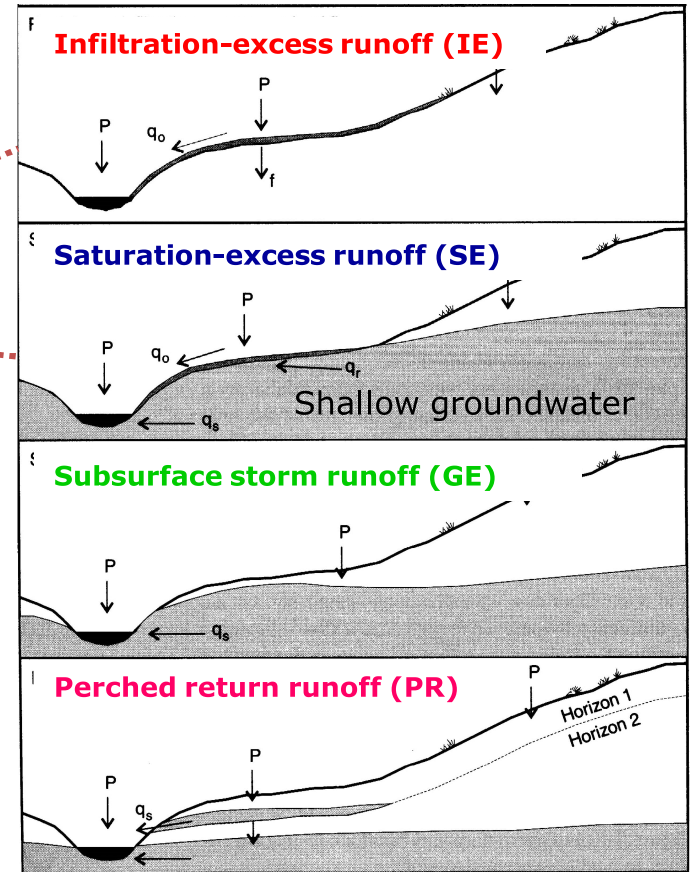


USGS Circular 1139

Surface-Groundwater Interactions in different Landscapes and Scales

Runoff is generated via multiple mechanisms depending on the interactions of infiltration fronts and the water table.
Runoff types can differ in time and among cells.

Hillslope runoff processes



Beven (2002) Rainfall-Runoff Modeling

tRIBS: Applications

tRIBS applications

- Multiyear, continuous simulations using NEXRAD (*Ivanov et al., 2004a, 2004b*).
- Event-based hydrograph predictions based on radar now-casting fields (*Vivoni et al., 2006*) or short-lead-time NWP fields.
- Track hydrologic response to coarse satellite-derived or climate models precipitations forcing downscaled with two different disaggregation schemes (*Forman et al., 2008; Mascaro et al., 2010*) .
- Assess the impact of climate change (*Liuzzo et al., 2010*).
- Assess the effects of different initialization on hillslopes and basin response (*Noto et al. 2008*).

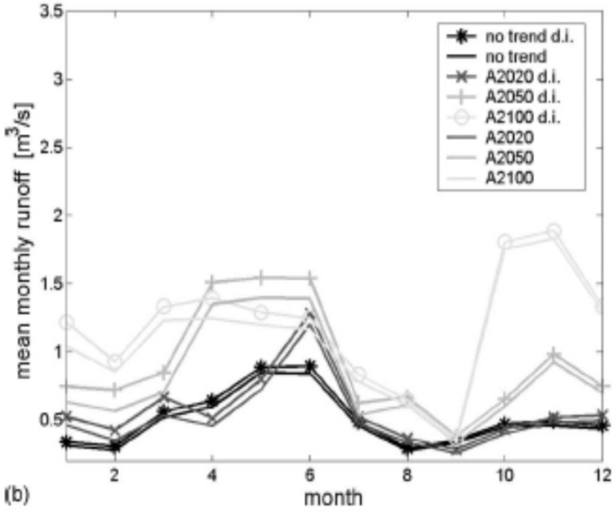
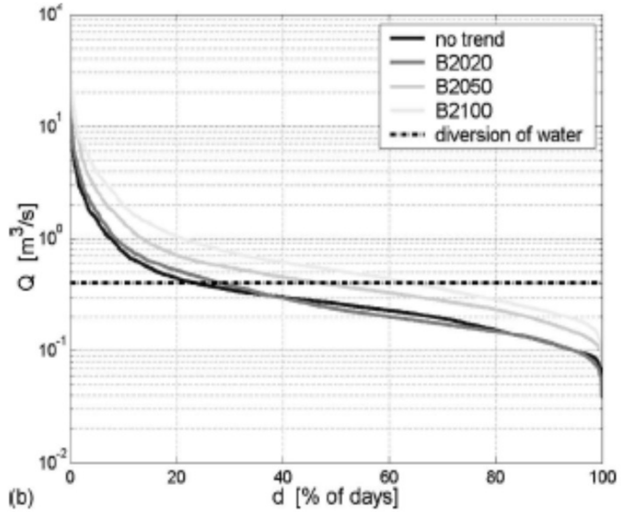


Fig. 4. Mean monthly runoff (mm) for: (a) Group A; (b) Group B scenarios

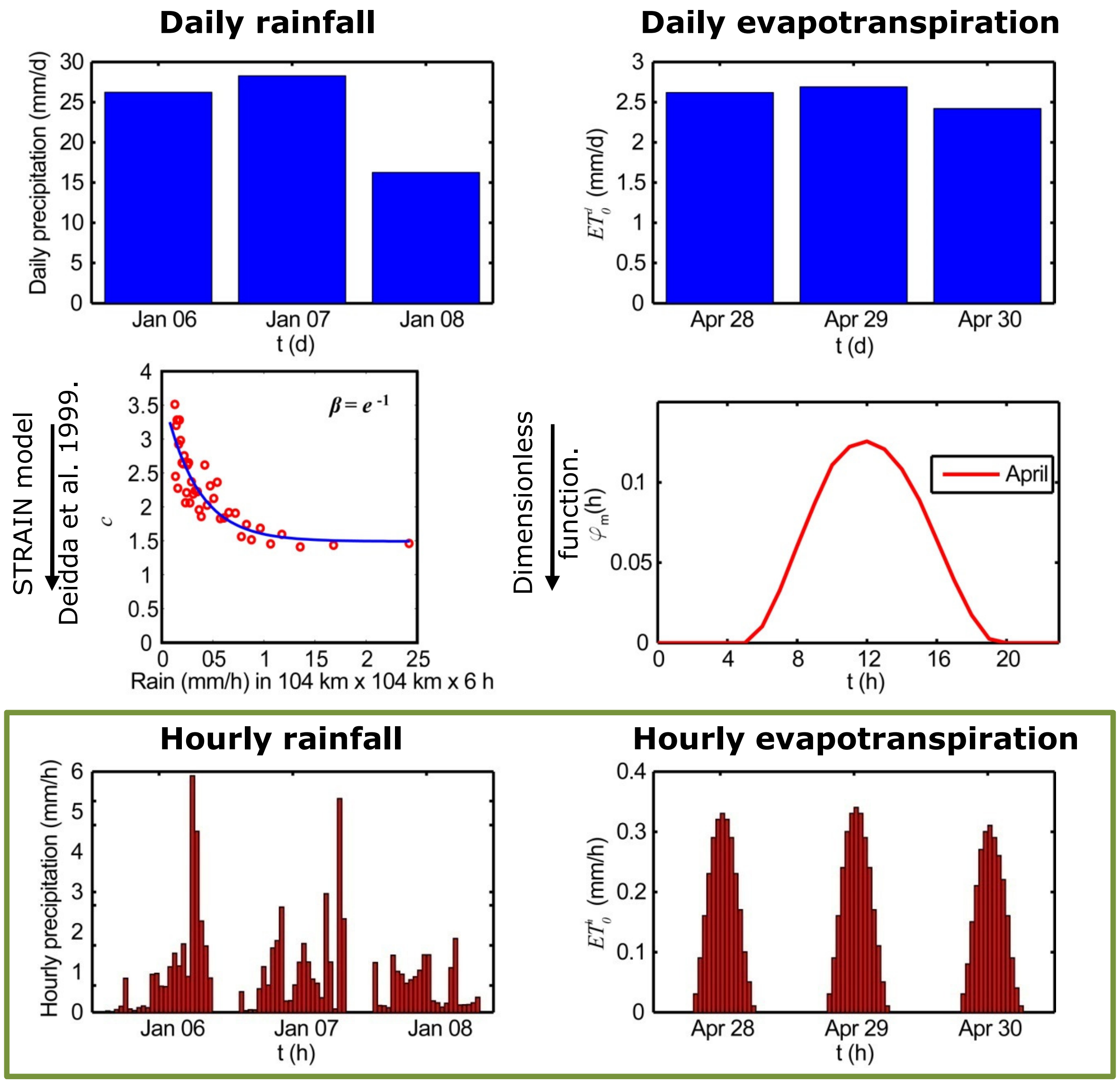


Liuzzo et al. (2010). →

Fig. 6. Exceedance curves for the climate scenarios in: (a) Group A; (b) Group B for the same initial groundwater table positions

Downscaling strategies

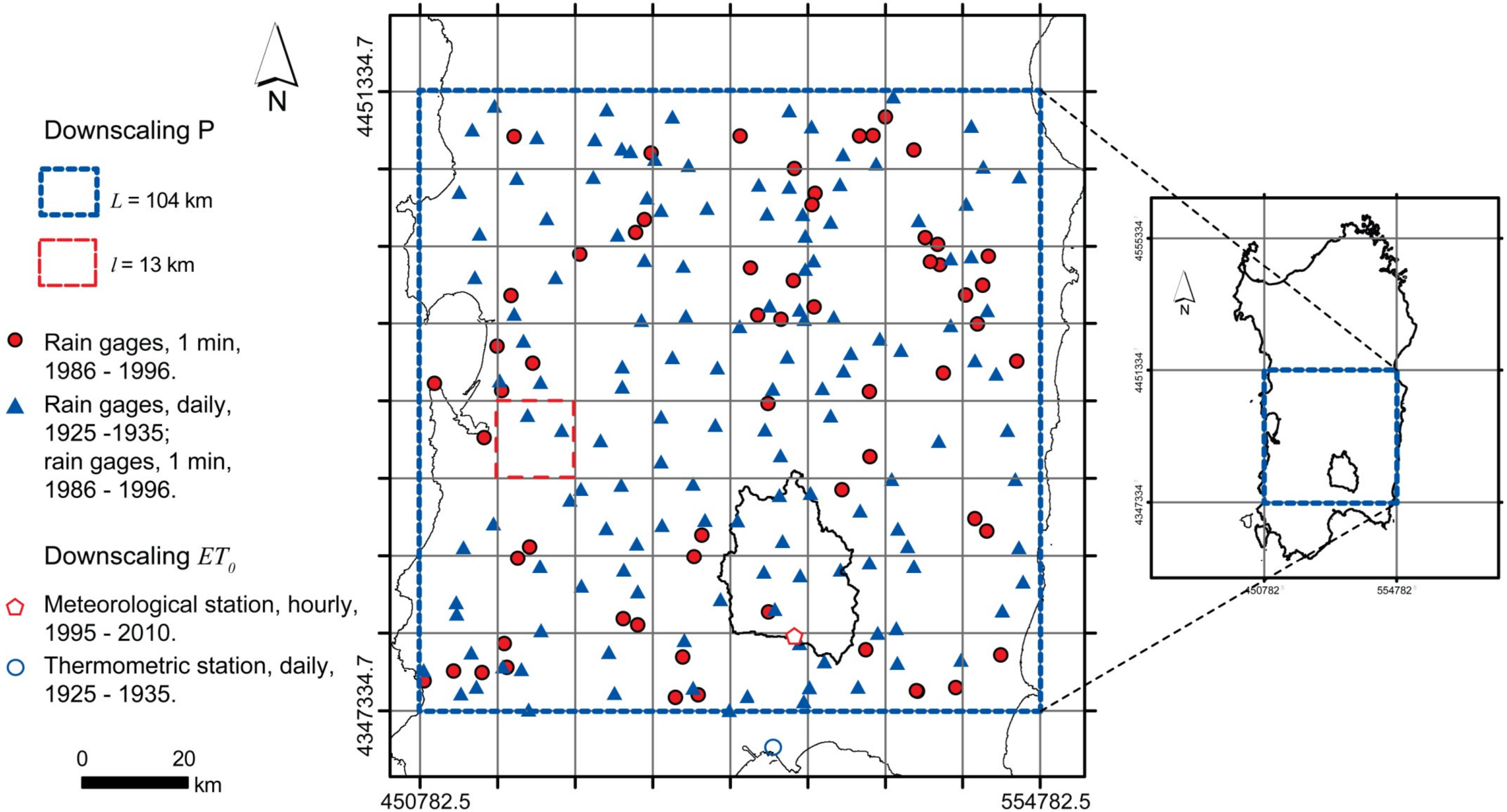
Downscaling of daily hydrometeorological data (*Mascaro et al., 2013*).



- tRIBS requires hourly hydrometeorological variables as inputs.
- Observed hydrometeorological data in the calibration period have daily resolution.
- Two downscaling strategies have been implemented to disaggregated daily precipitation and potential evapotranspiration (*Mascaro et al., 2013*).

Downscaling strategies

Database used to calibrate the downscaling tools

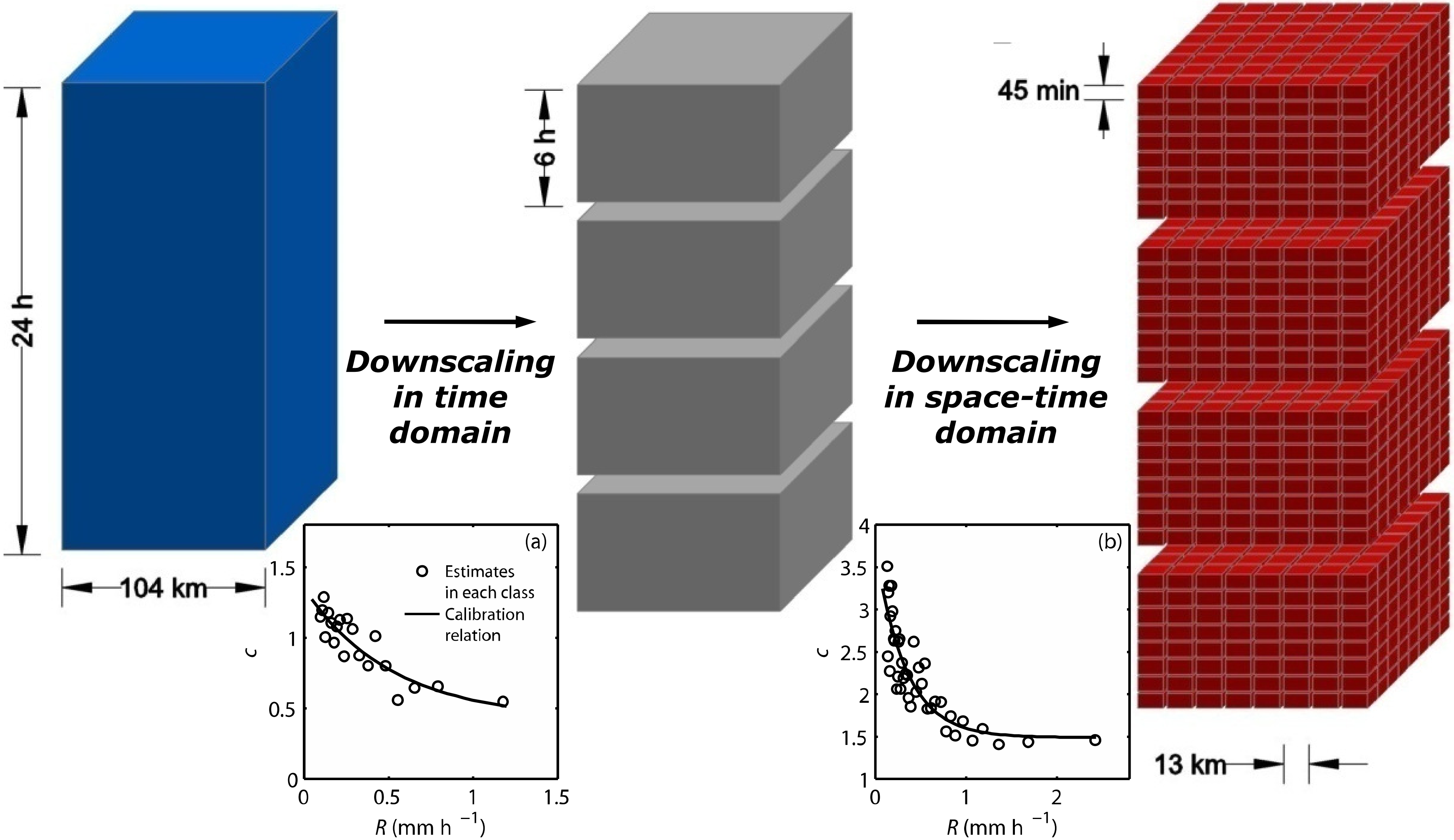


Mascaro et al. (2013).

Downscaling strategies

Downscaling strategy for precipitation

A spatio-temporal precipitation downscaling algorithm (*Deidda, 1999, 2000*) has been calibrated in the period 1986–1996 and applied in the period 1925-1935.



Downscaling strategies

Downscaling strategy for ET_0

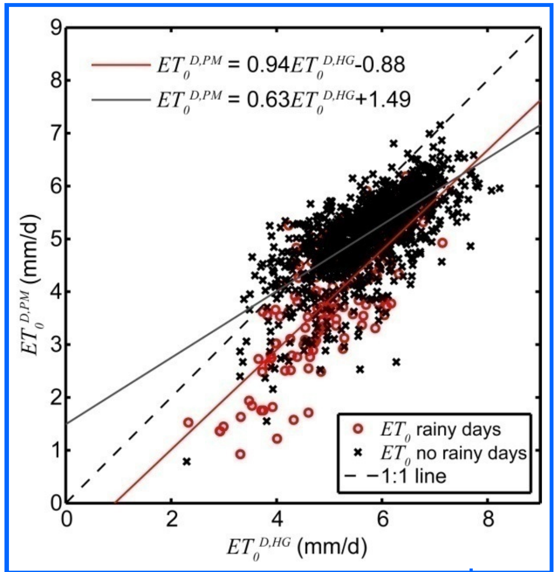
Calibration

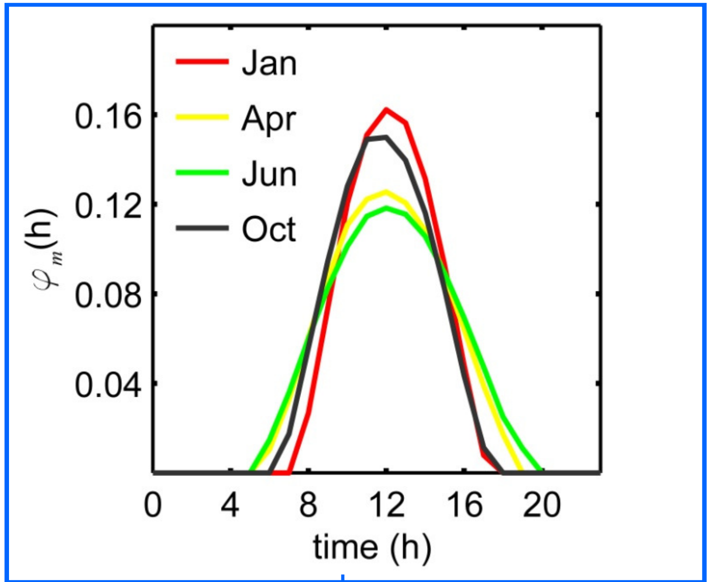
Hourly meteorological variables 1995-2010 → Penman-Monteith → $ET_0^{H,PM}$ → **Dimensionless function** $\varphi_m(h) = \frac{\langle ET_0^H(h,m)\rangle}{\langle ET_0^D(m)\rangle}$

Hargreaves → $ET_0^{D,HG}$

$ET_0^{D,PM}$

Scatterplot between $ET_0^{D,PM}$ and $ET_0^{D,H}$





Application

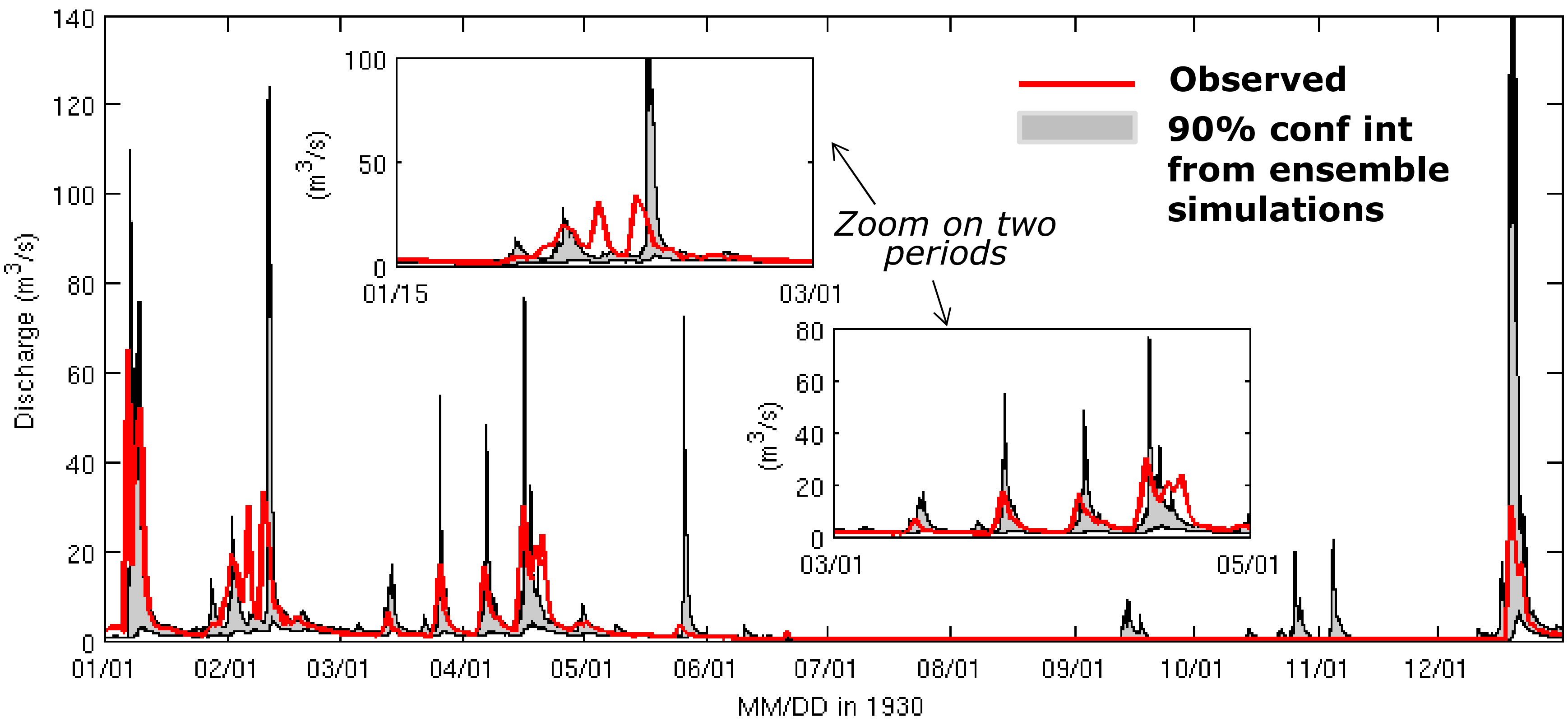
Mascaro et al. (2013).

1925 -1935 T_{max} and T_{min} **(daily)** → $ET_0^{D,HG}$ → Regression line / Rainy and no rainy days → $\hat{ET}_0^{D,PM}$ → $\varphi_m(h)$ → $ET_0^{H,PM}$

tRIBS calibration

- We selected the **year 1930** as calibration period due to higher streamflow variability and higher confidence in published discharge data (*Mascaro et al., 2013*).
- We created an **ensemble of 50 disaggregated rainfall fields** and run the tRIBS model.

Time scale	Calibration NSC Min, Mean, Max
Daily	-3.53, 0.07, 0.61
Weekly	-5.50, 0.46, 0.83
Monthly	-0.06, 0.55, 0.89



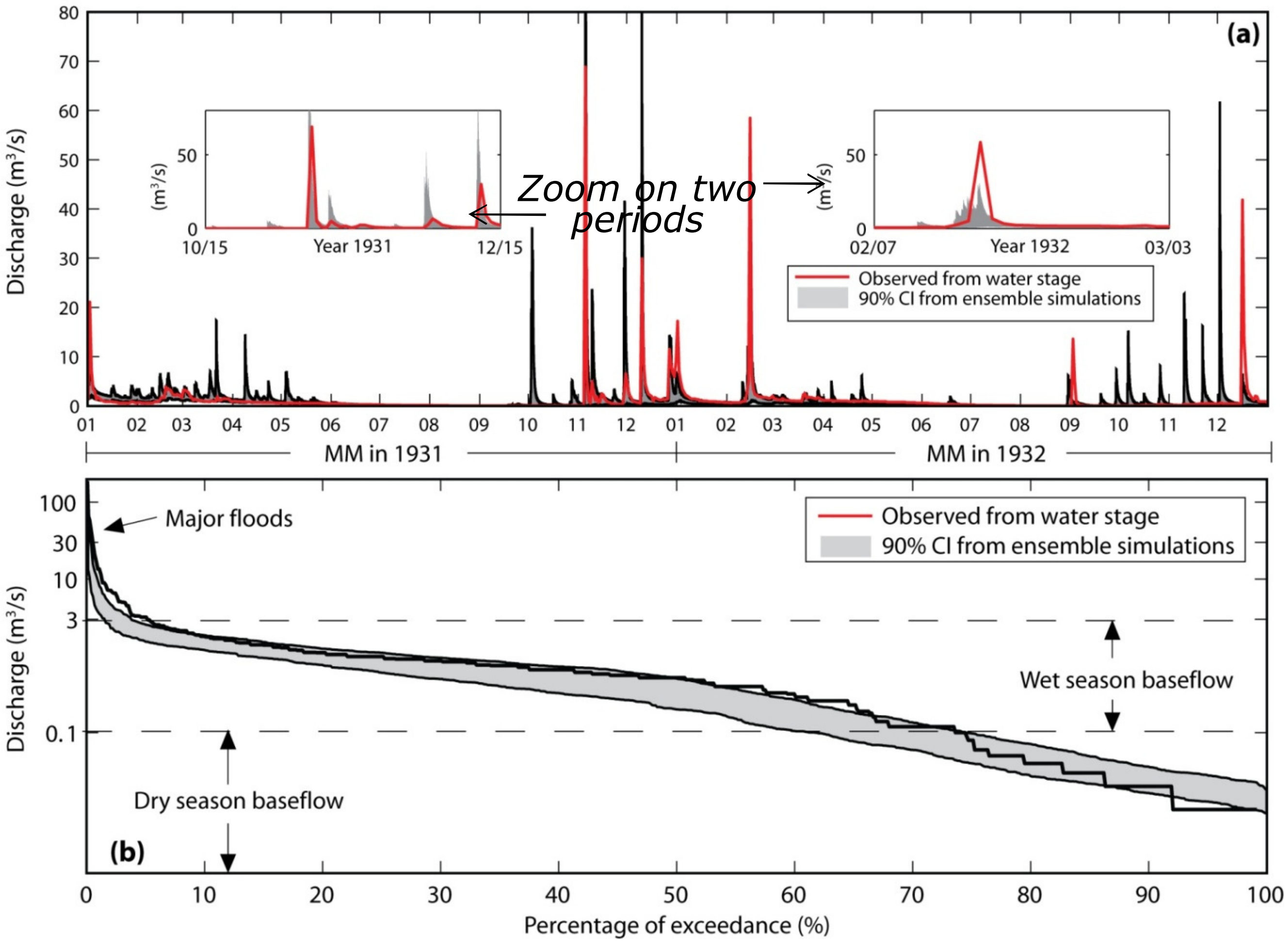
tRIBS validation

- **Years 1931-1932** were used as validation period (*Mascaro et al., 2013*).

Good performances in reproducing the discharge time series over year 1931 and most of 1932.

Excellent agreement between the shapes of observed and simulated FDCs, even in the range of the dry season base flow.

Time scale	Validation NSC Min, Mean, Max
Daily	-0.99, 0.02, 0.42
Weekly	-0.72, 0.13, 0.47
Monthly	0.30, 0.25, 0.74



Outline

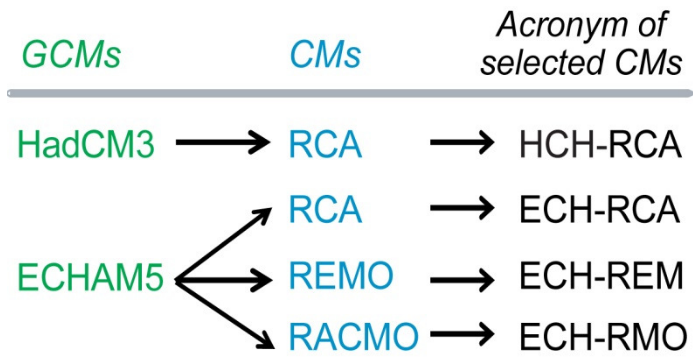
- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

Climate models outputs

Selection and validation of climate models

- Climate models of the ENSEMBLES project have been analysed and validated by comparison with CRU E-OBS data (*Deidda et al., 2013*).
- Future previsions are based on the emission scenario A1B (*Nakićeović et al., 2000*).
- Selection of 4 models: best combination of 2 GCMs and 3 RCMs.

	Climatological center and model	Acronym	
GCMs	Hadley Centre for Climate Prediction, Met Office, UK HadCM3 Model (high sensitivity)	HadCM3	H
	Max Planck Institute for Meteorology, Germany ECHAM5 / MPI OM	ECHAM5	E
RCMs	Swedish Meteorological and Hydrological Institute (SMHI), Sweden RCA Model	RCA	RC
	Max Planck Institute for Meteorology, Hamburg, Germany REMO Model	REM	RE
	Koninklijk Nederlands Meteorologisch Instituut (KNMI), Netherlands RACMO2 Model	RMO	RM

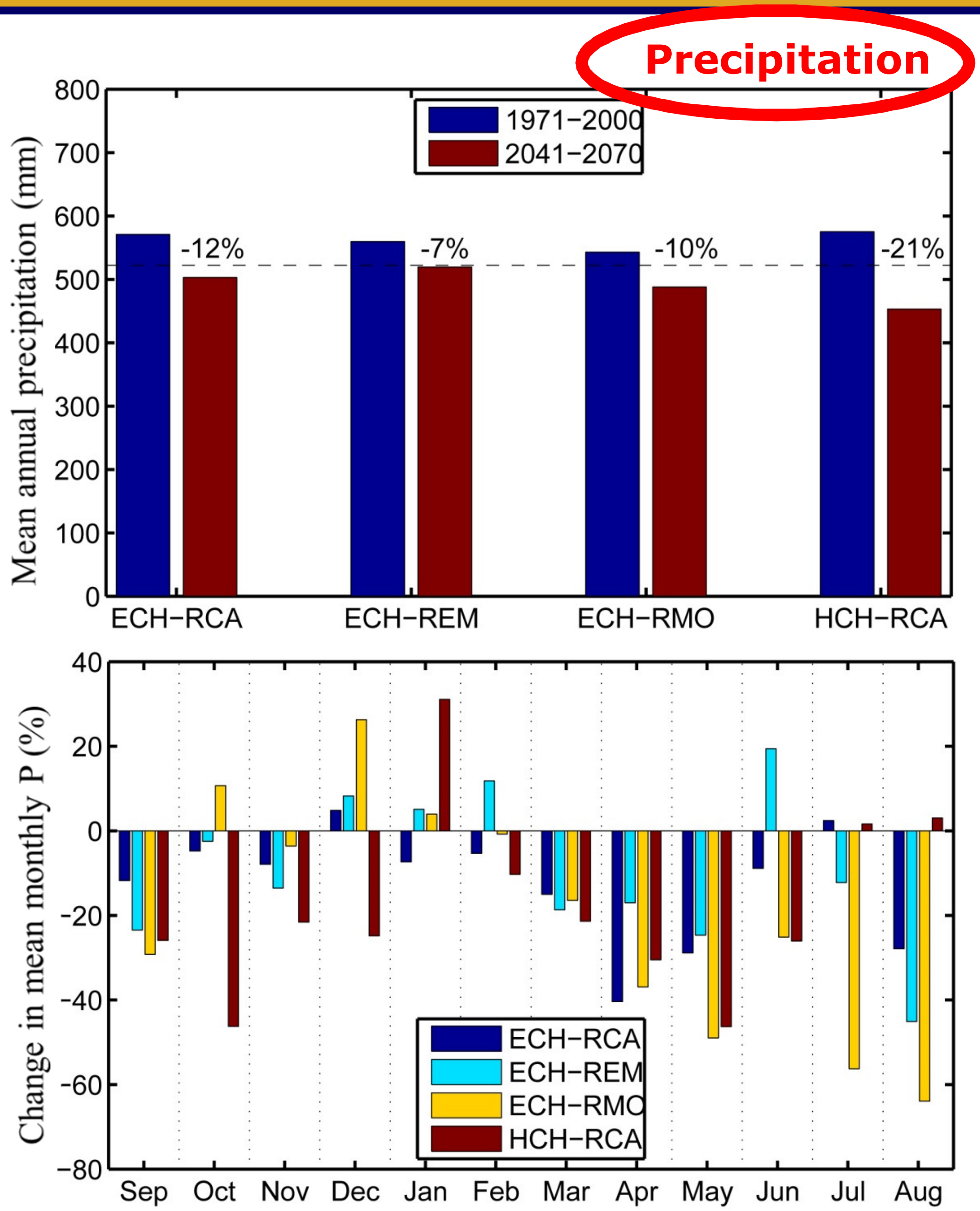


- Outputs of the 4 climate models have been downscaled and bias corrected to be used as input for hydrologic models.

Climate models outputs

Analyses of RCMs outputs

- Comparison between **reference (1971-2000)** and **future (2041-2070)** periods.
- All climate models predict decreasing mean annual precipitation, P (average ~12%).
- According to some CMs, precipitation could increase in winter months.
- Slight changes in seasonality of precipitations is observed.



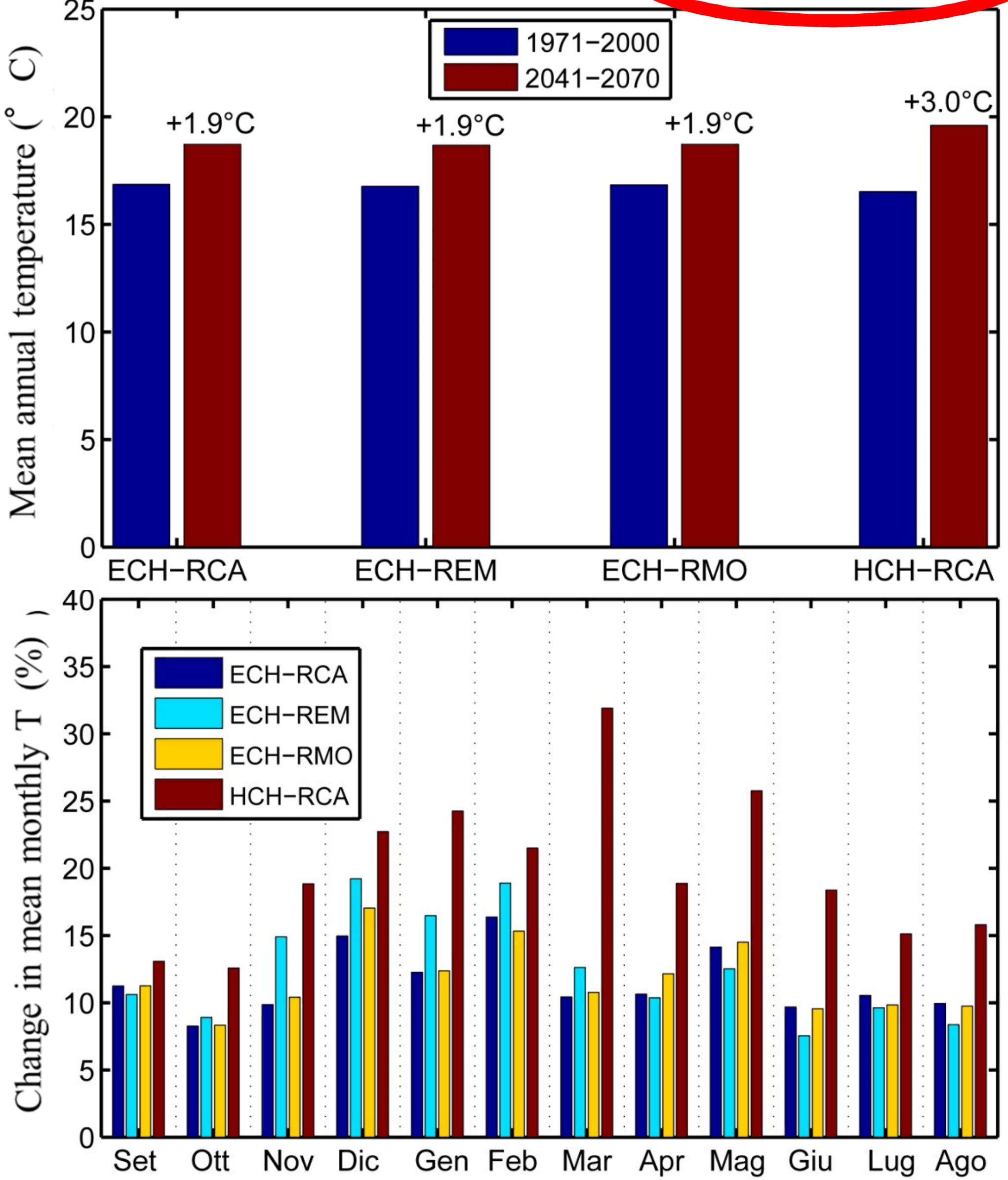
Climate models outputs

Analyses of RCMs outputs

- All climate models predict increasing annual temperatures (average of ~2.2° C). The HCH-RCA model predicts the most increasing temperate (3.0° C).

- Temperatures raise in FUT is confirmed by monthly mean values where again the HCH-RCA model gives the highest increases.

Temperatures



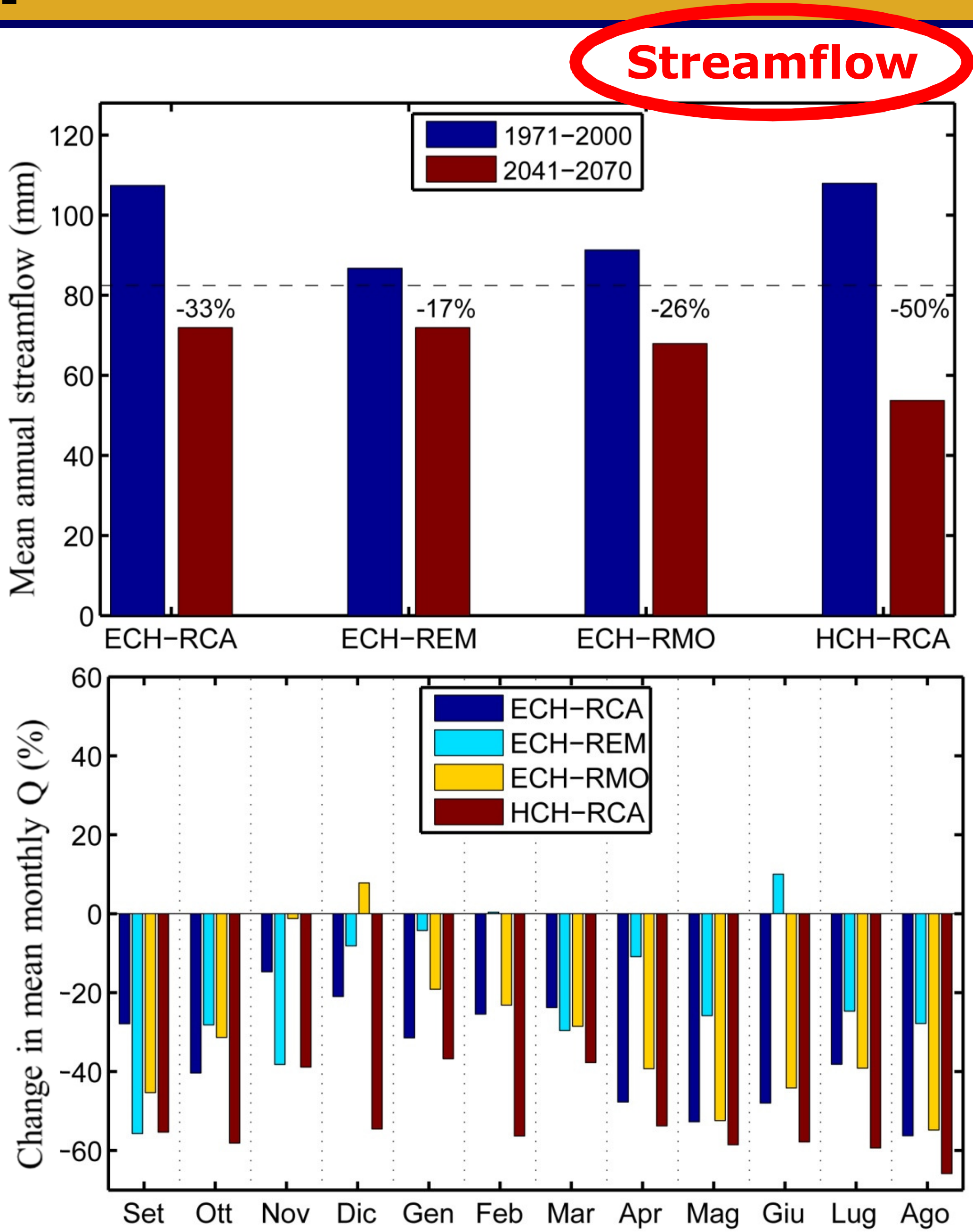
Outline

- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

Hydrologic impact of CC

Simulations results:

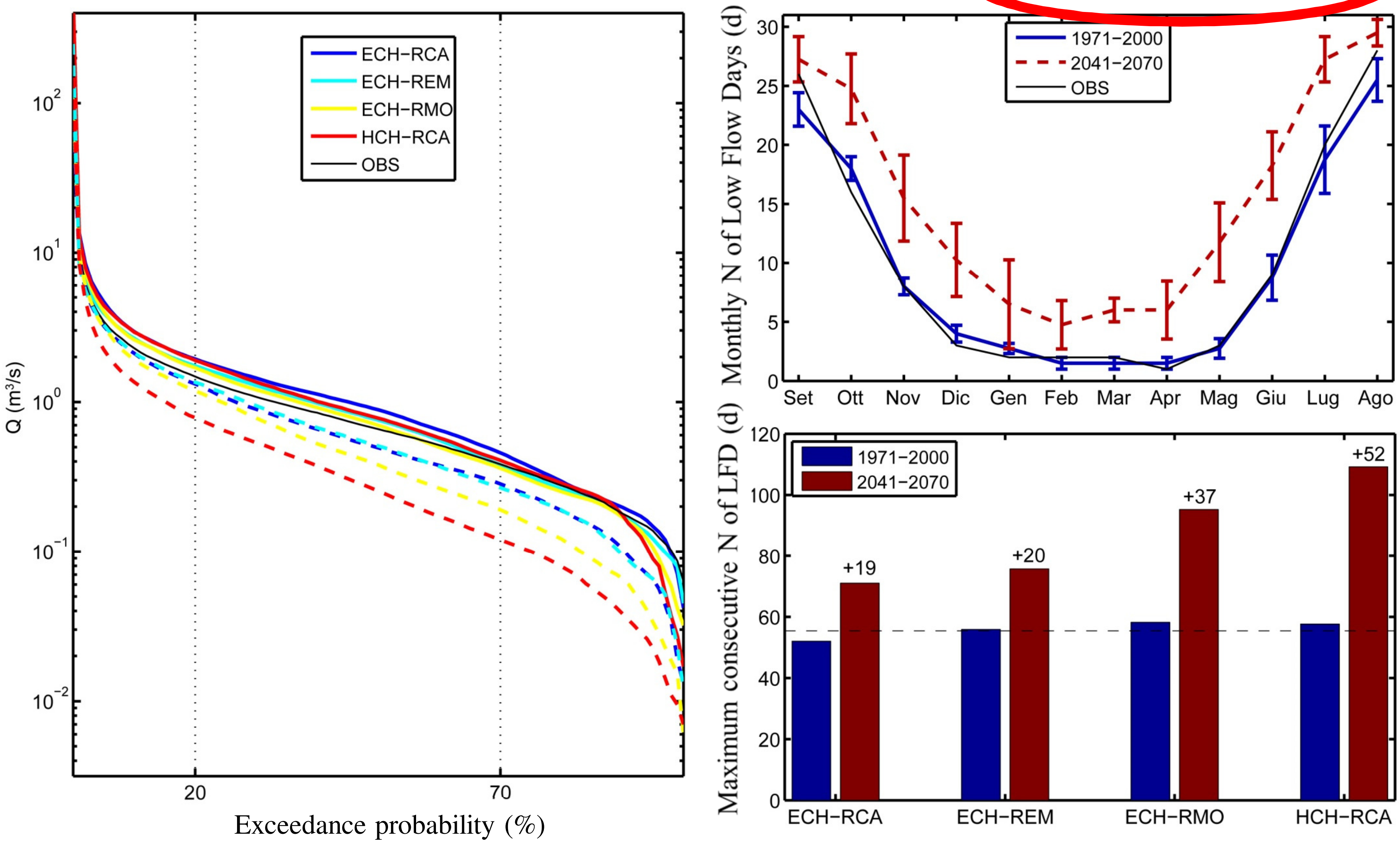
- **Outputs** of the 4 **CMs** have been **downscaled** at hourly resolution, applying the same downscaling strategies used in the calibration period.
- The calibrated tRIBS model has been forced with hourly disaggregated data using a super computer of ASU.
- **Outputs** of **tRIBS** are post-processed to evaluate the possible change in the **hydrological response** of the Rio Mannu (*Piras et al., 2014*).
- All simulations predict a **reduction** of the mean annual **streamflow Q**.
  Monthly streamflow will decrease throughout the year.



Hydrologic impact of CC

Simulations results:

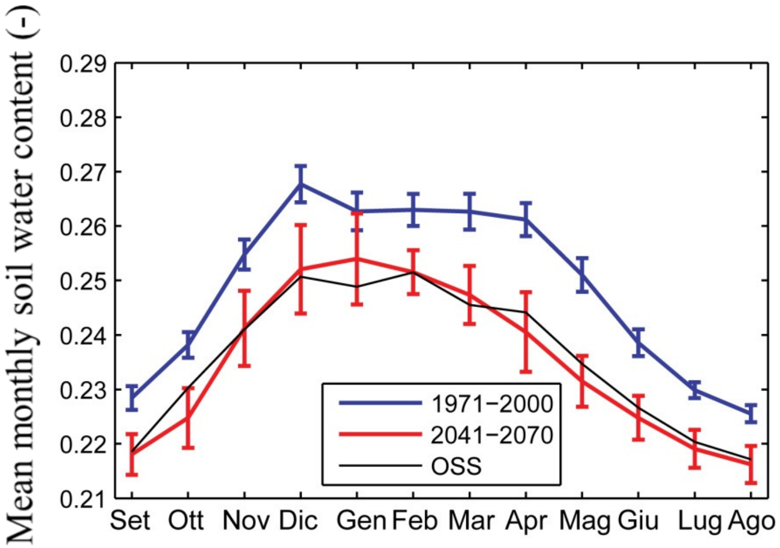
Flow Duration Curves



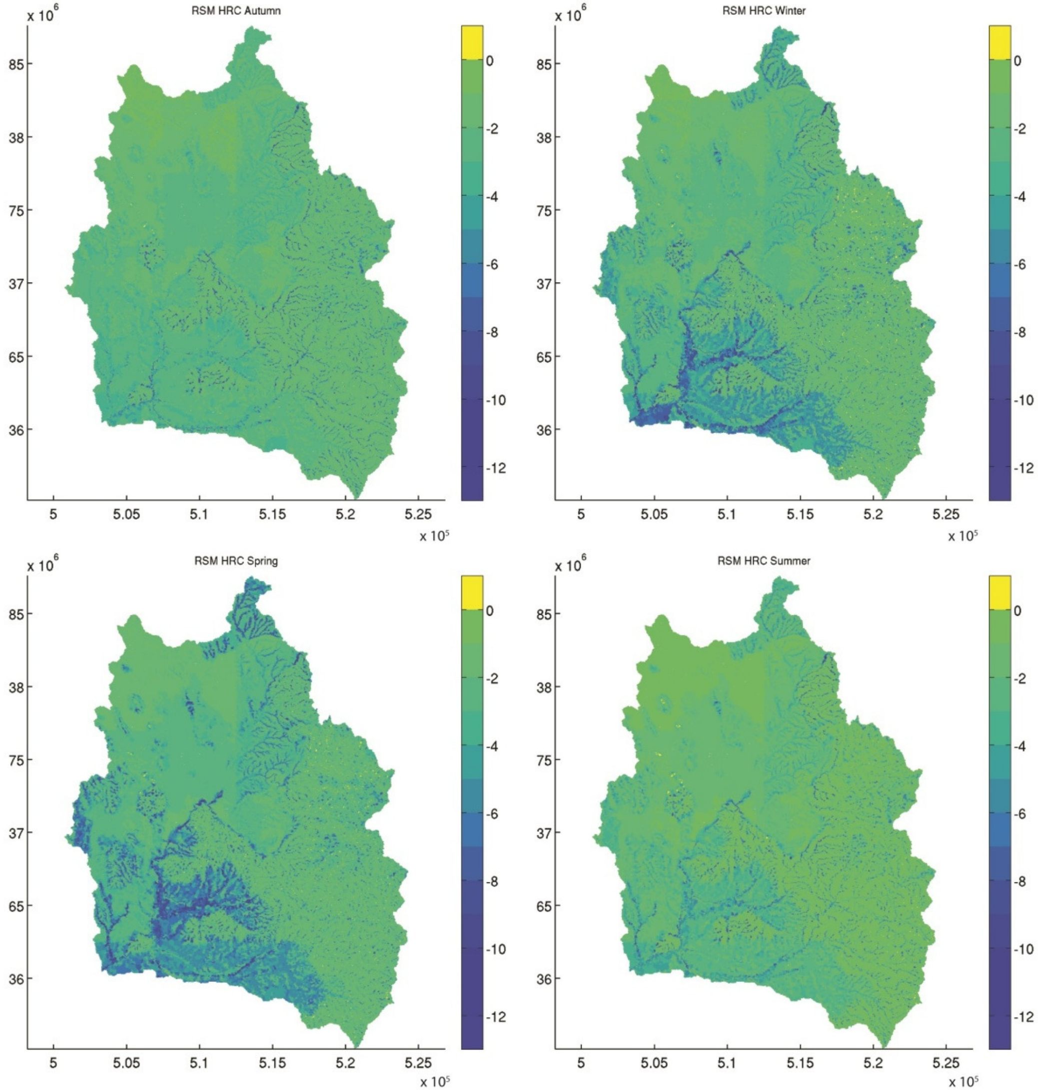
Hydrologic impact of CC

Simulations results: soil water content

- All configurations predict a reduction of soil water content at the different depths (10 cm, 1 m) in future period.
- Variations in soil humidity are affected by terrain, with higher decreases in areas of saturation close to the drainage network.



Variation of soil humidity predicted by HCH-RCA configuration

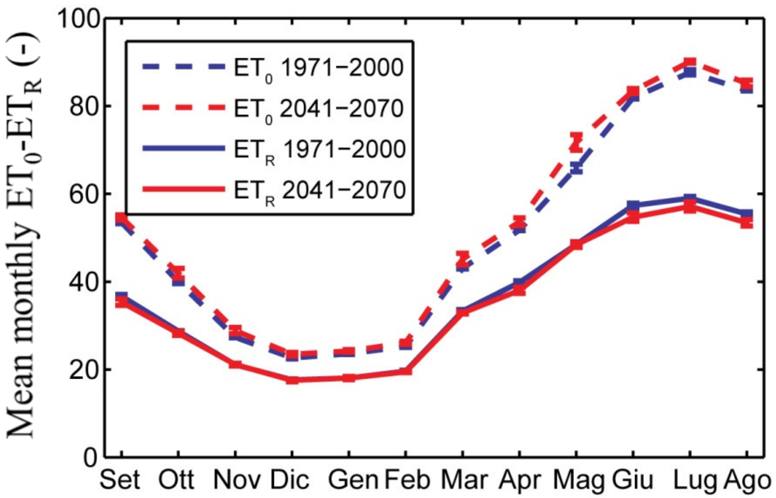


Hydrologic impact of CC

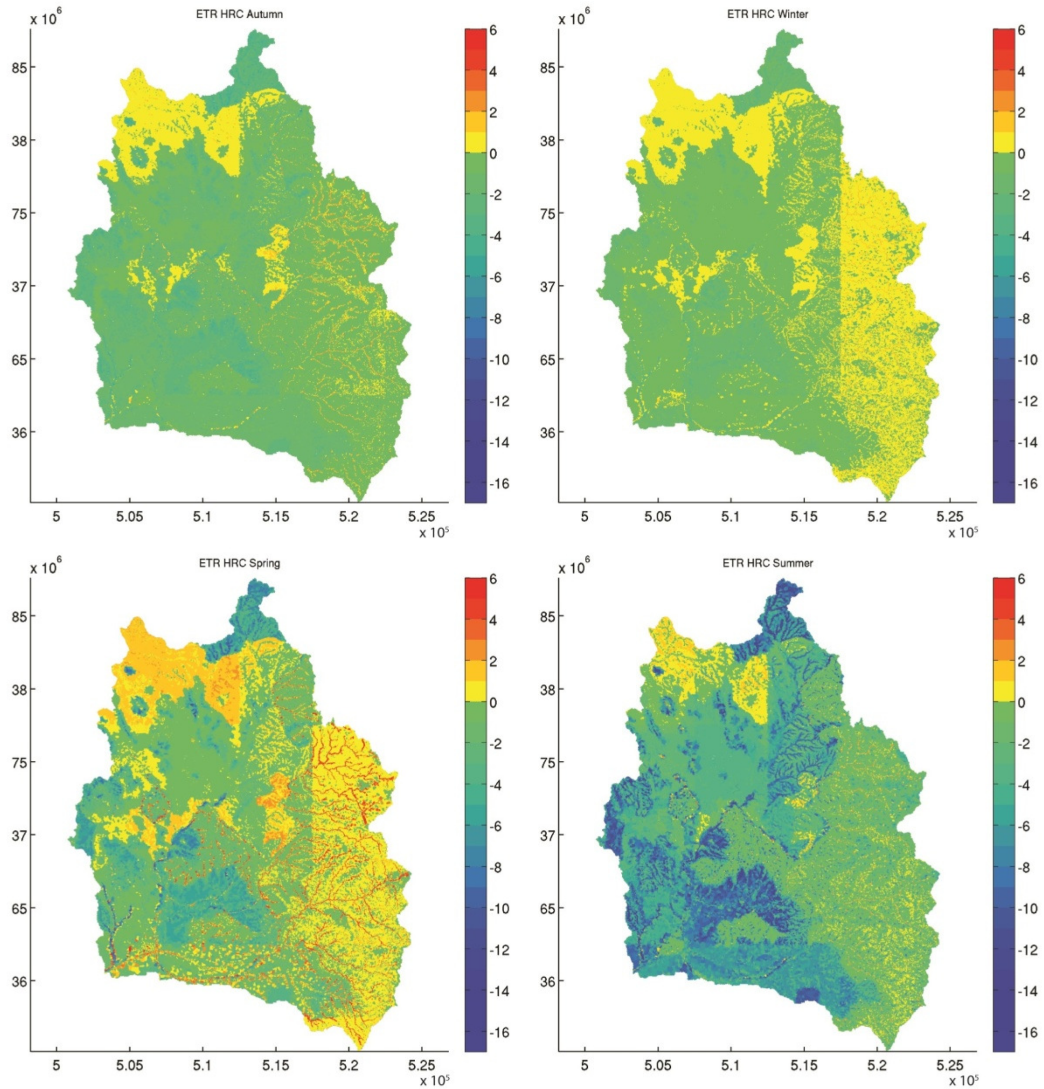
Simulations results: evapotranspiration

- Hydrologic simulations predict a decrease in actual evapotranspiration (ET_a) despite a slight increase in ET_0 due to drier soils.

- Variation in ET_a are influenced by terrain attributes, soil texture and patterns of gridded inputs.



Variation of actual evapotranspiration predicted by HCH-RCA configuration

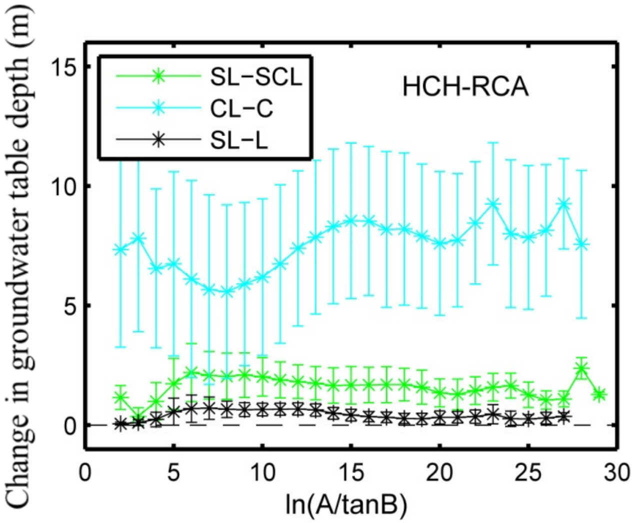


Hydrologic impact of CC

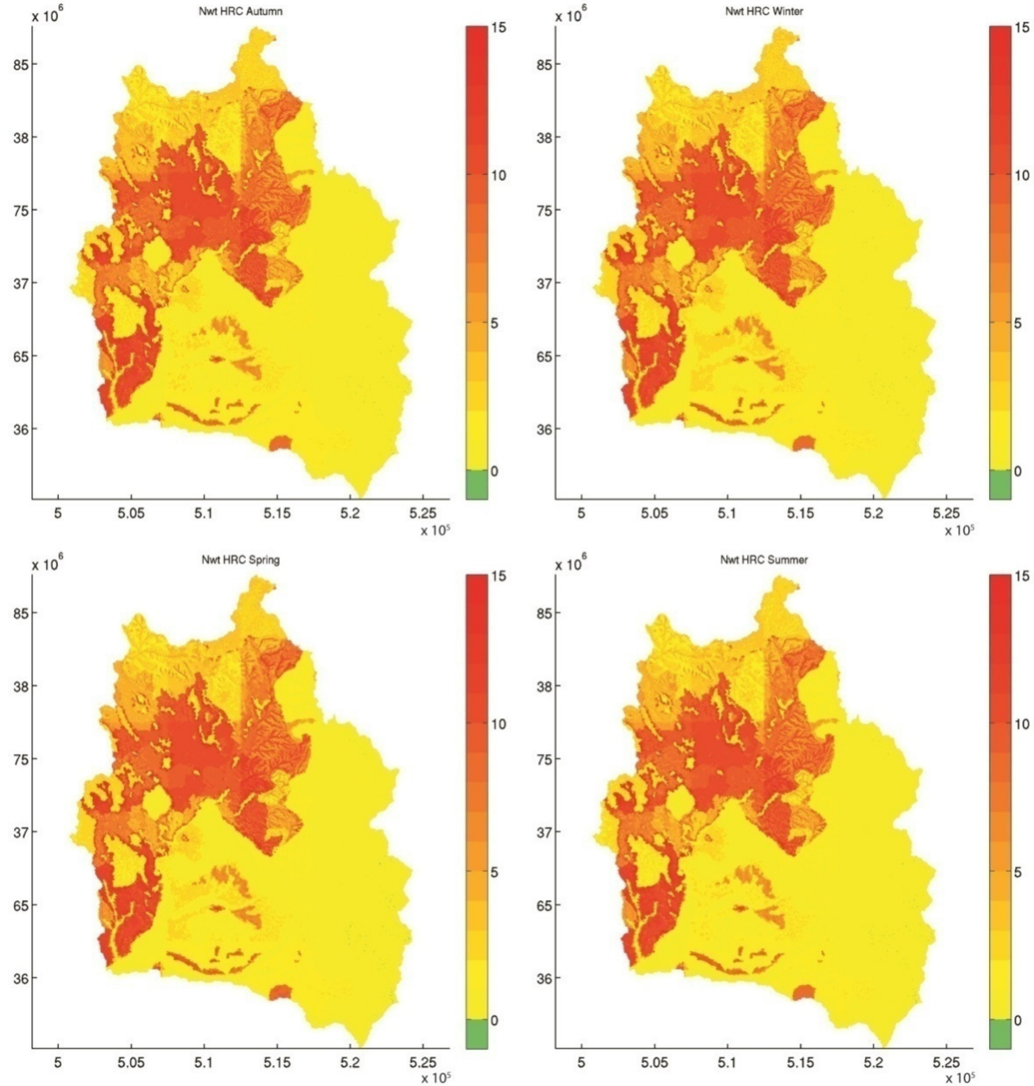
Simulations results: groundwater

- All simulations predict a drop in the water table depth, meaning a reduction in groundwater resource.

- Variations in water table depth are related to soil texture, with higher drops of the water table in clay soils.



Change in groundwater table depth predicted by HCH-RCA configuration



Outline

- Case study and data collection
- Hydrologic model tRIBS:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

Analyses of P and Q extremes

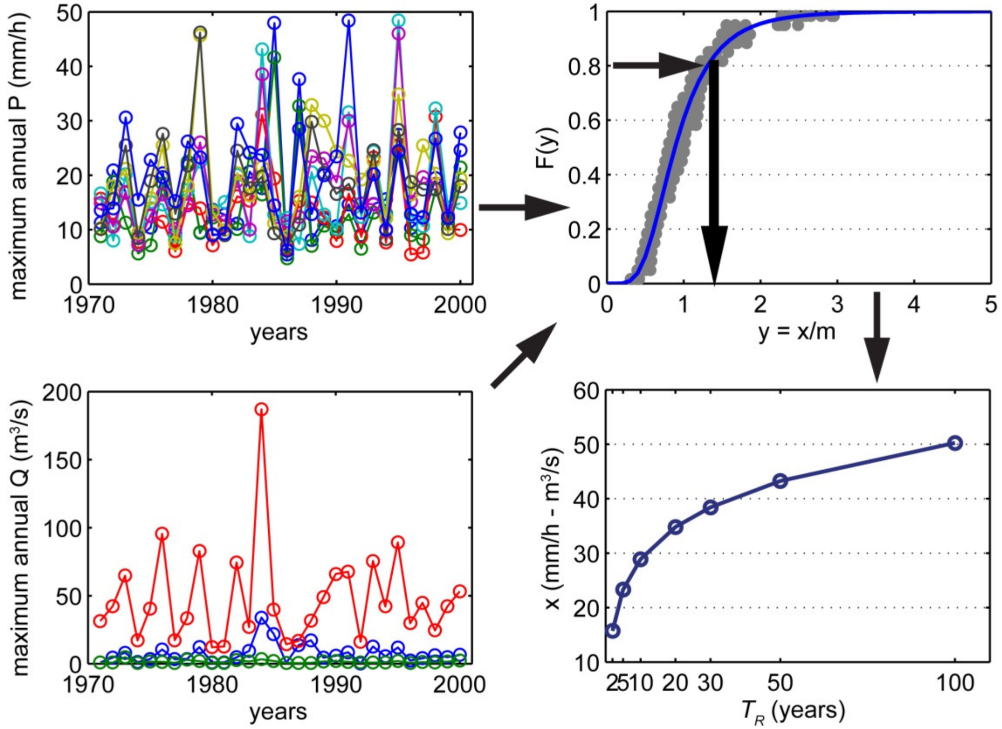
Analyses of extreme events with GEV distribution

- Representation of the statistical distribution of annual maximum P and annual maximum peak Q with the Generalized Extreme Value (GEV) distribution.
- Assumption of homogeneous regions with identical frequency distributions at the sites and a multiplicative factor varying from site to site:

$$x(F) = m \cdot y(F)$$

m = index-precipitation or index-flood,
y(F) = dimensionless function (regional growth curve).

- Assumption of a single homogeneous region for both P and Q, given the relatively small size of the study area.



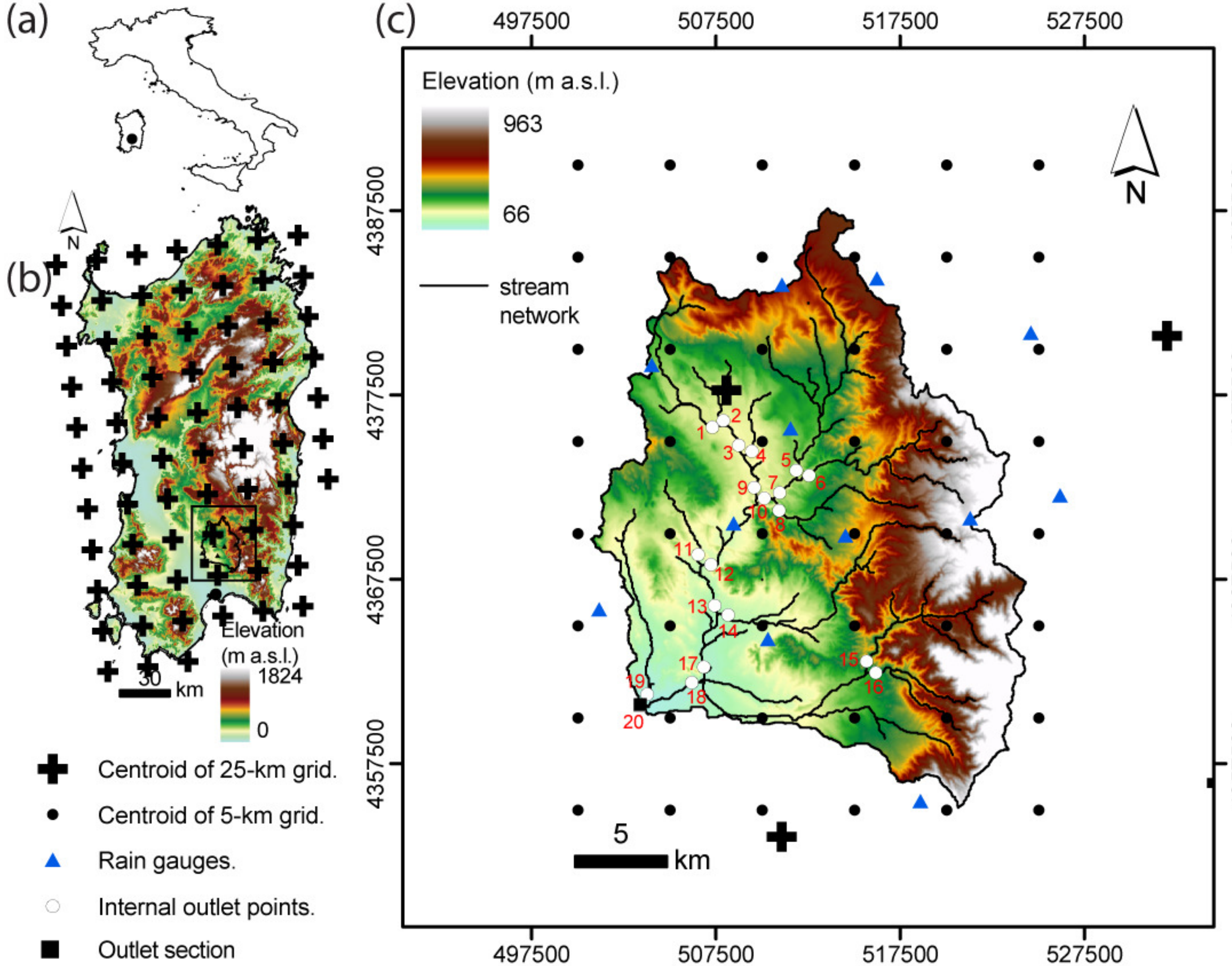
$$F(x;\mu,\sigma,k)=\begin{cases}\exp\left\{-\left[1+k\left(\dfrac{x-\mu}{\sigma}\right)\right]^{-1/k}\right\} & k\neq 0\\ \exp\left\{-\exp\left[-\left(\dfrac{x-\mu}{\sigma}\right)\right]\right\} & k=0\end{cases}$$

$\sigma > 0$ = scale parameter
μ $(-\infty,+\infty)$ = location parameter
k $(-\infty,+\infty)$ = shape parameter
$k = 0$ Type I Gumbel distribution
$k > 0$ Type II Fréchet distribution
$k < 0$ Type III Weibull distribution

Analyses of P and Q extremes

Analyses of extreme events with GEV distribution

- For P the samples at the 48 grid points belong to the same homogeneous zone.
- For Q the series of annual maxima at the outlet and nineteen internal sections were considered to be part of a unique region.



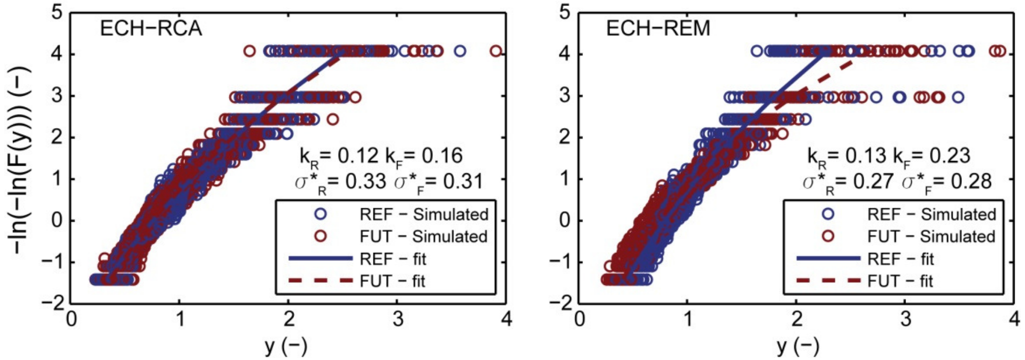
Analyses of P and Q extremes

Analyses of extreme P events with GEV distribution

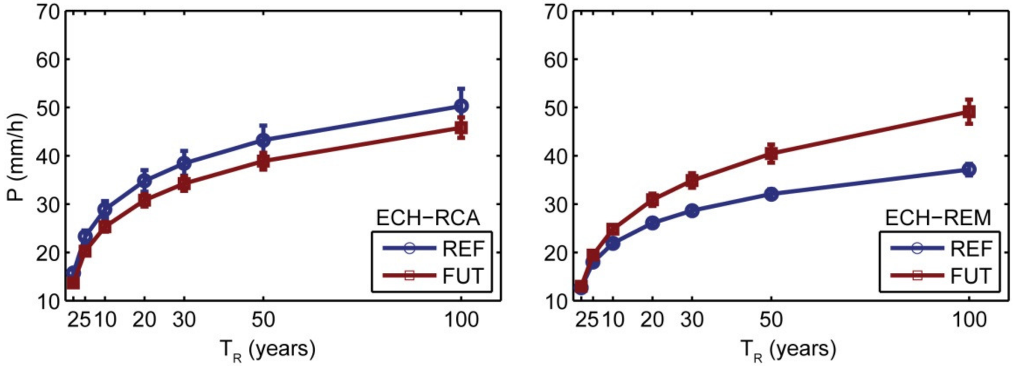
- GEV parameters differ across the 4 CMs, for daily and hourly maxima, in **REF** and **FUT** period.

	Res	k		σ*		Res	k		σ*	
ECH-RCA		0.12	0.16	0.33	0.31		0.02	0.08	0.32	0.30
ECH-REM		0.13	0.23	0.27	0.28		0.13	0.15	0.23	0.26
ECH-RMO	h	0.12	0.17	0.32	0.33	d	0.09	0.03	0.30	0.31
HCH-RCA		0.27	0.16	0.31	0.37		0.21	0.07	0.28	0.36
CV		*0.46*	*0.19*	*0.08*	*0.11*		*0.69*	*0.59*	*0.12*	*0.14*

- Maxima follow the Frèchet distribution (k > 0) with heavy right tails, hence high probability of extreme storms.



- Expected increase of max annual P for all TR for ECH-REM and ECH-RMO, the opposite is true for ECH-RCA and HCH-RCA.



Analyses of P and Q extremes

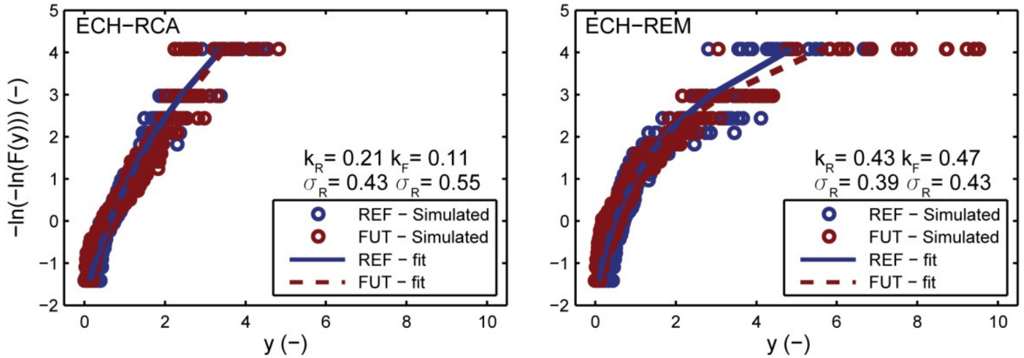
Analyses of extreme Q events with GEV distribution

- Amplification of the outcomes obtained with P: k estimates differ among configurations and in REF and FUT periods.

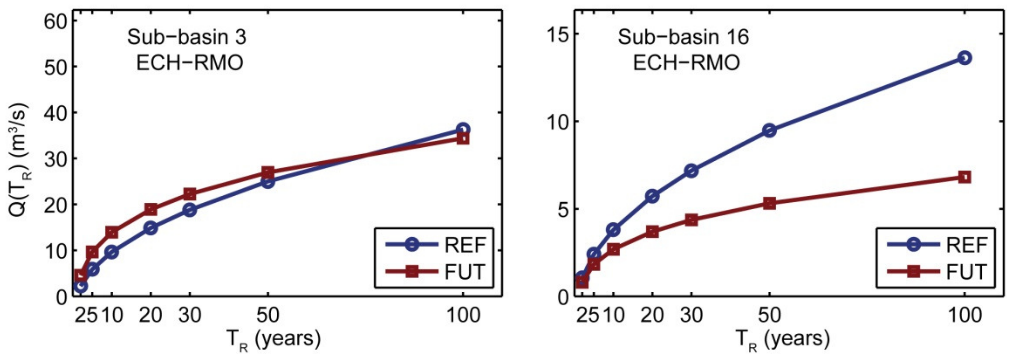
	k		σ*	
ECH-RCA	0.21	0.11	0.43	0.55
ECH-REM	0.43	0.47	0.39	0.43
ECH-RMO	0.49	0.26	0.37	0.50
HCH-RCA	0.61	0.28	0.32	0.56
Mean	*0.43*	*0.28*	*0.38*	*0.51*
CV	*0.38*	*0.52*	*0.12*	*0.12*

Sub-basin ID	A_c (km²)	Slope (%)	Main soil texture classes SL-SCL	CL-C	SL-L
3	50.17	8.96	7.44	89.02	0.00
16	23.96	34.58	5.57	0.09	94.18
20 (Outlet)	472.50	17.30	19.61	36.67	31.91

- Frèchet family (k > 0), general tendency of all simulations except ECH-REM to shift towards lower k from REF to FUT.



- The relations between T_R and the corresponding Q values from the GEV distribution reveal the dependence of Q extremes on sub-basins characteristics and CMs.



Outline

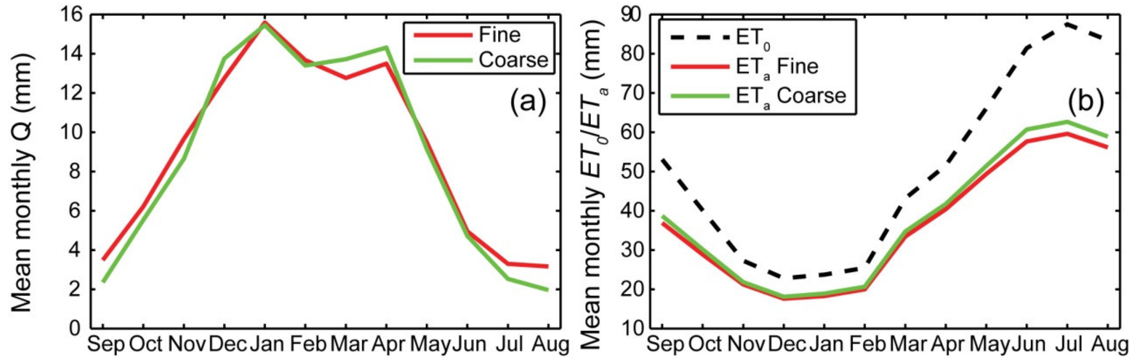
- Case study and data collection
- Hydrologic model calibration:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Analyses of precipitation and discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

Coarse and Fine simulations

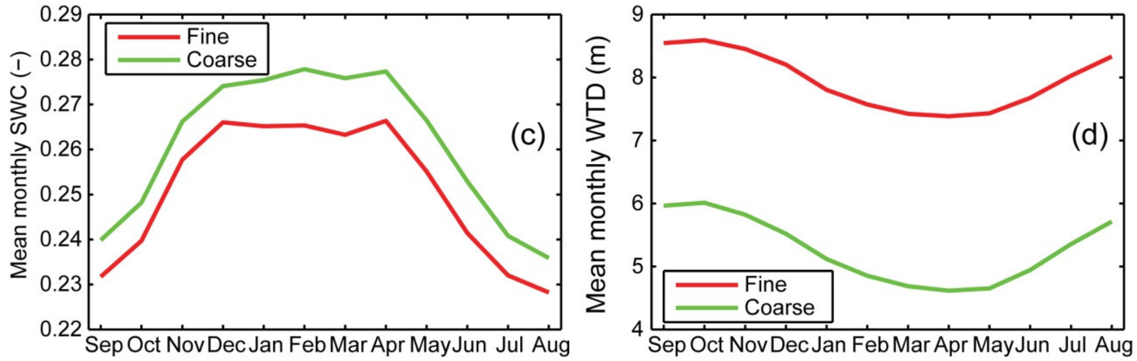
Effect of climate model resolution on hydrologic components

- Comparison of two sets of hydrologic simulations: **Fine** (fine-resolution disaggregated P forcings) and **Coarse** (P outputs at the original resolution of the ECH-RCA climate model).

- The total P is almost the same in the two cases. Hence, the mean monthly Q at the basin outlet and the ETa do not significantly change.



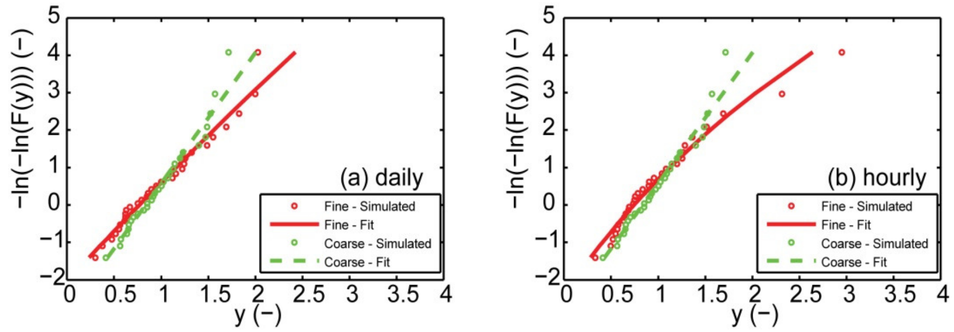
- Soil water content in the top 1 m and water table depth present instead more differences for the Fine and Coarse simulations.

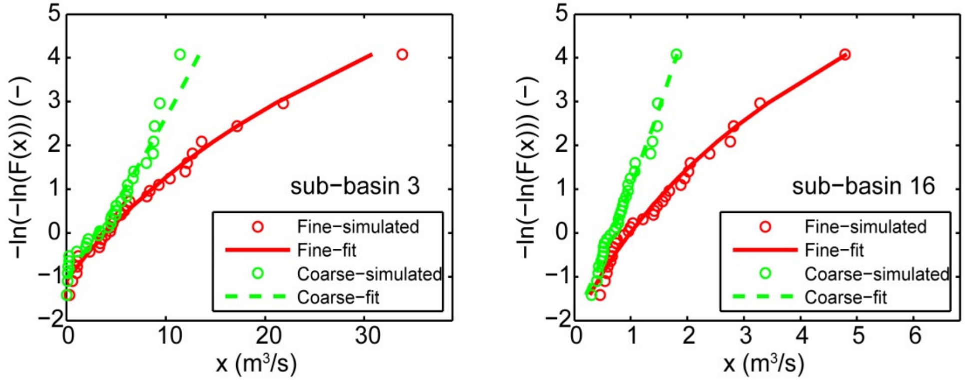


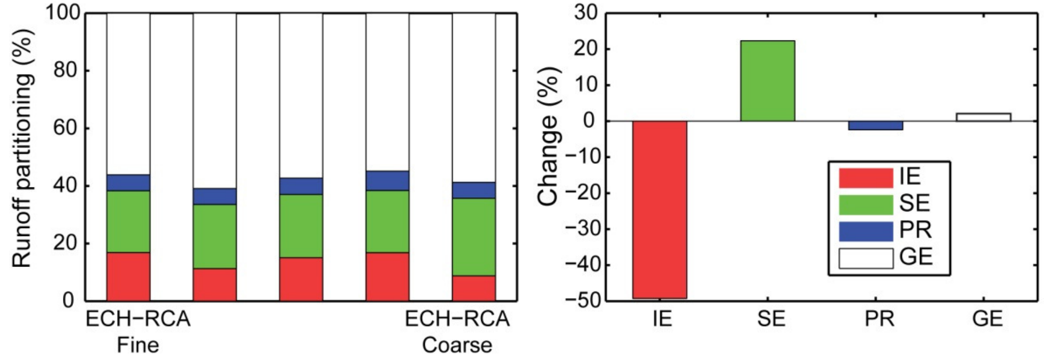
Coarse and Fine simulations

Effect of climate model resolution on extremes

- For Coarse simulation the distribution of both hourly and daily maxima result the same (k = 0.024). For Fine simulation the distribution switches to Fréchet domain (k = 0.124).
- The distribution of annual maximum Q switches from Gumbel (k ~ 0) to Fréchet (k = 0.212) when hydrologic simulations are conducted with Coarse and Fine P forcings, respectively.
- The use of coarse P forcings impacts the occurrence of the two types of surface runoff, with IE sensibly decreasing (~50%) and SE growing (~22%).







Outline

- Case study and data collection
- Hydrologic model calibration:
  - Overview of the tRIBS model
  - Description of the downscaling strategies
  - Calibration and validation in Rio Mannu basin
- Evaluation of local hydrologic impact of climate change:
  - Climate models outputs
  - Hydrologic impact of CC
  - Propagation of precipitation extremes into discharge extremes
  - Comparison of Coarse and Fine simulations
- Conclusions

Conclusions

Conclusions

- This study is part of the **EU CLIMB** project (*Ludwig et al., 2010*).
- We focused on the **Rio Mannu** basin in Sardinia, a study site with **limited data availability**.
- Using **two downscaling strategies**, we **calibrate**, with reasonable accuracy, a **distributed hydrologic model, tRIBS** (*Mascaro et al., 2013*).
- We applied the downscaling strategies to disaggregate outputs of 4 selected CMs in the **reference (1971-2000)** and **future (2041-2070)** periods.
- The impact of future climate change on **the hydrologic response** of the Rio Mannu basin was quantified by combining the process-based distributed hydrologic model with outputs of the four CMs (*Piras et al., 2014*).
- All CMs predict **lower mean annual precipitation and higher mean temperatures** in the future period.
- The **hydrologic simulations** under future climate forcing **indicate a decrease in mean annual runoff,** in **mean real evapotranspiration,** likely due to **drier soil moisture conditions,** and in mean level of the **groundwater table.**

Conclusions

Conclusions

- The future changes in the mean values of the hydrologic variables are influenced by the spatial patterns of **topography** and **soil texture**.
- Our results predict that in the future the Rio Mannu basin will be affected by **decreasing water resources conditions** with possible effects on agriculture activities and on the water demand for different sectors.
- There is **high uncertainty** in the **statistical analyses of P and Q extremes**, which both show a tendency towards the Fréchet distribution, significant variations of the shape parameter. Parameters estimated for Q have larger variability.
- The comparison of **coarse** and **fine simulations** highlights the **benefit of applying downscaling algorithms** to climate model outputs better capturing the small-scale variability of precipitation.
- All phases of this study are affected by **uncertainties and limitations**, hence the **results** should be considered as **possible scenarios** obtained with the best information currently available.

Thank you!

References

Beven, K.: On subsurface stormflow: an analysis of response times, Hydrol. Sci. J., 505-521, 1982.

Beven, K.: Infiltration into a class of vertically non-uniform soils, Hydrol. Sci. J., 425-434, 1984.

Beven, K.: Runoff generation in semi-arid areas, in: Dryland Rivers, Bull LJ, Kirkby MJ (eds), J. Wiley & Sons, pp. 57–105, 2002.

Cabral, M. C., Garrote, L., Bras, R. L. & Entekhabi, D.: A kinematic model of infiltration and runoff generation in layered and sloped soils, Adv. Water Resour. 311-324, 1992.

Childs, E. C. and Bybordi, M.: The vertical movement of water in stratified porous material. 1. Infiltration, Water Resour. Res., 5. 446-459, 1969.

Deardorff, J. W.: Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation, J. Geophys. Res., 120, 1132-1139, 1978.

Deidda, R.: Multifractal analysis and simulation of rainfall fields in space, Phys. Chem. Earth, 24(1–2), 73–78, 1999.

Deidda, R.: Rainfall downscaling in a space-time multifractal framework, Water Resour. Res., 36(7), 1779–1784, 2000.

Deidda, R., Marroccu, M., Caroletti, G., Pusceddu, G., Langousis, A., Lucarini, V., Puliga, M., and Speranza, A.: Climate model validation and selection for hydrological applications in representative Mediterranean catchments, Hydrol. Earth Syst. Sci., 17, 5041-5059, doi:10.5194/hess-17-2013, 2013.

Forman, B.A., Vivoni, E.R., and Margulis, S.A.: Evaluation of Ensemble-based Distributed Hydrologic Model Response with Disagregated Precipitation Products, Water Resour. Res., 44: W12410, doi:10.1029/2008WR006983, 2008.

Garrote, L. and Bras, R. L.: A distributed model for real time flood forecasting using digital elevation models, J. Hydrol., 167, 279-306, 1995.

Hu, Z. and Islam, S.: Prediction of ground surface temperature and soil moisture content by the force-restore method, Water Resour. Res., 31, 2531-2539, 1995.

References

Ivanov, V. Y., Vivoni, E. R., Bras, R. L., and Entekhabi, D.: Catchment hydrologic response with a fully-distributed triangulated irregular network model, Water Resour. Res., 40(11), 1–23, doi:10.1029/2004WR003218, 2004a.

Ivanov, V. Y., Vivoni, E. R., Bras, R. L. & Entekhabi. D.: Preserving high-resolution surface and rainfall data in operational-scale basin hydrology: a fully distributed physically-based approach, J. Hydrol., 80-111. 2004b.

Lin, J. D.: On the force-restore method for prediction of ground surface temperature, J. Geophys. Res., 85, 3251-3254, 1980.

Liuzzo, L., Noto, L. V., Vivoni, E. R., and La Loggia, G.: Basin-scale water resources assessment in Oklahoma under synthetic climate change scenarios using a fully distributed hydrological model, J. Hydrol. Eng., 15(2), 107–122, doi:10.1061/ASCEHE.1943-5584.0000166, 2010.

Ludwig, R., et al.: Climate-induced changes on the hydrology of Mediterranean basins - A research concept to reduce uncertainty and quantify risk, Fresen. Environ. Bull., 19 (10 A), 2379–2384, 2010.

Mascaro, G., Vivoni, E. R., and Deidda, R.: Implications of ensemble quantitative precipitation forecast errors on distributed streamflow forecasting, J. Hydrometeorol., 11(1), 69–86, doi:10.1175/2009JHM1144.1, 2010.

Mascaro, G., Piras, M., Deidda, R., and Vivoni, E. R.: Distributed hydrologic modeling of a sparsely monitored basin in Sardinia, Hydrol. Earth Syst. Sci., 17, 4143–4158, doi:10.5194/hess-17-4143-2013, 2013.

Morel-Seytoux, H.J., and J. Khanji, Derivation of an equation of infiltration, Water Resour. Res., 10(4), 795-800, 1974.

Neuman, S.P., Wetting front pressure head in the infiltration model of Green and Ampt, Water Resour. Res., 12(3), 564-565, 1976.

Nakićeović, N., Alcamo, J., Davis, G., de Vries, H. J. M., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., La Rovere, E. L., Michaelis, L., Mori, S., Morita, T., Papper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N., and Dadi, Z.: Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge; 559, 2000.

Noto, L. V., Ivanov, V. Y., Bras, R. L., and Vivoni, E. R.: Effects of initialization on response of a fully-distributed hydrologic model, J. Hydrol., 352(1-2), 107–125, doi:10.1016/j.jhydrol.2007.12.031, 2008.

References

Piras, M., Mascaro, G., Deidda R., Vivoni, E. R.: Quantification of hydrologic impacts of climate change in a Mediterranean basin in Sardinia, Italy, through high-resolution simulations, Hydrol. Earth Syst. Sci., 18, 5201–5217, doi:10.5194/hess-18-5201-2014, 2014.

Rutter A. J., Kershaw, K. A., Robins, P. C. & Morton, A. J.: A predictive model of rainfall interception in forests, 1. derivation of the model from observations in a plantation of Corsican pine, Agr. Meteorol., 9 367-384,1972.

Smith, R. E., Corradini, C. and Melone, F.: Modeling infiltration for Multistorm Runoff Events, Water Resour. Res., 29, 133-144, 1993.

Tucker, G. E., Lancaster, S. T., Gasparini, N. M. and Bras, R. L.: The Channel-Hillslope Integrated Landscape Development (CHILD) model, in Landscape erosion and sedimentation modeling, edited by R. S. harmon and W. W. Doe, pp. 349-388, Kluwer Acad., Norwell, Mass., 2001.

Vivoni, E. R., Ivanov, V. Y., Bras, R. L. & Entekhabi. D.: Generation of Triangulated Irregular Networks based on Hydrological Similarity, J. Hydrol. Eng. ASCE, , 288-302, 2004.

Vivoni, E. R., Ivanov, V. Y., Bras, R. L. & Entekhabi. D.: On the effects of triangulated terrain resolution on distributed hydrologic model response, Hydrol. Process. 19, 2101-2122, 2005.

Vivoni, E. R., Entekhabi, D., Bras, R. L., Ivanov, V. Y, Van Horne, M. P, Grassotti, C., and Hoffman, R.N.: Extending the predictability of hydrometeorological flood events using radar rainfall nowcasting, J. Hydrometeorol., 7(4), 660–677, 2006.

Wigmosta, M. S., Vail L. W. and Lettenmaier, D. P.: A distributed hydrology-vegetation model for complex terrain, Water Resour. Res., 30, 1665-1679, 1994.