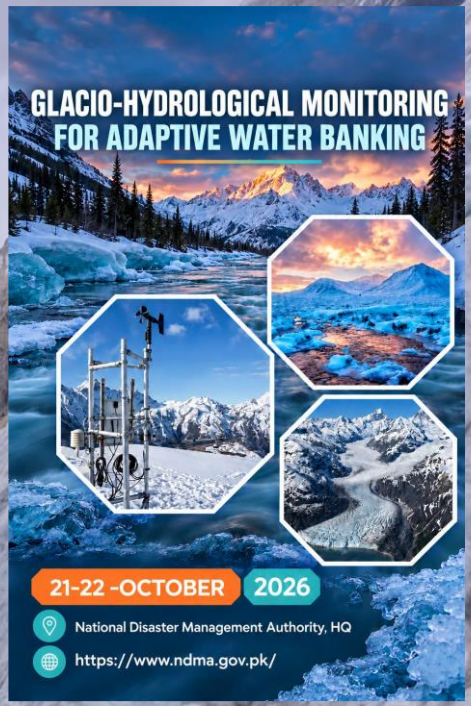


Water budget and hydrology in high altitude catchments



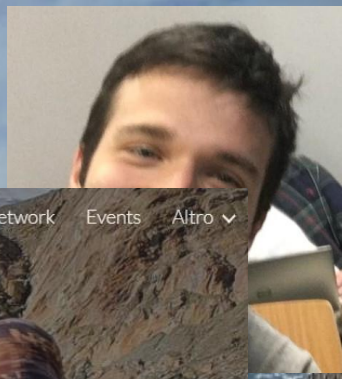


Prof. Daniele Bocchiola, EvK2CNR, Politecnico di Milano
daniele.bocchiola@polimi.it
www.climatelab.polimi.it

Poli-High Group



Daniele Bocchiola



Leonardo Stucchi

Climate-Lab

Home page | Mission | People | Projects-Thesis | Funded research | Available services and models | Cooperation-network | Events | Altro

Climate-Lab

An Interdepartmental Laboratory on Climate Change @ Politecnico di Milano

lessi









2007-2009 CARiPANDA, Cambio climatico e risorsa idrica nel Parco Naturale dell'Adamello, Fondazione Cariplo.

2009-2010 Budget idrologica del ghiacciaio Dosdè (Valtellina, Italy). LEVISSIMA Italia.

2009-2015. IDRO-STELVIO. Una rete idrometrica per il Parco dello Stelvio, Finanziato da Parco Stelvio.

2010-2012. SHARE-Stelvio. Un Parco – Osservatorio per lo studio dei Cambiamenti Climatici e Ambientali in alta quota. Finanz. Regione Lombardia.

2010-2013. Share-Paprika. Effects of climate change on water resources in the Karakoram range (Pakistan, Asia). EVK2CNR

2010-2013. SEED, Social, Economic and Environmental Development for the realization of Central Karakorum National Park (CKNP). EVK2CNR

2011-2013. I-CARE. Impact of Climate change on Alpine water REsources: the case of Italy and Switzerland. 5x1000 Politecnico di Milano

2012. Programa plan de acción para la conservación de glaciares ante el cambio climático, DGA Cile

2014-2015: Khumbu Hydrology, monitoring and modeling hydrology of the Khumbu glacier and Dudh Koshi basin, Nepal

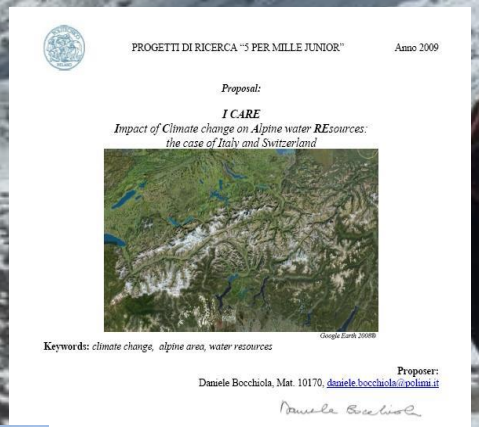
2014: ARARAT Expedition, 150 years of CAI.

2015-2016: POLIMI for KARAKORAM, 5x1000 Politecnico di Milano

…….

POLIMI & Climate change




PROGETTI DI RICERCA "5 PER MILLE JUNIOR" Anno 2009

Proposal:

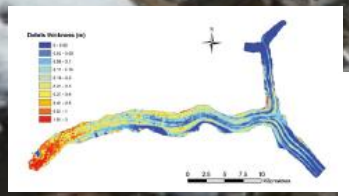
I CARE

Impact of Climate change on Alpine water REsources: the case of Italy and Switzerland

Keywords: *climate change, alpine area, water resources*

Proposer:

Daniele Bocchiola, Mat. 10170, daniele.bocchiola@polimi.it







High water resources under climate change (1)

Global warming has important consequences for the hydrological cycle, especially in regions where water supply is currently dominated by melting snow or ice. **With more than one-sixth of the Earth's population relying on glaciers and seasonal snowpack for their water supply**, the consequences of these hydrological changes for future water availability regions are likely to be severe.

Barnett *et al.*, 2005, Nature 438, 303-309.

Kaser et al. (2010) e.g. introduced PIX index, i.e. resident population times share of streamflows from ice melt for a number of rivers. Five out of the first eight rivers in the rank are from HinduKush, Karakoram, and Himalaya, HKH (Aral lake, Amu-Darya and Syr-Darya, Indus, Ganges, Yangtze, Brahmaputra).

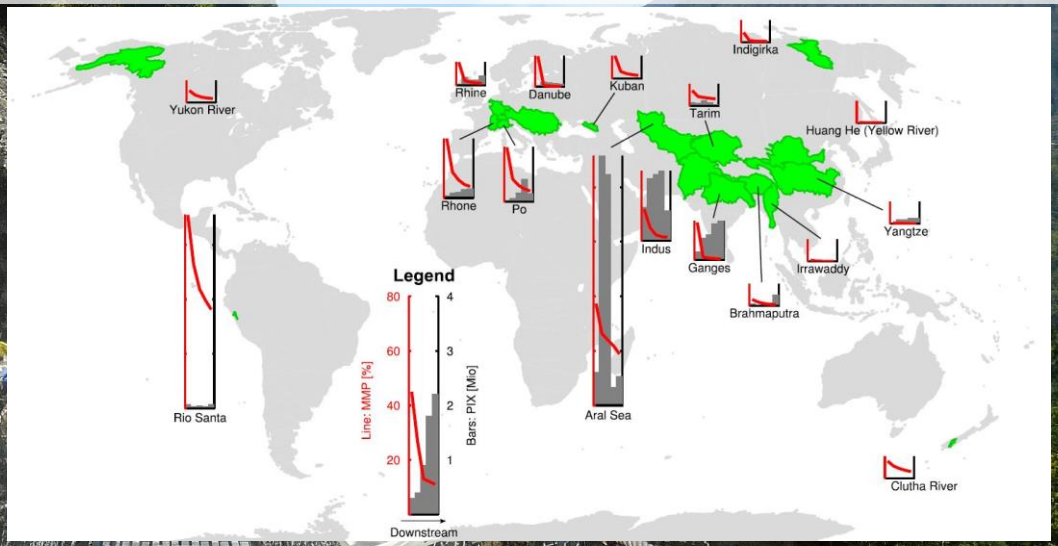


Table 1. Climatological and geographical characteristics of the river basins shown in Figs. 1 and 2, sorted by the PIX

Basin name	Basin area, km²	Glacier area, km²	Glacier area, %	Population, 10^6	PIX, 10^6
Aral Sea	1,234,075	11,319	0.92	41.01	10.29
Indus	1,139,814	20,325	1.78	211.28	4.82
Ganges	1,023,609	12,659	1.24	448.98	2.40
Po	73,297	818	1.12	16.55	0.81
Rhone	97,702	1,162	1.19	10.12	0.57
Rhine	190,713	459	0.24	59.07	0.52
Yangtze	1,746,593	1,895	0.11	383.04	0.37
Brahmaputra	527,666	16,118	3.05	62.43	0.31
Danube	794,133	617	0.08	81.38	0.31
Tarim	1,053,180	20,494	1.95	9.22	0.30
Rio Santa	11,901	503	4.23	0.57	0.27
Kuban	59,120	215	0.36	3.45	0.05
Huang He	988,702	172	0.02	162.70	0.02
Indigirka	341,577	338	0.10	0.04	0.00
Irrawaddy	410,376	25	0.01	35.26	0.00
Yukon River	830,257	9,070	1.09	0.13	0.00
Clutha River	17,182	147	0.86	0.03	0.00

PO !!!!

PNAS

Contribution potential of glaciers to water availability in different climate regimes

Georg Kaser, Martin Großhauser, and Ben Marzeion[1]

Institut für Geographie, Universität Innsbruck, Innrain 52, 6020 Innsbruck, Austria

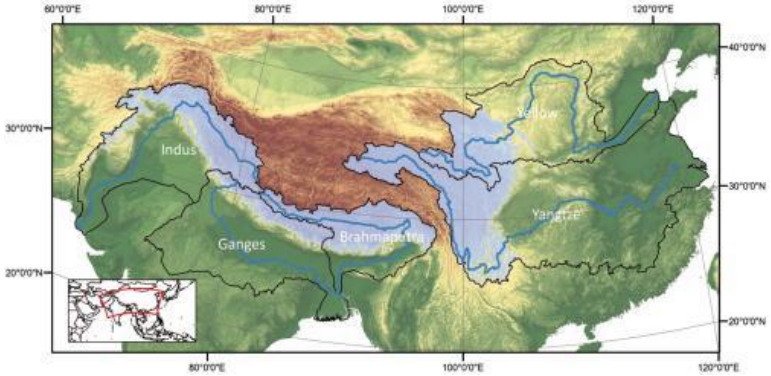
Edited by Roger G. Barry, University of Colorado, Boulder, CO, and accepted by the Editorial Board October 12, 2010 (received for review June 11, 2010)

Although reliable figures are often missing, considerable detrimental changes due to shrinking glaciers are universally expected for water availability in river systems under the influence of ongoing global climate change. We estimate the contribution potential of seasonally delayed glacier melt water to total water availability in large river systems. We find that the seasonally delayed glacier

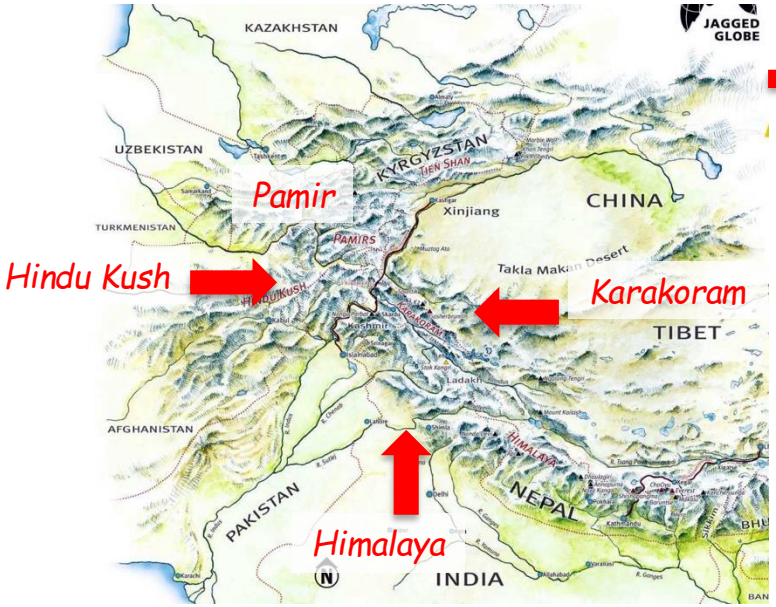
periods in a region coincide, the production of melt water and the increase of water storage occur at the same time, reducing the effect of seasonally delayed water release from the glaciers. The relative impact of glacier melt during wet and warm periods is further decreased through the general increase in water availability from precipitation.* Therefore, melt water runoff matters

Water resources from Asian water banks

The mountain range of the Hindu Kush, Karakoram and Himalaya (HKKH) contains a large amount of glacier ice, and it is the *third pole* of our planet.
The Indo-Gangetic plain (IGP, including regions of Pakistan, India, Nepal, and Bangladesh) is challenged by increasing food production to feed increasing population



Backbones of Asian water banks



The "triple point"

Latitude: 35°44'54.47"
Longitude: 74°37'45.98"



Water resources from Asian water banks

the RONGBOK GLACIER (Everest, HIMALAYA)
LOST 106m (in depth) from 1921 to 2008



Shrinking glaciers may initially provide more melt water, but later their amount may reduced.

On the other hand, growing glaciers store precipitation, reduce summer runoff, and can also trigger local hazards.

Water resources from Asian water banks

the front of BALTORO GLACIER (KARAKORAM) 1954/1958 to 2013





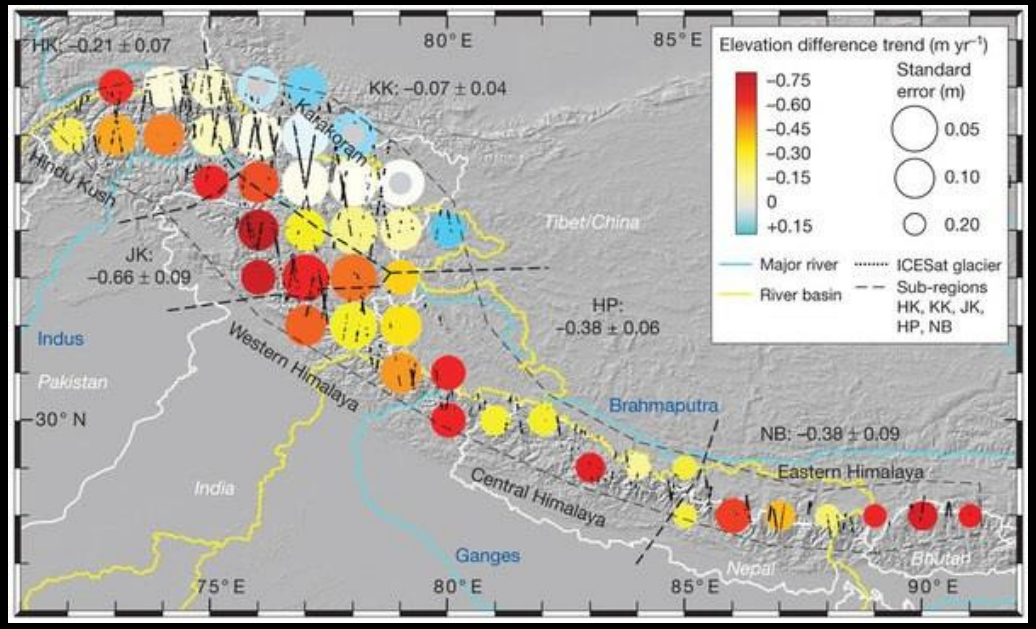


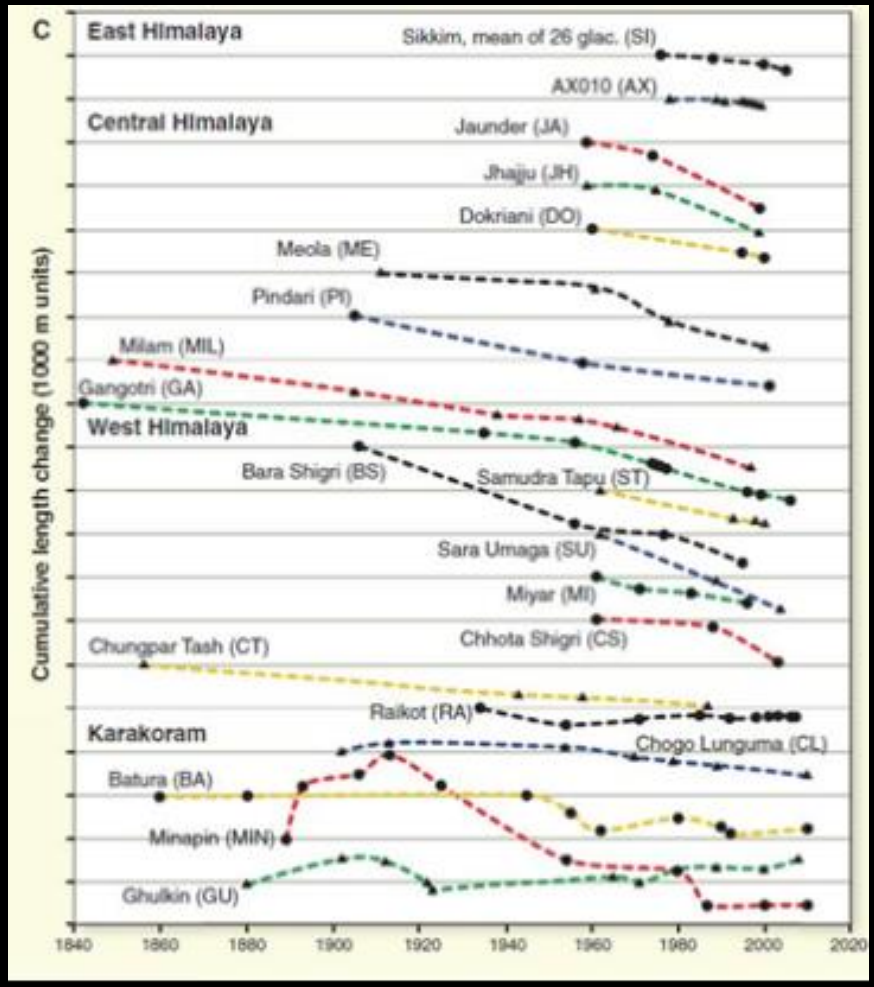


Recently observed stability in the Karakoram-Pamir area has taken the name of 'Karakoram anomaly'

Karakoram anomaly

Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J. G., Frey, H., Kargel, J. S., Fujita, K., Scheel, M., Bajracharya, S., Stoffel M. (2012). The State and Fate of Himalayan Glaciers, Science, 336, 310 (2012), doi: 10.1126/science.1215828.





Kaab, A., Berthier, E., Nuth, C., Gardelle, J., Arnaud, Y. (2012). Contrasting patterns of early 21st century glacier mass change in the Himalaya, Nature, 488, 495-498, doi:10.1038/nature11324, 2012.

PAPRIKA
Project

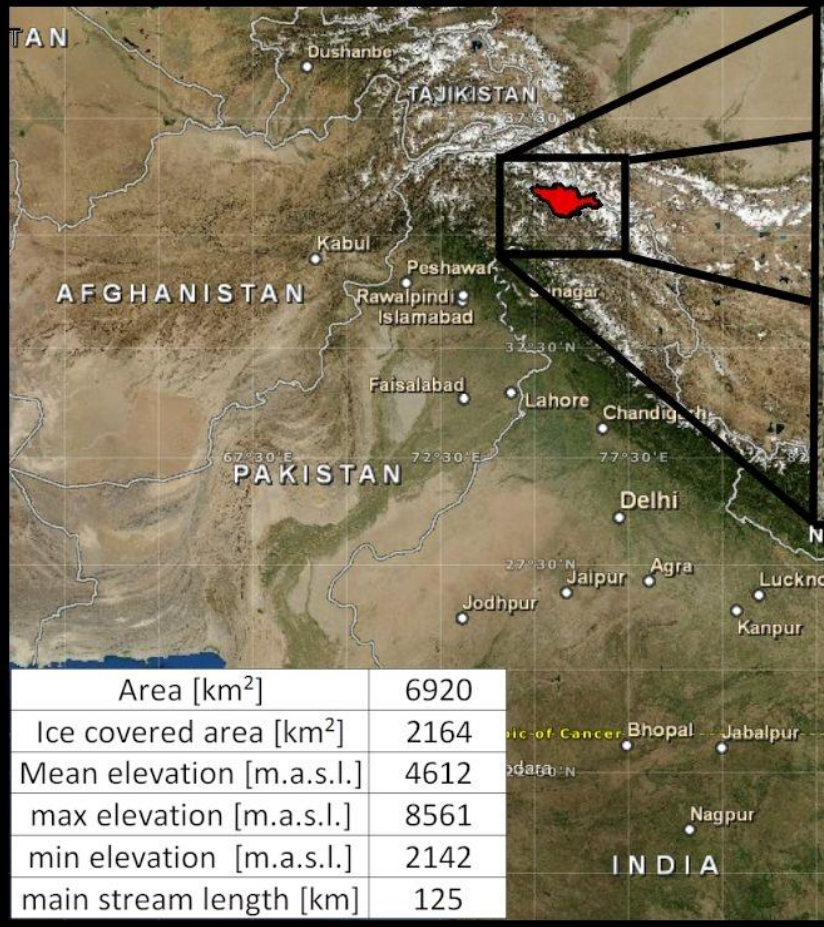
More info:
http://www.evk2cnr.org

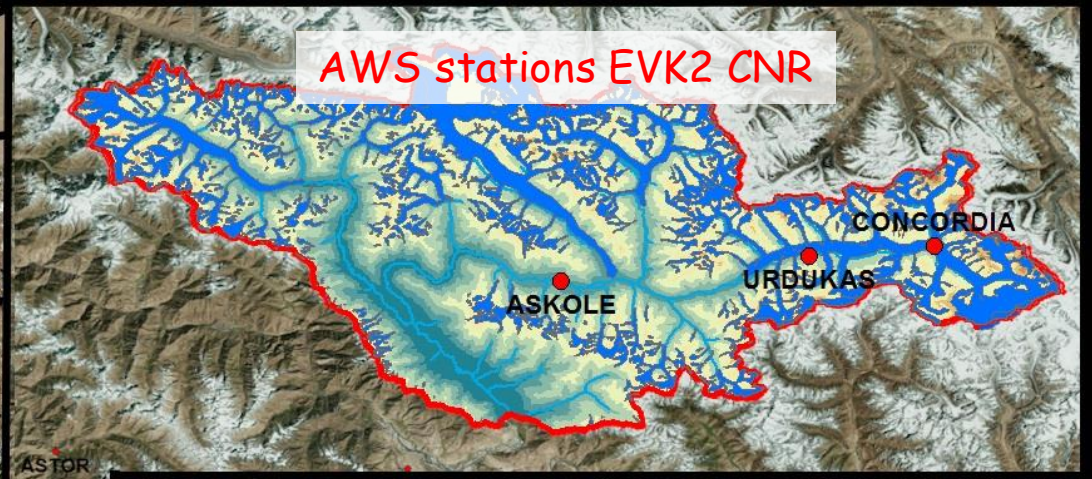
SHARE paprika
Stations at High Altitude for Research on the Environment

CryosPheric responses to Anthropogenic PRessures in the HIndukush-Karakoram-HimalayA regions: impacts on water resources and Availability

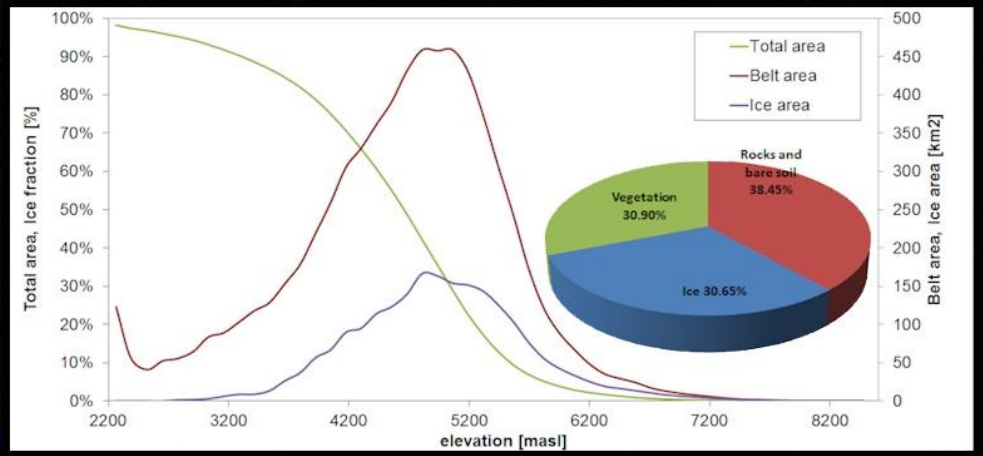
The PAPRIKA KARAKORUM Project focuses on current and future evolution of the cryospheric system in response to global and regional environmental changes and their consequences on water resources in main landscape units of PAKISTAN

Any change in water regime of HKKH region and in water availability could have critical consequences on local people, whose lives are strongly dependent upon these rivers





Area [km^2]	6920
Ice covered area [km^2]	2164
Mean elevation [m.a.s.l.]	4612
max elevation [m.a.s.l.]	8561
min elevation [m.a.s.l.]	2142
main stream length [km]	125







Shigar basin - PAKISTAN
Field work (2011-2013) summary



Hydrologic field work

Field campaigns during 2011-2013



Daily flow at Shigar
April 2011-May 2013











Ablation stakes
Summer 2011-
summer 2013



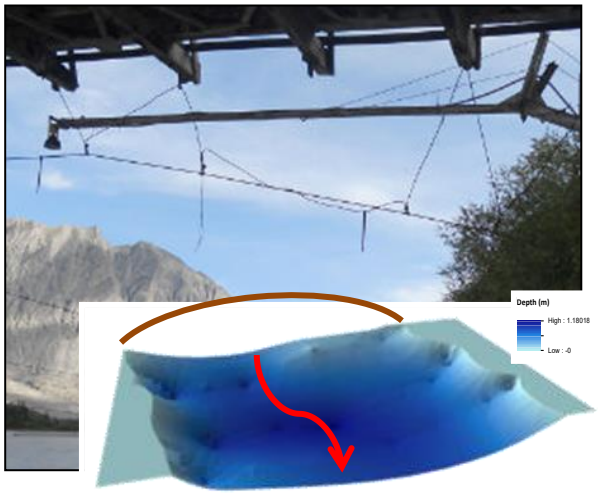


Daily flow at Paiju
Jun 2012-June 2013

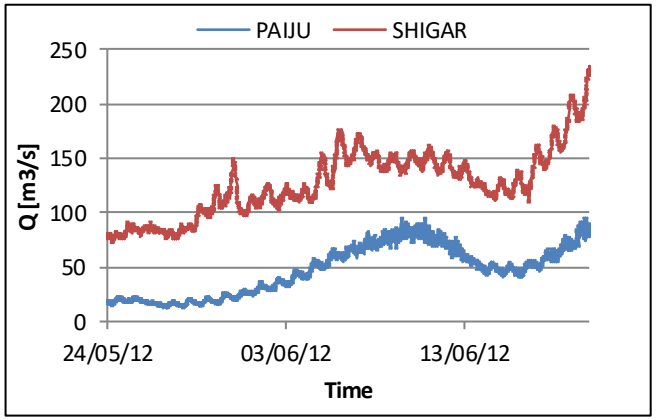
The hydro stations

Shigar gauge station (ultrasonic sensor) - April 2011





Altitude	2221 m a.s.l.
Watershed area	6923 km^2
Datalogger	Campbell Scientific - CR200X
Sensor	sonic sensor Vegason 63, 4-20 mA, 24V
Power supply	solar panel 20W + battery Pb 12V 40 Ah



Paiju gauge station - May 2012





Altitude	3356 m a.s.l.
Watershed area	1331 km^2
Datalogger	Campbell Scientific - CR200X
Sensor	piezometric sensor STS atm.eco/n, 4-20 mA, 12V
Power supply	solar panel 20W + battery Pb 12V 16 Ah

Hydrologic Analysis

The hydrologic model

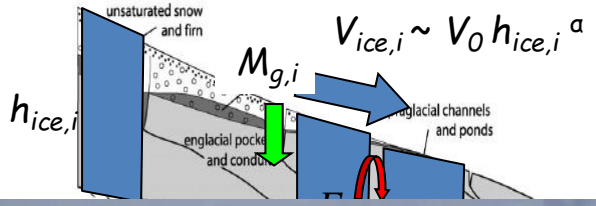
DEM

Snow and ice ablation

Meteo Data

Vertical gradient

Simplified ice flow model



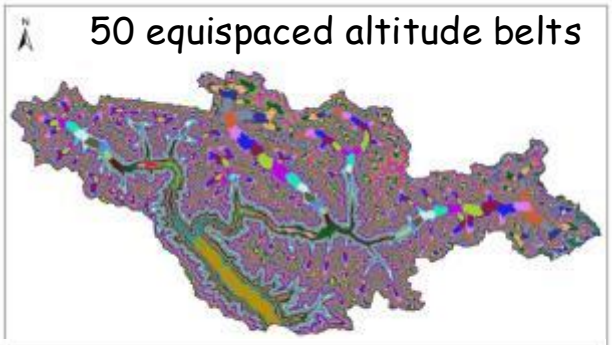
$V_{ice,i} \sim V_0 h_{ice,i}^{\alpha}$

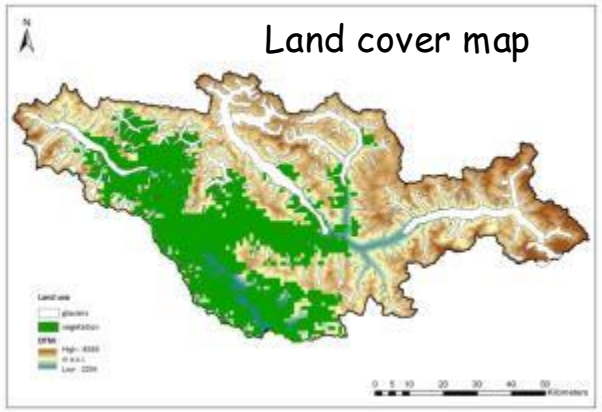
$M_{g,i}$

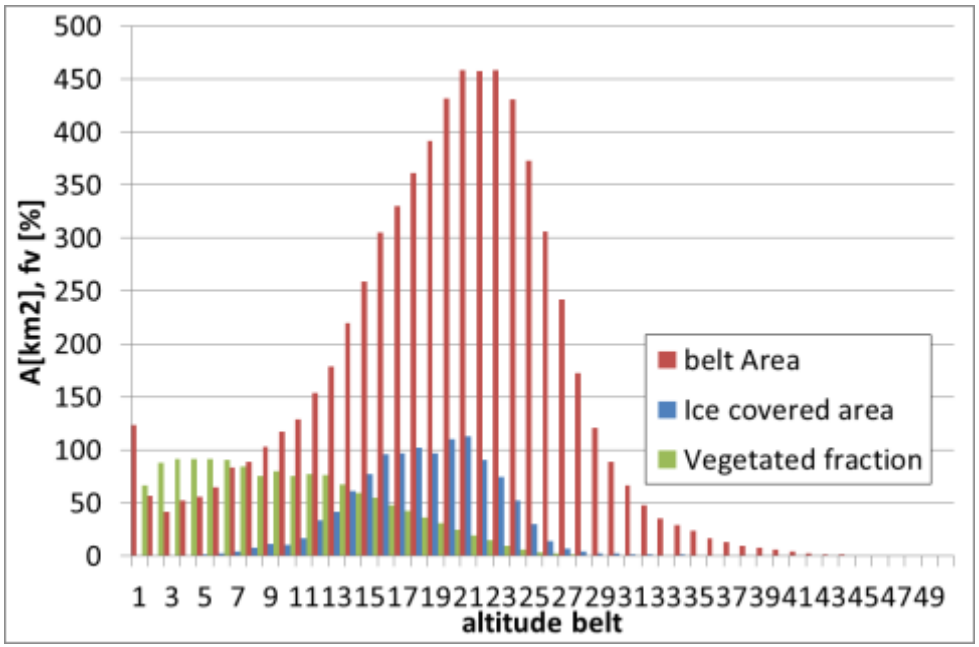
$h_{ice,i}$

Hydrologic model

Input





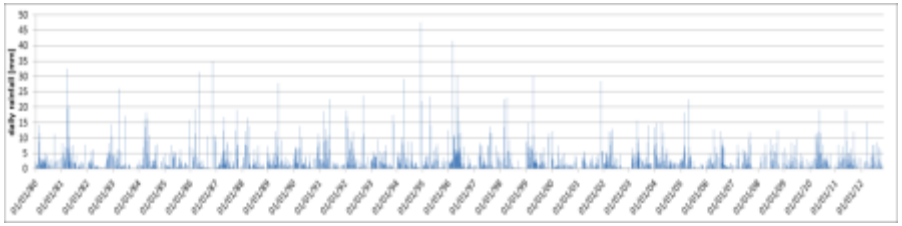


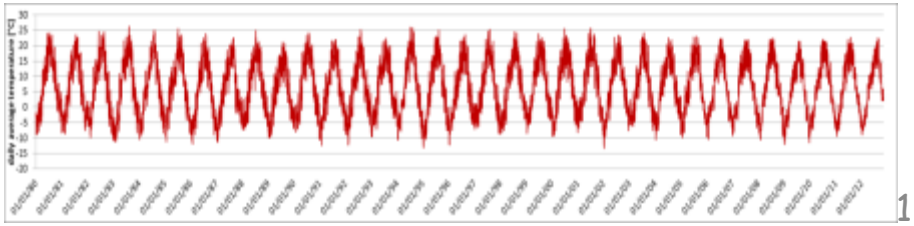
Available meteorological data

station	available data	temporal resolution
Askole	2005-2012	daily
Astore	1980-2009	monthly

Monthly mean flow data available at Shigar from 1985 to 1997

Statistical downscale on monthly Astore data based on daily Askole data



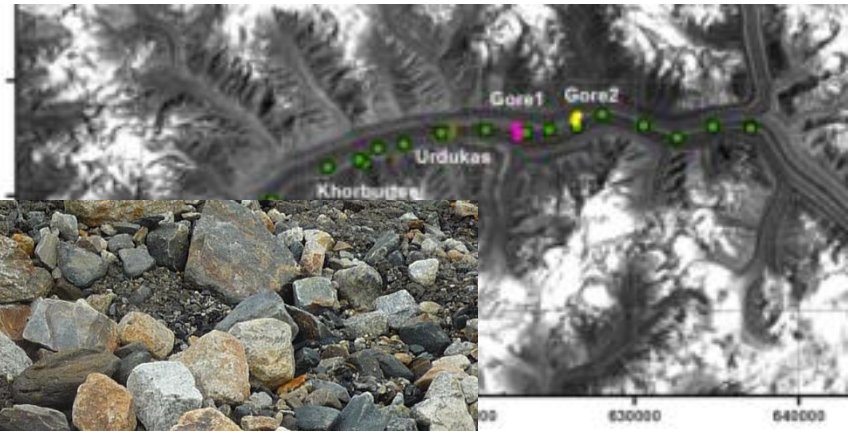


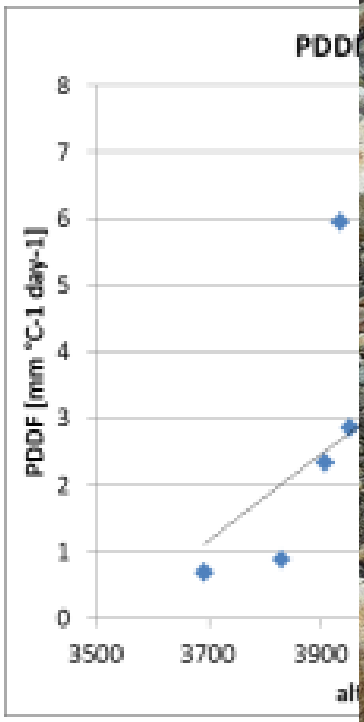
Hydrologic model

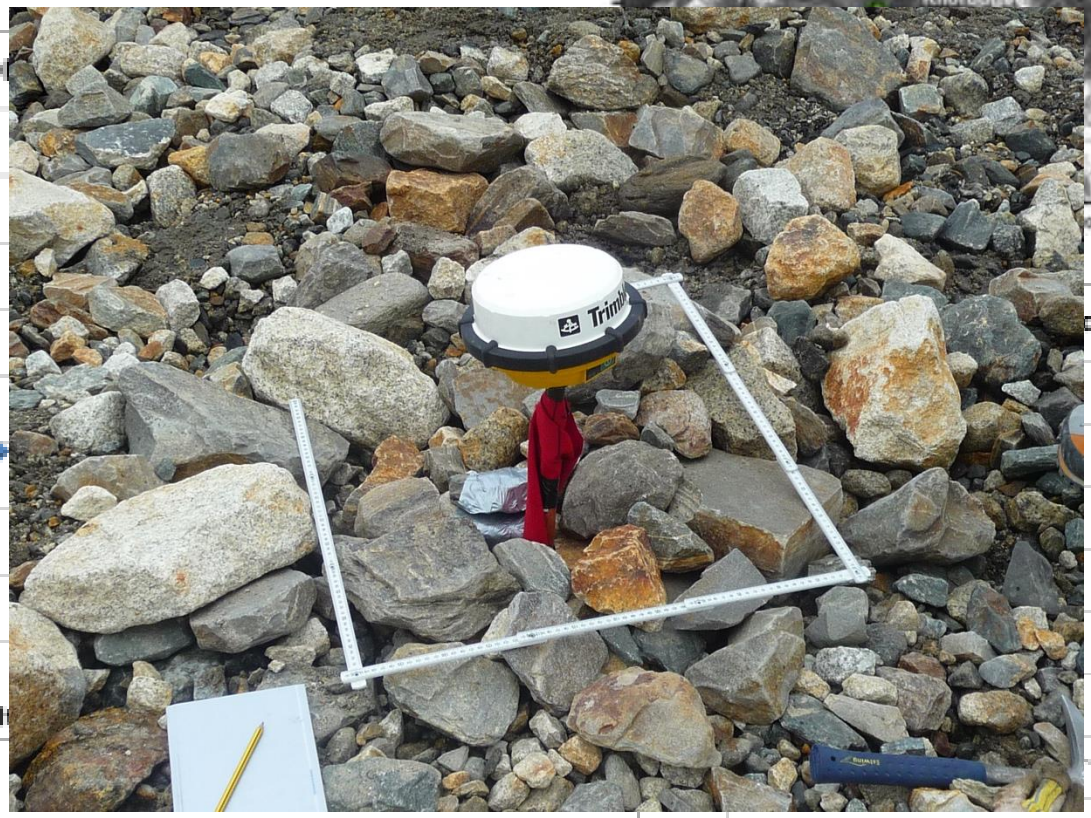
Ice Degree-Day Factor Estimation

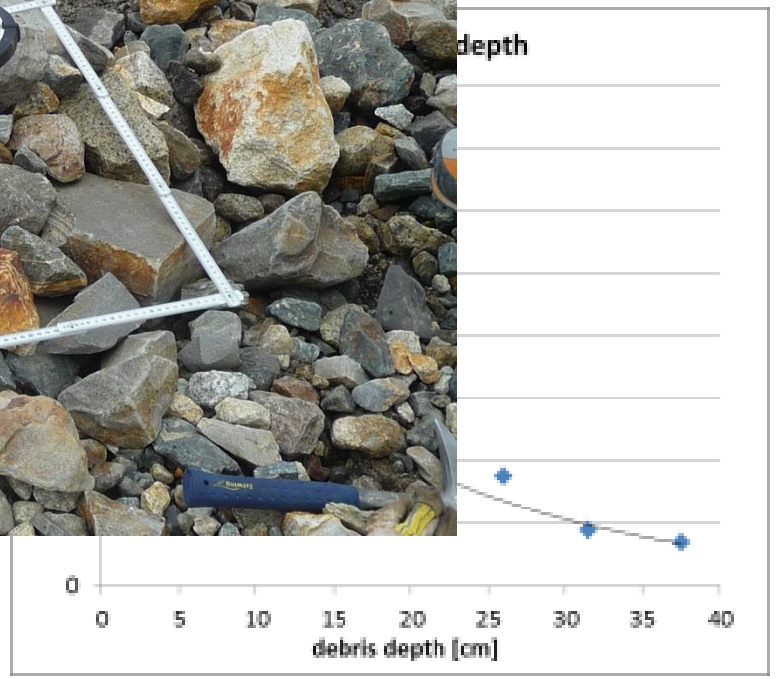
Ice ablation data collected in summer 2011 by a UNIMI_POLIMI field campaign:

- Debris depth at 17 points
- Ablation data at 17 ablation stakes







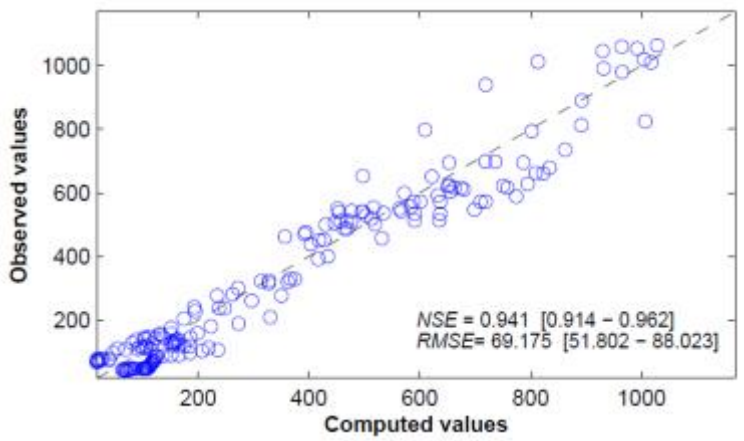


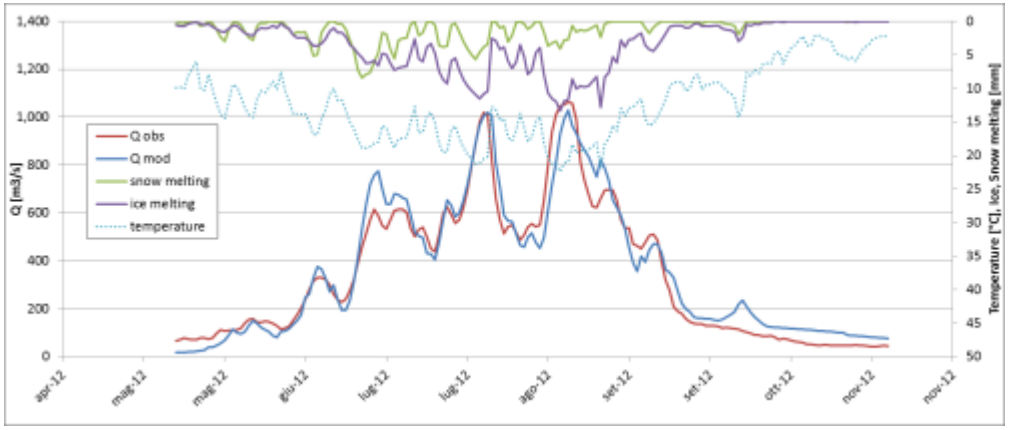


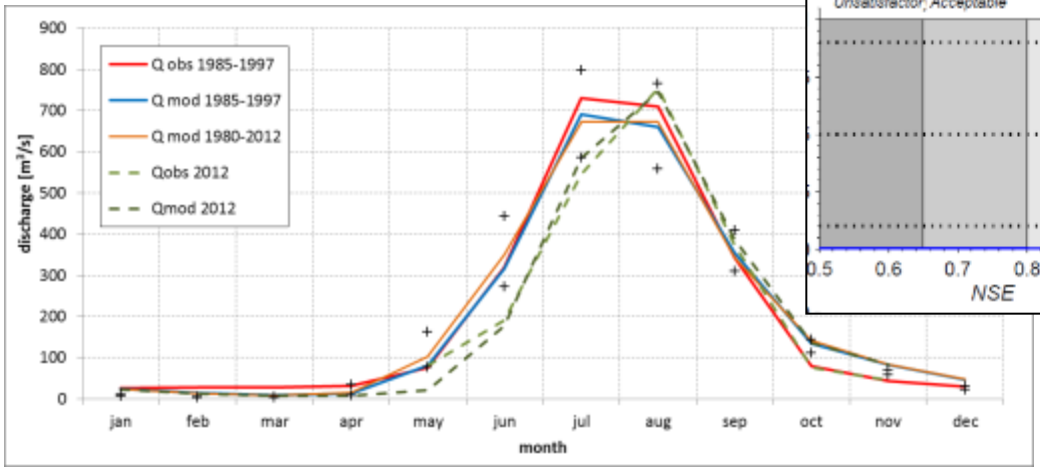
Multiple regression used to stimate PDDF at each altitude belt

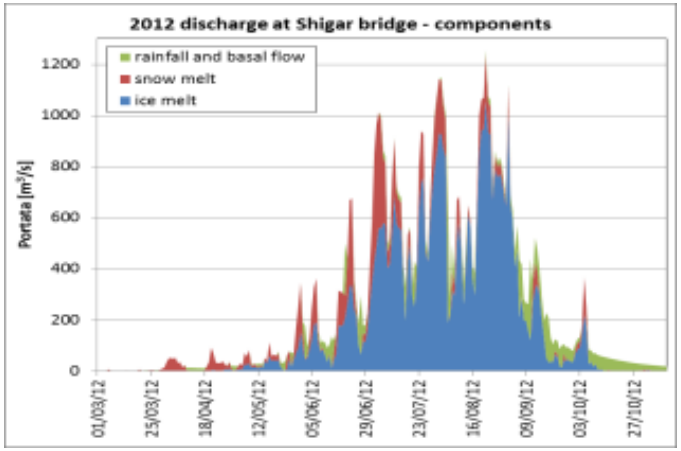
Hydrologic model

Calibration 1985-1997 monthly data at Shigar

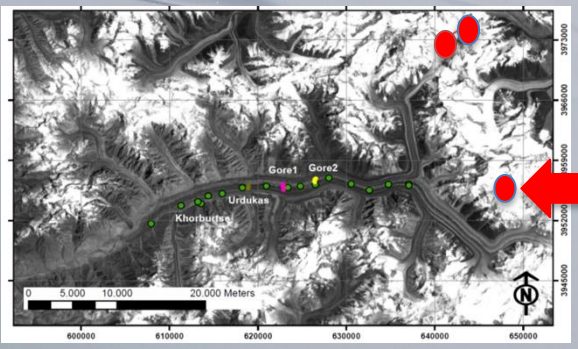






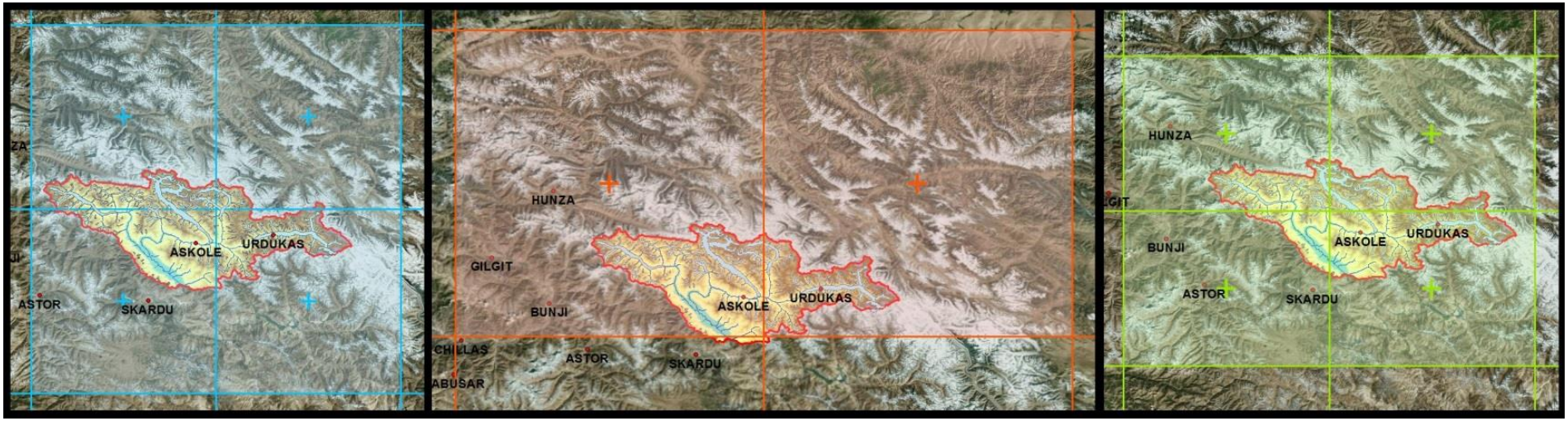


	jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec	average
observed 1985-1997	26.07	27.76	28.55	31.81	76.47	319.42	729.21	710.09	343.53	78.71	44.13	29.05	**203.73**
model 1985-1997	24.05	13.43	8.72	12.78	81.27	316.22	690.03	659.95	355.54	134.27	82.60	46.61	**202.12**
model 1980-2012	24.07	13.23	8.49	14.60	102.16	350.68	672.78	672.71	341.39	142.38	83.61	47.24	**206.11**
observed Shigar 2012	-	-	-	-	80.98	190.63	544.93	753.20	373.54	76.36	45.00	-	**294.95**
model Shigar 2012	22.13	12.16	7.24	7.57	21.21	177.61	583.76	746.11	387.16	136.55	82.80	-	**305.03**


Gore1
Gore2
Urdukas
Khorbuche
0 5.000 10.000 20.000 Meters
N
600000
610000
620000
630000
640000
650000
3973000
3966000
3959000
3952000
3945000

Hydrological projections
GCMs for scenario simulations

PAPRIKA used downscaled inputs from three different GCMs to project forward hydrology of the Shigar river over the investigated time horizon (until 2099)



Model	Research Centre	Nation	Grid size [°]	n° layers [.]	n° cells [.]
EC-EARTH	Europe-wide consortium	E.U.	1.125° x 1.125°	62	320x160
ECHAM6	Max Planck Institute for Meteorology	GER	1.875° x1.875°	47	192x96
CCSM4	National Center for Atmospheric Research	U.S.A.	1.25° x 1.25°	26	288x144

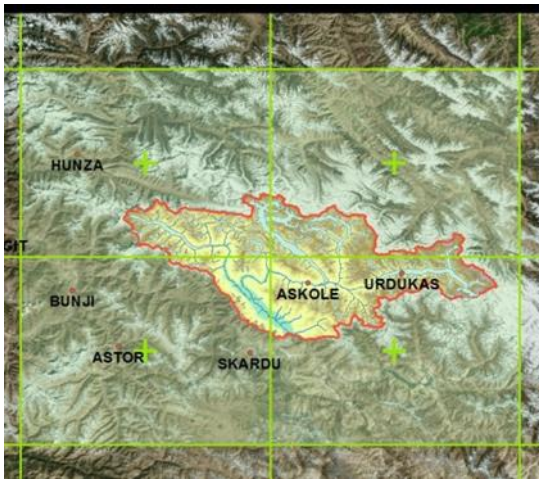
We use a random cascade approach (Groppelli et al., 2011) to obtain ground precipitation and temperature. The random cascade parameters are been calibrated using the observed data at Askole and the control run series for each model.
With the parameters we disaggregate the three future RCPs scenarios for each model, for the next century (2012-2100).

Short tutorial on GCMs model, and IPCC's RCPs

Besides models of hydrological response of Alpine areas, prediction of future climate requires use of climate feeding from AOGCMs (Atmospheric Oceanic Global Circulation Models).
Particularly critical is the **bias,** and the **tremendous mismatch** in scales between AOGCMs (100 km), and the hydrological models (1-10 km), as required by topographic control.



We need a tool to downscale projections of future precipitation from the AOGCM

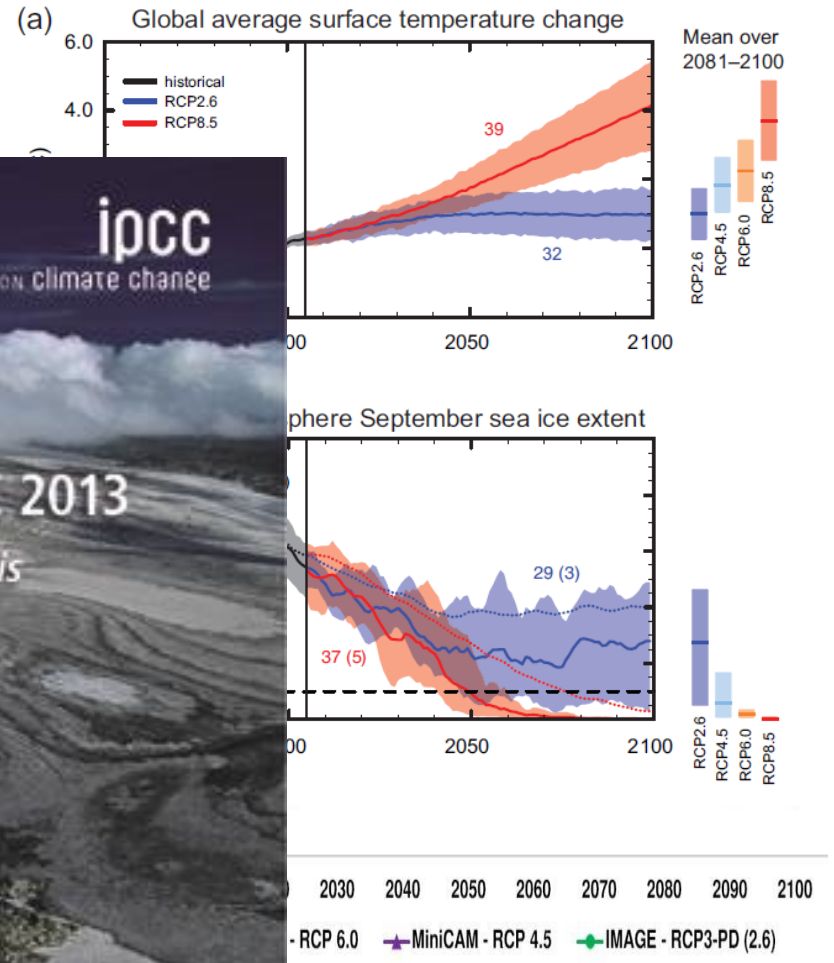


RCPs of IPCC

The Intergovernmental Panel for Climate Change IPCC gathers projection of future climate from AOGCMs from several institutes, summarized lately within t
Report (AR)5
http://www.ipcc.ch/repor
summary for policymakers
http://www.climatechange
port/WG1AR5_SPM_FIN

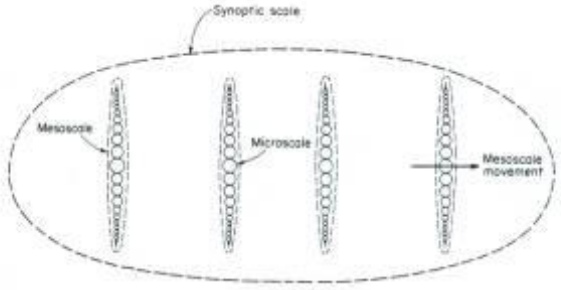
To lump the effect of gre
equivalent), an index of n
of the Earth-Atmosphere
called "Representative cor
RCP. Four RCPs were selec
broad range of climate ou
literature review, and are
nor policy recommendatio
potential "storylines".

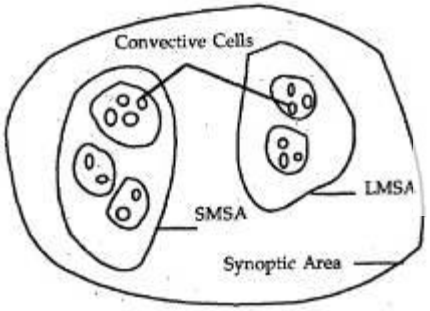




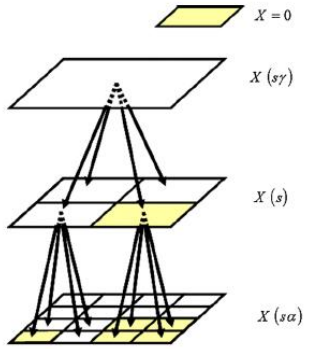
Downscaling using SRE+RC theory

Our downscaling approach uses concepts of scale variability of precipitation to obtain statistical downscaling techniques to convey information from GCMs to local scale of hydro-glacio investigation





We use random cascade (RC) theory and scale recursive estimation (SRE) for model estimation

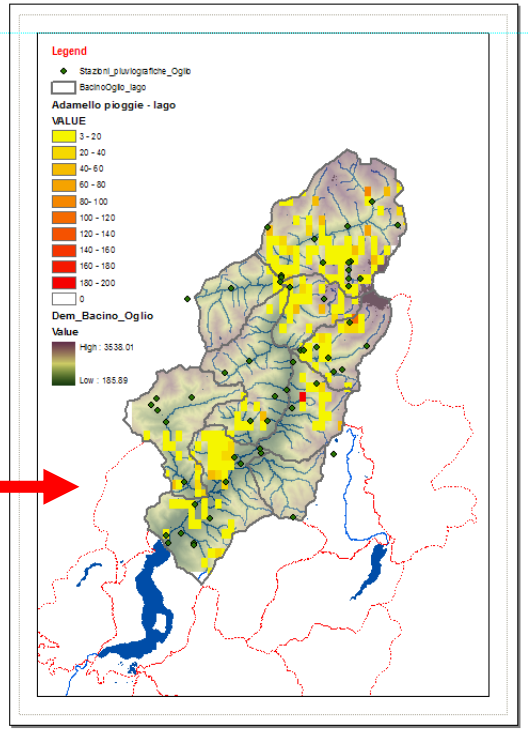


Using daily precipitation data from a ground network one can calibrate the downscaling model, and obtain projected precipitation at a fine resolution



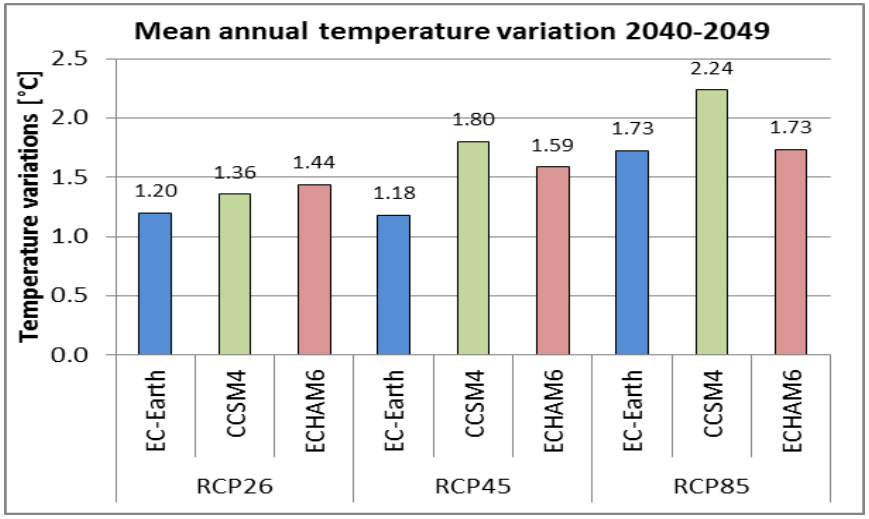
SRE(+EM)+RC

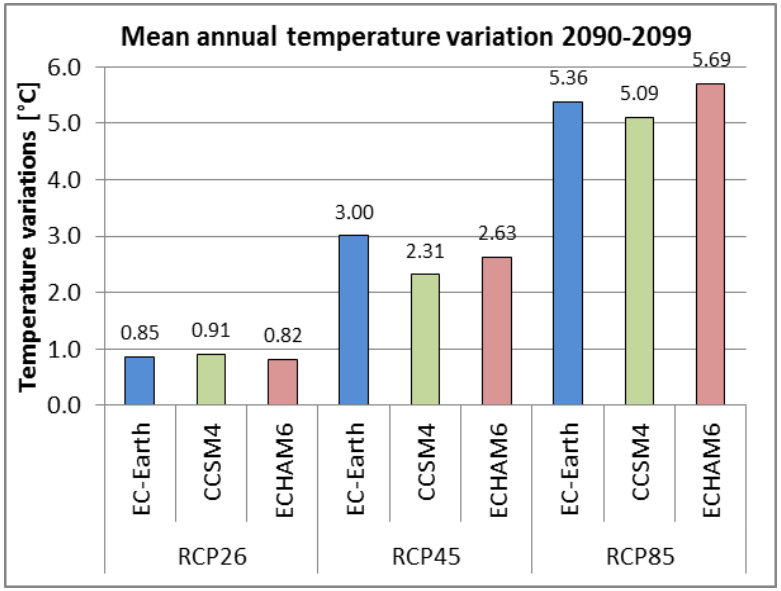
Projection of future precipitation (e.g. 1km here)



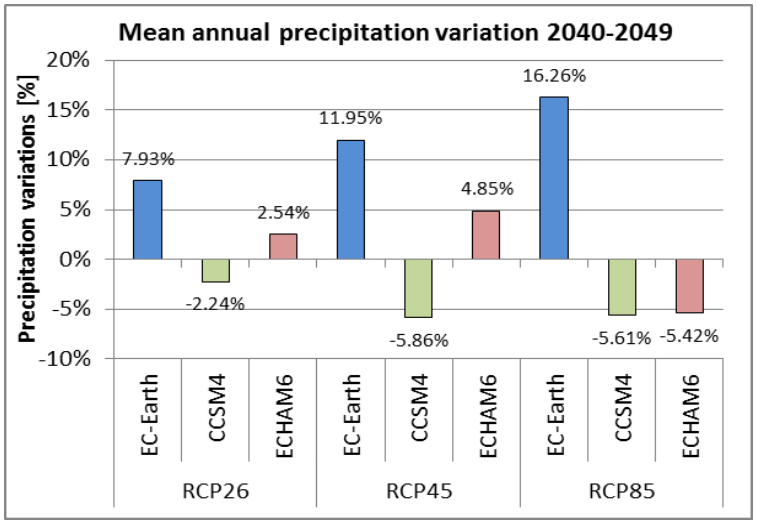
Hydrological projections

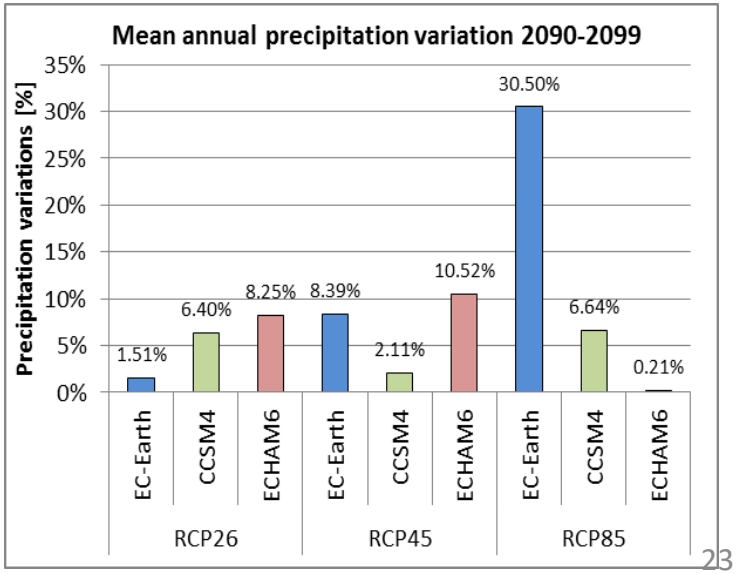
Temperature changes (yearly, Ref. 1980-2012)





Precipitation changes (yearly, Ref. 1980-2012)





Hydrological projections

Weather changes (monthly, Ref. 1980-2012)

Monthly temperature

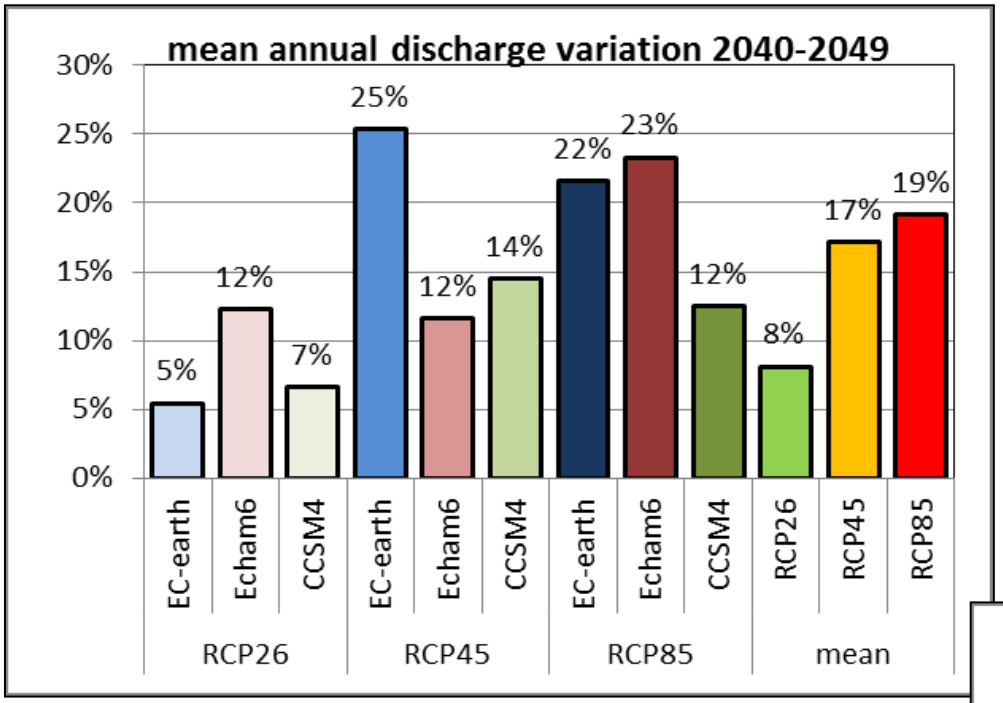
TEMPERATURE			jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
2040-2049	RCP26	EC-Earth	1.32	1.00	0.50	1.42	1.27	-0.61	1.34	1.31	0.95	1.39	2.80	2.19
		CCSM4	1.28	0.10	-0.33	-0.21	0.50	0.72	1.71	1.73	2.72	2.97	2.83	2.13
		ECHAM6	1.52	0.61	1.38	1.40	0.82	1.19	2.18	1.06	1.66	1.74	2.17	1.44
	RCP45	EC-Earth	0.89	1.86	1.54	0.45	0.92	1.68	2.02	1.95	2.05	1.75	-0.41	-0.01
		CCSM4	2.28	0.37	0.97	0.30	1.29	0.86	1.55	2.08	2.59	3.68	3.06	2.37
		ECHAM6	0.51	1.31	1.74	1.89	1.21	1.23	2.42	1.92	1.79	2.99	1.52	0.50
	RCP85	EC-Earth	1.64	1.57	1.80	2.19	1.91	1.75	0.76	1.00	2.58	2.35	2.05	1.65
		CCSM4	2.31	1.10	0.62	0.85	2.31	1.53	2.05	2.76	3.59	3.93	2.90	2.73
		ECHAM6	0.96	0.87	1.36	1.75	0.92	1.39	2.28	1.78	2.90	2.76	2.10	1.71
2090-2099	RCP26	EC-Earth	1.57	0.67	1.06	-0.34	1.88	0.40	0.94	1.15	0.82	0.88	-0.47	2.04
		CCSM4	0.47	0.66	0.27	0.35	-0.15	-0.61	0.72	1.25	2.64	2.19	2.08	0.98
		ECHAM6	-0.13	0.58	1.27	1.46	0.67	0.29	1.55	0.78	0.79	1.51	0.87	0.15
	RCP45	EC-Earth	3.61	3.28	2.36	2.87	3.01	2.76	3.13	3.37	3.93	3.19	2.89	2.14
		CCSM4	2.57	2.04	1.55	0.86	1.22	1.30	2.18	2.73	3.68	4.12	2.67	2.72
		ECHAM6	3.20	1.91	3.04	2.22	1.52	2.12	3.22	2.38	3.06	2.93	2.92	3.00
	RCP85	EC-Earth	4.02	3.79	5.91	5.69	5.29	4.65	5.08	5.97	5.68	6.57	6.78	5.29
		CCSM4	4.62	4.43	2.96	3.61	4.64	3.66	5.14	5.69	6.76	8.39	5.46	5.57
		ECHAM6	5.78	4.91	5.15	5.05	4.54	6.06	6.69	5.46	5.78	6.15	6.46	6.12

Monthly precipitation

PRECIPITATION			jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
2040-2049	RCP26	EC-Earth	13.4%	9.2%	22.4%	-10.6%	10.4%	23.5%	6.2%	16.0%	24.4%	-15.1%	5.0%	-20.7%
		CCSM4	-26.8%	14.8%	-31.9%	24.7%	-5.4%	-8.3%	2.8%	37.1%	-20.7%	-63.0%	75.7%	-14.0%
		ECHAM6	13.0%	-34.5%	25.8%	-12.8%	38.8%	0.4%	-6.2%	-5.0%	18.0%	-48.4%	-23.2%	22.0%
	RCP45	EC-Earth	10.8%	44.5%	4.9%	43.2%	-17.0%	-8.4%	14.5%	3.1%	-2.2%	50.5%	-27.6%	-4.4%
		CCSM4	54.9%	8.6%	-9.7%	22.3%	-23.9%	33.9%	-12.2%	-53.8%	-40.2%	-49.5%	-59.6%	-24.2%
		ECHAM6	10.3%	19.0%	-14.3%	3.1%	34.5%	-41.6%	-20.7%	16.0%	12.2%	-12.4%	-6.2%	33.8%
	RCP85	EC-Earth	17.0%	7.2%	-16.2%	46.8%	6.9%	11.7%	72.2%	2.2%	10.5%	34.8%	-40.8%	46.1%
		CCSM4	5.7%	14.2%	-28.5%	6.5%	-1.8%	51.2%	-21.4%	-17.0%	-22.3%	-30.1%	-35.9%	0.1%
		ECHAM6	-17.6%	-13.4%	-16.9%	-17.0%	26.0%	-29.3%	-8.5%	12.6%	-9.7%	19.2%	-27.4%	29.0%
2090-2099	RCP26	EC-Earth	8.0%	21.6%	-8.9%	23.0%	-45.5%	48.3%	-2.7%	10.3%	0.8%	21.0%	-31.8%	-14.2%
		CCSM4	36.1%	1.3%	-16.4%	55.6%	9.5%	-24.0%	1.2%	1.1%	-17.5%	-27.5%	-39.2%	11.2%
		ECHAM6	10.1%	-24.1%	17.6%	-14.6%	10.0%	-18.4%	6.5%	5.3%	2.0%	103.3%	-9.9%	64.4%
	RCP45	EC-Earth	-25.3%	28.1%	-18.0%	11.6%	15.5%	37.4%	22.9%	-10.8%	-17.0%	33.2%	-34.7%	76.6%
		CCSM4	5.8%	6.2%	0.2%	40.9%	-9.7%	-11.1%	-5.2%	-17.0%	-24.1%	-26.6%	-29.3%	15.0%
		ECHAM6	-32.5%	-0.5%	15.5%	24.5%	56.1%	-11.4%	1.9%	9.3%	-8.7%	-5.7%	-0.6%	4.1%
	RCP85	EC-Earth	36.8%	13.7%	70.0%	42.7%	9.0%	30.9%	39.1%	-27.9%	-11.5%	28.0%	-1.4%	93.2%
		CCSM4	-1.8%	-39.7%	-19.0%	27.0%	55.8%	102.8%	-30.9%	17.4%	-6.2%	-6.1%	24.3%	8.5%
		ECHAM6	22.2%	-34.3%	-2.5%	-15.3%	24.2%	-2.0%	-10.6%	-1.6%	62.5%	48.9%	-85.7%	22.8%

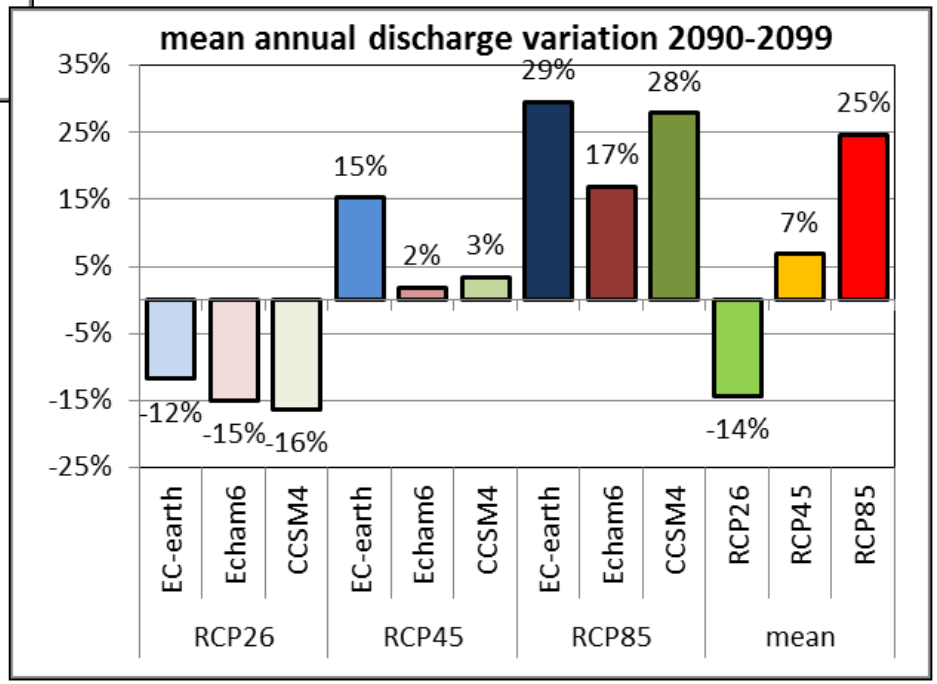
Projected Mean Annual Discharge

Hydrological projections
Hydrologic scenarios



Half century: increase

Half century: potential decrease

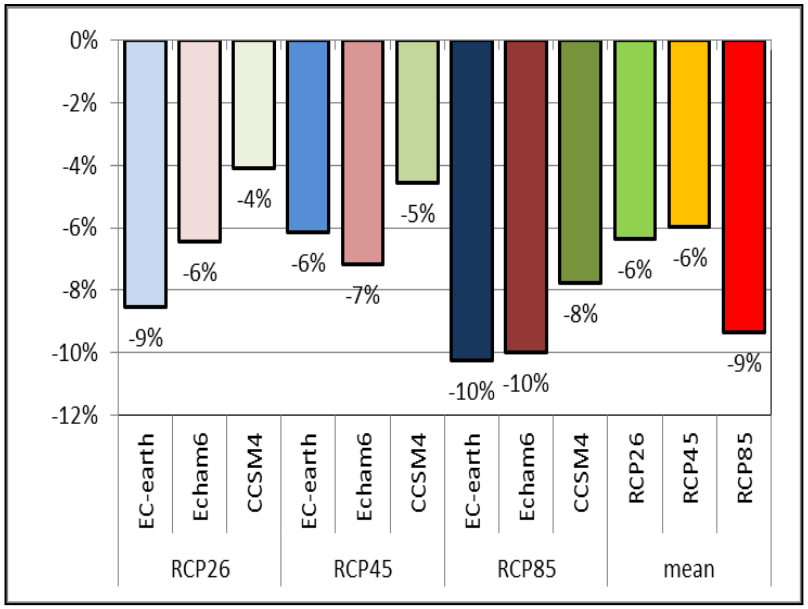


Hydrological projections

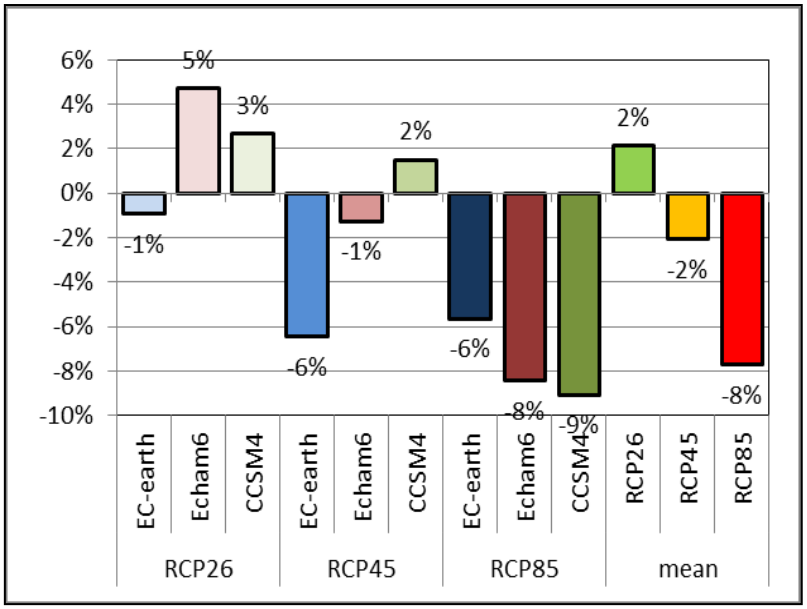
Changes in hydrological contribution (yearly, Ref. 1980-2012)

Snow melt

Half century

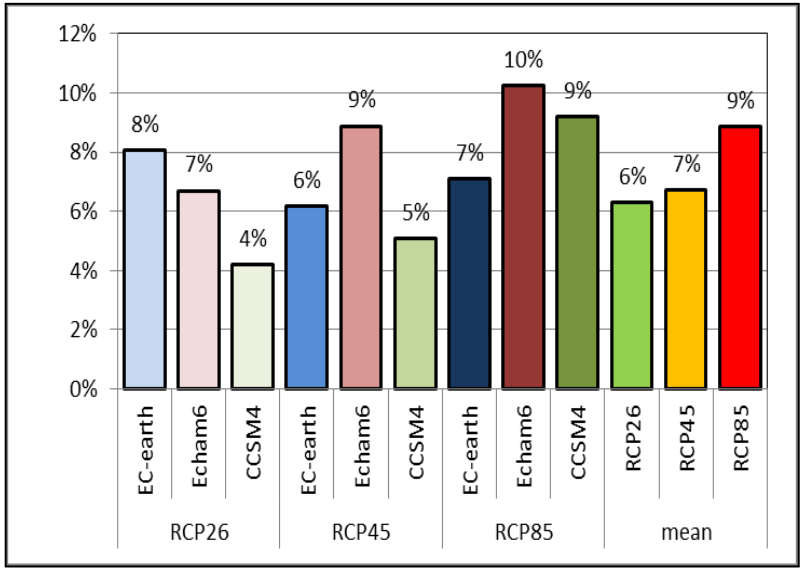


End of century

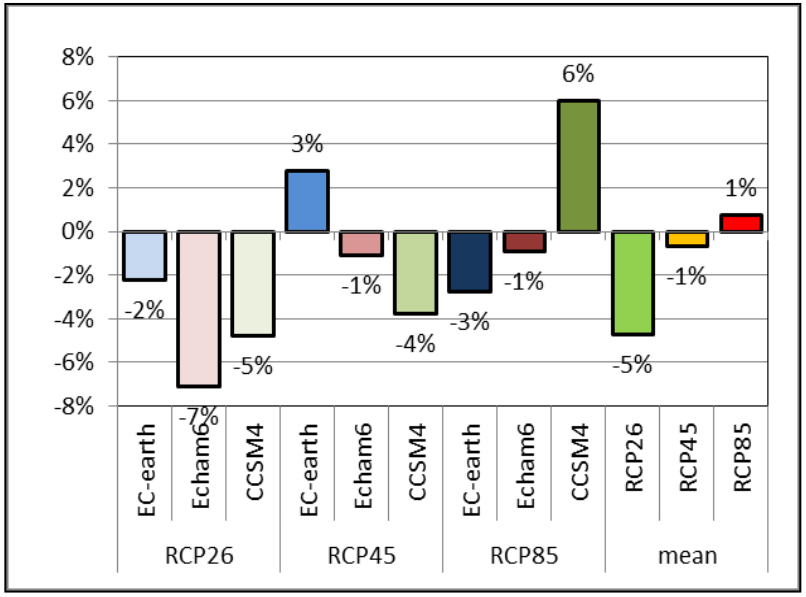


Ice melt

Half century

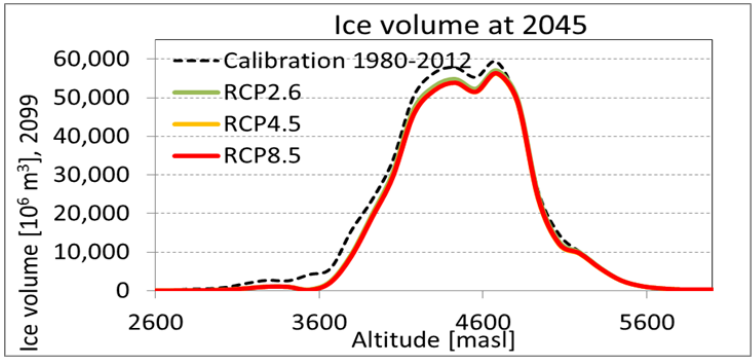


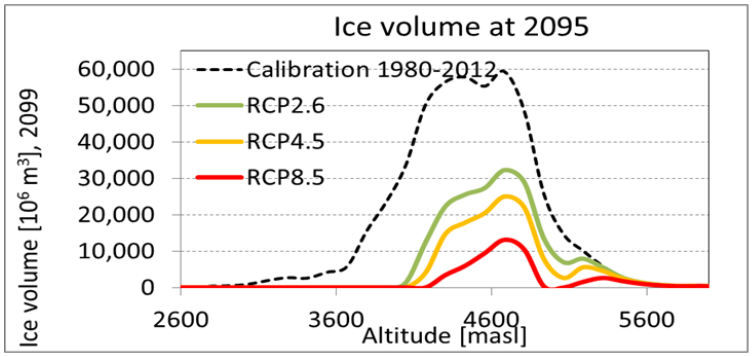
End of century




SEAHAWK 2

Hydrological projections: available ice volume as per altitude bins





RCP 2.6		
% ice volume lost	2040-49	2090-99
EC-earth	-8.4%	-63.9%
Echam6	-11.2%	-62.0%
CCSM4	-7.2%	-55.4%

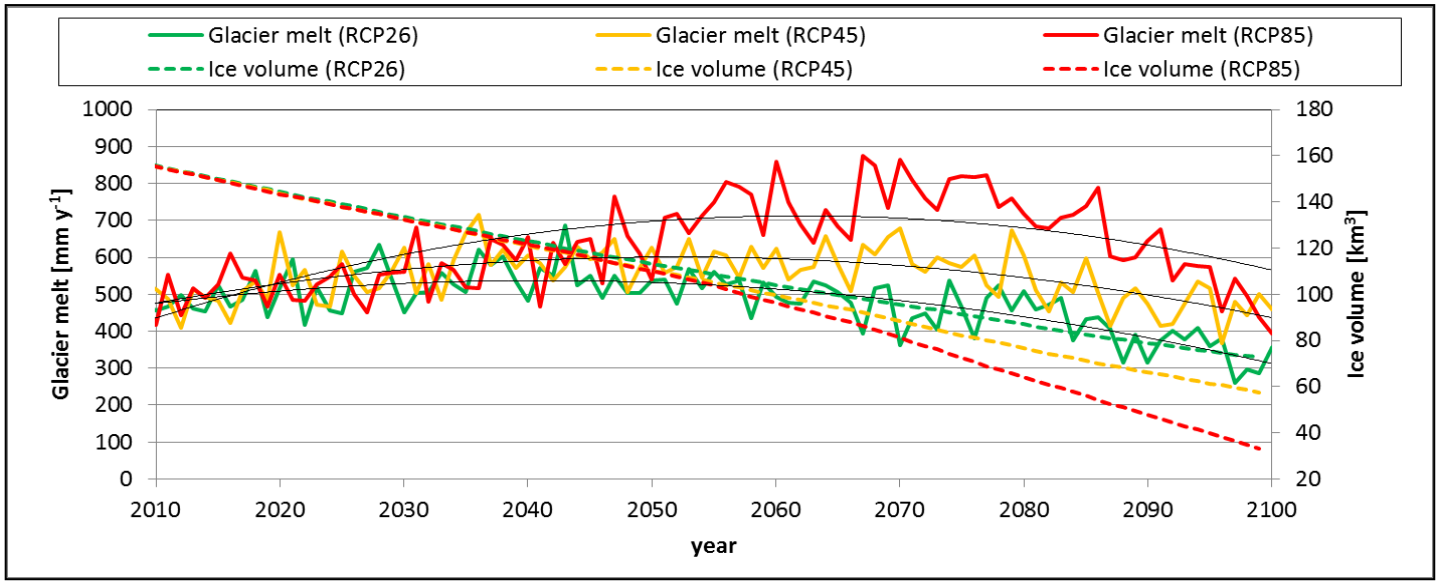
RCP 4.5		
% ice volume lost	2040-49	2090-99
EC-earth	-11.3%	-76.6%
Echam6	-10.5%	-71.8%
CCSM4	-7.2%	-70.1%

RCP 8.5		
% ice volume lost	2040-49	2090-99
EC-earth	-11.2%	-91.0%
Echam6	-14.2%	-90.7%
CCSM4	-7.4%	-86.0%

Accelerated ice melting will lead **to rapidly decreasing ice thickness**, with potential thinning, especially towards the end of the century.

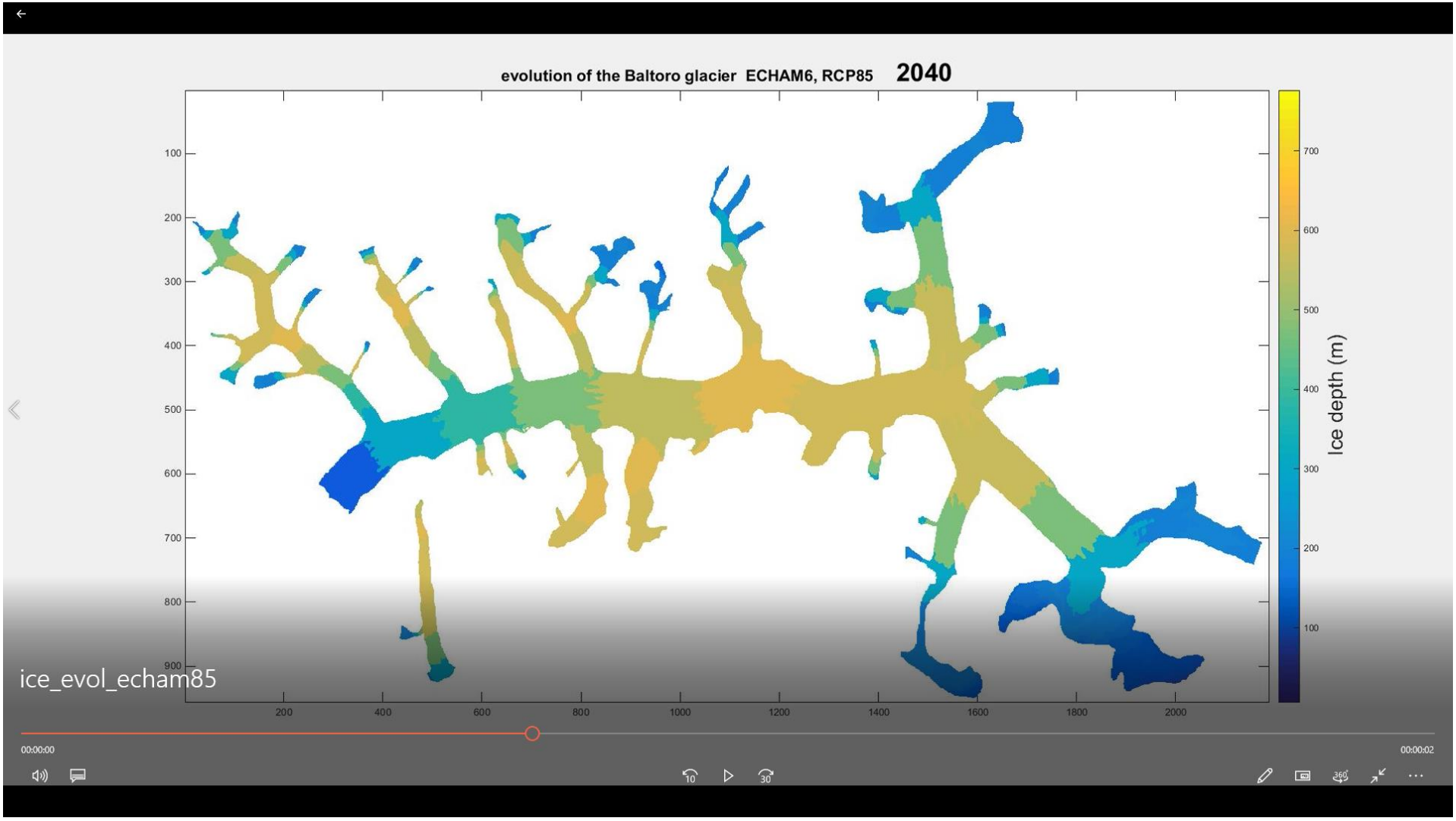
The "Karakoram anomaly" may last until half century, but break down thereafter

Down wasting of ice cover may have several implication, hydrologically, ecologically, climatically, and touristically



The future Baltoro glacier, a movie

ECHAM6, "worst case" RCP8.5 scenario



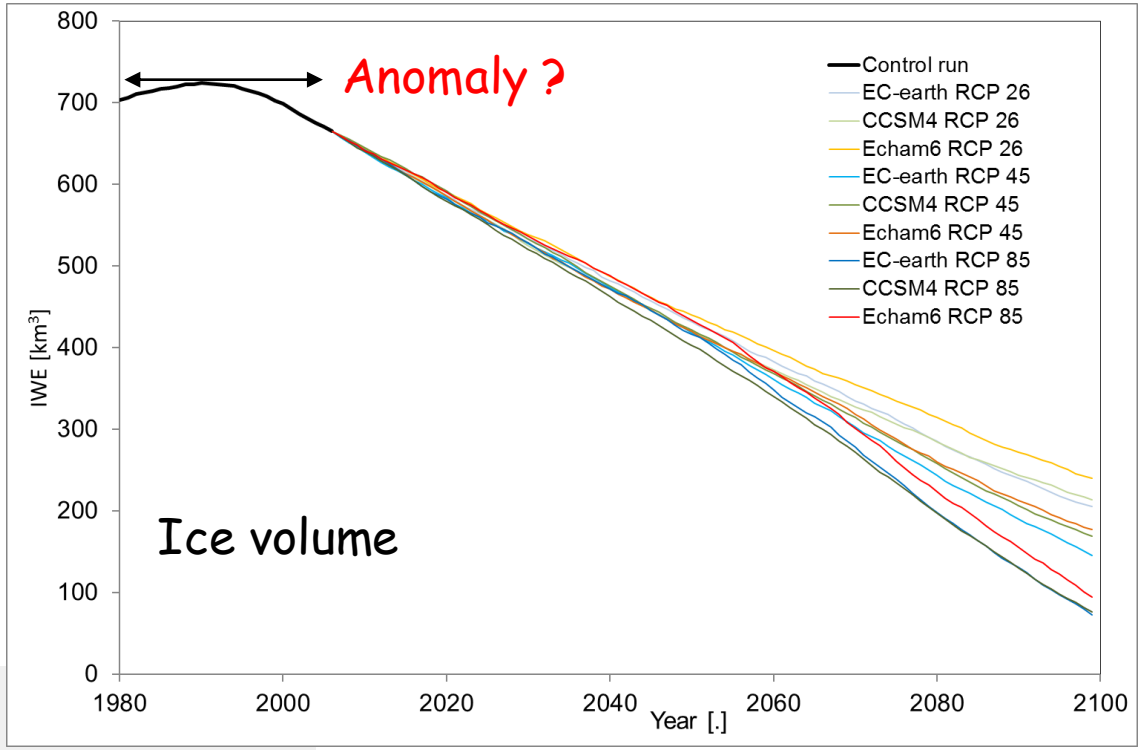
The animation displays ice thickness in each altitude belt on the Baltoro glacier during 2020-2100. Worst case scenario, Model ECHAM6, RCP8.5

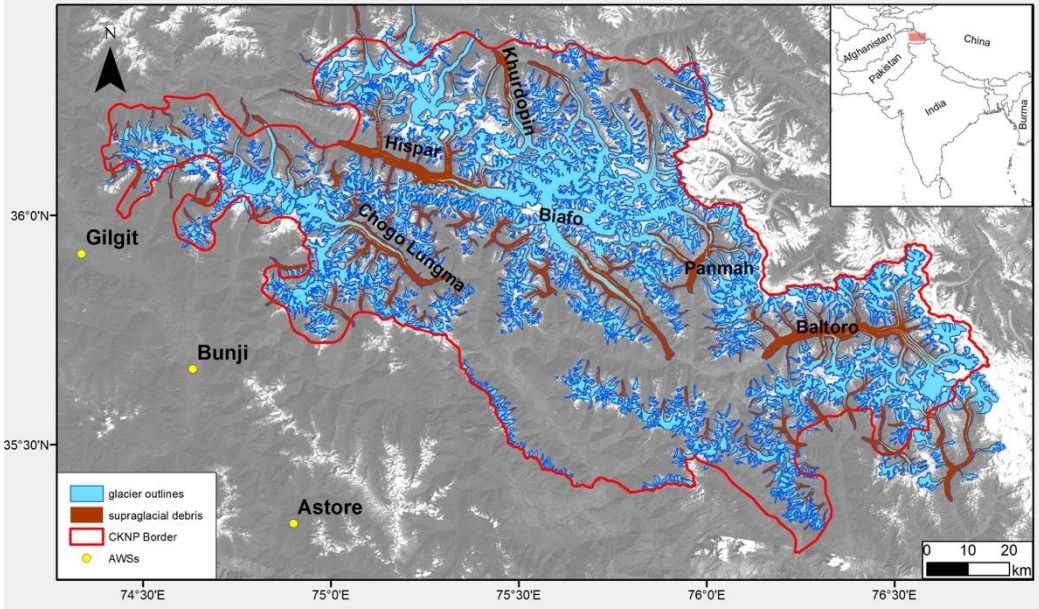
The Karakoram anomaly ???

Article

Progress in Physical Geography
1–32
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DOI: 10.1177/0309133316643926
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SAGE

Glacier area stability in the Central Karakoram National Park (Pakistan) in 2001–2010: The "Karakoram Anomaly" in the spotlight

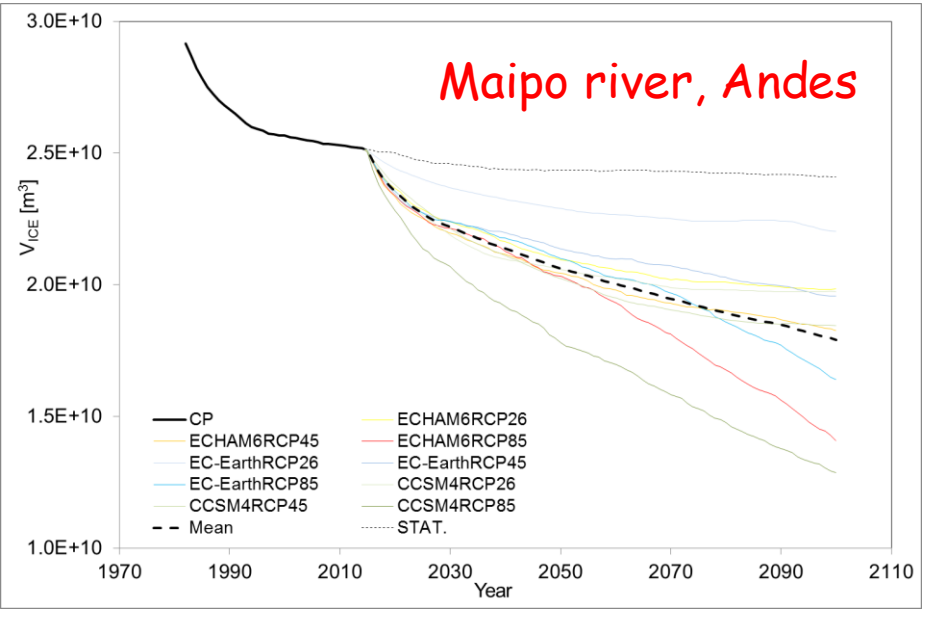


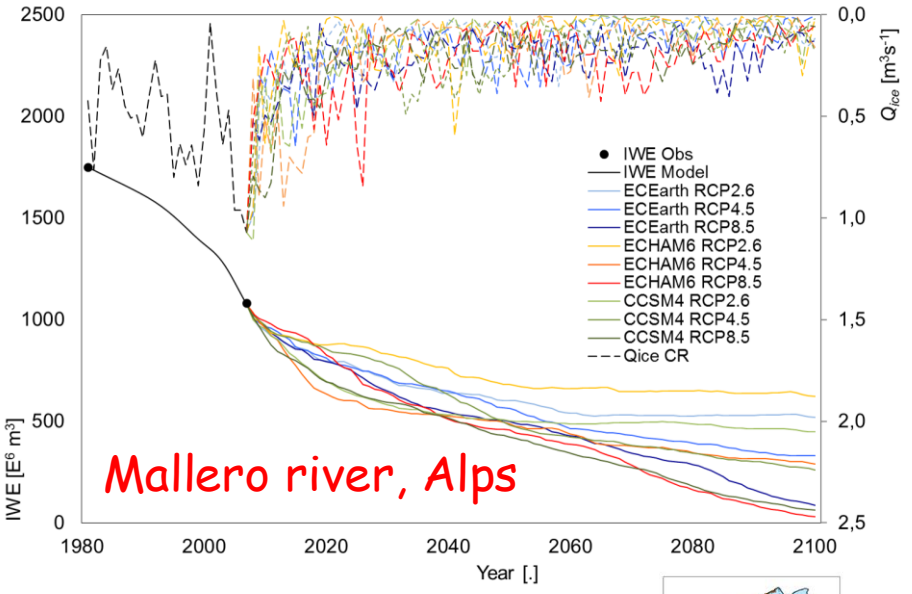




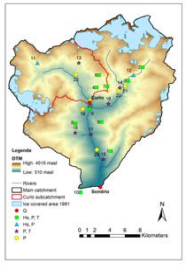
Common traits arising

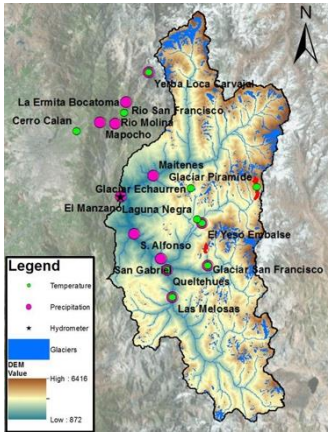
A comparison of (projected) glaciers' evolution in our case study area

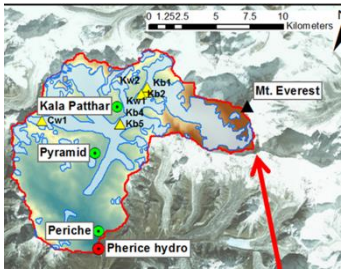


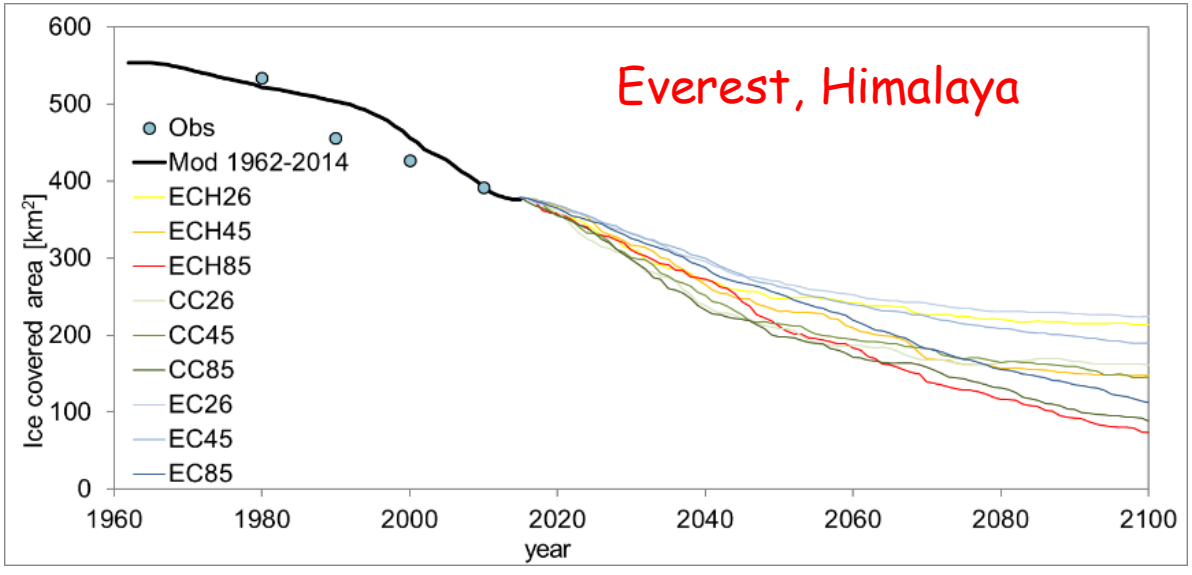


Different stages of the same process !!!



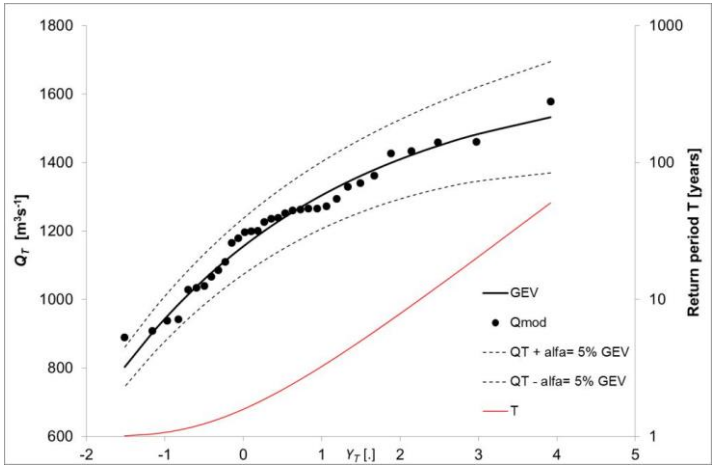






Hydrologic model: flash floods

Using yearly maximum value of simulated daily discharges (1980-2012), we assessed extreme floods, according to theory of extreme values, within the Shigar river, under the present climate, and under prospective climate change, until 2099.

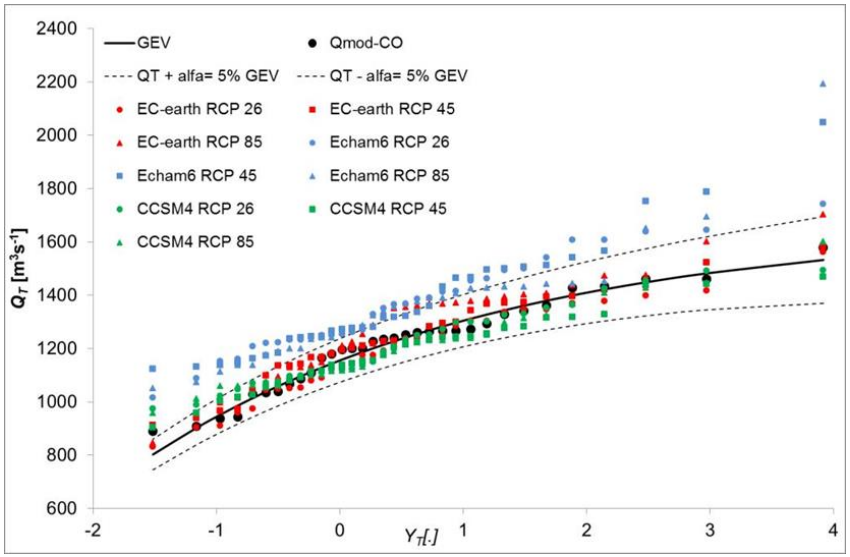


T-years return period in stream discharge is expressed as

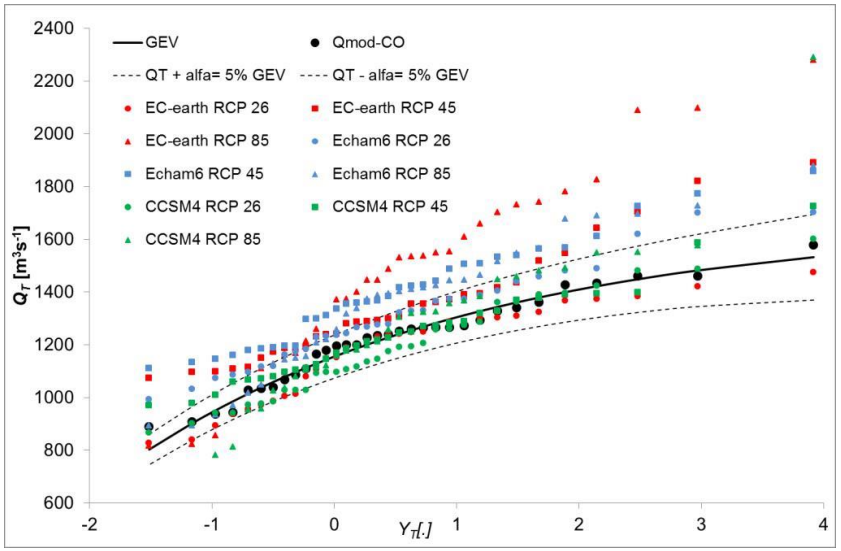
$$Q(T) = Q_{in}\left\{\varepsilon + \frac{\alpha}{k}\left[1-\left(-\ln\left(1-1/T\right)\right)^{k}\right]\right\}$$

$$Q_{in} = E[Q_{AFS}] = \frac{1}{n}\sum_{j=1}^{n} Q_j$$

Projected samples during 2024-2056



Projected samples during 2068-2100



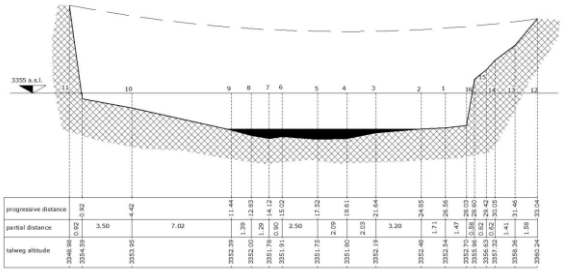
INTEGRATED PARK MANAGEMENT PLAN (IPMP)

FOR CENTRAL KARAKORUM NATIONAL PARK

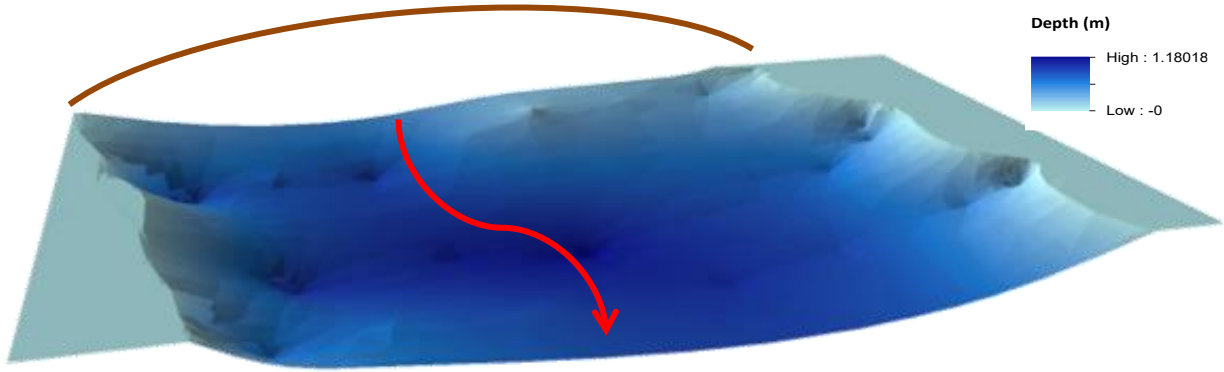
"It is tremendously important that water resources and their dynamics …are being continuously monitored, by starting as soon as possible. Building a clear picture of the surface water availability, and temporal dynamics in the area are necessary for developing accurate water management strategies"….. and early warning of floods

STREAM FLOW MEASUREMENT PROTOCOL





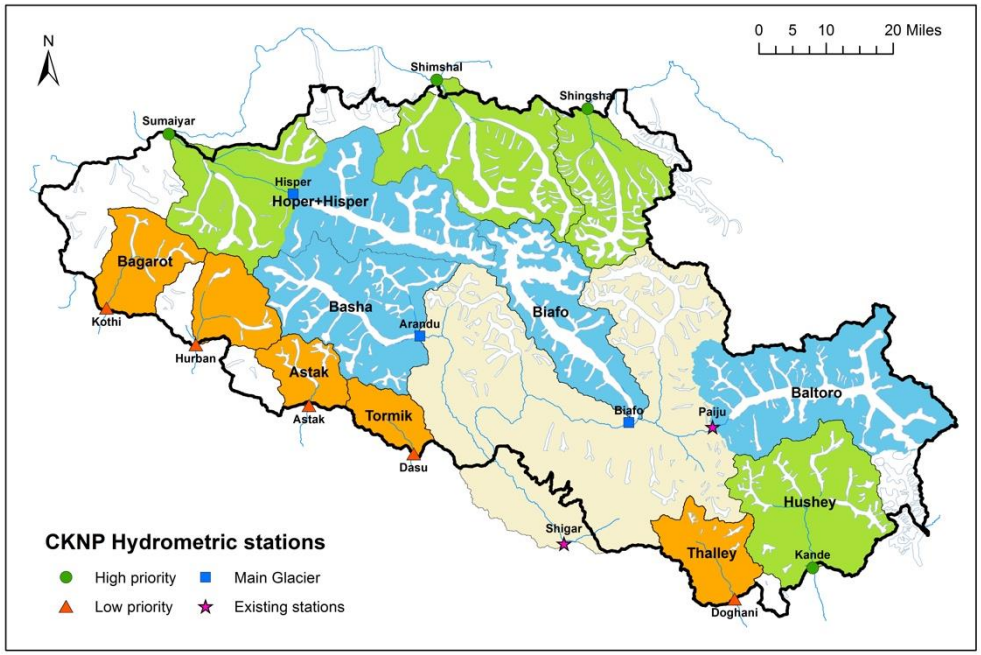




We report here suggestions for assessment of water resources and their timing, based upon:

1) Installation of a hydrometric network;
2) Modeling of hydrological regime.

Here it was proposed (2015) a preliminary layout of a hydrometric network [for CKNP].
We propose to install a number of stations allowing to measure outflow from the Park at their outlet sections. One may monitor with special emphasis smaller catchments, at the outlet of some especially significant glaciers, sensitive to climate warming



Flood forecasting, and early warning

Based upon

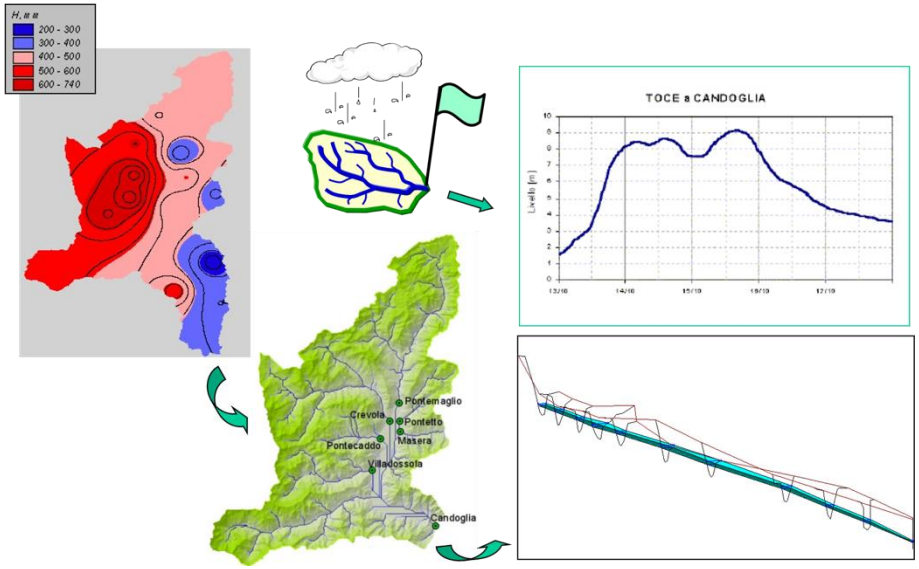
1) Real time meteorological data (precipitation, and temperature), weather now-forecasting, and thresholds

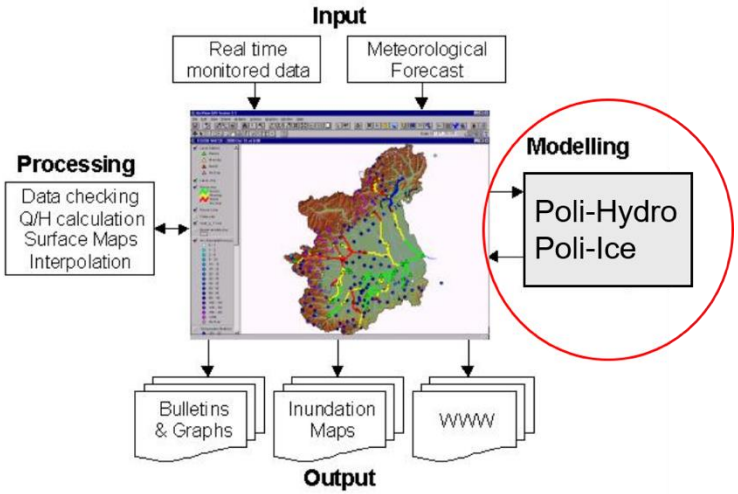
2) Real time hydrological data (level h, and stage-discharge conversion to stream flow Q)

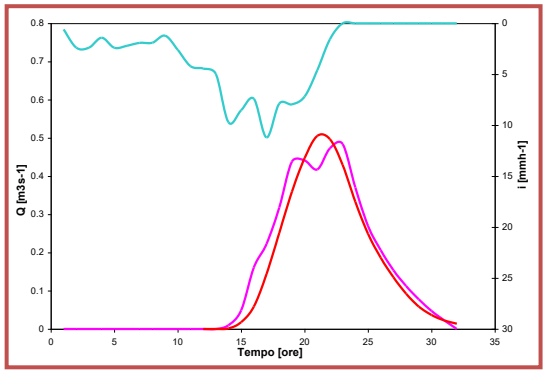
3) Hydrological modeling, with off-line, or on-line tuning, including snow/ice melting

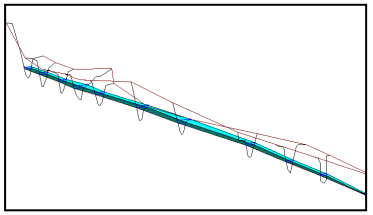
4) Whenever possible, hydraulic sections, and 1D-2D hydraulic modeling for flood routing

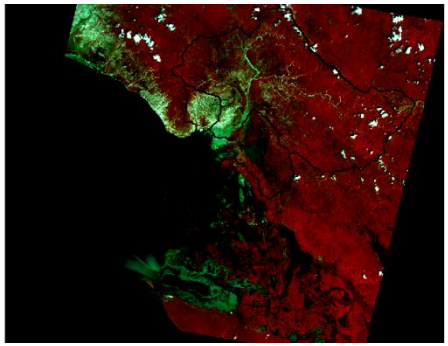
One can provide hydrological now-forecasting of peak flows, and floods.

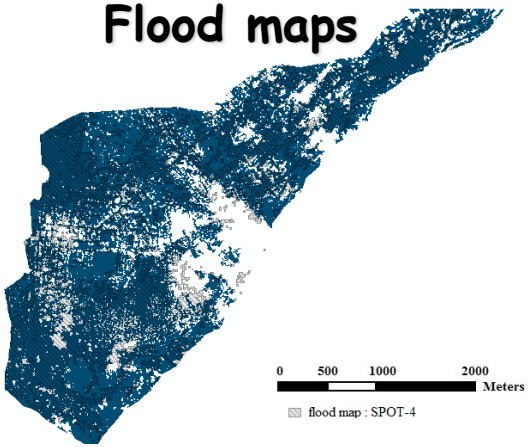


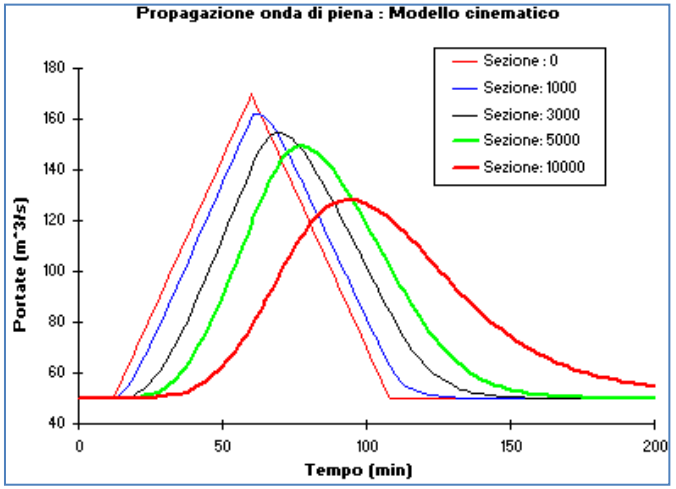

Input
Real time monitored data
Meteorological Forecast
Processing
Data checking
Q/H calculation
Surface Maps
Interpolation
Modelling
Poli-Hydro
Poli-Ice
Bulletins & Graphs
Inundation Maps
WWW
Output

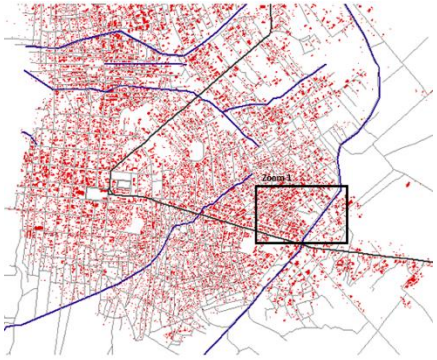

Q [m3s-1]
i [mmh-1]
Tempo [ore]

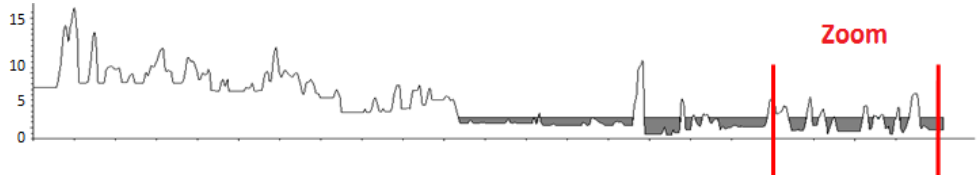





Flood maps
0 500 1000 2000
Meters
flood map : SPOT-4


Propagazione onda di piena : Modello cinematico
Sezione : 0
Sezione: 1000
Sezione: 3000
Sezione: 5000
Sezione: 10000
Portate (m^3/s)
Tempo (min)


Zoom 1


Zoom

Thanks you for your attention



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