A GIS embedded approach for Free & Open Source Hydrological Modelling

Massimiliano Cannata,
Institute of Earth Sciences (SUPSI),
Lugano, Switzerland

Maria Antonia Brovelli,
Politecnico di Milano,
Como, Italy

The project: Interreg IIIA (Switzerland-Italy)

ARPA PIEMONTE
Area Previsione e Monitoraggio Ambientale
C.so Unione Sovietica, 216
10134 TORINO

SCUOLA UNIVERSITARIA PROFESSIONALE DELLA SVIZZERA ITALIANA
Istituto di Scienze della Terra
Centro Studi Trevano, c.p. 72
6952 CANOBBIO

REGIONE LOMBARDIA
Unità Organizzativa Protezione Civile
Via Fara, 26
20124 MILANO

PROVINCIA DEL VERBANO CUSIO OSSOLA
Settore Protezione Civile
Via dell'Industria, 25
28924 VERBANIA Fondotoce

UFFICIO FEDERALE DI METEOROLOGIA E CLIMATOLOGIA METEOSVIZZERA
via ai Monti della Trinità, 146
6605 LOCARNO MONTI

REGIONE PIEMONTE
Direzione Opere Pubbliche
C.so Marche, 79
10146 TORINO
Direzione Difesa Suolo
Via Petrarca, 44
10100 TORINO

REPUBBLICA E CANTONE DEL TICINO
Dipartimento del Territorio
Ufficio dei corsi d'acqua
Viale Franscini, 17
6501 BELLINZONA

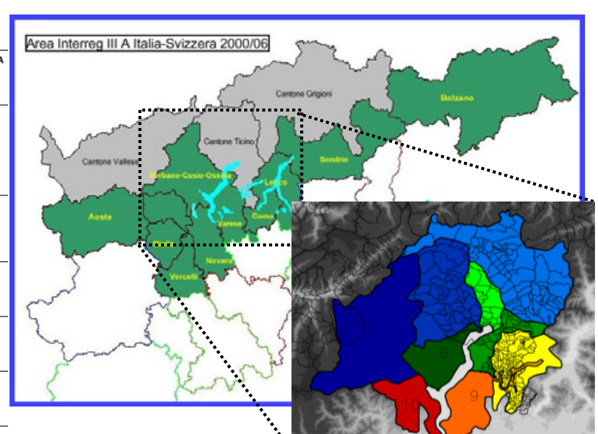
REGISTRO ITALIANO DIGHE
Ufficio Idraulica
Via Curtatone, 3
00185 ROMA

CONSIGLIO NAZIONALE DELLE RICERCHE
Istituto di Ricerca per la Protezione Idrogeologica
Strada delle Cacce, 73
10135 TORINO

POLITECNICO DI TORINO
Dipartimento di Idraulica Trasporti e Infrastrutture Civili
C.so Duca degli Abruzzi, 24
10129 TORINO

POLITECNICO DI MILANO
Dipartimento di Elettronica
Piazza L. Da Vinci, 32
20133 MILANO

Development of an hydro-geological risk management system in the Lake Maggiore area.



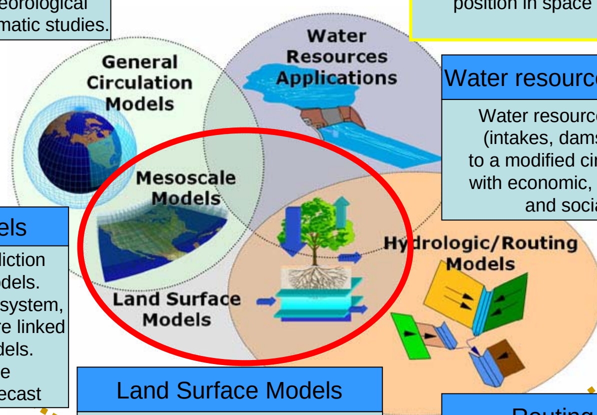
Managment System Components

General Circulation Model

GCMs describe climate behavior by means of physically based atmospheric modelling and are used to produce meteorological forecasts or perform climatic studies.

Space-time

Every physical phenomena is a direct function of its position in space and time.



Water resource Applications

Water resource exploitation (intakes, dams, etc.) leads to a modified circulation model with economic, environmental and social goals.

Mesoscale Models

Numerical weather prediction models and climate models. They work in a projected system, use observed data and are linked with other surface models. They usually provide short/medium term forecast

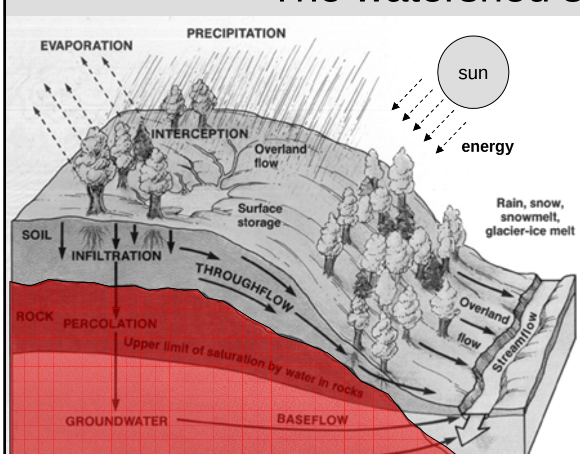
Land Surface Models

Simulation of the water resource distribution at the ground with estimates of each water component quantity.

Routing Models

Solve mass balance equations to evaluate water discharges through and over the soil.

The watershed system



Distributed, represents the hydrologic variables continuously in the space (raster maps);

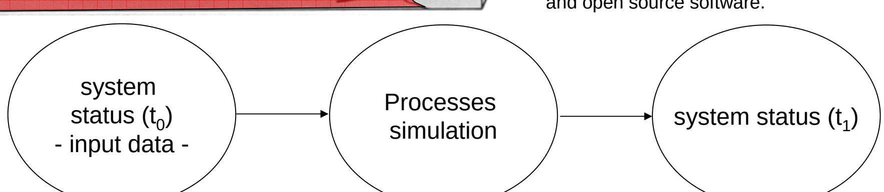
Physically based: all the used variables has a physical meaning;

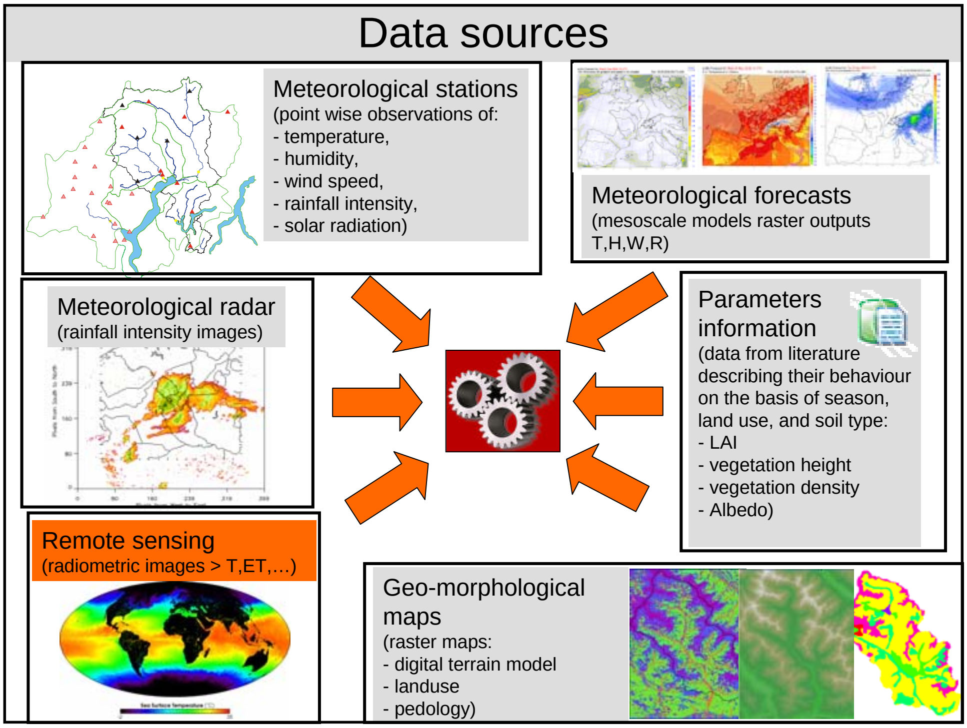
Continuous: generates estimations at consecutive time steps (hourly resolution);

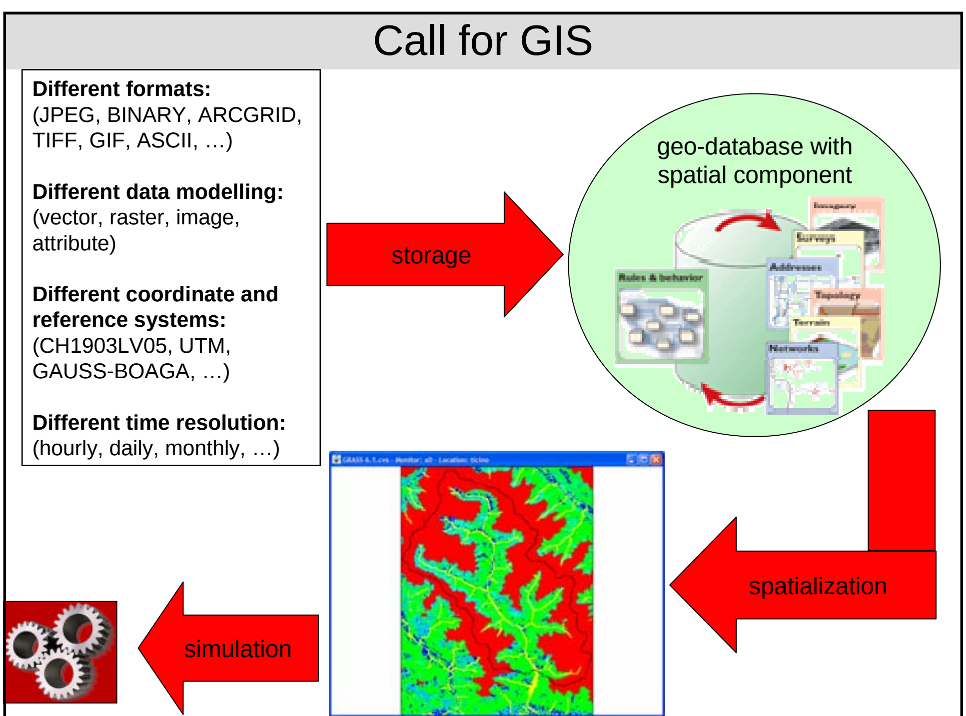
Modular: assembled by means of the combination of different stand-alone sub-models simulating different rainfall-runoff involved processes.

Fully embedded: all the routines developed by using GIS commands or GIS libraries.

Open Source: generated by using only free and open source software.

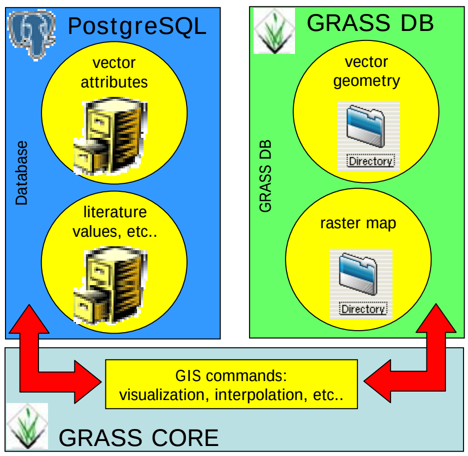


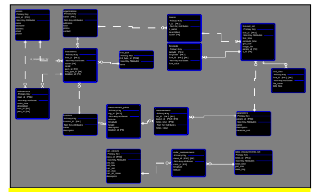

Data sources
Meteorological stations
(point wise observations of:
- temperature,
- humidity,
- wind speed,
- rainfall intensity,
- solar radiation)
Meteorological forecasts
(mesoscale models raster outputs
T,H,W,R)
Meteorological radar
(rainfall intensity images)
Parameters information
(data from literature describing their behaviour on the basis of season, land use, and soil type:
- LAI
- vegetation height
- vegetation density
- Albedo)
Remote sensing
(radiometric images > T,ET,…)
Geo-morphological maps
(raster maps:
- digital terrain model
- landuse
- pedology)


Call for GIS
Different formats:
(JPEG, BINARY, ARCGRID, TIFF, GIF, ASCII, …)
Different data modelling:
(vector, raster, image, attribute)
Different coordinate and reference systems:
(CH1903LV05, UTM, GAUSS-BOAGA, …)
Different time resolution:
(hourly, daily, monthly, …)
storage
geo-database with spatial component
spatialization
simulation

Geo-database with time component

Free & Open Source





on-line stations database

vector time series data format definition

raster time series data format definition

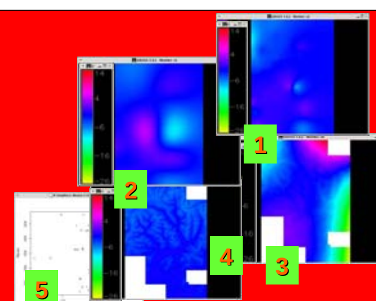
Disk space management (1 month ~ 2GB)

Spatializzation

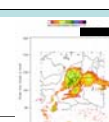
Temperature: 5 model analyzed with leave-one-out cross-correlation approach:

1. INVERSE DISTANCE (idw)
2. SPLINES
3. POLINOMY OF DEGREE 3 IN X,Y PLUS ONE Z TERM
4. POLINOMY OF DEGREE 1 IN Z
5. POLINOMY OF DEGREE 2 IN Z

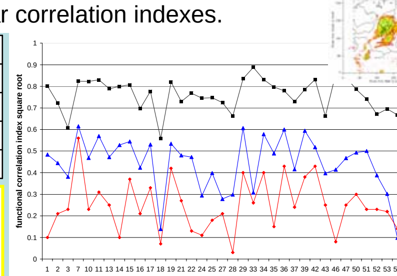
Following the MAE criteria the best model is the linear gradient (model 4) in Z



Rainfall: meteorological radar data validation with rain gauge observations by using semi-variograms, linear and non linear correlation indexes.

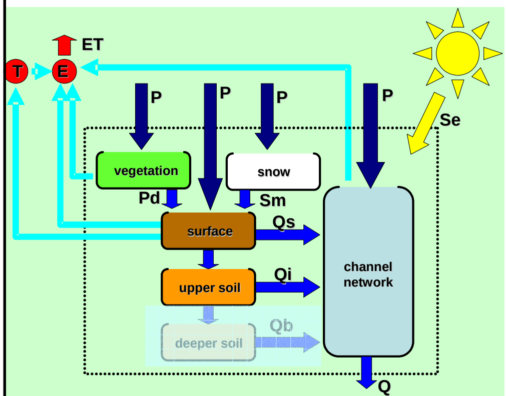


		RAIN GAUGE		
		rain	no-rain	tot
RADAR	rain	16218	6482	22700
	no-rain	18050	210318	228368
	tot	34268	216800	251068



The spatial component of radar data is quite good while the magnitude is not comparable with gauges data.

Processes



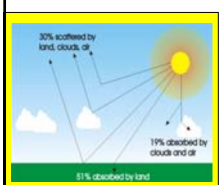
global radiation

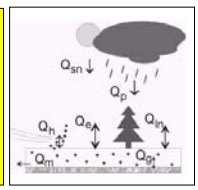
snow melt and accumulation

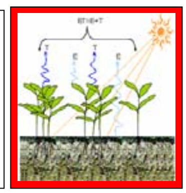
evapotraspiration

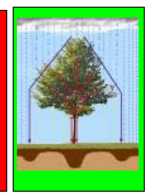
canopy interception

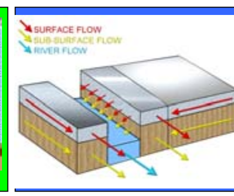
runoff









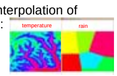


Modules implementation

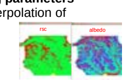
New modules were implemented either by using GRASS libraries and Shell script for the sub-process simulation. The results were validated.

INPUT MAP GENERATION

- **Meteorological maps** from interpolation of climatic stations observations:
  - ❑temperature
  - ❑humidity
  - ❑wind velocity
  - ❑solar radiation
  - ❑rain

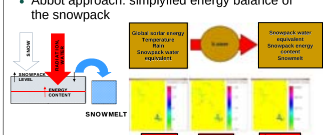


- **Watershed characterizing parameters maps:** Spatio-temporal interpolation of literature values:
  - ❑Albedo
  - ❑LAI
  - ❑Linke
  - ❑Vegetation height
  - ❑Vegetation cover



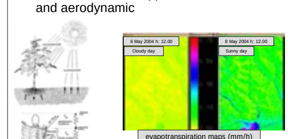
SNOWMELT AND ACCUMULATION

- Abbot approach: simplyfied energy balance of the snowpack



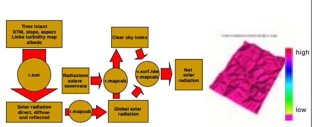
POTENTIAL EVAPOTRANSPIRATION

- Penman-Monteith approach: radiative term and aerodynamic



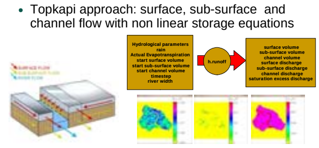
NET SOLAR RADIATION

- Calculated in function of the date, the hour and the cloudiness



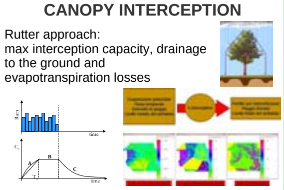
RUNOFF

- Topkapi approach: surface, sub-surface and channel flow with non linear storage equations



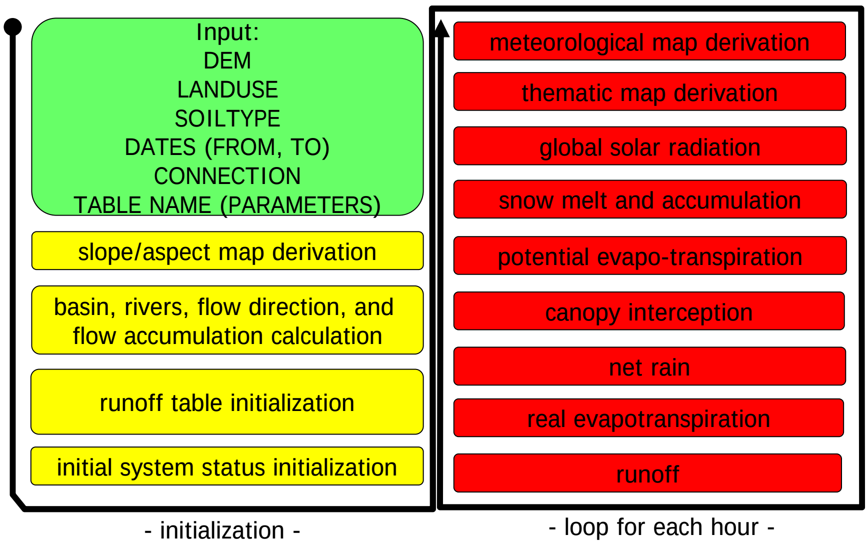
CANOPY INTERCEPTION

- Rutter approach: max interception capacity, drainage to the ground and evapotranspiration losses



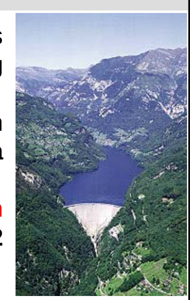
HydroFOSS

The general model (HydroFOSS) is assembled by a shell script linking and running in the correct sequence all the required modules and commands. (data access, spatialization, simulation, results storage)

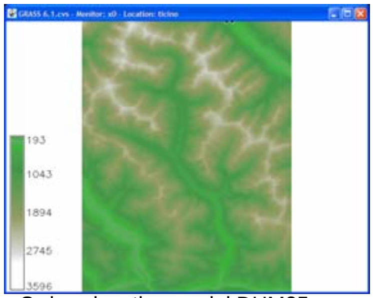


Case study: the Verzasca basin

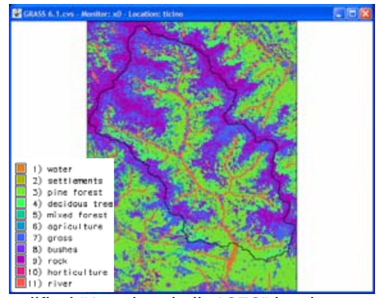
- The Verzasca river flows from the Alps to the Lake Maggiore and has a **length of 34 Km** with a **mean discharges of 1 m³/s** that, during **floods events**, can easily rise up to **250 m³/s**.
- The drained area has an **extension of 218 Km²** and registers a mean annual precipitation of **1976 mm** with a mean of **129 rainy days a year**.
- The basin shows the **typical Alpine characteristics** with its **high elevation ranges** (**from 193 m to 3596 m a.s.l.**), **narrow valley** (**2 Km wide**), and **high mean slope** (**33.93°**).



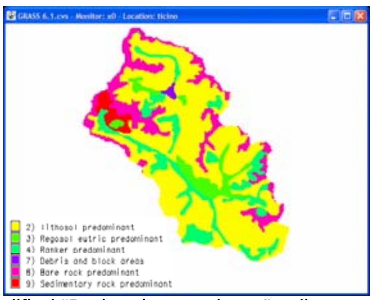
Case study: basic data



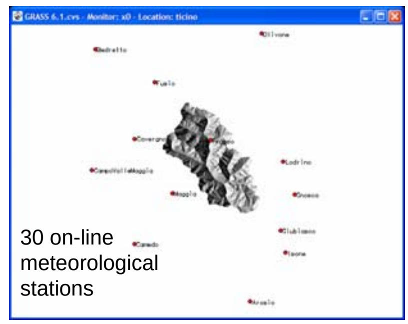
Swiss elevation model DHM25 map



modified “Arealstatistik 1972” landuse map



modified “Bodeneignungskarte” soiltypes map

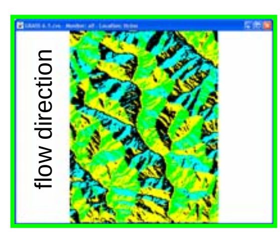


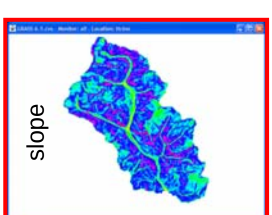
Case study: derived data

r.slope.aspect

r.watershed

r.mapcalc





Case study: spatialized climatic data

v.surf.idw (npoints=1)

linear regression + r.mapcalc

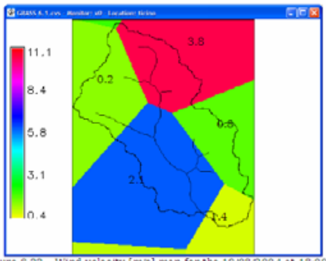


Figure 6.22 – Wind velocity [m/s] map for the 19/08/2004 at 18:00

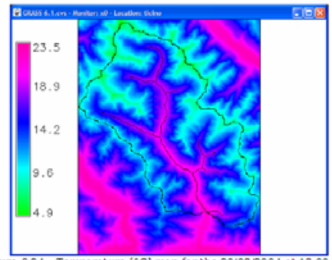


Figure 6.24 – Temperature [°C] map for the 20/08/2004 at 18:00 (day)

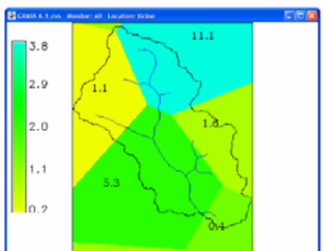


Figure 6.23 – Wind velocity [m/s] map for the 20/08/2004 at 18:00

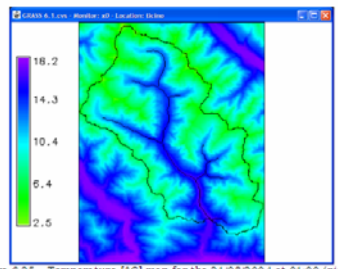


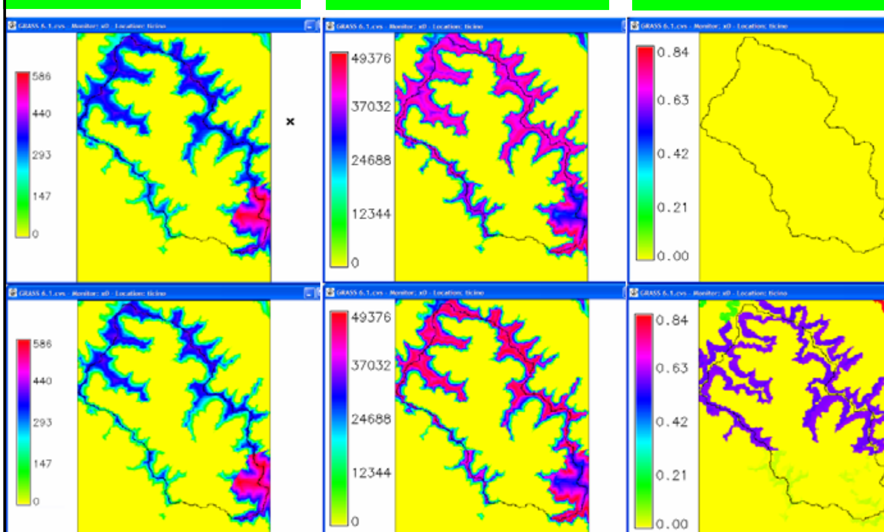
Figure 6.25 – Temperature [°C] map for the 21/08/2004 at 01:00 (nigth)

Case study: the snow module

snowpack water equivalent [mm]

snowpack energy content [Kcal/m^2]

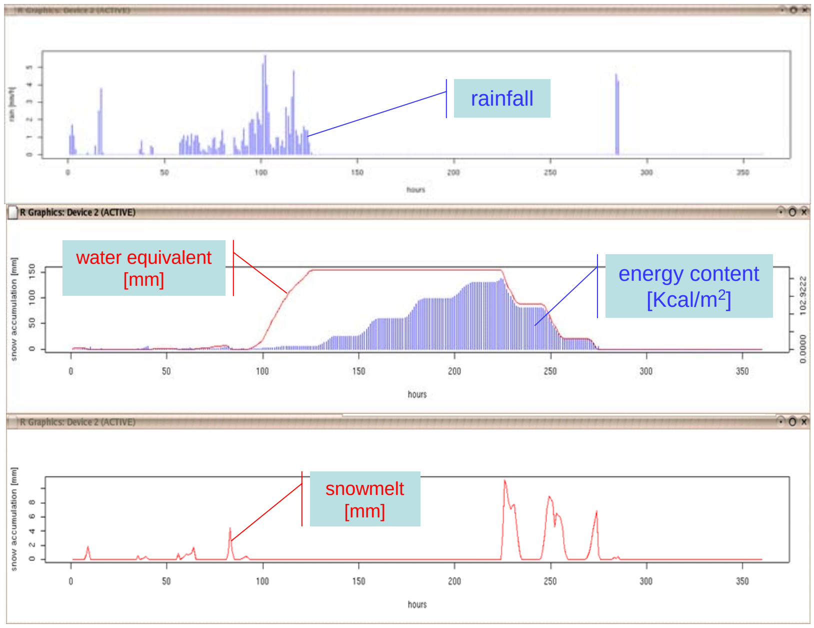
snowmelt [mm]



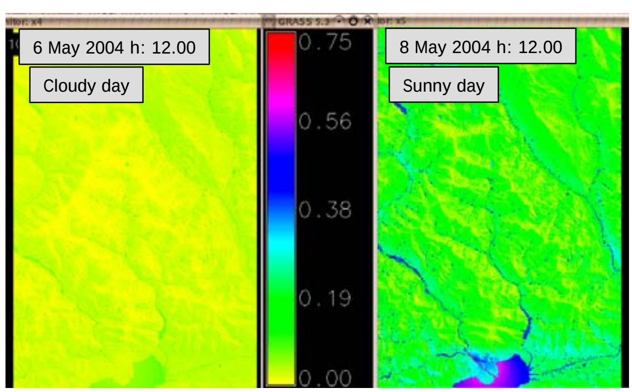
17th Aug. 2004 h. 00:00 am.

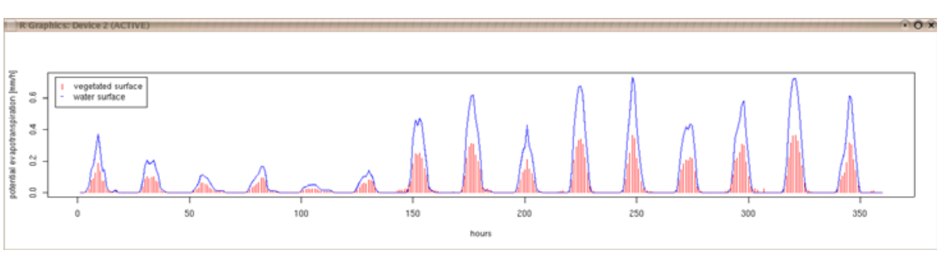
18th Aug. 2004 h. 10:00 am.

Case study: the snow module



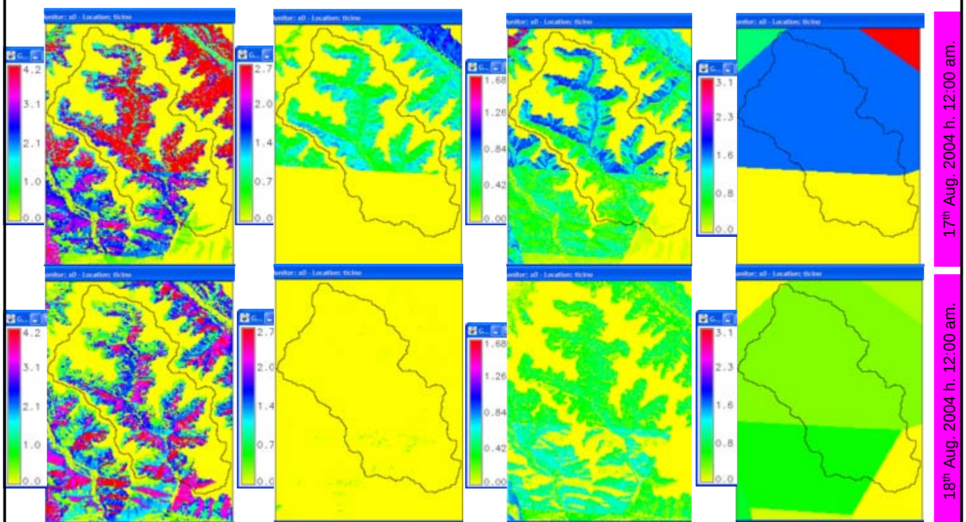
Case study: the evapotranspiration module



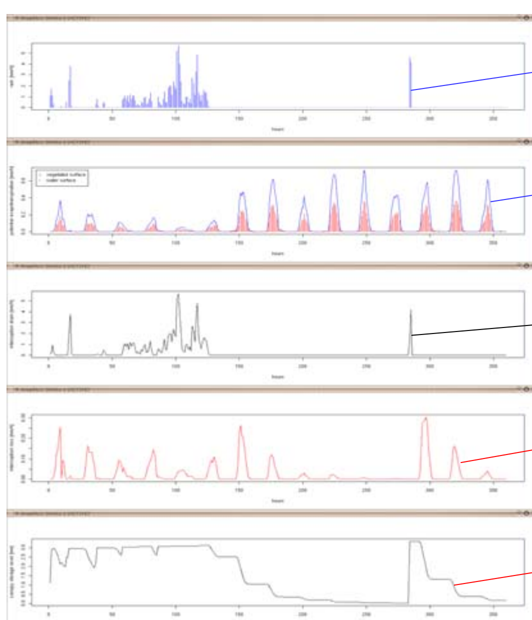


Case study: the canopy interception module

canopy storage level [mm] | interception drainage [mm/h] | interception losses [mm/h] | rainfall [mm/h]



Case study: the canopy interception module



Rainfall [mm/h]

Evaporation from liquid surface [mm/h]

Interception drainage [mm/h]

Interception losses [mm/h]

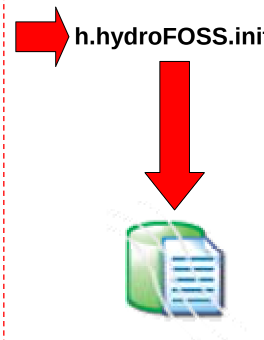
Canopy storage level [mm]

Case study: runoff initialization

- **Ks** – the saturated hydraulic conductivity; p(S_Type) **[*]**
- **Teta_s** – the saturated soil water content; p(S_Type)**[*]**
- **Teta_r** – the residual soil water content; p(S_Type) **[*]**
- **Alfa** – the soil type dependent parameter; p(S_Type)**[*]**
- **L** – the soil thickness; p(S_Type) **[*]**

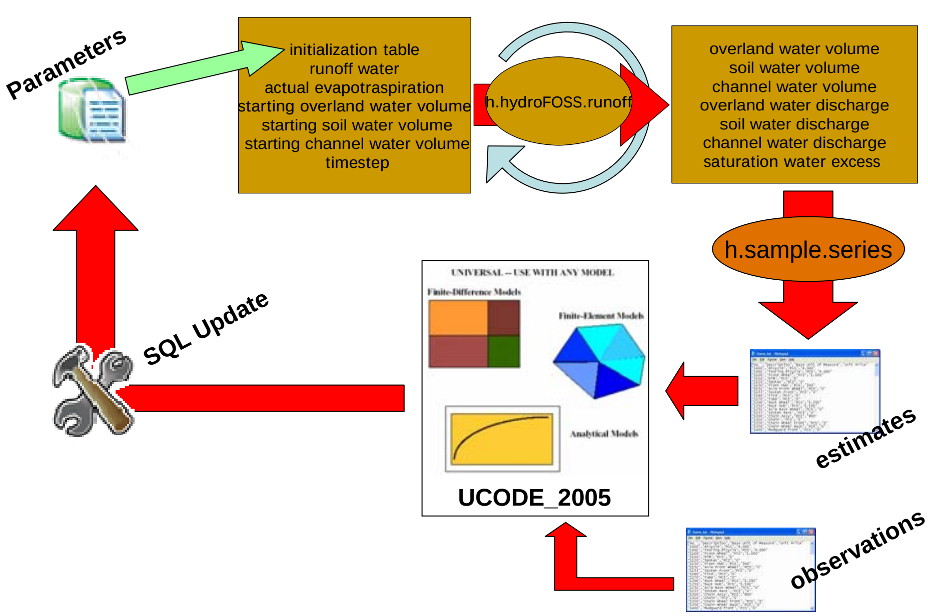
- **n** – the Manning coefficient; p(LU) **[*]**

- **Basin** – the basin index; (rast)
- **Direction** – the flow direction index; (rast)
- **Accumulation** – the flow accumulation value; (rast)
- **Slope** – the terrain slope; (rast)
- **h_type** – the hydrological type; (rast)
- **width** – the riverwidth; (rast)
- **L_use** – the landuse category; (rast)
- **S_type** – the soiltype category; (rast)



[*] --> parameters suitable for calibration

Case study: sensitivity analysis & calibration



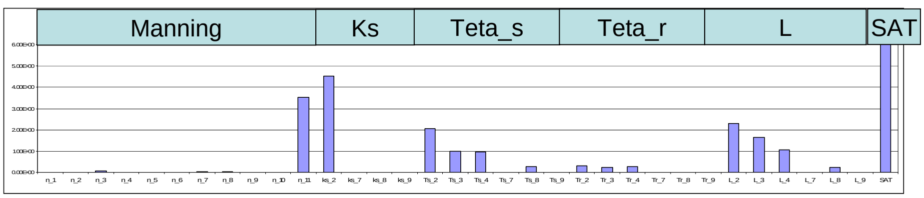
Case study: sensitivity analysis

Simulations are computationally expensive (~30 s/h).

In calibration phase multiple model running over long periods (months) are needed.

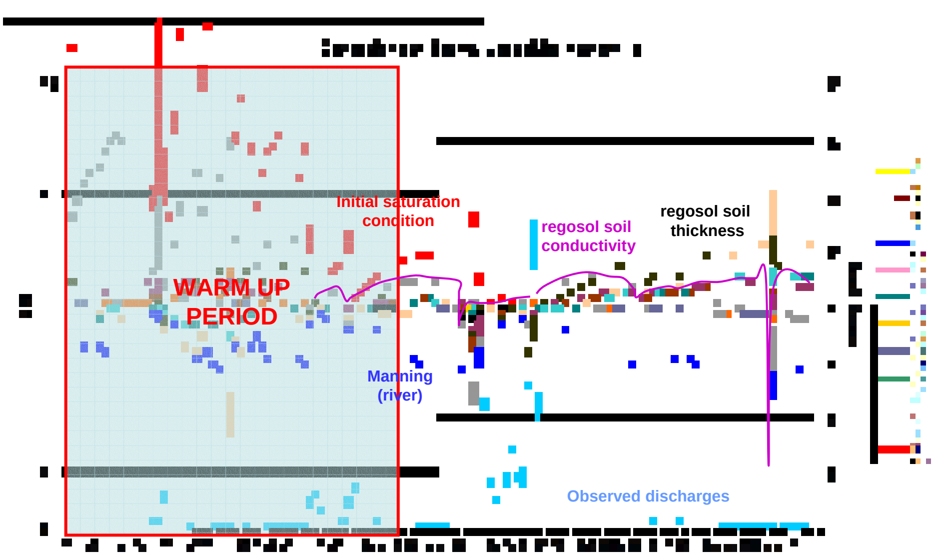
Collaboration with the Swiss National Supercomputing Centre (CSCS) to reduce computational time.

Composite Scaled Sensitivity (CSS)
The total amount of information provided by the observations for the estimation of the parameter *j*
(summarize all the sensitivities for one parameter)

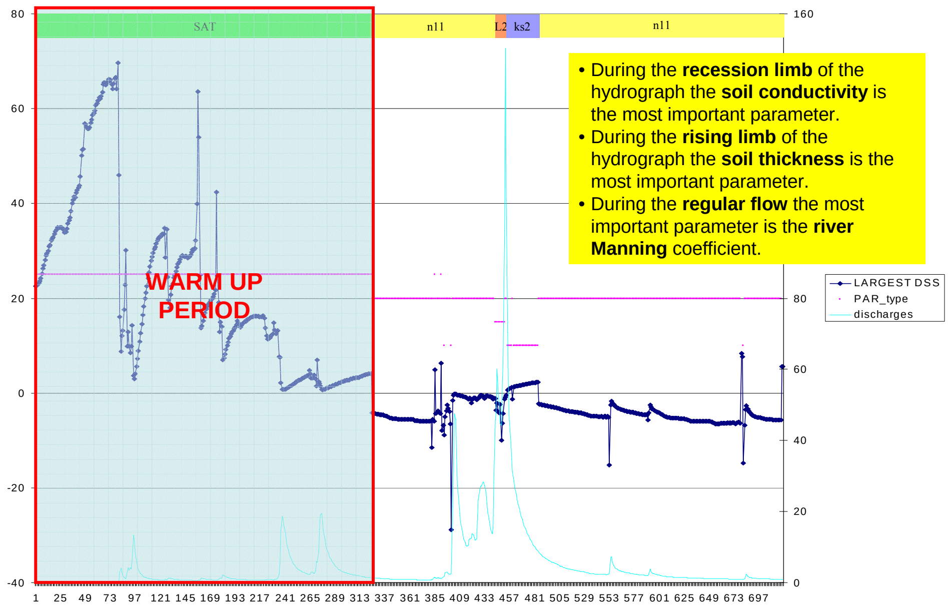


Case study: sensitivity analysis

Dimensionless Scaled Sensitivity (DSS_{ij})
The importance of the parameters *j* to the calculation of an observed value *i*



Case study: sensitivity analysis

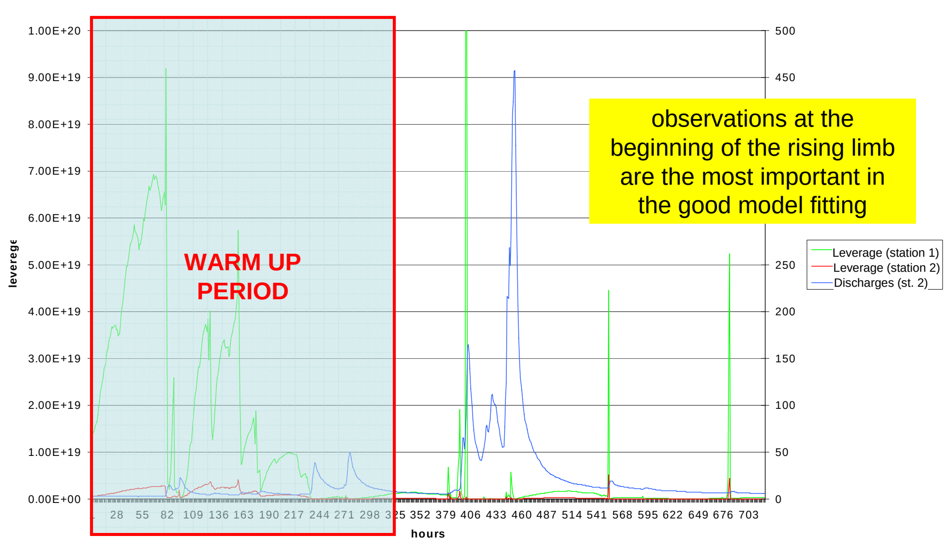


- During the **recession limb** of the hydrograph the **soil conductivity** is the most important parameter.
- During the **rising limb** of the hydrograph the **soil thickness** is the most important parameter.
- During the **regular flow** the most important parameter is the **river Manning** coefficient.

Case study: sensitivity analysis

Leverage

measures the influence of the observation *i* on the regression due to its location in the space of the inputs

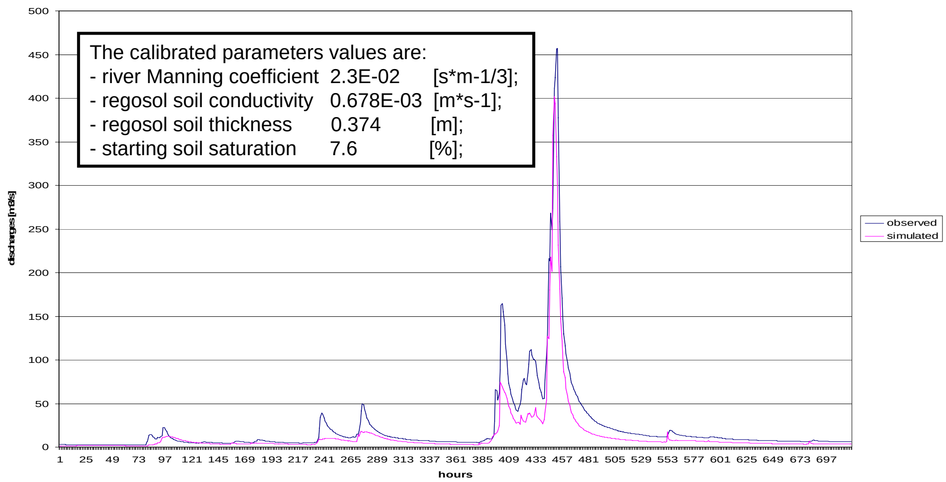


observations at the beginning of the rising limb are the most important in the good model fitting

Case study: runoff calibration

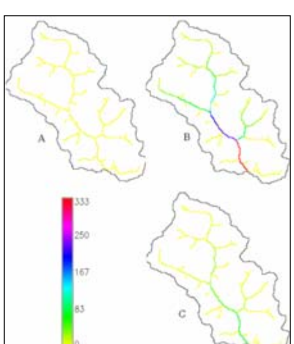
calibration process upon 8 parameters:
n_11, ks_2, ks_3, ks_4, L_2, L_3, L_4, and SAT

In order to reduce the iterations, only the most important parameter of ks and L set was directly calibrated. The others parameters were proportionally scaled

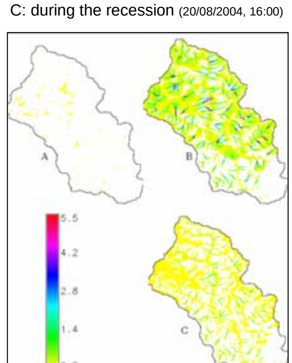


Case study: runoff calibration

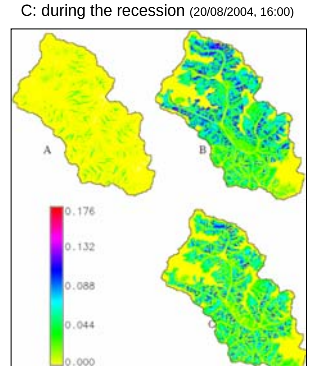
channel
water discharge [m³/s]
A: before the event (17/08/2004, 16:00).
B: during the peak (20/08/2004, 06:00).
C: during the recession (20/08/2004, 16:00)



overland
water discharge [m³/s]
A: before the event (17/08/2004, 16:00).
B: during the peak (20/08/2004, 06:00).
C: during the recession (20/08/2004, 16:00)



subsurface
water discharge [m³/s]
A: before the event (17/08/2004, 16:00).
B: during the peak (20/08/2004, 06:00).
C: during the recession (20/08/2004, 16:00)



Conclusions

Geographical Information Systems are projected in the era of modelling in order to allow a conscientious environmental management of the resources.

- The **GIS capability to model the rainfall-runoff has been proven** by means of the development of procedures and new commands simulating all the physical processes driving the water flows (HydroFOSS model).
- A **GIS embedded approach** establishes a valuable resource **for** solving numerous **management** problems.
- Free and Open Source (**FOSS**) GIS Software, **largely facilitates** the task of **new** procedures and model **development** due to the accessibility of its code, and availability of documentation.
- The followed modular approach, in conjunction with the standard GIS commands and the accessibility of the code, guarantees, to an expert user, to fully customize the application.
- A new standard model for time series data has to be defined as a key point in GIS embedded modelling.

Future work

- Definition of a **standard time series data format** (raster and vector).
- Development of **new modules** (for a **lumped model** and different time resolution).
- **Validation** of the single developed **modules** (lumped and distributed).
- Development of data **pre-processing procedures.**
- Further **sensitivity analysis & calibration** of the models and **comparison** with commercial models.
- Development of **Web Interface** for a distributed user friendly model usage (GRASS+PHP+AJAX).
- Writing of a **user manual** book.
- Code optimization to speed up prtocessing.

References

http://w3.ist.supsi.ch/geomatica/

http://grass.itc.it/

http://www.postgresql.org

UCODE

http://water.usgs.gov/software/ucode.html

Contacts:

massimiliano.cannata@supsi.ch

maria.brovelli@polimi.it