Integrated modelling of hydrological processes and groundwater dynamics at the river basin scale

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Goal

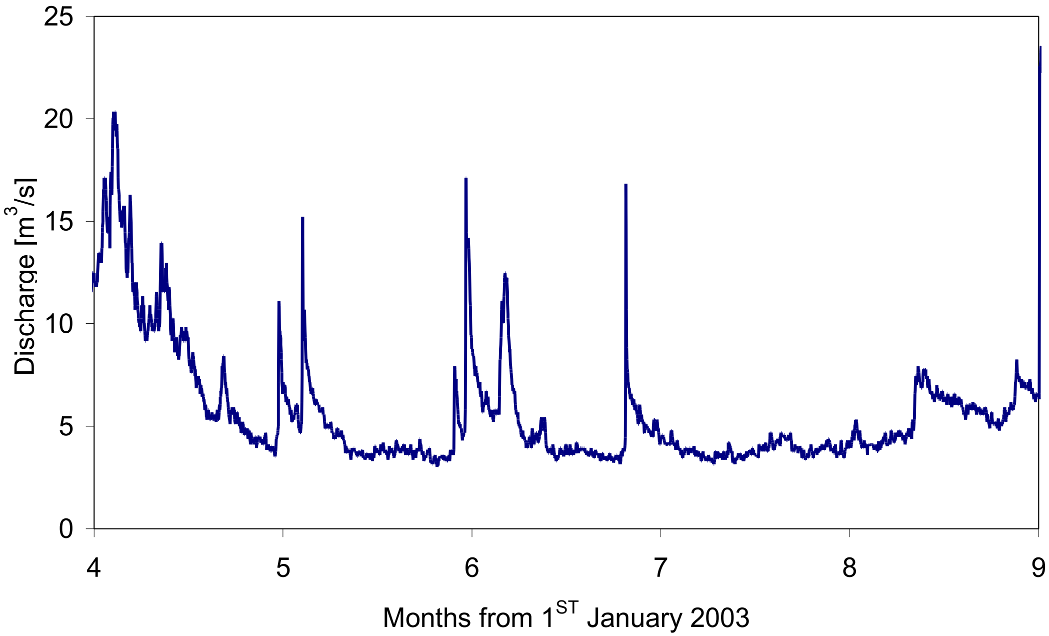
Modelling Serio's river flow (Italy)

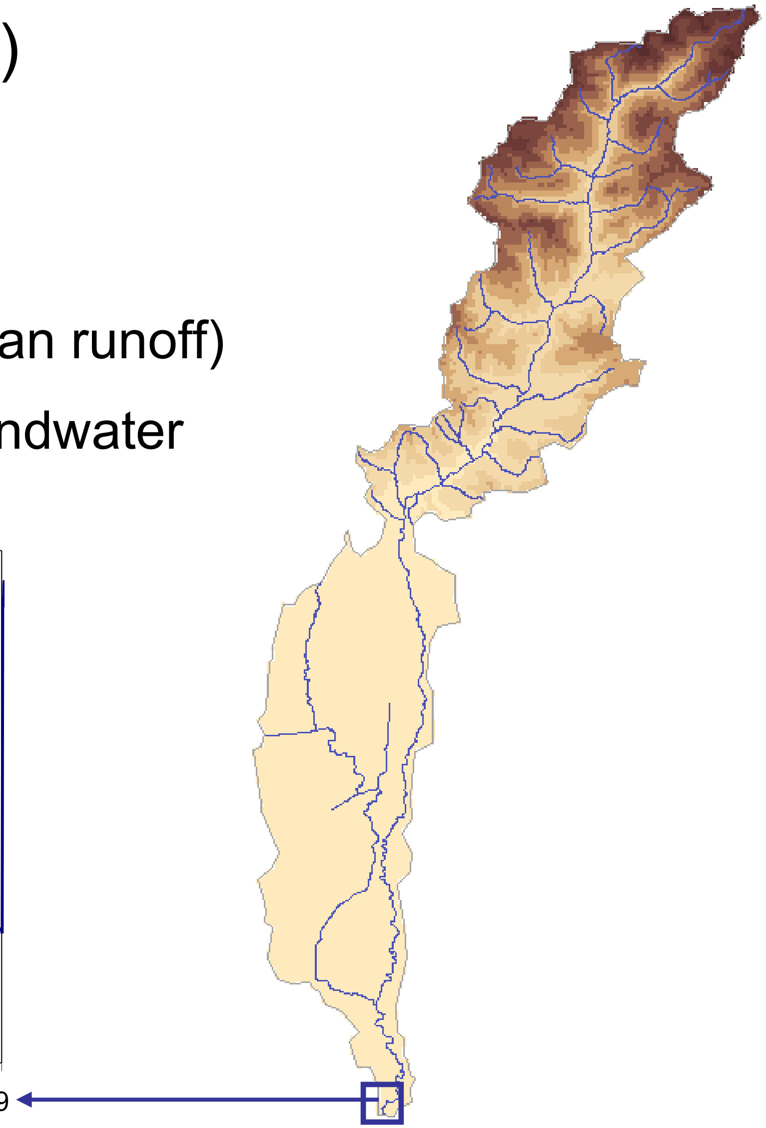
Area: 1050 km^2

Basin outlet: Montodine

Upstream basin: Mountainous (Hortonian runoff)

Downstream basin: flat landplain (groundwater contribution to river flow)

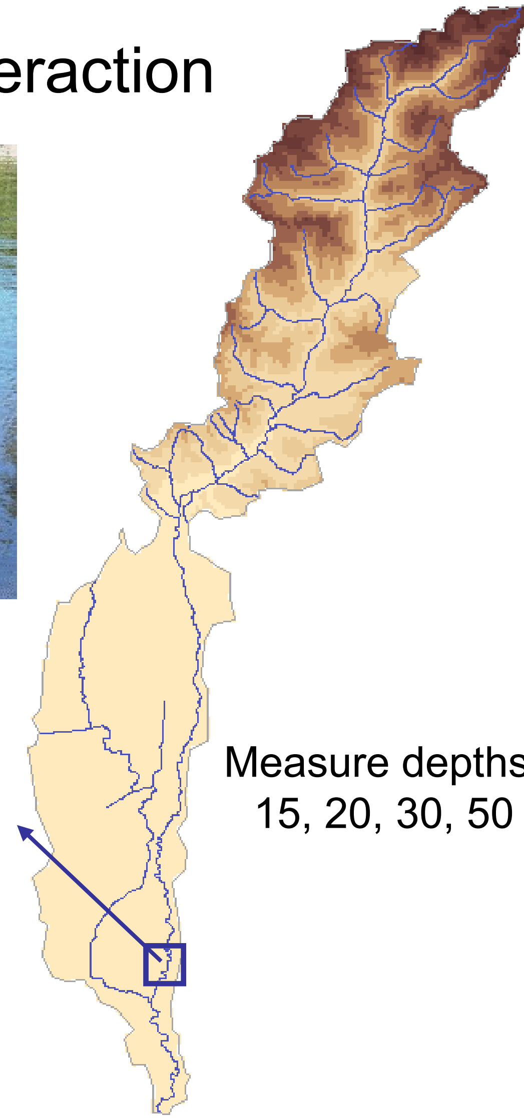




Field Campaign – 1 (Introduction)

Assessing groundwater-stream water interaction

Christian Schmidt from Helmholtz Centre for Environmental Research in Leipzig, Germany



Measure depths: 10, 15, 20, 30, 50 cm

Schmidt, C., Bayer-Raich, M., Schirmer, M, Characterization of spatial heterogeneity of groundwater-stream water interactions using multiple depth streambed temperature measurements at the reach scale, ***Hydrol. Earth Syst. Sci***., 10, 849-859, **2006**.

Field Campaign – 2 (Theory)

With the assumption that water flow in the streambed is essentially vertical, the governing equation for onedimensional conductive and advective heat transport is:

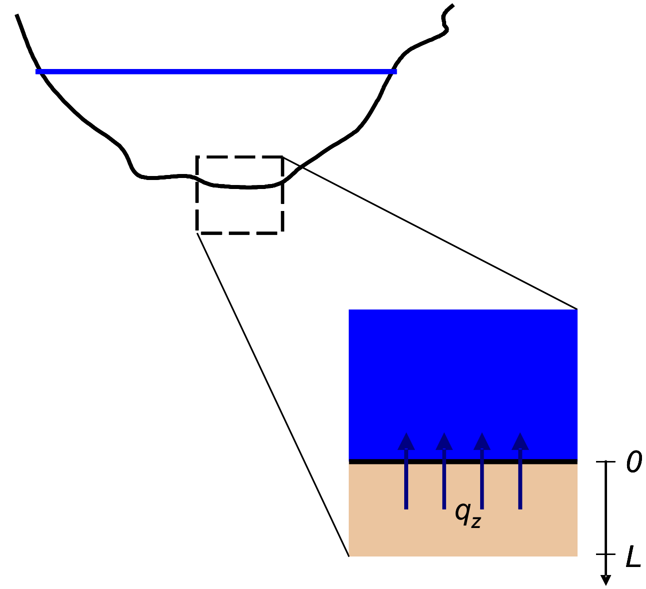
$$\frac{K_{fs}}{\rho c}\nabla^2 T(z) - \frac{\rho_f c_f}{\rho c}\nabla\left[T(z)q_z\right] = \frac{\partial T}{\partial t} \qquad \textbf{(1)}$$

where T_z[°C] is the streambed temperature at depth z; t is time [s]; q_z is the vertical Darcy velocity [m/s]; ρc is the volumetric heat capacity of the solid –fluid system; K_{fs} is the thermal conductivity of the saturated sediment [$Js^{-1}m^{-1}K^{-1}$].

Whit boundary conditions $T=T_0$ for $z=0$, and a fixed temperature T_L for $z=L$, where L [m] is the vertical extent of the domain, the solution can be obtained as (Bredehoeft and Papadopolus, 1965):

$$\frac{T(z)-T_0}{T_L - T_0} = \frac{\exp\left(\frac{q_z \rho_f c_f}{K_{fs}} z\right) - 1}{\exp\left(\frac{q_z \rho_f c_f}{K_{fs}} L\right) - 1} \qquad \textbf{(2)}$$

Equation (2) can be solved for q_z for a given L.



The objective function for obtaining q_z is given with:

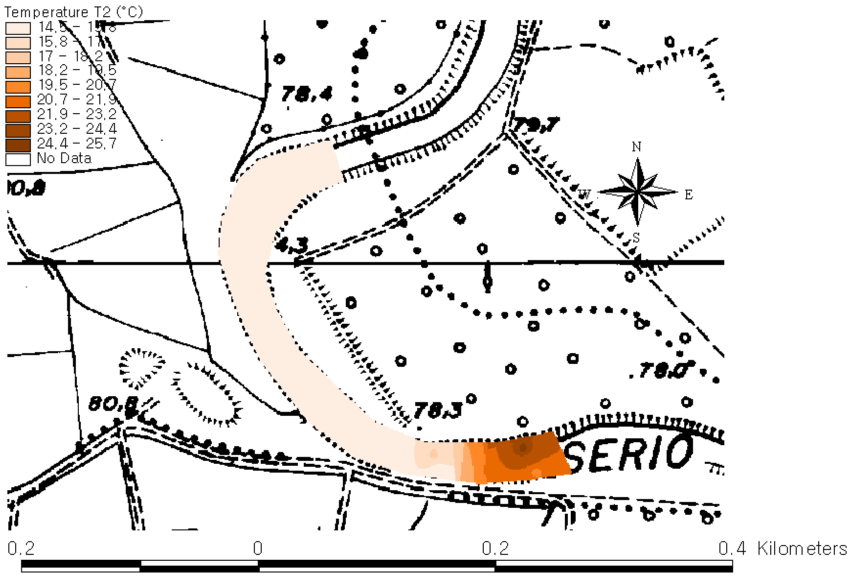
$$Error_k(L) = \sum_{j=1}^{5}\left[T_{jk} - \left(\frac{\exp\left(\frac{q_{zk}\rho_f c_f}{K_{fs}} z_j\right) - 1}{\exp\left(\frac{q_{zk}\rho_f c_f}{K_{fs}} L\right) - 1}(T_L - T_0) + T_0\right)\right]^2 \qquad \textbf{(3)}$$

Where q_{zk} is the value of q_z that minimizes $Error_k(L)$ for a given L at each temperature profile consisting of j=5 temperature observations.

Field Campaign – 3 (Results)

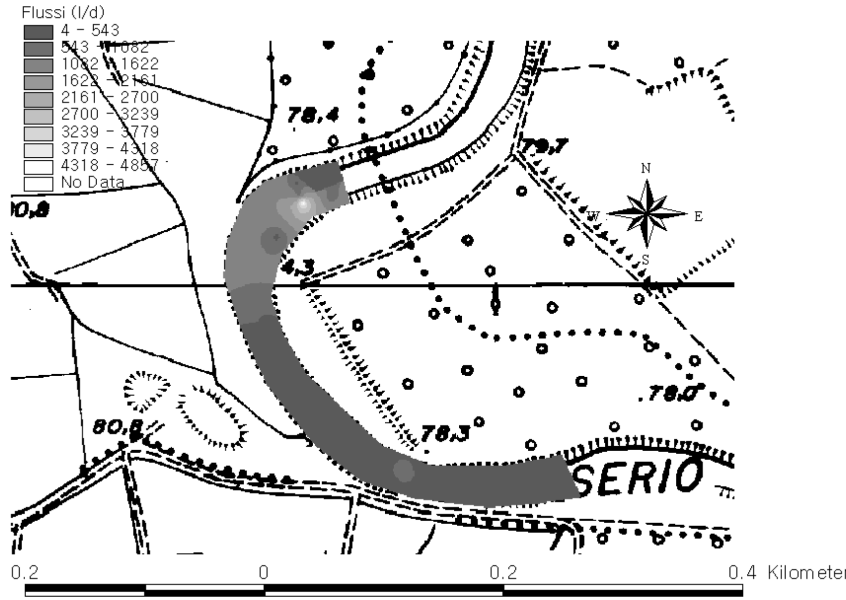
River reach (area = 17869 m², length = 470 m)

Spatial interpolation of measured temperature at 30 cm depth



Range: 14.5 – 26.7 °C

Spatial interpolation of estimated vertical flux



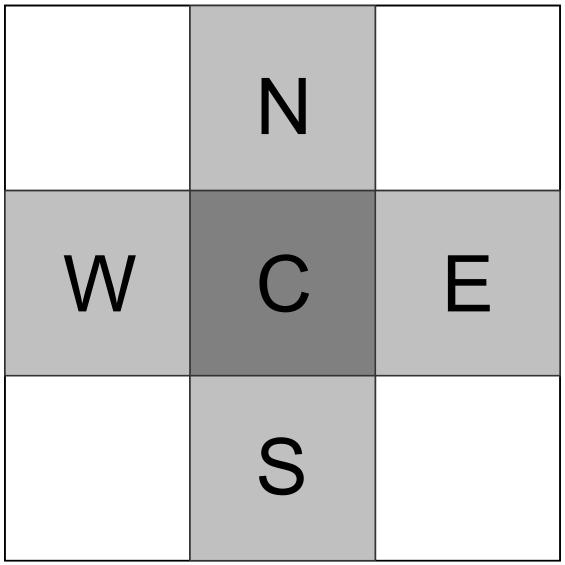
Average flux = 647 l/d/m²

Reach average flux = 11561243 l/d

Reach average flux = **0.28 m³/s/km**

Groundwater model – Development (CA)

Von Neumann neighbourhood definition



Scheme for the calculation of water fluxes

W_C

Q_{WC}

Q_{NC}

Q_{EC}

Q_{SC}

Local flux calculation

$$Q_C = Q_{NC} + Q_{EC} + Q_{SC} + Q_{WC} + W_C$$

$$Q_{NC} = \frac{2T_N T_C}{T_N + T_C}\left(h_N^t - h_C^t\right) \qquad Q_{EC} = \frac{2T_E T_C}{T_E + T_C}\left(h_E^t - h_C^t\right)$$

$$Q_{SC} = \frac{2T_S T_C}{T_S + T_C}\left(h_S^t - h_C^t\right) \qquad Q_{WC} = \frac{2T_W T_C}{T_W + T_C}\left(h_W^t - h_C^t\right)$$

Hydraulic head updating

$$h_C^{t+1} = h_C^t + \frac{1}{S}\frac{Q_C}{\Delta s^2}\Delta t$$

h = hydraulic head

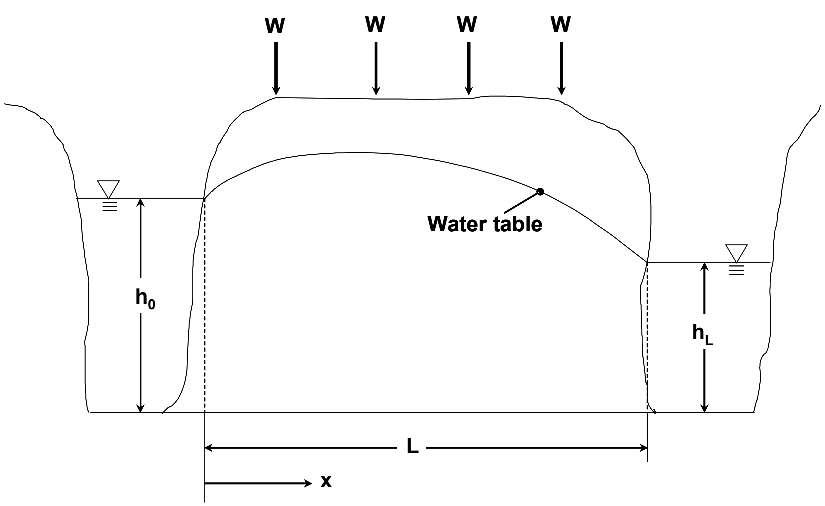
T = transmissivity [L^2/T]

S = storativity [-]

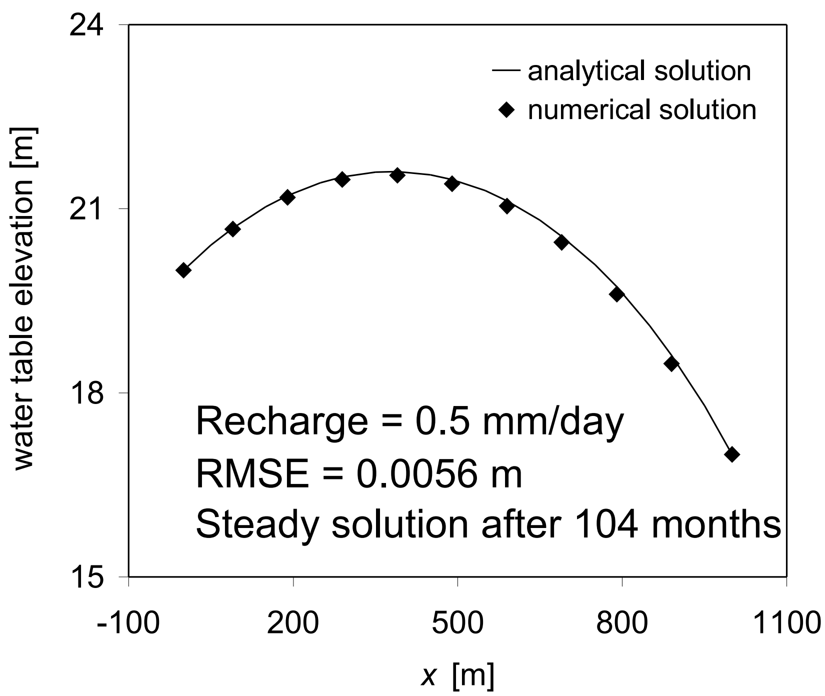
W_C = sources (+) or sinks (-)

Groundwater model – Validation (steady)

Steady flow between two streams in response to uniform recharge



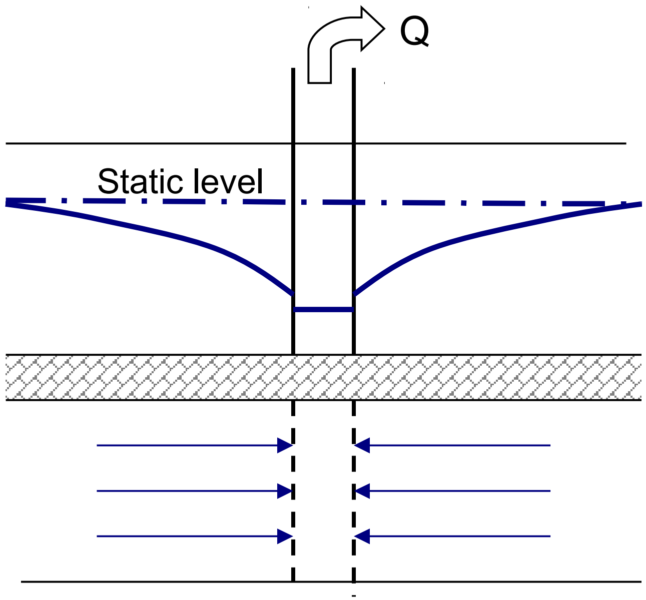
$$h^2 = h_0^2 - \frac{\left(h_0^2 - h_L^2\right)x}{L} + \frac{W}{K_S}\left(L - x\right)x$$

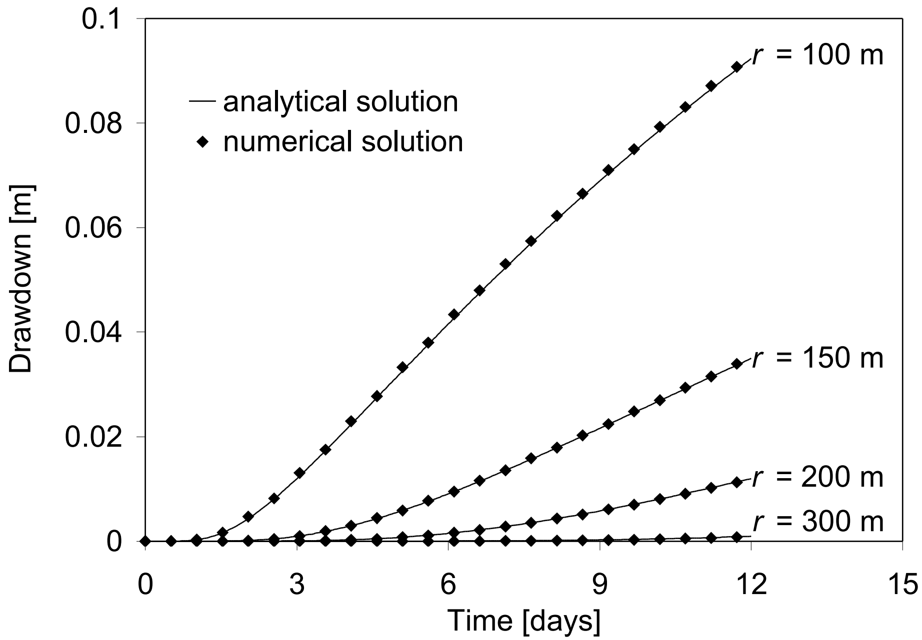


Ravazzani, G., Rametta, D., Mancini, M., Macroscopic Cellular Automata for groundwater modelling, ***Environmental Modelling & Software***, submitted, **2009**.

Groundwater model – Validation (unsteady)

Drawdown due to a constant pumping rate from a well



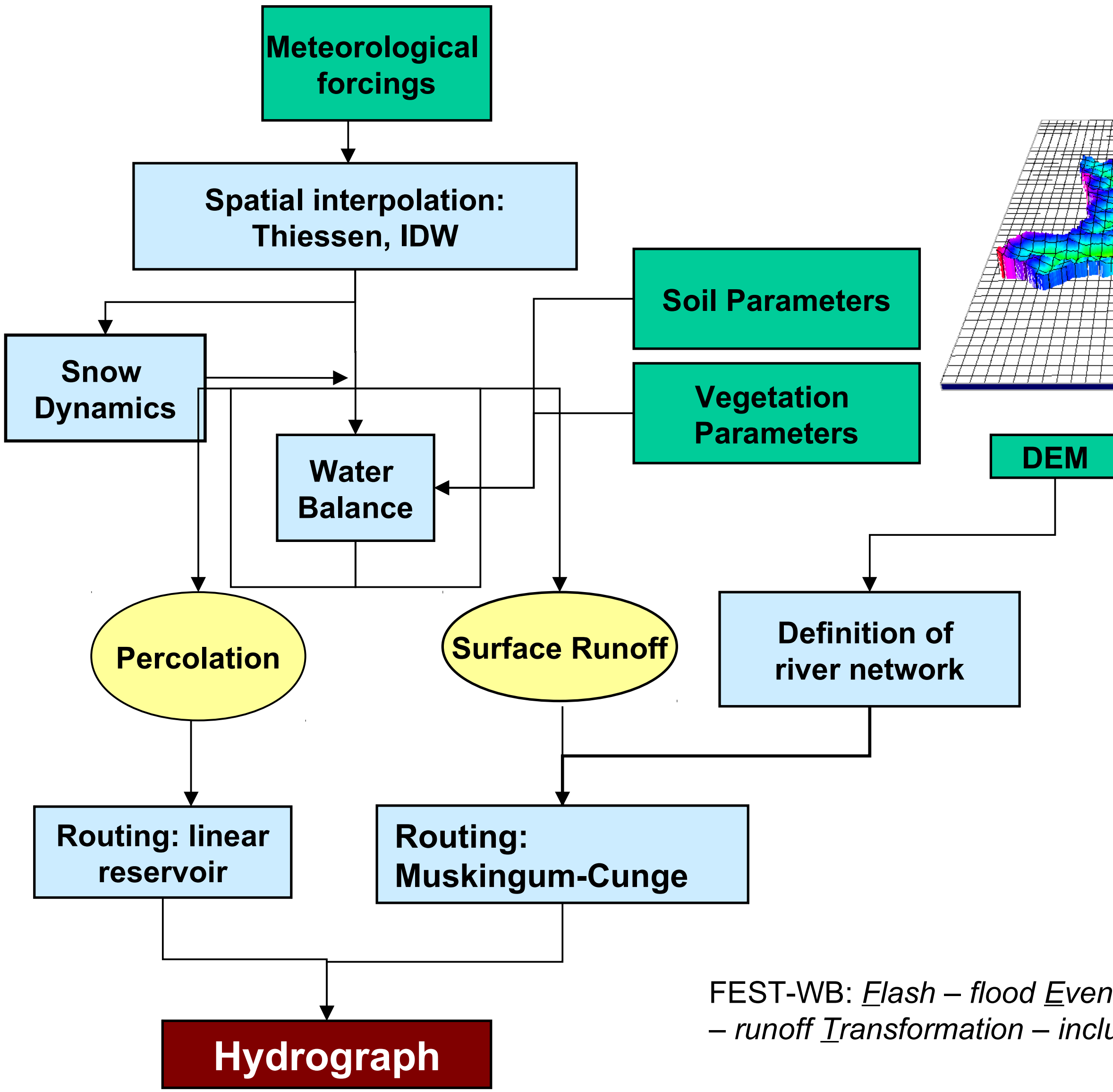


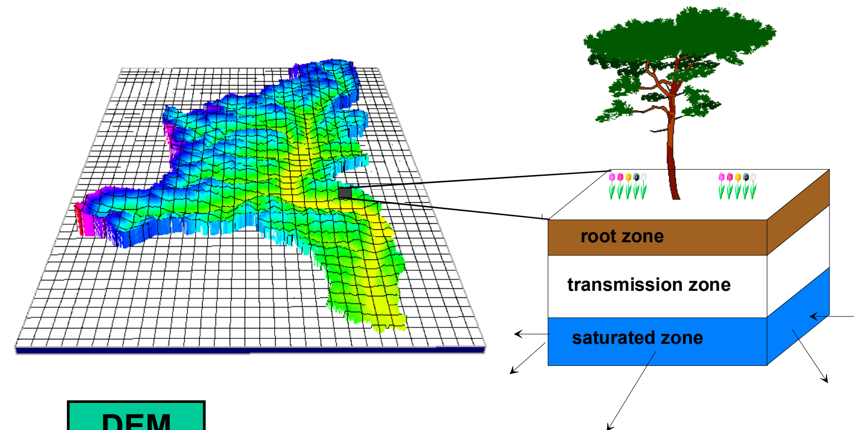
Theis (1935): $s(r,t) = \frac{Q}{4\pi T} \cdot W(u)$

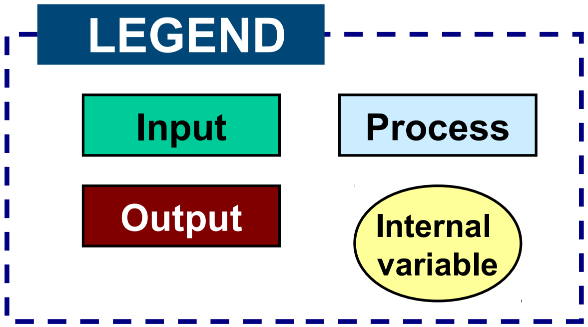
$$\begin{cases} u = \dfrac{r^2 \cdot S}{4tT} \\ W(u) = \cdot \displaystyle\int_u^\infty \dfrac{e^{-z}}{z} \end{cases}$$

Ravazzani, G., Rametta, D., Mancini, M., Macroscopic Cellular Automata for groundwater modelling, ***Environmental Modelling & Software***, submitted, **2009**.

Hydrological model FEST-WB



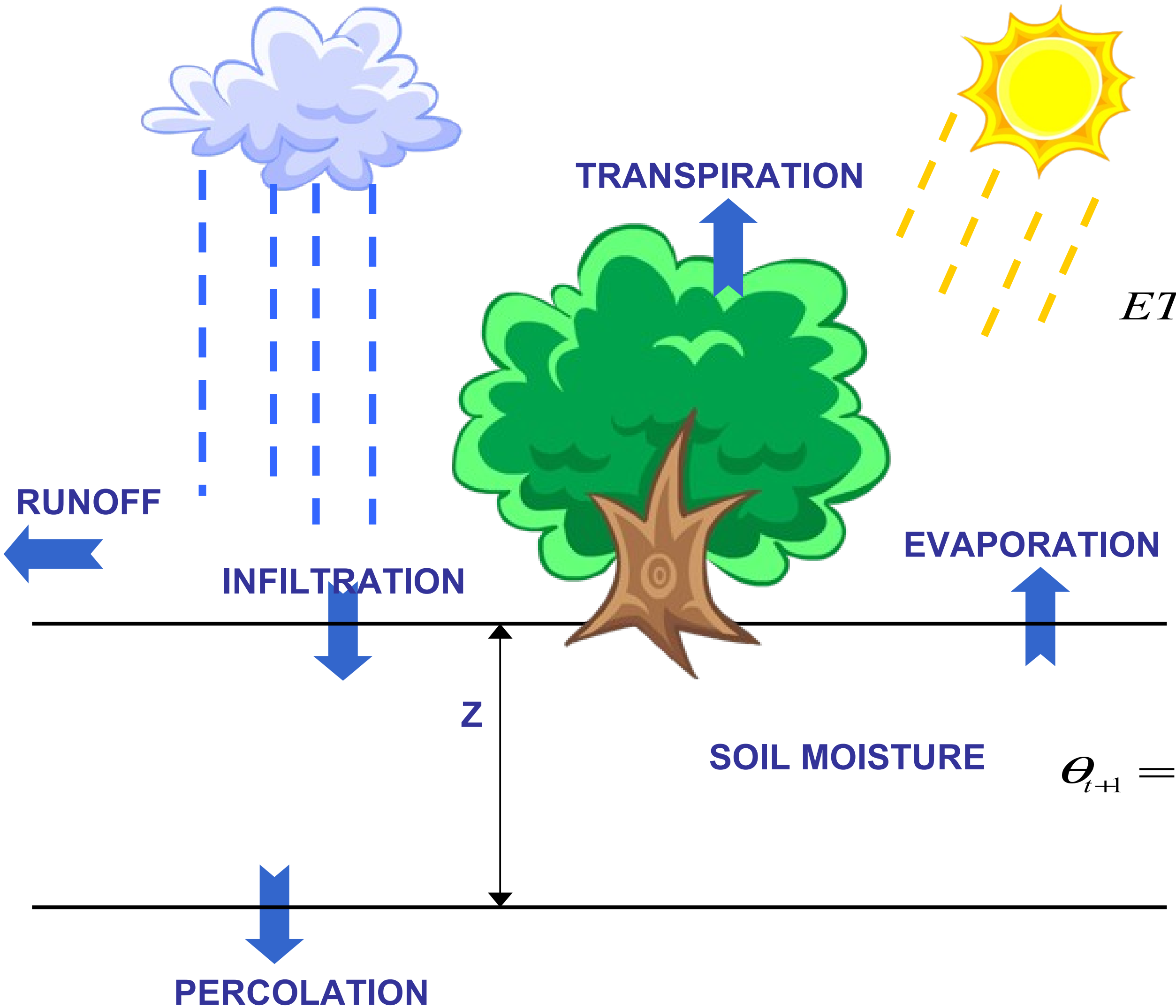




FEST-WB: *<u>F</u>lash – flood <u>E</u>vent – based <u>S</u>patially – distributed rainfall – runoff <u>T</u>ransformation – including <u>W</u>ater <u>B</u>alance*

THE FEST-WB MODEL

Soil water balance



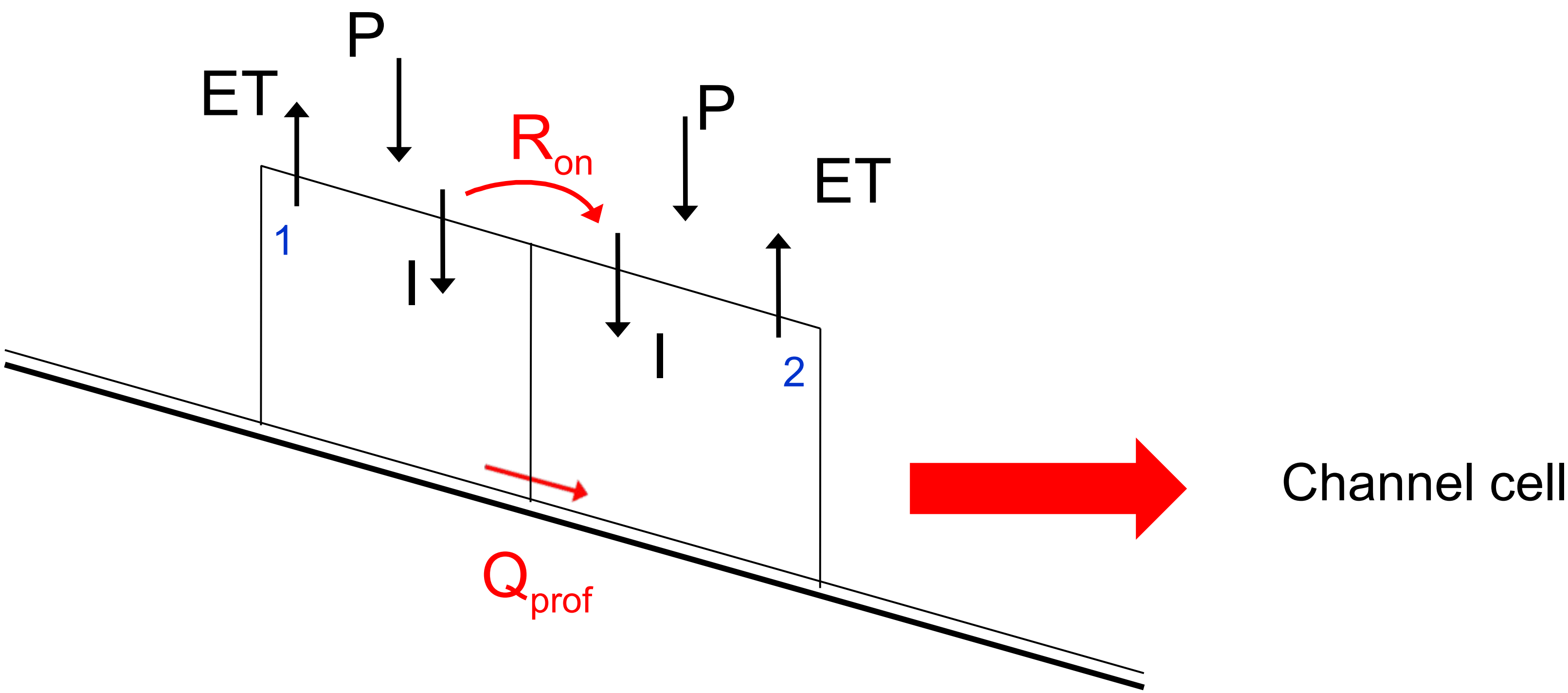
$$ETeff = ETP \cdot \frac{\theta_{t-1} - WP}{FC - WP}$$

β - function

$$\theta_{t+1} = \theta_t + \frac{(I - PERC - ET)}{Z}$$

HILLSLOPE SIMULATION SCHEME

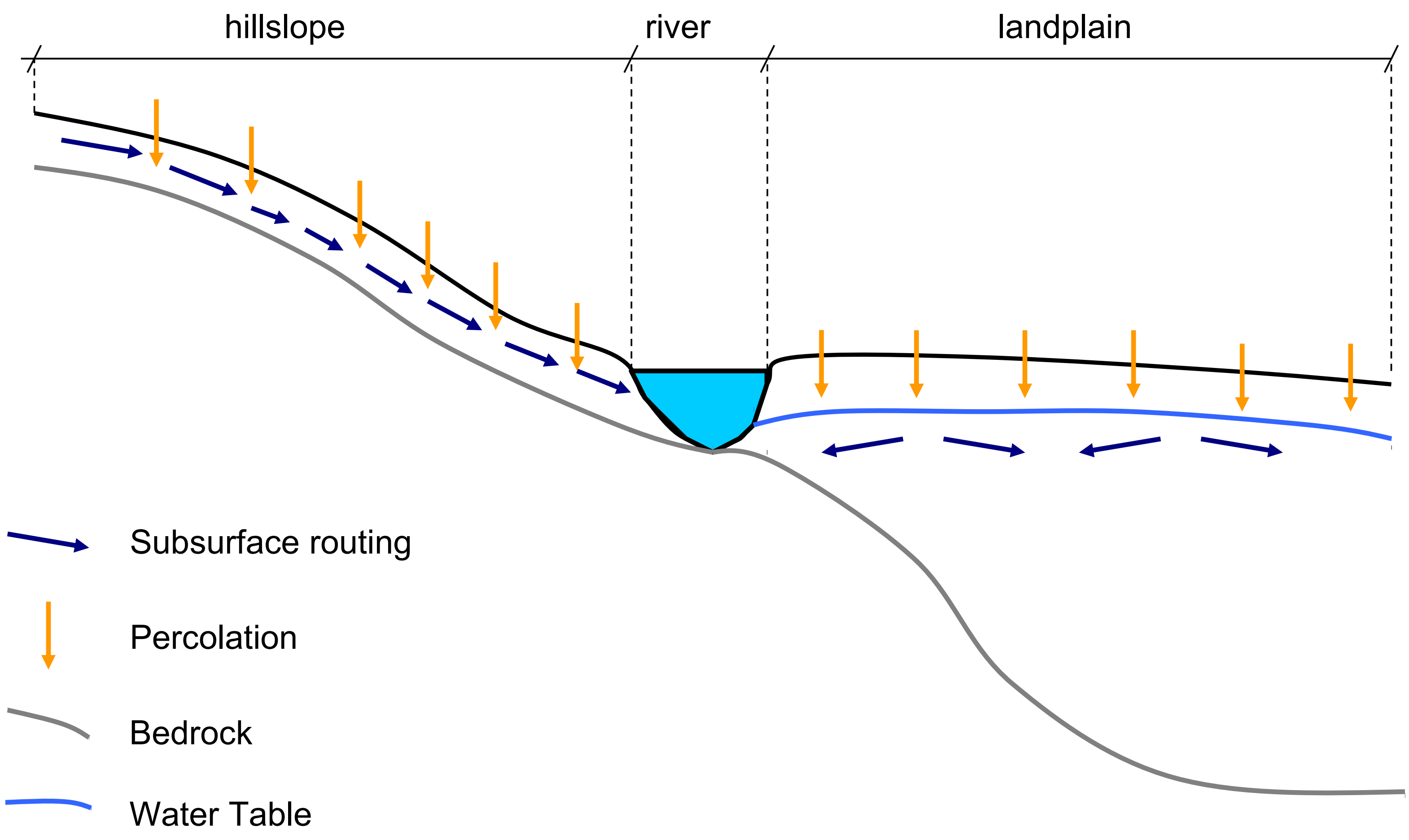
1 – Upstream cell
2 – downstream cell



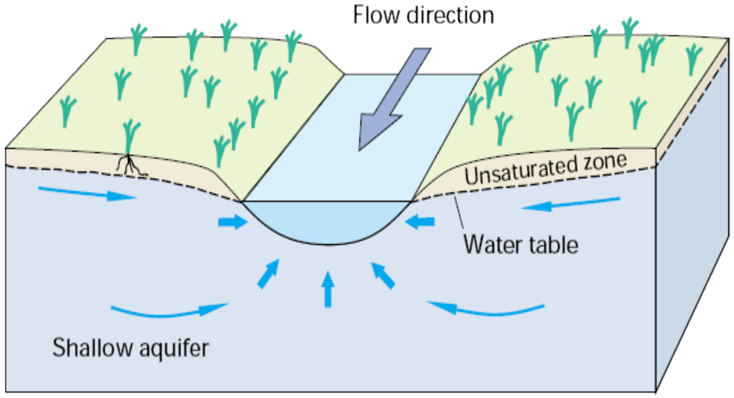
R_{on} → Muskingum routed: sums to P in the downstream cell

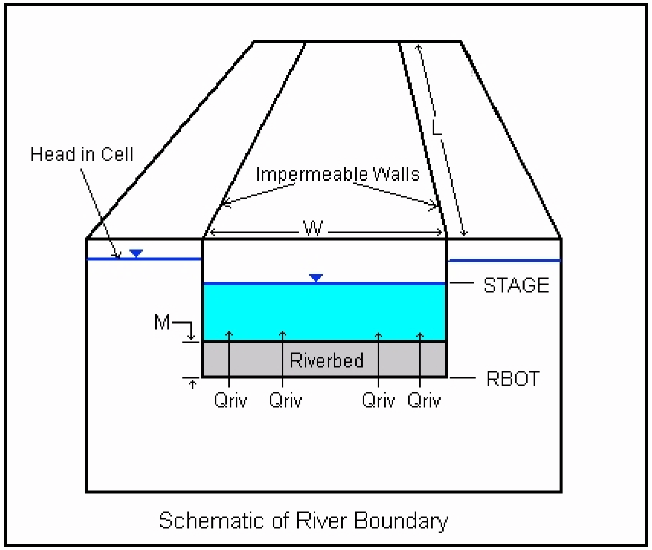
Q_{prof} → linear reservoir till when meets a channel cell

Model coupling



River-Groundwater interaction

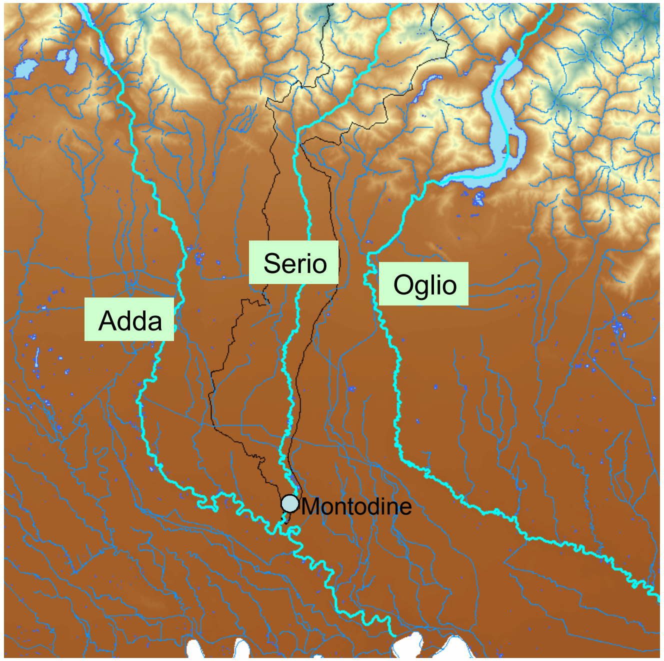


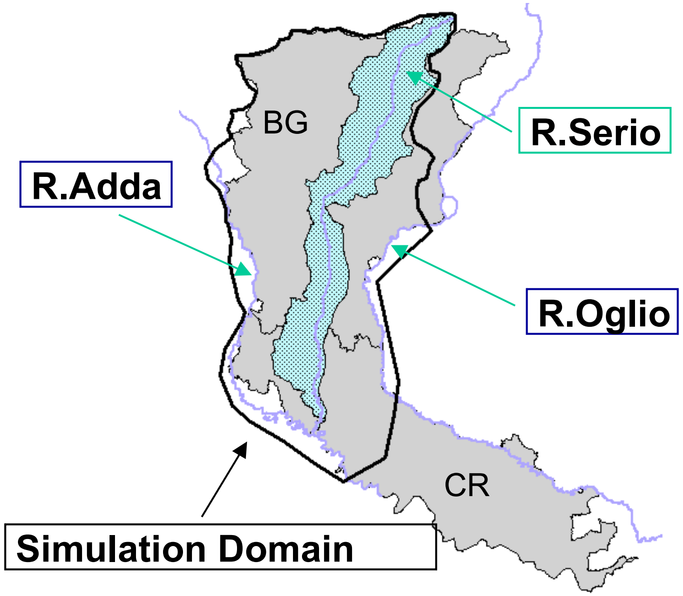


Same scheme adopted for River boundary condition in MODFLOW, but with variable river water level

$$Q = \frac{k_T \cdot L \cdot W}{M} \left(h_{watertable} - h_{river} \right)$$

Simulation Domain



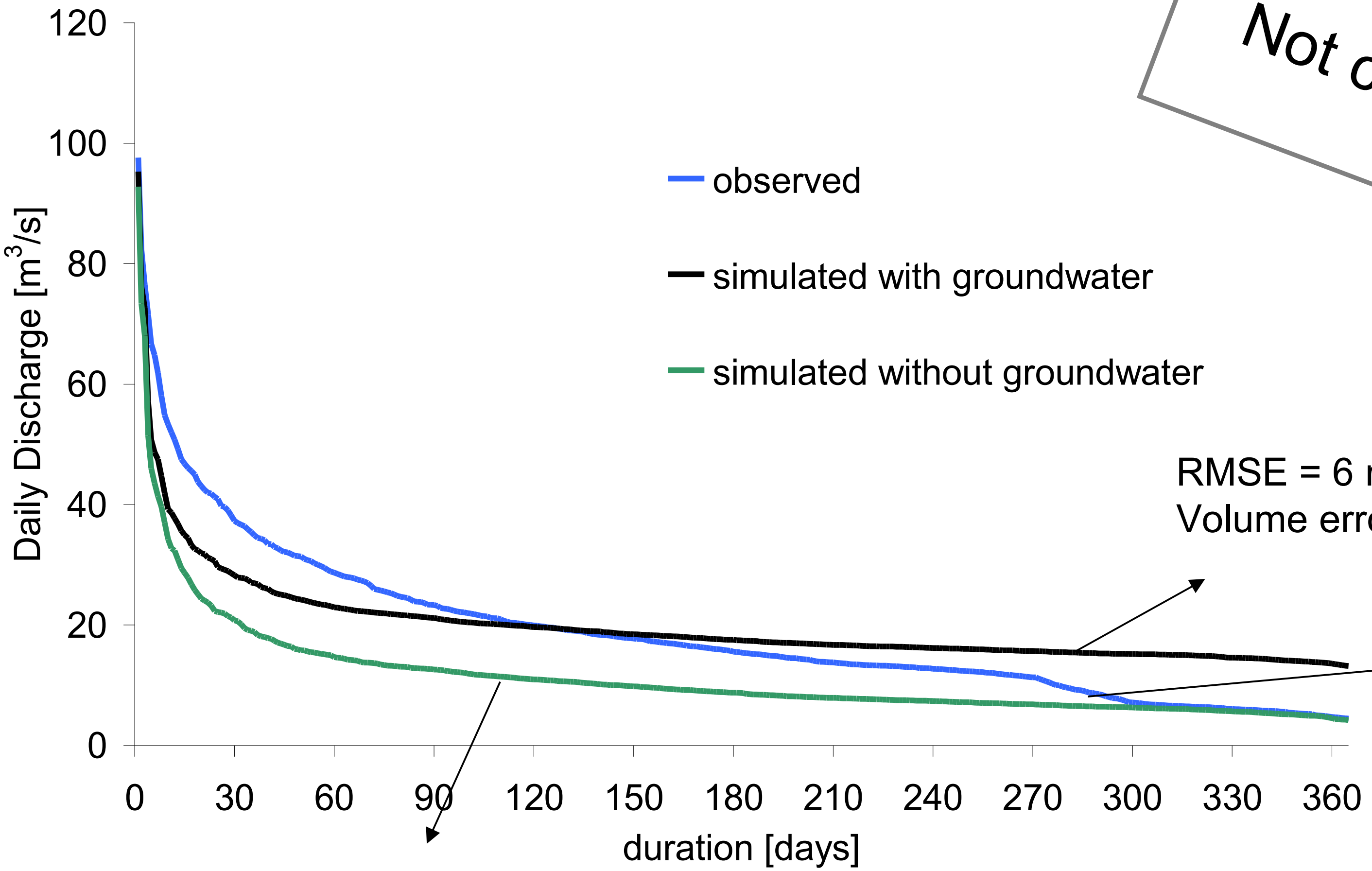


- Total area: 3600 km^2
- Cell resolution 300x300 m^2.
- Time step: hourly
- Simulation period: 1STJanuary 2003 – 31ST December 2008

Results: Flow Duration Curve

Average FDC (2005-2008)

Not calibrated

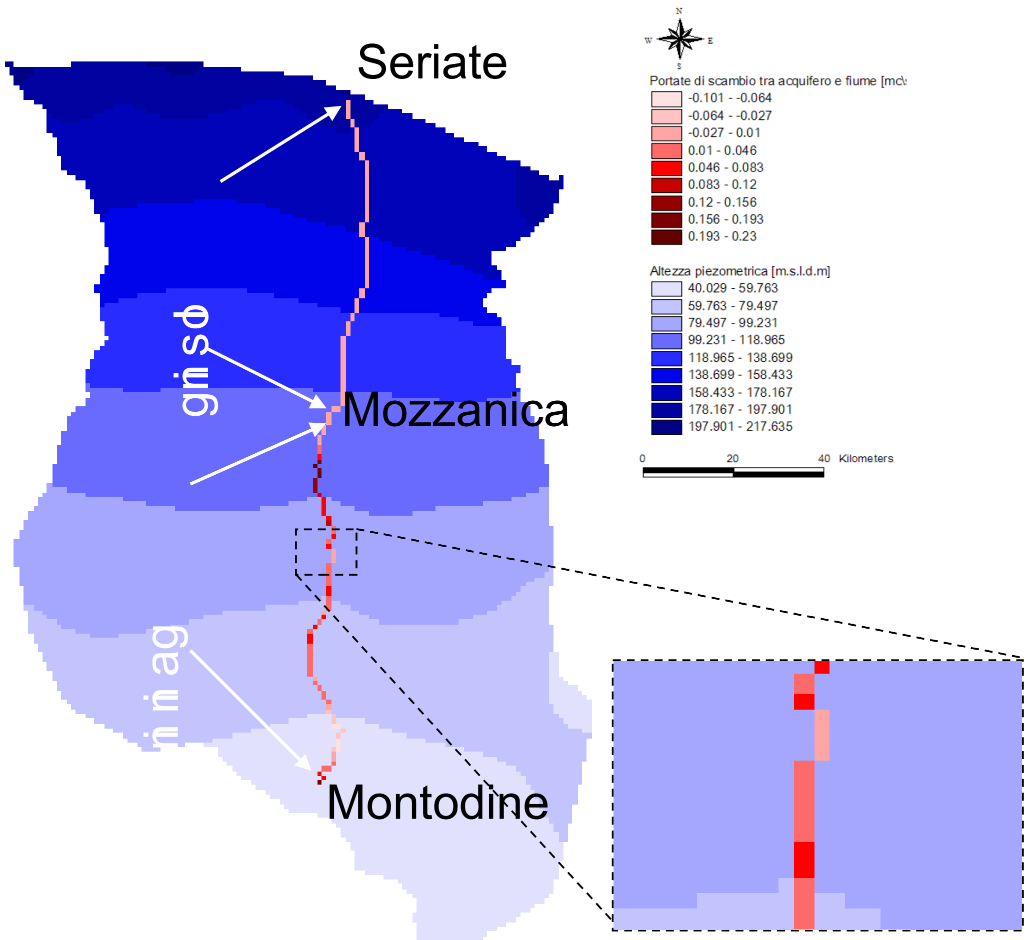


RMSE = 6 m^3/s
Volume error = 5.4%

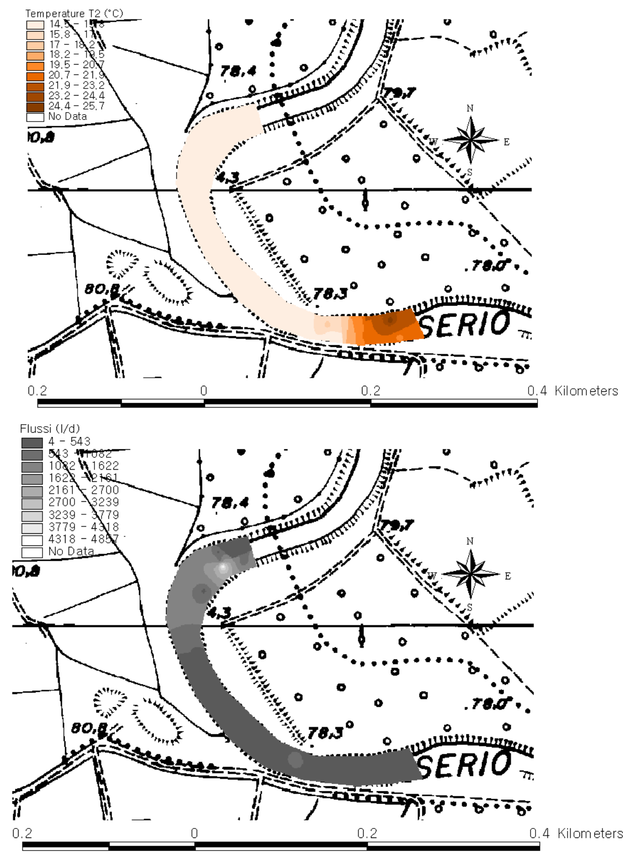
Reduction due to anthropic effect (intakes for irrigation)

RMSE = 9 m^3/s
Volume error = -39%

Piezometric head and Fluxes



Field Campaign, July 2007



Simulated flux: **0.235 $m^3/s/km$**

Reach average flux = **0.28 $m^3/s/km$**

Summary and Conclusions

• The field campaign demonstrated that contribution of groundwater to river flow is significant: necessity to use integrated models to perform hydrological analysis

•The cellular Automata approach seems a promising tool to simulate groundwater dynamics to be coupled to existing distributed hydrological model in order to perform integrated analysis.

•Taking into account the interaction between river netwotk and groundwater, can reduce error on flow duration curve and on annual flow volume

Acknowledgments

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THANK YOU FOR YOUR ATTENTION !

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