Flash flood warning system based on fully dynamic hydrology modelling

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Numerical hydrologic modeling

- Hydrology modelling – one of most important component in goobal climate models to appropriatelly represent
  - hydrological cycle
  - energy fluxes in the Earth's atmosphere and at the surface
- Significant room for further impeovements
- limited success in the past due to lack of adequate input data
- More recent improvements:
  - More accurrate and high-resolution data on
    - topography, river routing, and soil types
    - Precipitation observations/predictions
- More recent improvements:
  - variety of hydrology modeling approaches:
  - simplifiedconceptual
  - kinematic methods
  - complex dynamic methods

- The most complex models include full dynamic governing equations
  - momentum equations, along with the equation of mass continuity, are used in their full extent.
  - Such approach
    - permits representation of hydrology scales ranging from flash floods to flows of large slow river watersheds.
    - do not need model callibration
    - could be unstable for vanishing surface water hight if not appropriatly numerically treated

Kinematic approximation: the the most used method in hydrology modelling

- Continuity equation - prognostic
- Momentum equations – diagnostic
  - Manning velocities calculates from the balance between the gradient and the friction slope forces
  - Advantage: no numerical instability
  - Disadvantage: simplified governing equations

$$u_M = \sqrt{\frac{h^{4/3}}{n^2\sqrt{u^2+v^2}}\frac{\partial h}{\partial x}}$$

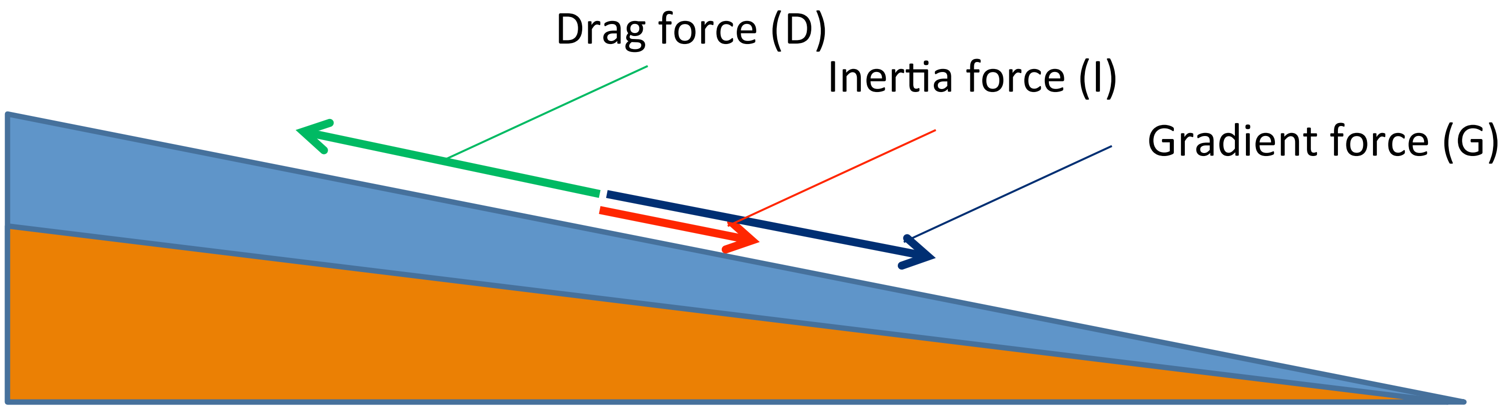
$$v_M = \sqrt{\frac{h^{4/3}}{n^2\sqrt{u^2+v^2}}\frac{\partial h}{\partial y}}$$

Full dynamics (FD) vs. kinematics (KN)

- FD model more accurate
- FD: friction slope term requires special treatment (Froude number <2)
- KN: simplifications avoids problem but simplifies the equations (Froude number >2)
- Most watershed models adapt KN approach
- KN cannot accurately represent large-scale, more inert processes

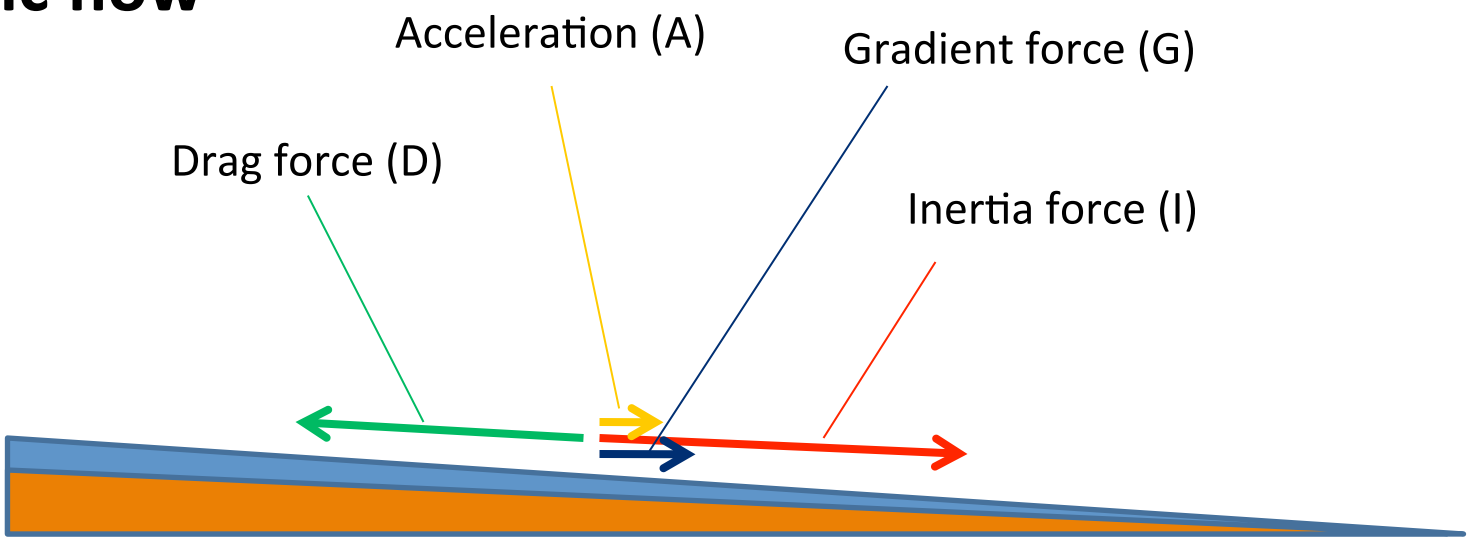
$$Froude \quad number(Fr) = \frac{Inertia \ forces}{Kinematic \ forces} = \frac{V}{\sqrt{gh}}$$

Kinematic flow



- **<u>steep</u>** topography
- Gradient force dominant over inertia force (advection)
- → Fr < 1
- kinematic approximation D ~ (I+G)
- inappropriate for slow flows

Full dynamic flow



- **<u>weak</u>** topography slope
- Inertia force (advection) dominant over gradient force
- → Fr > 1
- kinematic approximation A~ (I+G) - D
- appropriate for both fast and slow flows

HYPROM (*) approach

- Aim: to avoid a kinematic or other restrictive approximation

- Dynamics based on the Saint-Venant equations

- Both momentum and continuity equations are prognostic

(*) Nickovic, S., G. Pejanovic, V. Djurdjevic, J. Roskar, and M. Vujadinovic (2010), HYPROM hydrology surface-runoff prognostic model, *Water Resour. Res.*, 46, W11506, doi:10.1029/2010WR009195

HYPROM - Full dynamic (FD) equation concept

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\left[\frac{\partial h}{\partial x}+S_{fx}-S_{0x}\right]=0$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\left[\frac{\partial h}{\partial y}+S_{fy}-S_{0y}\right]=0$$

$$\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}+\dot{H}=0$$

Friction slope terms

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}}$$

$$S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}}$$

$$\boxed{}=0$$

Kinematic approximation

neglects inertia forces !! which we want to avoid

$=0$

Kinematic approx

Acceptable for **flesh floods** (where friction and gradient forces are in approx. balance)

Not appropriate for basins with **slow flows**

➔ **Full dynamic system to be used**

HYPROM governing equations:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\left[\frac{\partial h}{\partial x}+S_{fx}-S_{0x}\right]=0$$

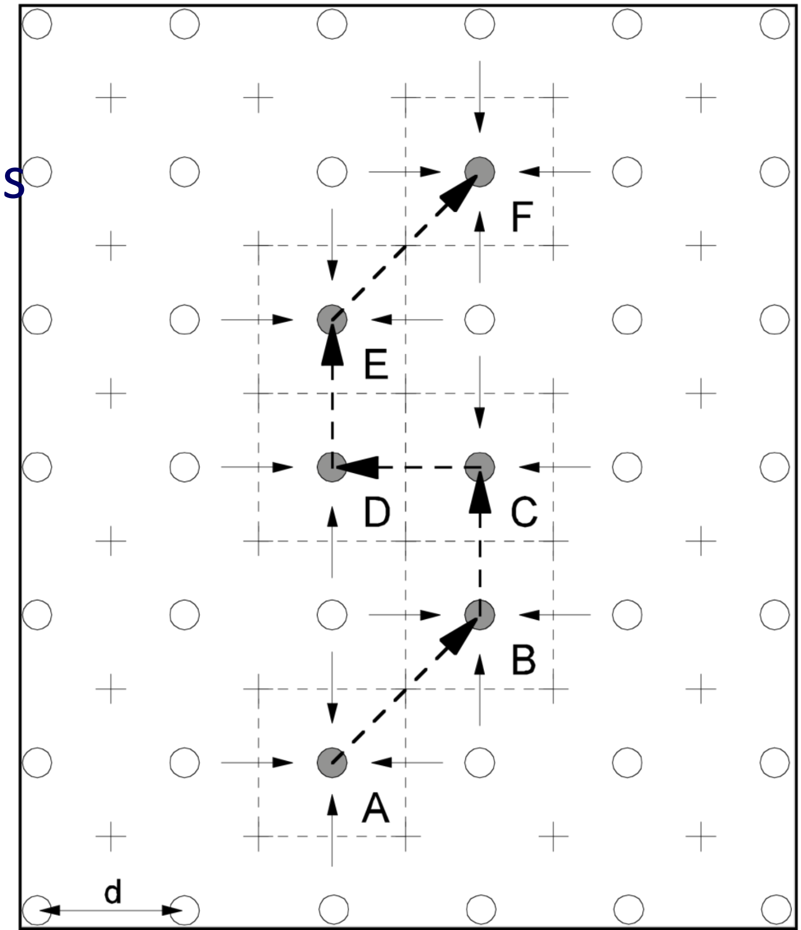
$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\left[\frac{\partial h}{\partial y}+S_{fy}-S_{0y}\right]=0$$

$$\frac{\partial h}{\partial t}+\frac{\partial(hu)}{\partial x}+\frac{\partial(hv)}{\partial y}+\dot{H}=0$$

○ h - points
✦ u,v -points

A-B-C-D-E-F river points

river routing



Novel components in HYPROM

- NO approximation in the governing eq-s
- numerically stabile numerics
- new numerical technique for preventing grid decoupling noise
- suitable for scales ranging from local (flash floods) to climate (large rivers, e.g. Danube)
- computationally very efficient

Full Dynamics approach requires completely different numerical approach to resolve the Instability due to vanishing water heights!

Friction slope

$$S_{fs} = \frac{n^2 \sqrt{u^2 + v^2}}{h^{4/3}} U$$

Potential source of model instability when $h \rightarrow 0$

Fiedler and Ramirez (2002) suppress the instability by imposing an artificial threshold for the minimum water depth $h_c = 10^{-10}$ m

Friction slope numerics – HYPROM approach

Implicit time scheme applied

Unconditionally stable method

Convergent for $\Delta t \to 0$ $h \to 0$ $u, v \to 0$

$$u^{n+1} = \left[\frac{u - g \dfrac{\partial h}{\partial x} \Delta t}{1 + B\Delta t} \right]^{n}$$

More info in *Nickovic et al (2010)*

Friction slope numerics in HYPROM

[29] We propose instead an unconditionally stable integration scheme for the friction slope terms that is physically sound. For simplicity, let us consider a system composed of friction and height gradient terms,

$$\frac{\partial u}{\partial t} + \frac{gn^2\sqrt{u^2+v^2}}{\left(\overline{h}^{x}\right)^{4/3}}u + g\delta_x h = 0,$$
$$\frac{\partial v}{\partial t} + \frac{gn^2\sqrt{u^2+v^2}}{\left(\overline{h}^{y}\right)^{4/3}}v + g\delta_y h = 0. \qquad (10)$$

System (10) can be written in a simpler form as

$$\frac{\partial u}{\partial t} + B(u - u_M) = 0,$$
$$\frac{\partial v}{\partial t} + B(v - v_M) = 0, \qquad (11)$$

if we define the following parameters,

$$B \equiv \frac{gn^2\sqrt{u^2+v^2}}{\left(\overline{h}^{x}\right)^{4/3}}, \quad u_M = \frac{h^{4/3}}{n^2\sqrt{u^2+v^2}}\frac{\partial h}{\partial x},$$
$$v_M = \frac{h^{4/3}}{n^2\sqrt{u^2+v^2}}\frac{\partial h}{\partial x} \qquad (12)$$

Note that the equations in (11) are of a Newtonian-nudging type in which velocities are relaxed toward the Manning velocities u_M and v_M. We apply an implicit time scheme to (11) and obtain the following:

$$\frac{u^{n+1} - u^n}{\Delta t} + B^n u^{n+1} + g(\delta_x h)^n = 0,$$
$$\frac{v^{n+1} - v^n}{\Delta t} + B^n v^{n+1} + g(\delta_y h)^n = 0. \qquad (13)$$

By solving the equations for level $n + 1$, we finally get a numerical scheme of the following form,

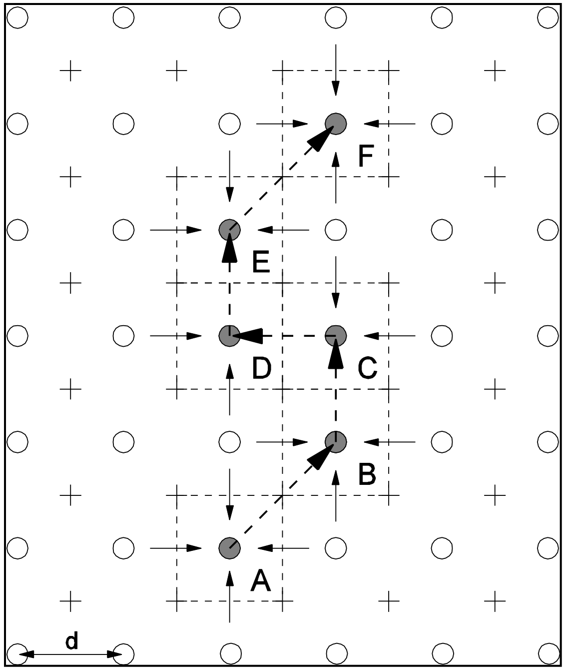
$$u^{n+1} = \left[\frac{u - g\Delta t\delta_x h}{1 + B\Delta t}\right]^n,$$
$$v^{n+1} = \left[\frac{v - g\Delta t\delta_y h}{1 + B\Delta t}\right]^n. \qquad (14)$$

River routing

$$\frac{\partial U}{\partial t}+U\delta_s\overline{U}^s+g\delta_s\left(R+h_s\right)+\frac{n^2|U|}{\overline{R^{4/3}}^s}U=0$$

$$\frac{\partial R}{\partial t}+\delta_s\left(\overline{R}^sU\right)+\dot{R}=0$$

s – river direction



River path:
A-B-C-D-E-F

- River – a water collector from surrounding points
- Same numerics as for non-river points

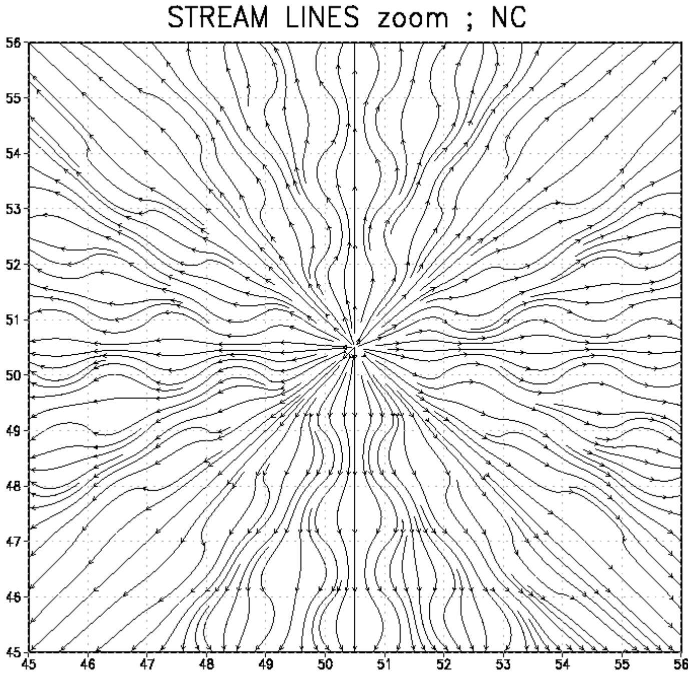
A numerical method proposed for the source term: averaging method which redistributes water mass to neighbouring points and avoids two-grid interval noise in the E or B horizontal grids

$$\frac{\partial h}{\partial t} + H\left(\delta_x u + \delta_y v\right) - \frac{1}{2}\left(\dot{H} + \overline{\dot{H}}^{xy}\right) = 0$$

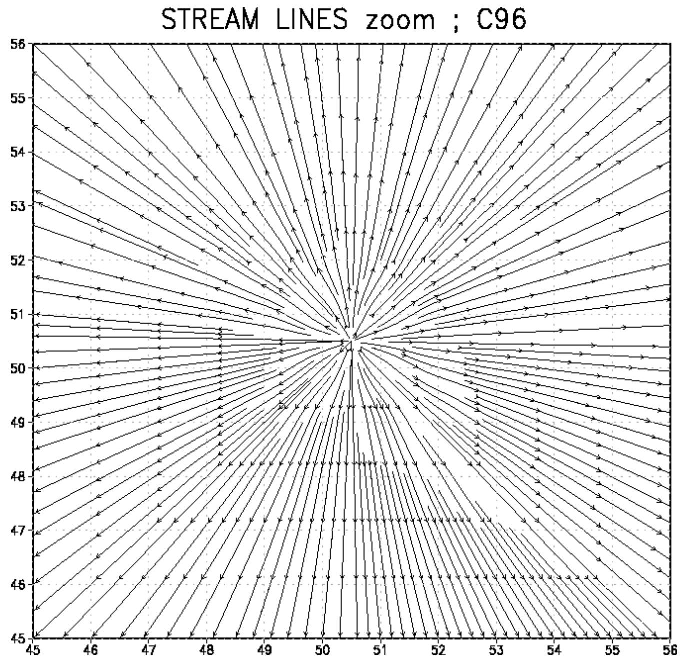
Nickovic et al (2011): Method for efficient prevention of gravity wave decoupling on rectangular semi-staggered grids". Journal of Computational Physics, 230(5), 1865-1875

Synthetic experiment with HYPROM

(1pt source forcing)

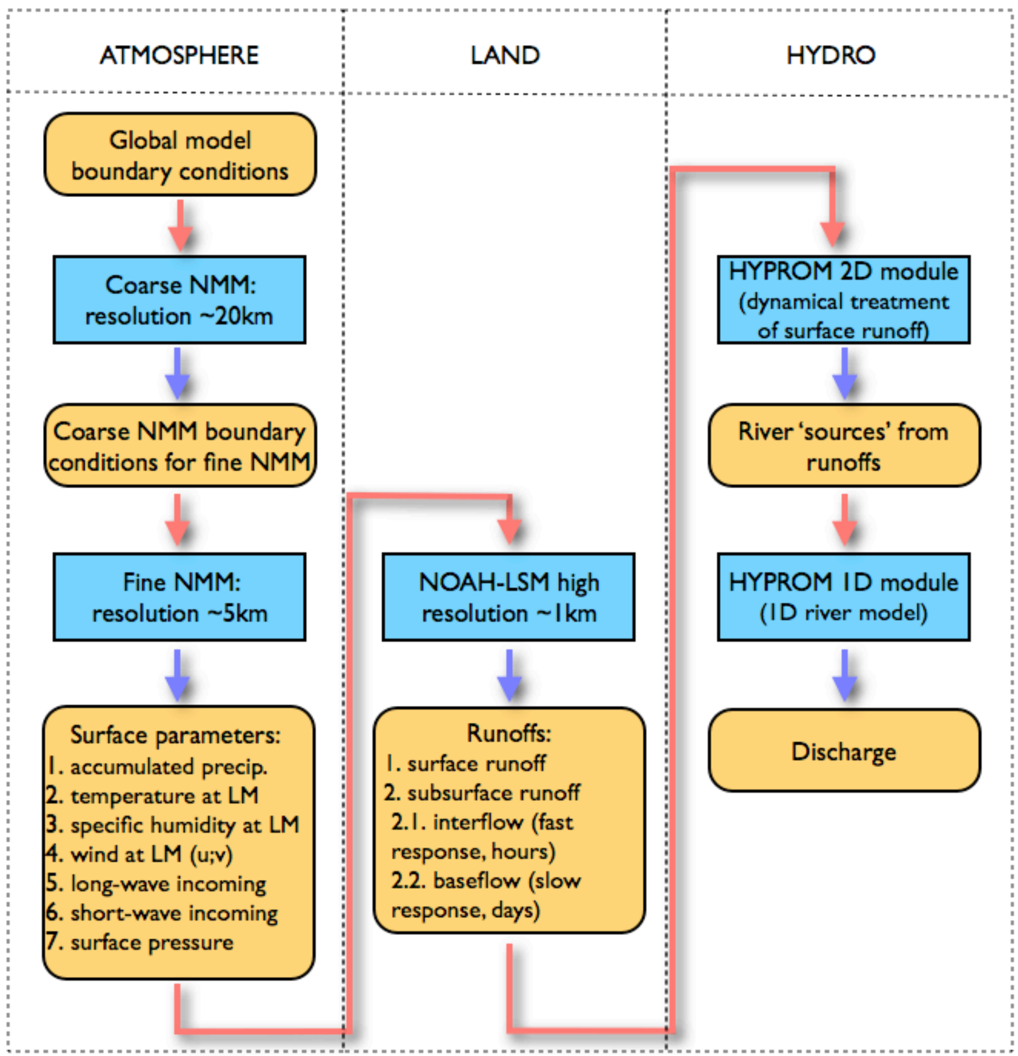


Without modification



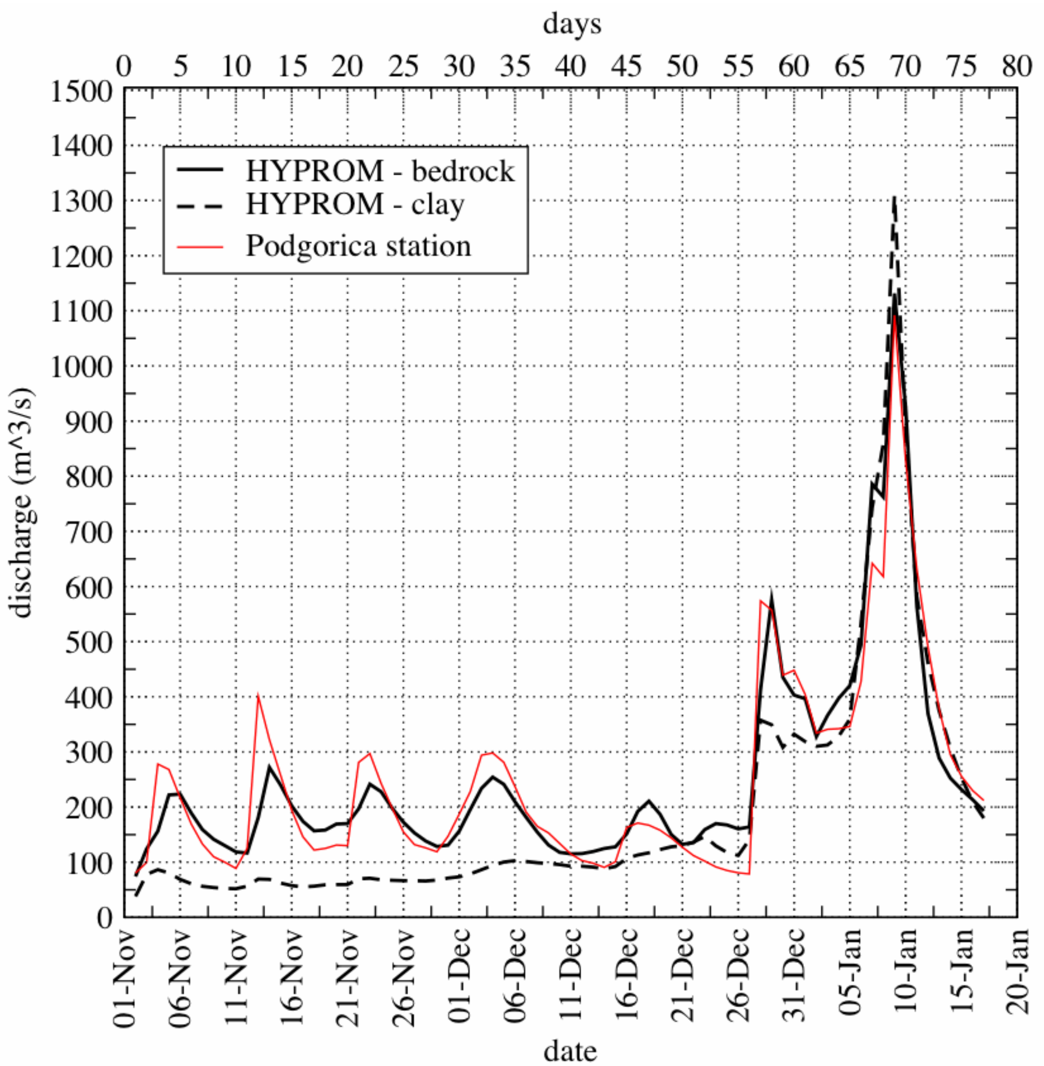
With modification

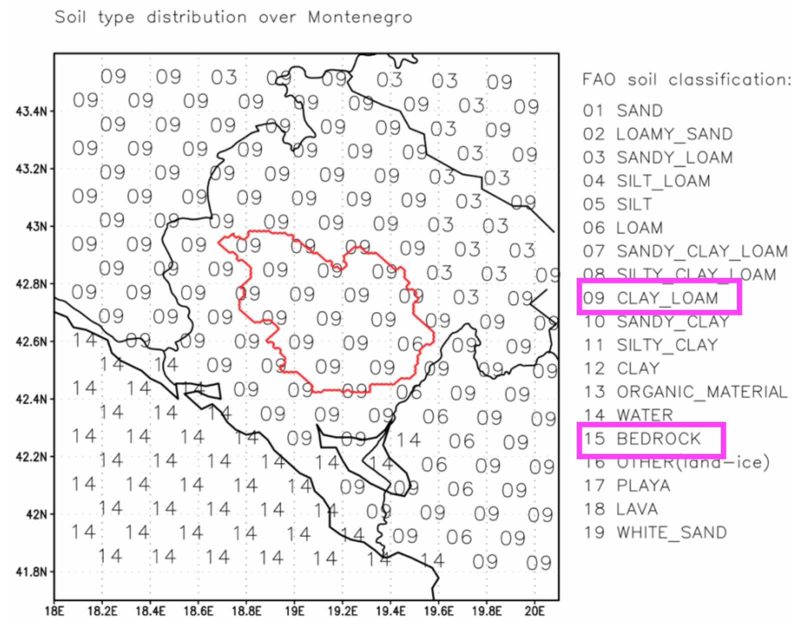
HYPROM integrated with the NCEP/NMM atmospheric model



LM - lowest atmospheric model level

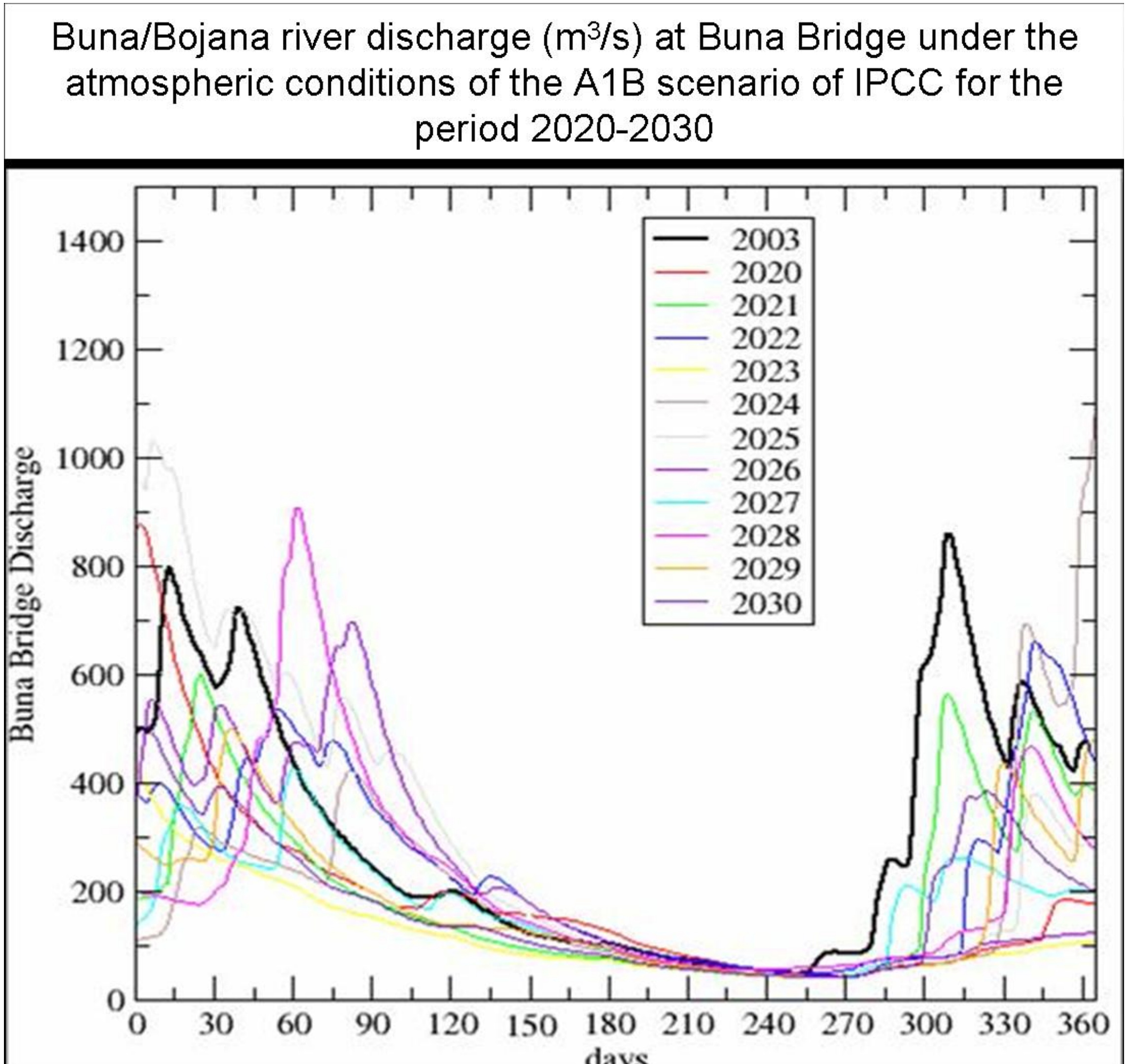
Moraca river - Sensitivity to soil type
Small catchment case



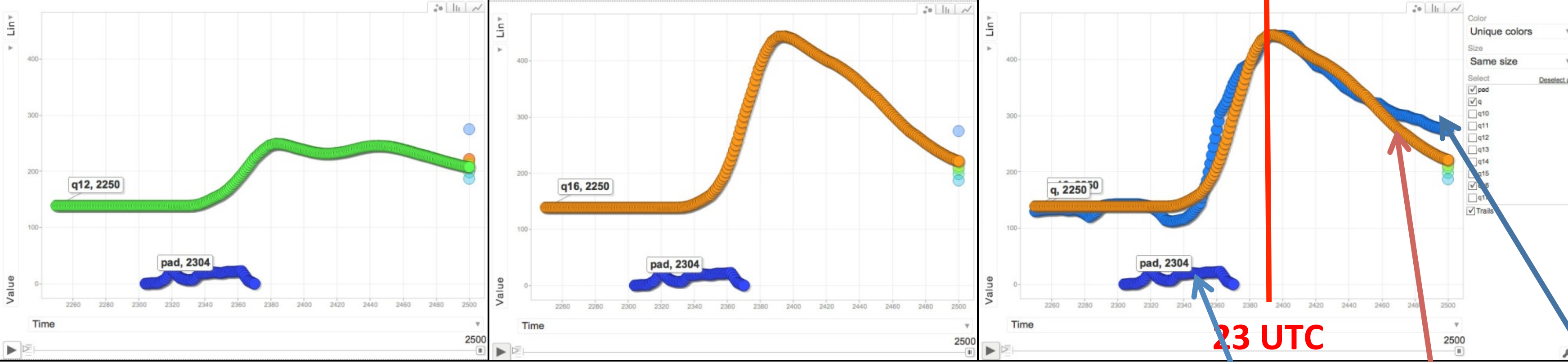


parameter	Clay Loam (09)	Bedrock (15)
sat. diffusivity	0.113×10^{-4}	0.136×10^{-3}
sat. conductivity	2.45×10^{-6}	1.41×10^{-4}
porosity	0.465	0.20
CH constant	8.17	2.79

HYPROM and climate/seasonal assessments



Djurdjevic et al, 2011



12UTC 14UTC 16UTC

Observed Q

Predicted Q

Radar P

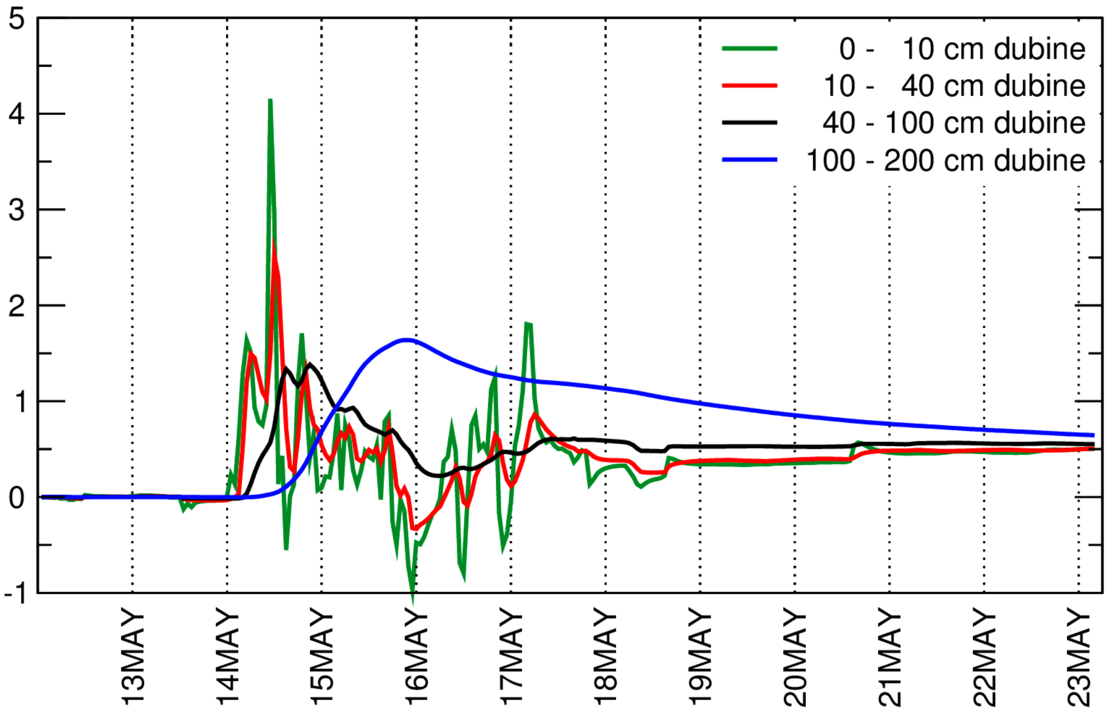
S. Morava River flash flood case
23 Jan 2015
disasterous consequences

HYPROM run
Driven by radar precipitation

Predicted correctly the max discharge 7 hours in advance

Most recent developments

- HYPROM dynamics has been fully coupled with the NCEP/ NMMB non-hydrostatic atmospheric model
- a two-way interaction (atmosphere-hydrology feedbacks) *(Vujadinovic-Mandic, 2015; PhD Thesis)*



Volumetric soil moisture difference ctrl-feedback exp at 4 model soil levels