CNR - IRPI

Research Institute for Geo-Hydrological Protection

(National Research Council)

Streamflow Measurements: Ground and Satellite Observations

Tommaso Moramarco and IRPI's hydrology group

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2019 Edition
Doctoral Winter School
DATA RICH HYDROLOGY

PERUGIA (Italy), January 28 – February 1, 2019 – Villa Colombella

Istituto di Ricerca per la Protezione Idrogeologica

Overview of IRPI

The “*Research Institute for Geo-Hydrological Protection*” (IRPI), of the Italian *“National Research Council”* (CNR), has a consolidated experience on geo-hydrological hazards assessment (landslides and floods), at various scales and in different physiographical and geographical environments.

CNR IRPI

- Hydrological Section http://hydrology.irpi.cnr.it/
- Hydrogeological Section
- Geomorphological Section

Overview of IRPI

The "*Research* ... *on*" (IRPI), of the Italian "*Natic* ... consolidated experience on ge ... andslides and floods), at vari ... graphical and geographical env...

branches

A network of labs and scientific and technological expertise distributed throughout the country.

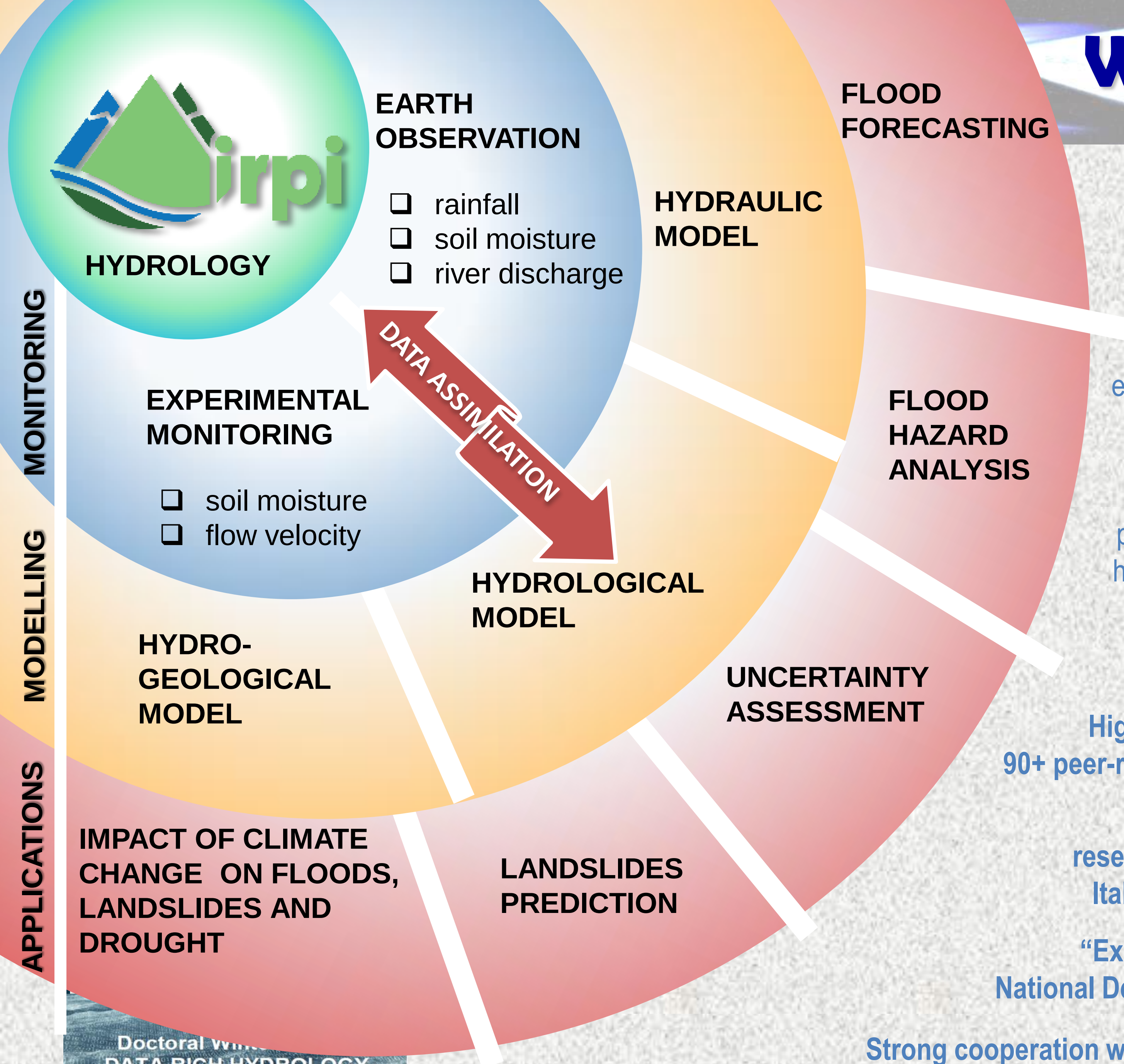
The headquarters are in **Perugia**, and other branches are in **Bari**, **Rende** (CS), **Padova** and **Torino**. The geographical distribution facilitates the study of geo-hydrological phenomena where these take place, or where they are more frequent or abundant, and the collaboration with public bodies and others interested in the research activities and in the products & services offered by the Institute.

www.irpi.cnr.it/offices/

Hydrological ... gical Section
http://hydrolog...

Geomorphological Section

Who we are



The "**Hydrology Group**" of "Istituto di Ricerca per la Protezione Idrogeologia" of the "Consiglio Nazionale delle Ricerche" (CNR-IRPI), has an internationally recognized excellence on the exploitation of remote sensing and ground observations for improving our understanding of hydrological processes as well as advancing hydrological/hydraulic modelling for the mitigation of natural hazards such as floods, landslides and drought.

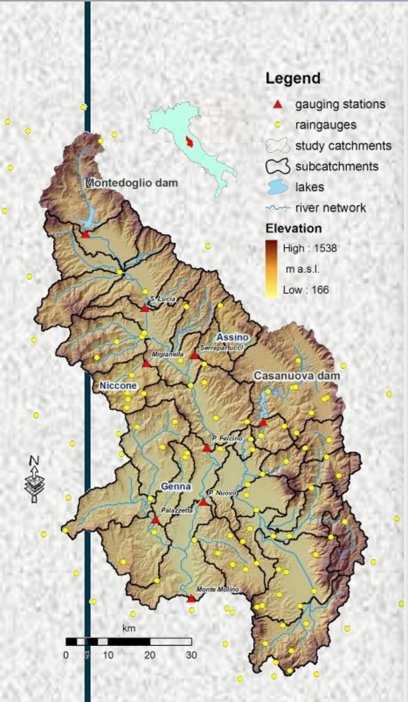
High level scientific production: 90+ peer-reviewed papers \ last 5 years

Involvement in research projects in the frame of Italian and European programs

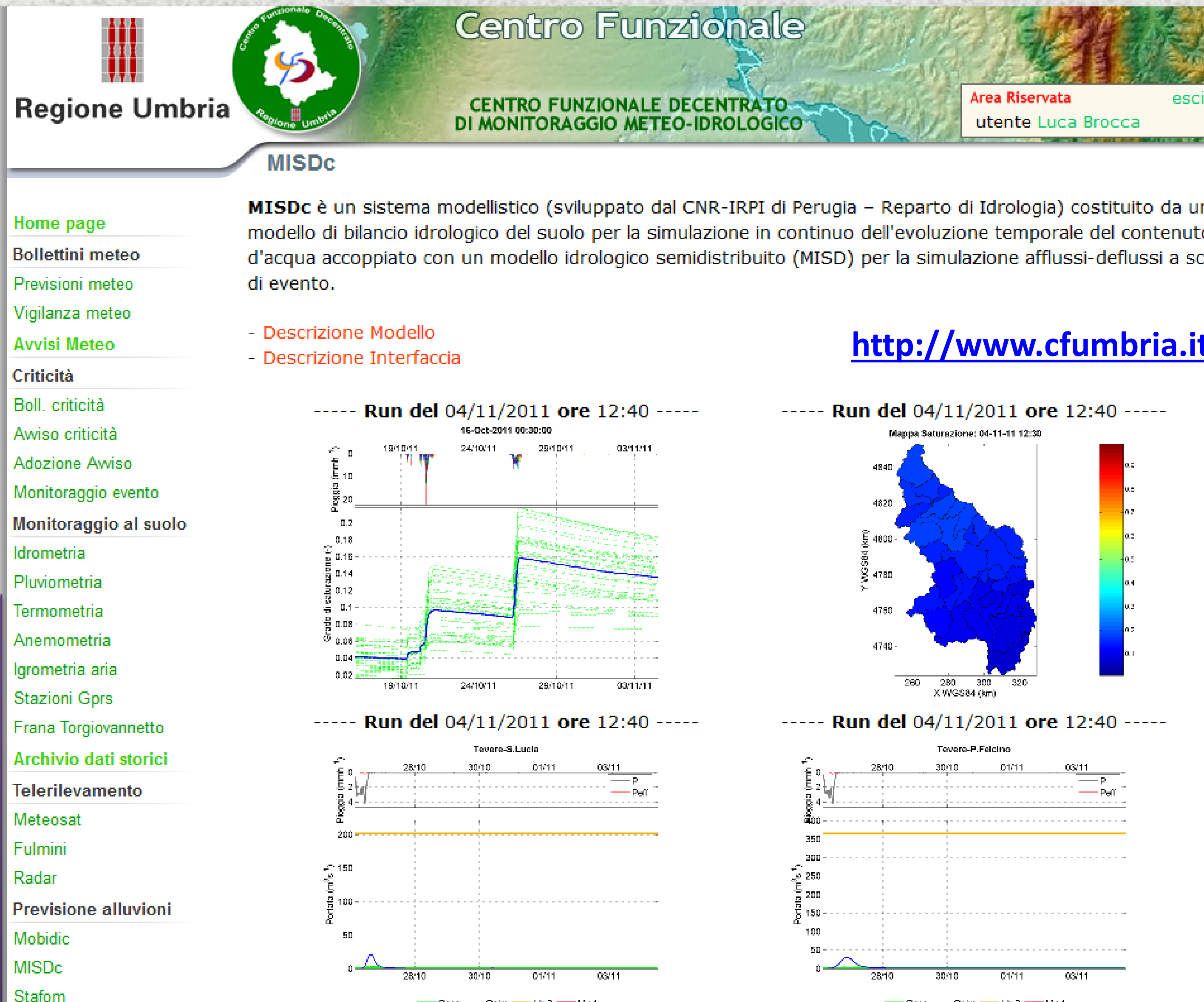
"Excellent Centre" by the Italian National Department of Civil Protection

Strong cooperation with national and international research institutes worldwide

Operational Modeling for Civil Protection Department

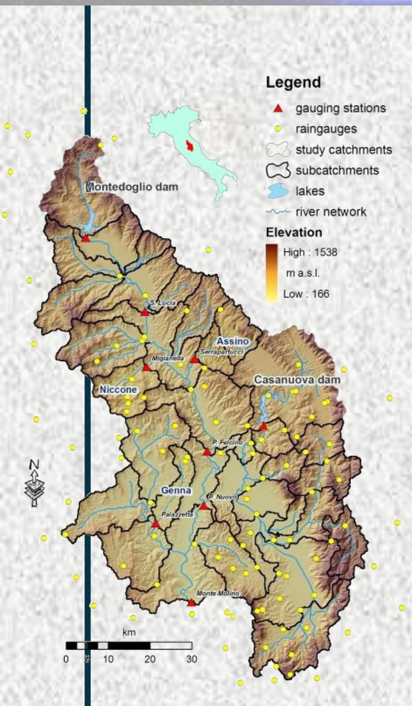


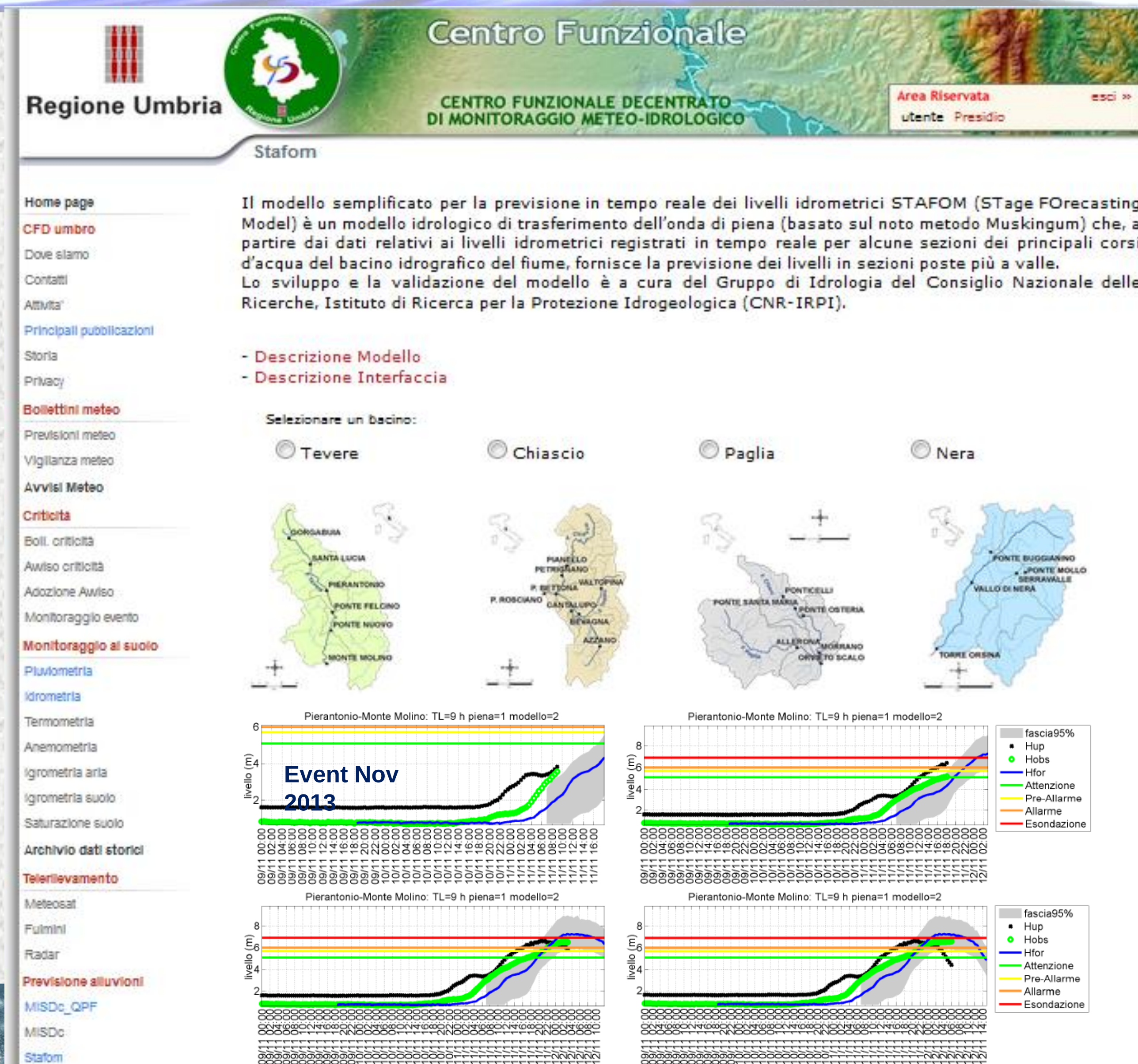
OPERATIONAL FLOOD FORECASTING SYSTEMS FOR UMBRIA REGION CIVIL PROTECTION CENTRE



http://www.cfumbria.it/

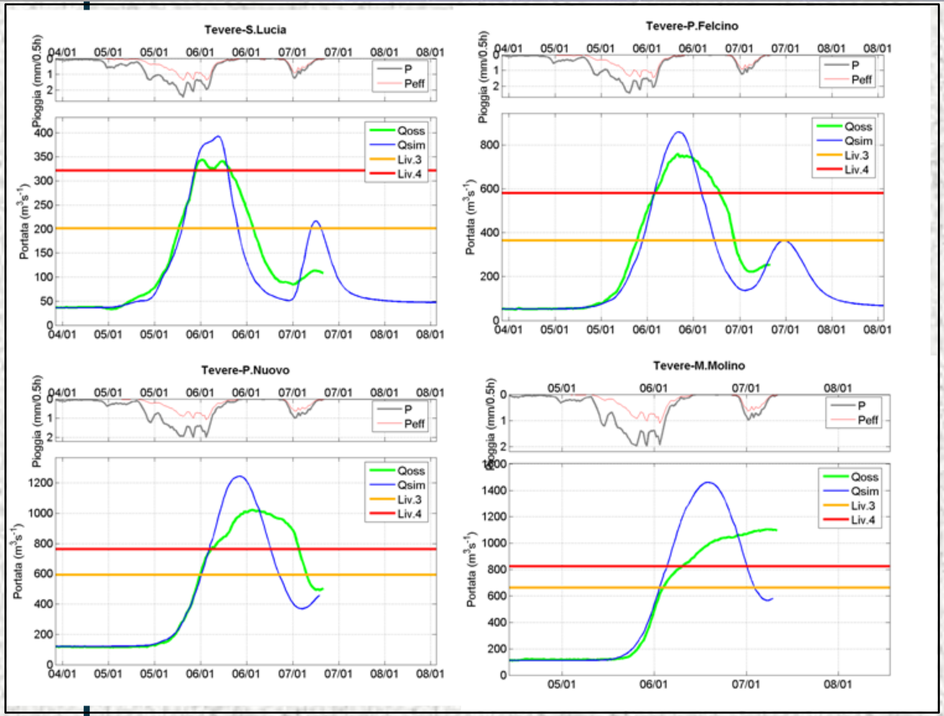
Operational Modeling for Civil Protection Department



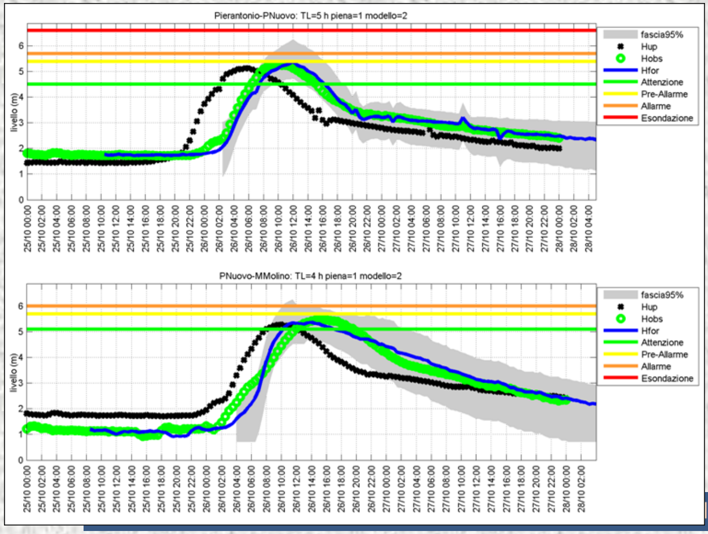


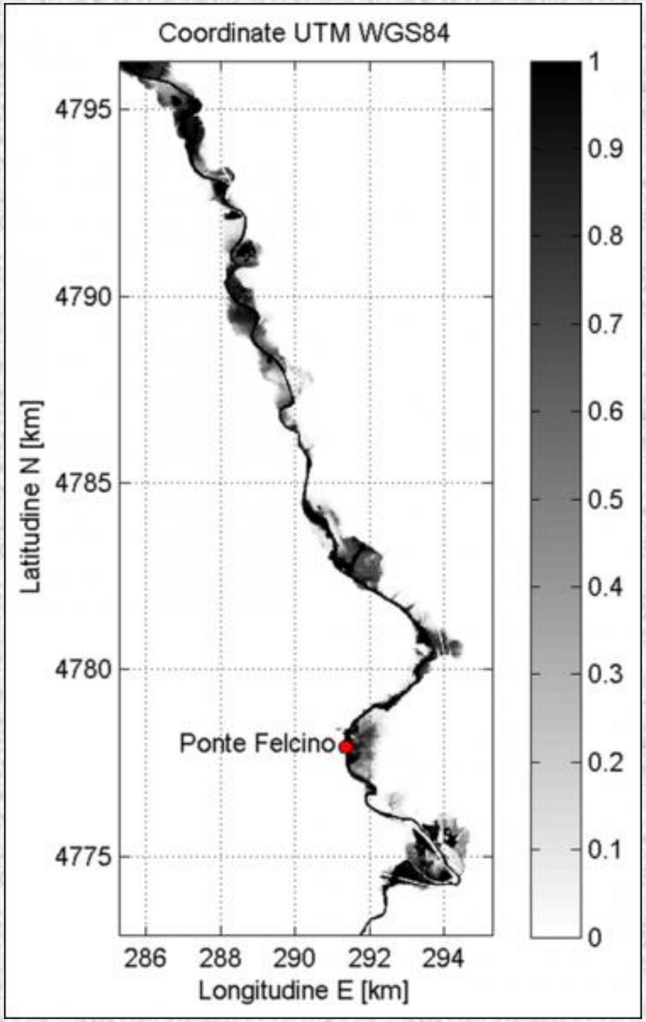
OPERATIONAL FLOOD FORECASTING SYSTEMS FOR UMBRIA REGION CIVIL PROTECTION CENTRE

Operational Modeling for Civil Protection Department



MISDc



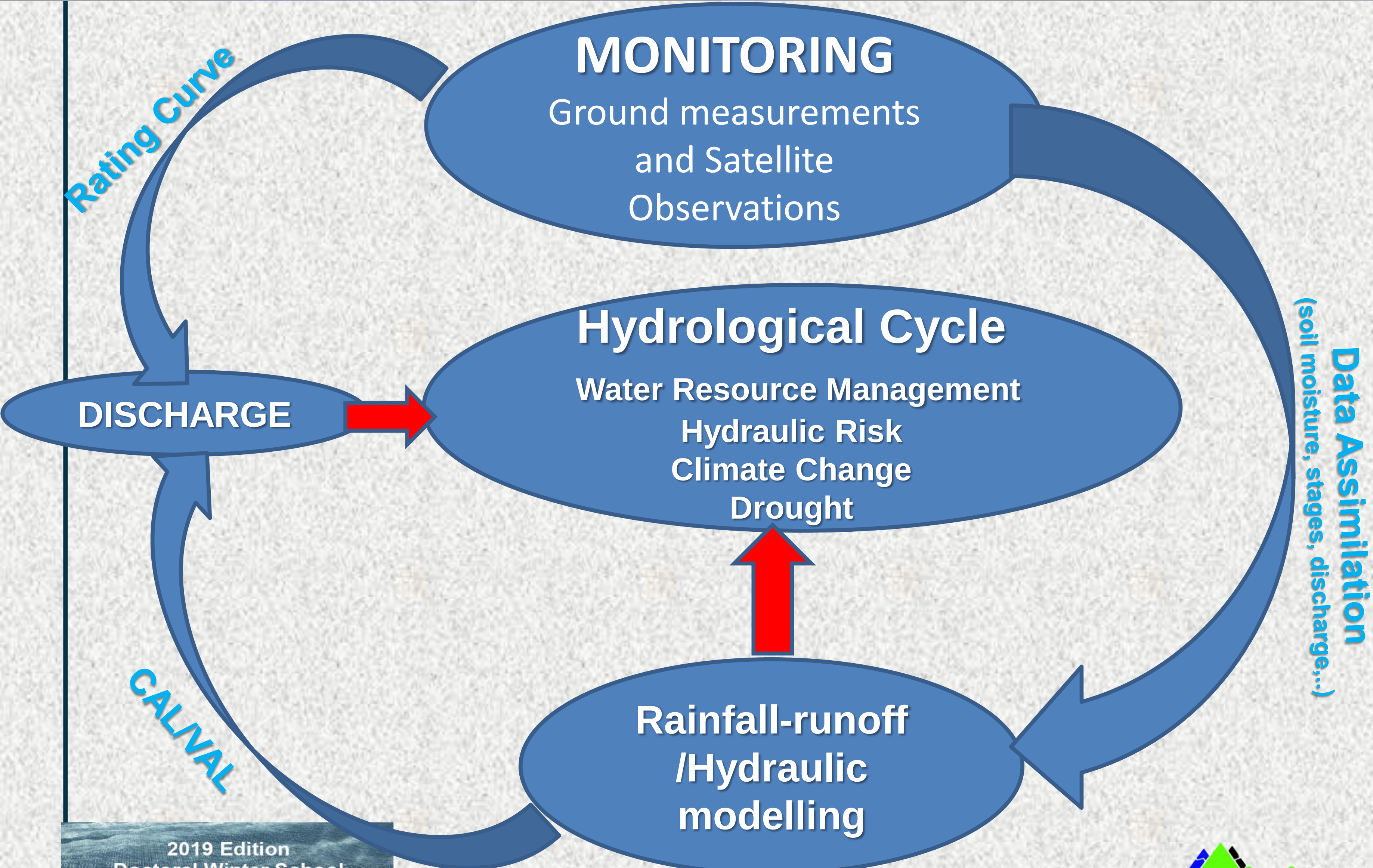


KSM

STAFOM-RCM

Istituto di Ricerca per la Protezione Idrogeologica

DISCHARGE: key variable of hydrological cycle



Streamflow measurements

Water level

Flow Velocity

Discharge assessment – Rating curves

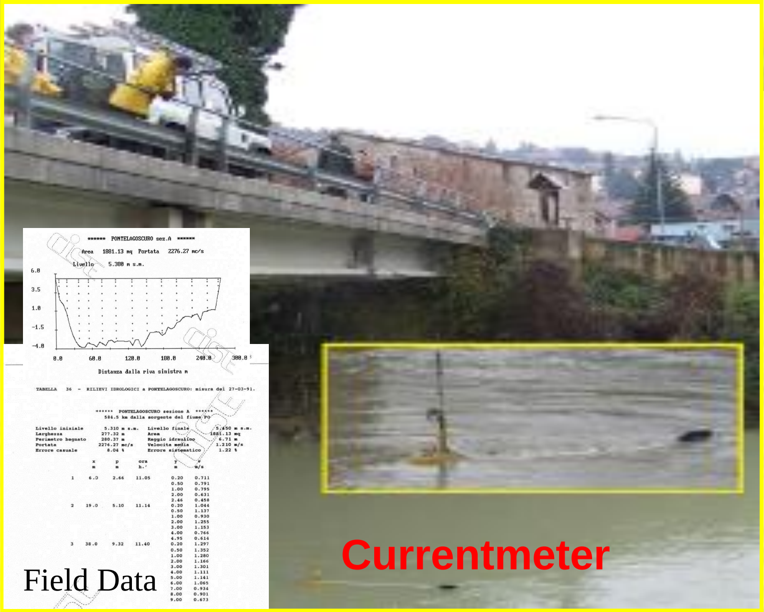
1) Stage Monitoring

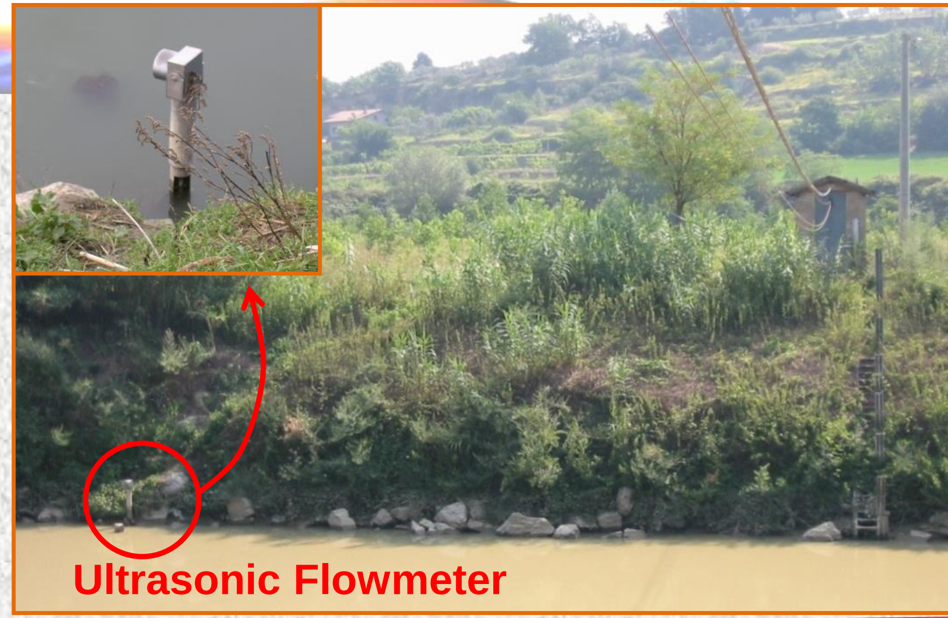
2) Flow monitoring

by contact sensor

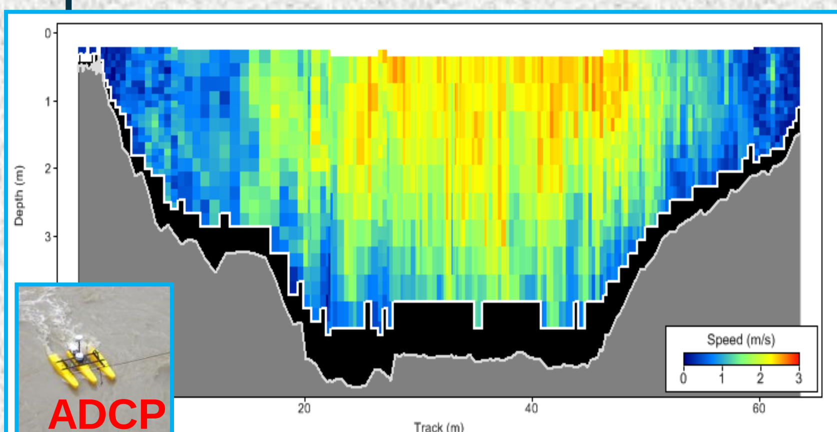
by no-contact sensor (remote)

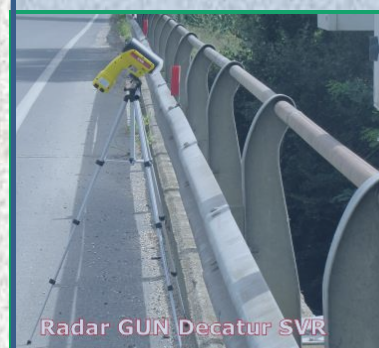
Type of Streamflow Measurements





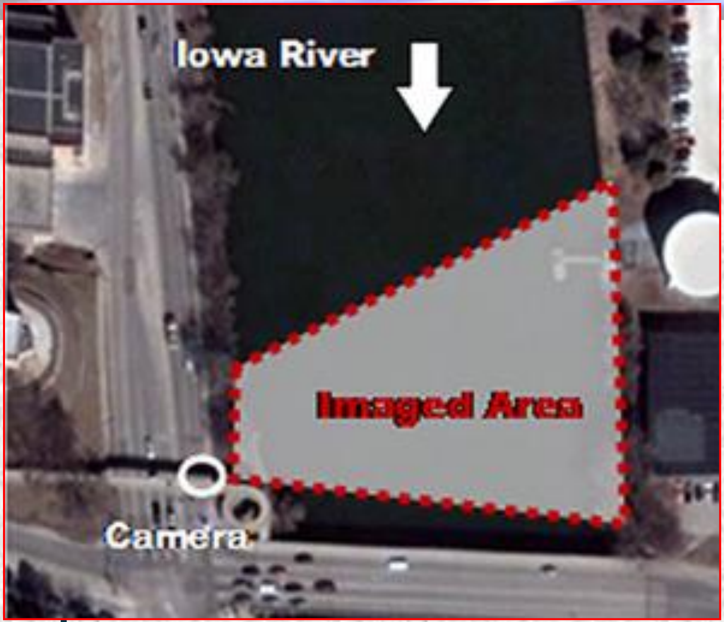
CONTACT





NO CONTACT

Type of Streamflow Measurements

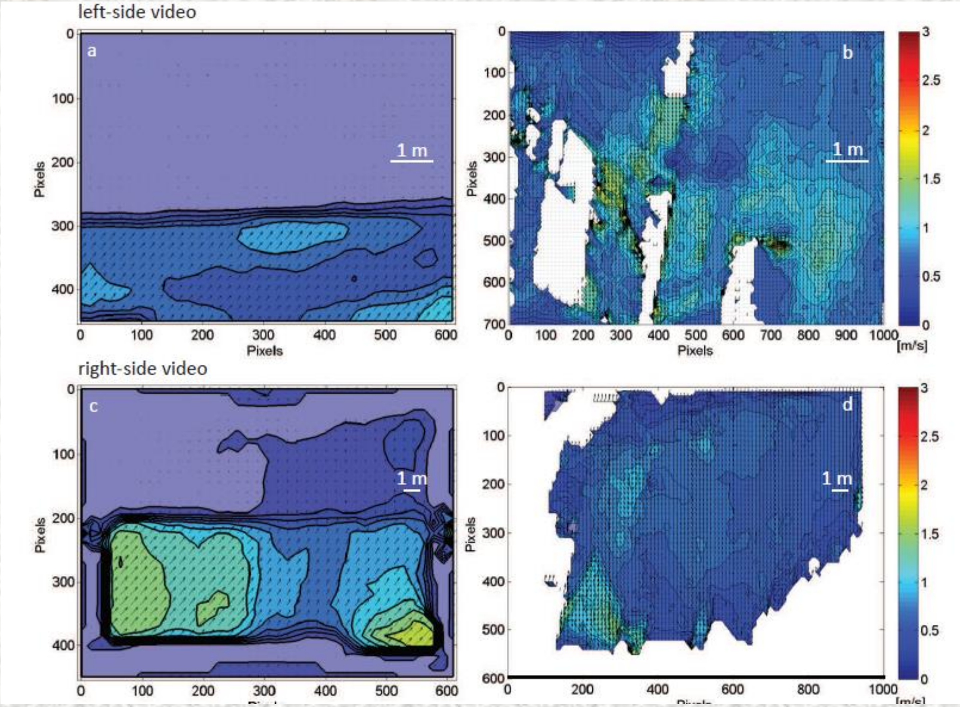


LSPIV

Large-Scale Particle Image Velocimetry

PTV

Particle tracking velocimetry



Tauro et al. 2016

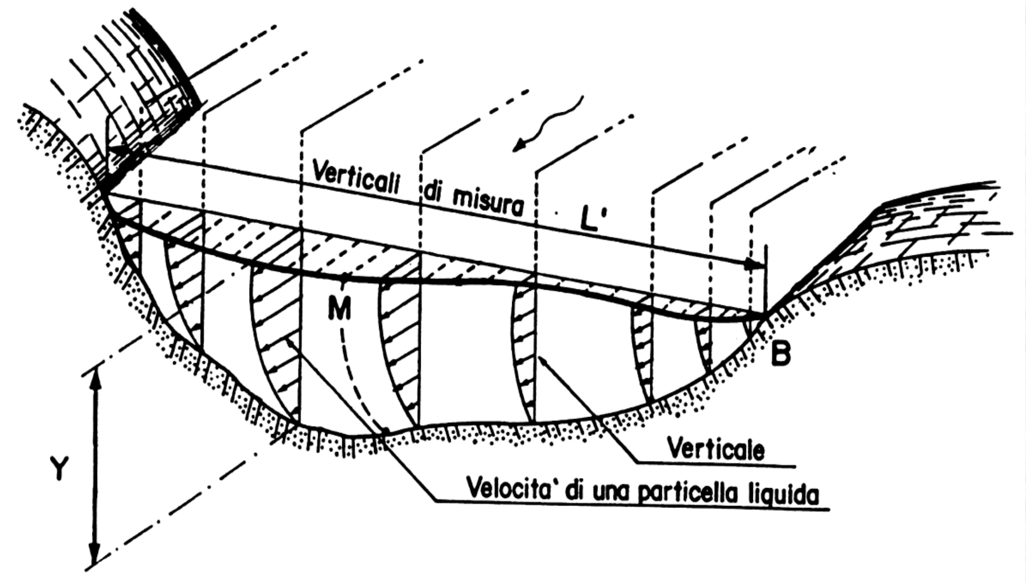
NO CONTACT

ISSUE

Depth-averaged velocity ?

Flow Velocity measurements

Velocity-Area Method



Considering a section of river normal to the flow direction.
The discharge is given by:

$$Q = \int_x \int_y v(x, y)\, dx\, dy$$

where v is the velocity of the flow normal to the section. In the equation it is necessary to know the velocity in each point of the section.

Estimate of Discharge

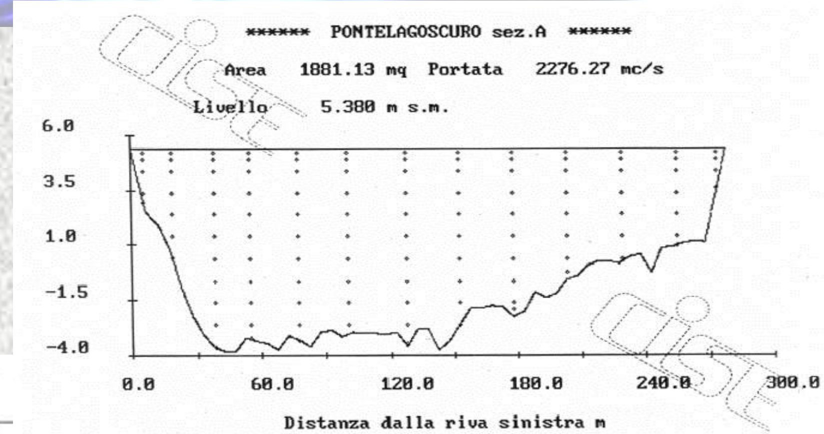


TABELLA 36 – RILIEVI IDROLOGICI a PONTELAGOSCURO: misura del 27-03-91.

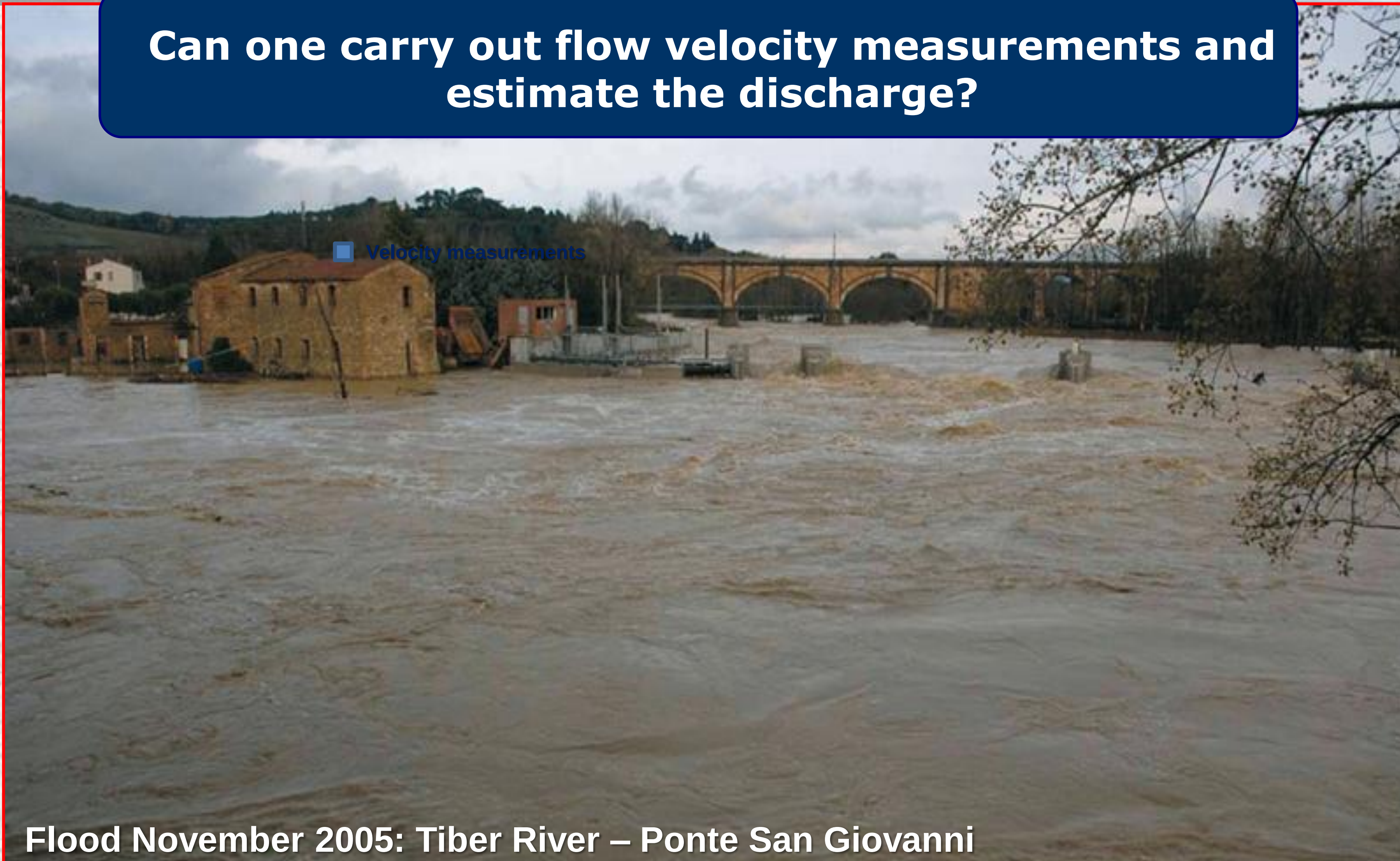
****** PONTELAGOSCURO sezione A ******
584.5 km dalla sorgente del fiume PO

Livello iniziale	5.310 m s.m.	Livello finale	5.450 m s.m.
Larghezza	277.32 m	Area	1881.13 mq
Perimetro bagnato	280.37 m	Raggio idraulico	6.71 m
Portata	2276.27 mc/s	Velocita media	1.210 m/s
Errore casuale	8.04 %	Errore sistematico	1.22 %

	x m	p m	ora h.'	y m	v m/s
1	6.0	2.66	11.05	0.20	0.711
				0.50	0.791
				1.00	0.795
				2.00	0.631
				2.46	0.458
2	19.0	5.10	11.14	0.20	1.044
				0.50	1.137
				1.00	0.930
				2.00	1.255
				3.00	1.153
				4.00	0.766
				4.95	0.614
3	38.0	9.32	11.40	0.20	1.297
				0.50	1.352
				1.00	1.280
				2.00	1.166
				3.00	1.301
				4.00	1.111
				5.00	1.141
				6.00	1.065
				7.00	0.934
				8.00	0.901
				9.00	0.673

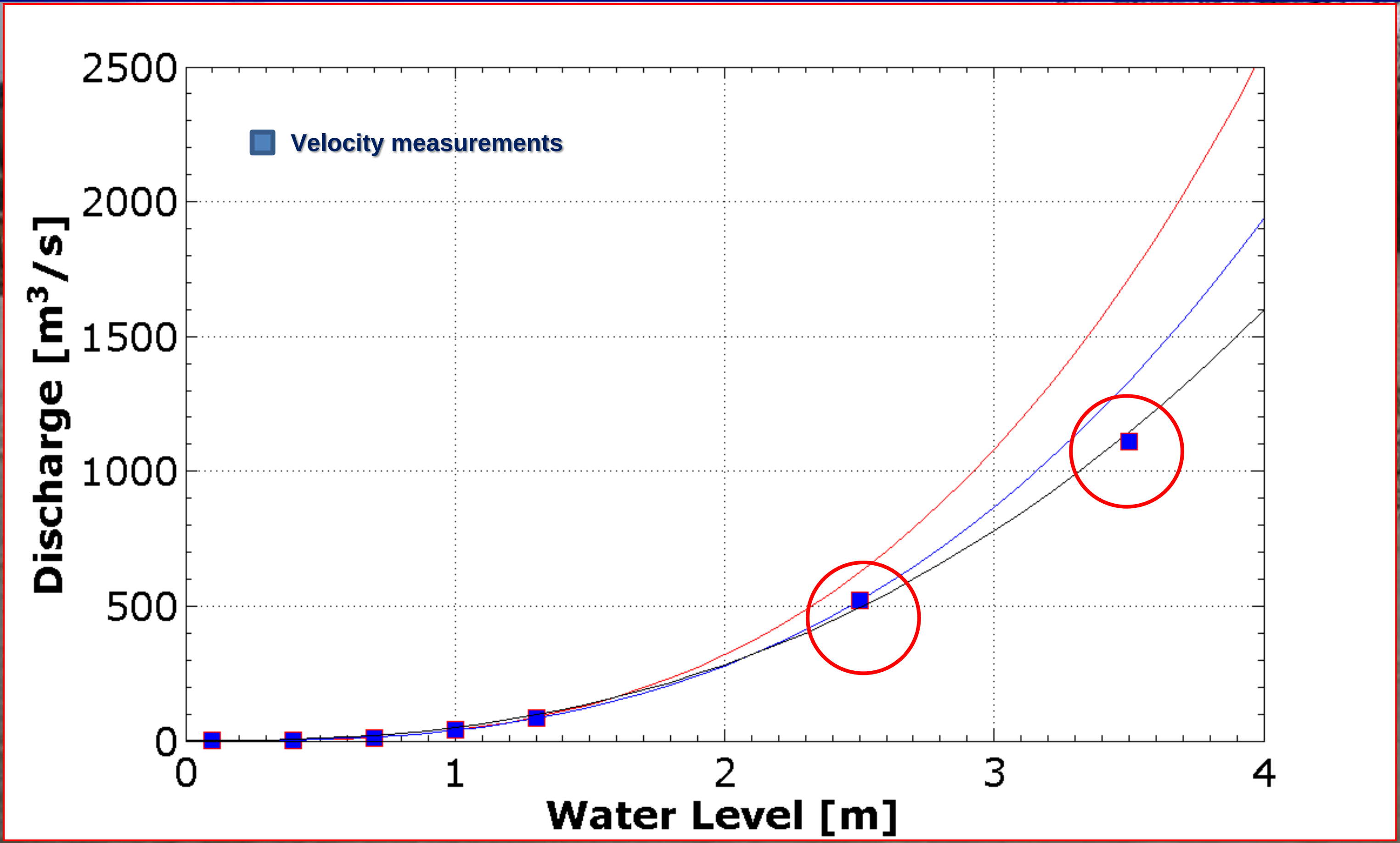
Scheda dati misure

Can one carry out flow velocity measurements and estimate the discharge?



Flood November 2005: Tiber River – Ponte San Giovanni

Can one carry out flow velocity measurements and estimate the discharge?



Flood November 2005: Tiber River – Ponte San Giovanni

Can one carry out flow velocity measurements and estimate the discharge?

No Bridges – No Sensors

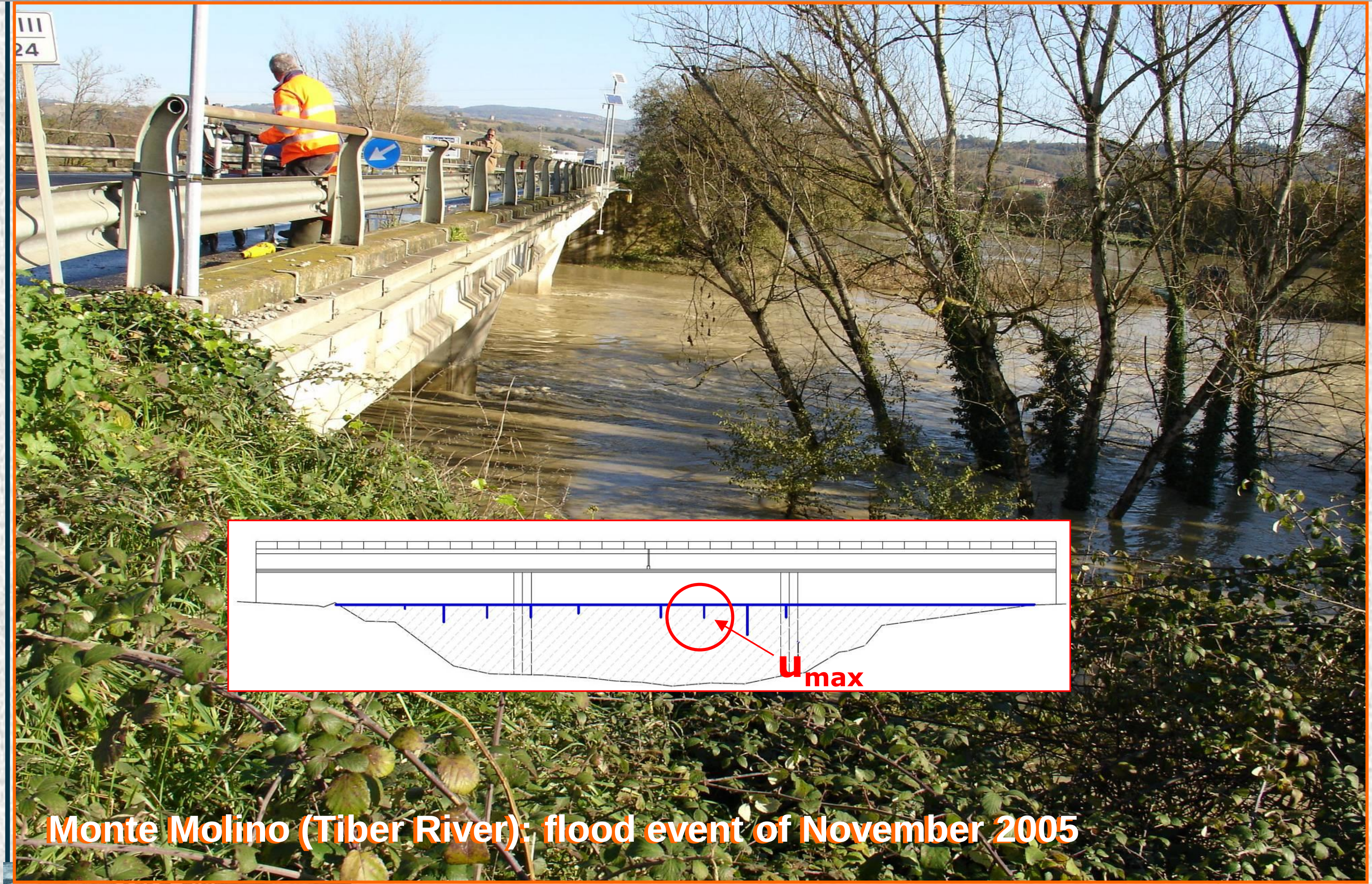
Need to exploit new technolgy for ground and satellite observations

Drone - UAV

Sentinel 3

Flood November 2005: Tiber River – Ponte San Giovanni

Velocity measurements for high flow



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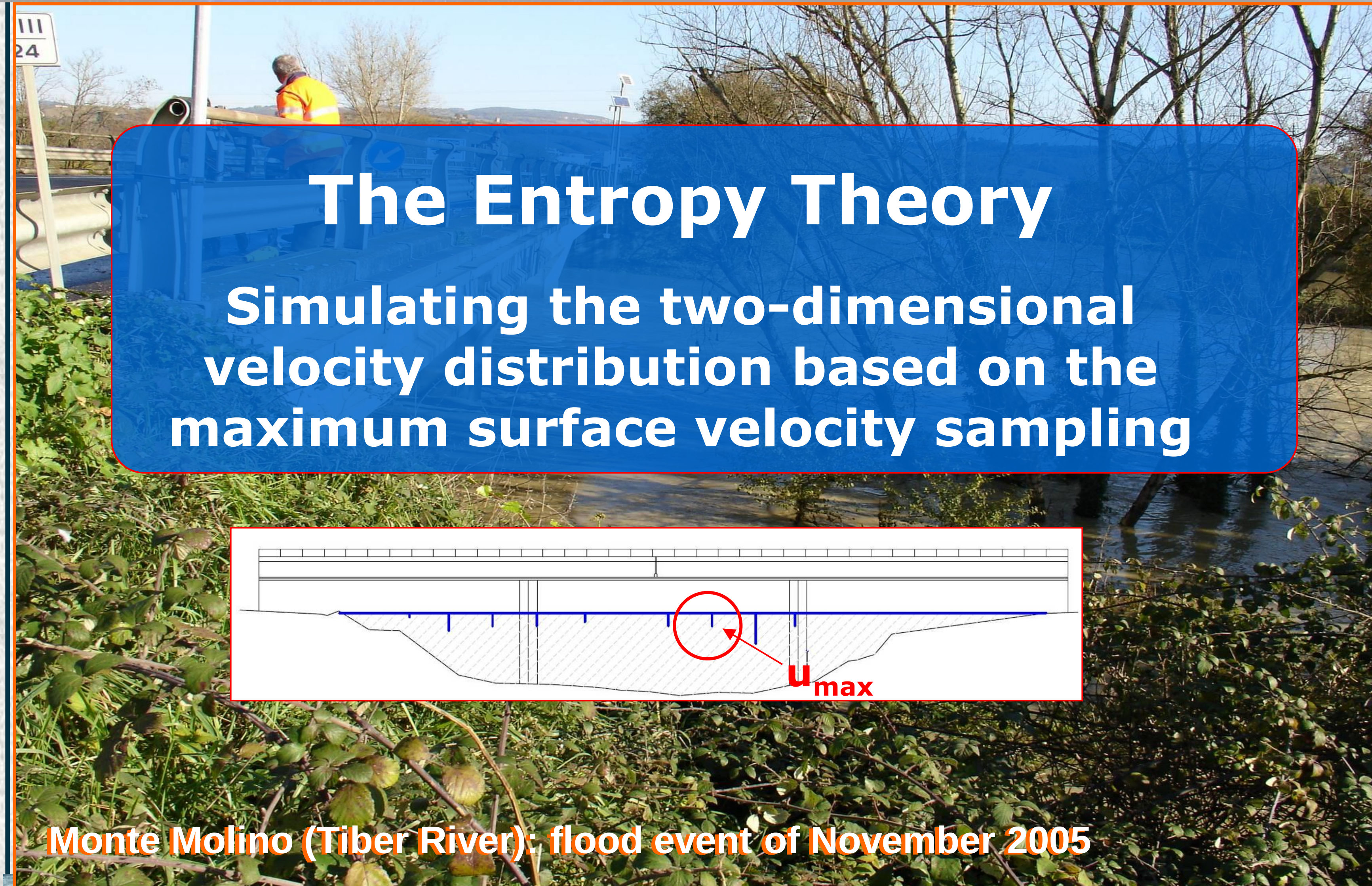
Velocity measurements for high flow



Monte Molino (Tiber River): flood event of November 2005

Entropy Theory

Shannon(1948): **a physical system, X,** may have a large number **of states, X_j,** of assigned **probability $P(X_j)$**

Entropy Theory

Shannon(1948): **a physical system, X,** may have a large number **of states, X_j,** of assigned **probability $P(X_j)$**

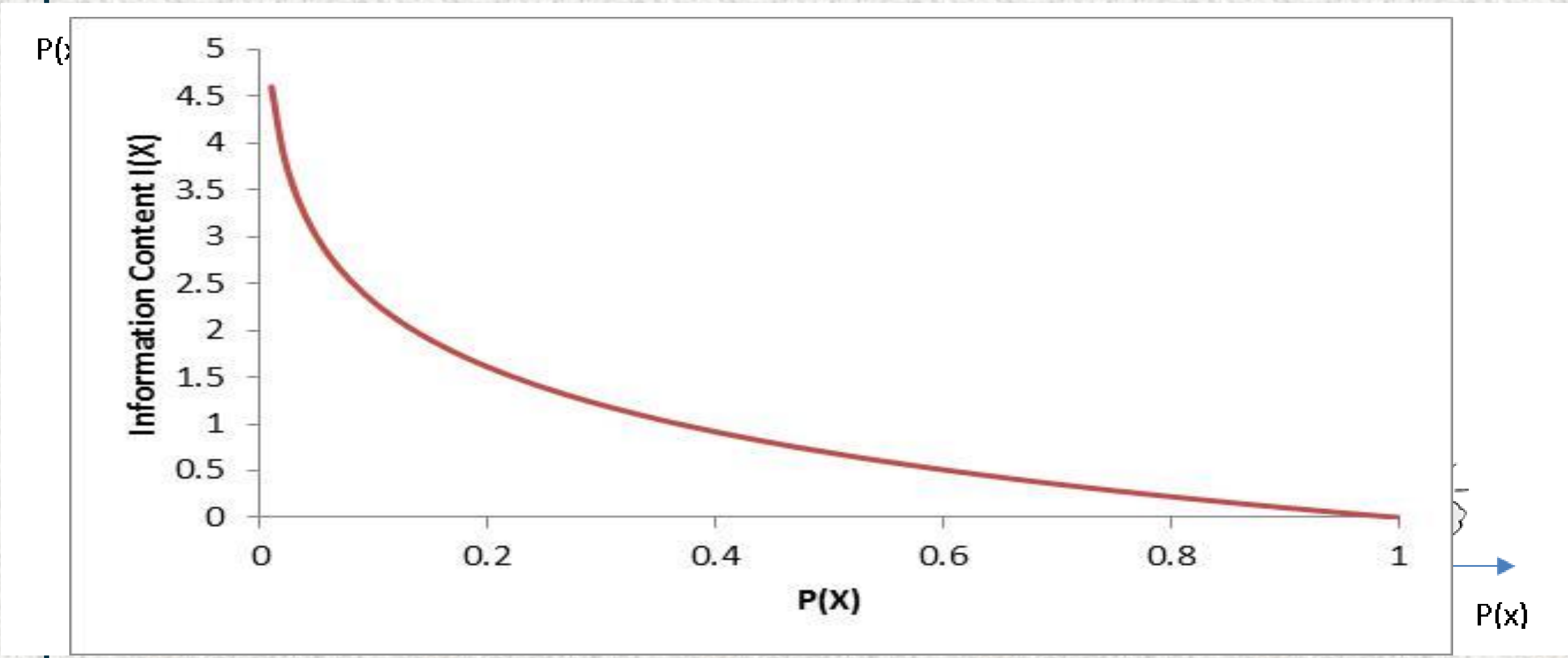
- In a **physical system with** certain **assigned constraints**, the **ENTROPY (H(X))** tends to a **maximum value** as random **events tend to occur in the greatest possible disorder**

- The connection between Entropy and Probability is the **Theory of Information**: the **information content I(X)** associated to a state Xj is represented by the quantity:

$$I(X) = -\ln P(X_j)$$

- I(X) function provides the following two insights:
  1. the **quantity of information if the event X=Xj occurs**;
  2. the **uncertainty on the event X=Xj**

Entropy Theory



I(X) = - ln P(Xj)

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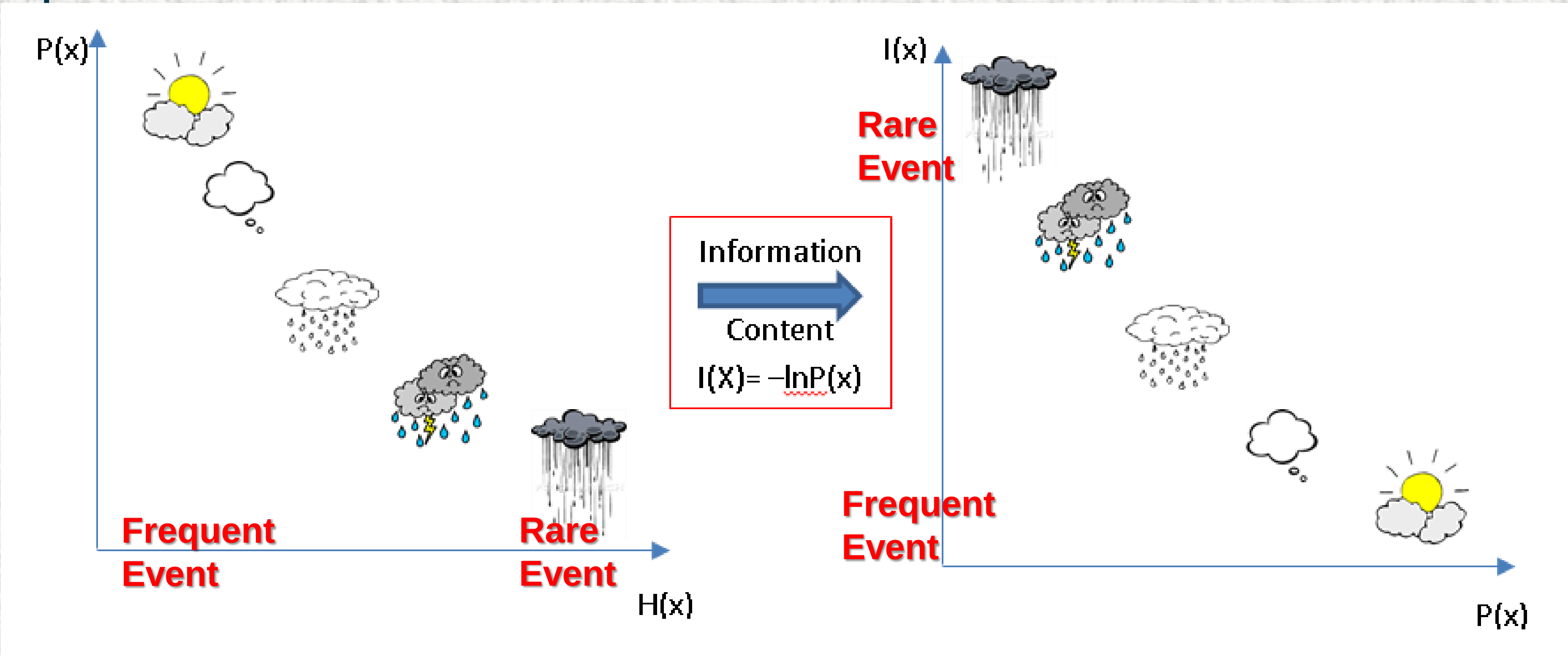
Entropy Theory



Standard **floods** furnish a **low information**; on the contrary **high floods with low probability to occur** provide a **high quantitative of information**

Entropy is statistically defined through the mean of Information Content I(X) for a discrete system in the form (Janes 1957) :

$$H(X) = \sum_j P(X_j) I(X_j) = -\sum_j P(X_j) \ln P(X_j)$$

If X=Xj is a **rare event** its probability P(X) tends to 0, hence, **H(X) tends to ∞**; while if X=Xj is a **certain event** its **entropy goes to zero**.

- The **probability distribution that maximizes the entropy of the system** is the distribution that **produces greater information, i.e. it is more close to the real P(X)**

Therefore, **Entropy is used for statistical inference** to solve for a **probability distribution** function when **the information available about the variable is limited to some average quantities**, defined as **constraints**, such as **mean, and variance**

$$G_i = \int_a^b \psi_i(X,p)dX \qquad i = 1,2\ldots n$$

$$\int_0^{u_{max}} p(u)du = 1 \qquad \int_0^{u_{max}} u\, p(u)du = \bar{u}$$

$\Psi_1(X,p)=p(u)$

$\Psi_2(X,p)=u\,p(u)$

where *$\Psi i(X,p)$* are the specified functions, **the probability density function p(X) which maximizes entropy can be obtained by (Chiu, 1988)**

$$\frac{\partial I(X,p)}{\partial p} + \sum_{i=1}^{n} \lambda_i \frac{\partial \psi_i(X,p)}{\partial p} = 0$$

λ_i are the Lagrange multipliers

2D Entropic Velocity Distribution

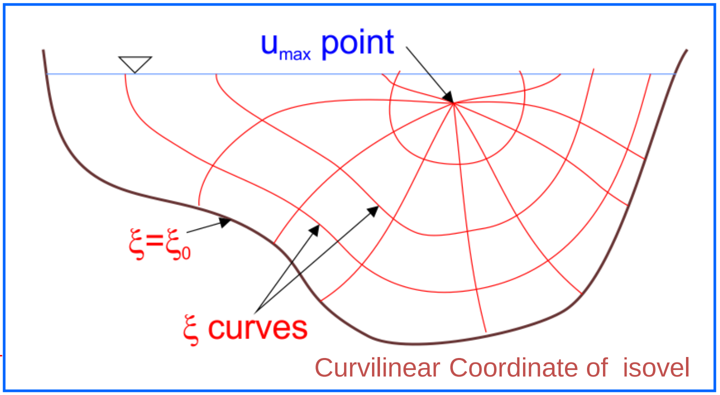
The 2D velocity distribution can be simulated by using the entropic model

Pioneer was Chiu (1988):

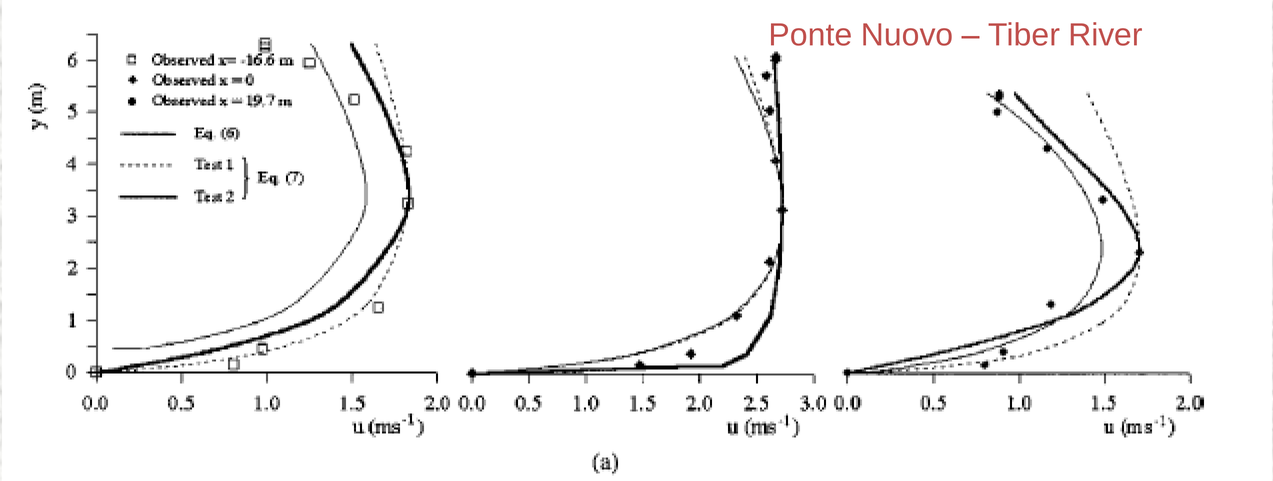
$$u(\xi) = \frac{u_{max}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{\xi - \xi_0}{\xi_{max} - \xi_0}\right]$$

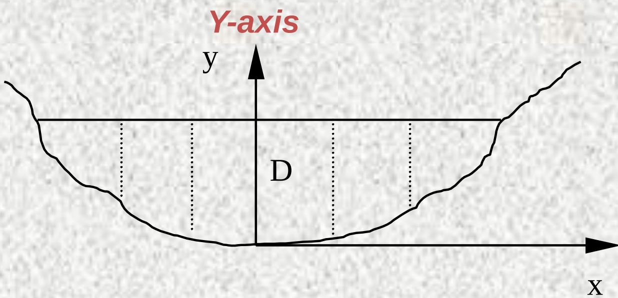
$$\frac{\xi - \xi_0}{\xi_{max} - \xi_0}$$ Cumulatiive Probability Distribution

$$\frac{u_m}{u_{max}} = \Phi(M) = \frac{e^M}{e^M - 1} - \frac{1}{M}$$



Too many parameters are involved in the 2D velocity and the performance are poor close to the side walls (Moramarco et al. 2004)





Estimation of Mean Velocity in Natural Channels Based on Chiu's Velocity Distribution Equation

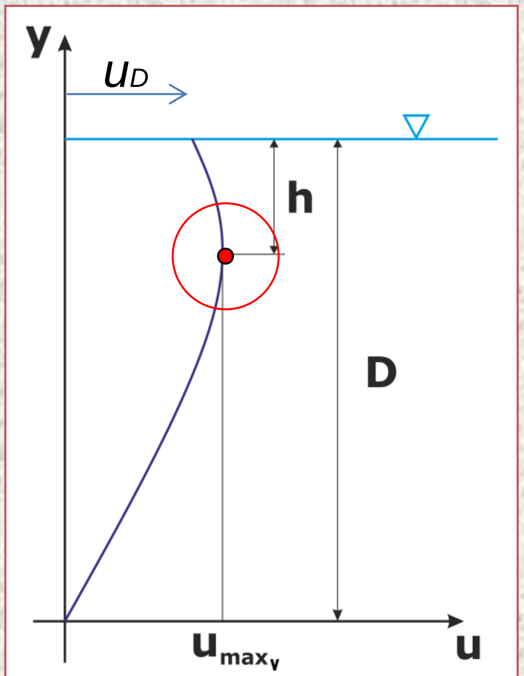
Tommaso Moramarco[1]; Carla Saltalippi[2]; and Vijay P. Singh, F.ASCE[3]

Journal of Hydrologic Engineering, Vol. 9, No. 1, ASCE, ISSN 1084-0699/2004/1-42–50/$18.00.

Alternative of Chiu's model

Velocity profile:

$$u(x,y)=\frac{u_{max}(x)}{M}\ln\left[1+\left(e^{M}-1\right)\frac{y}{D(x)-h(x)}\exp\left(1-\frac{y}{D(x)-h(x)}\right)\right]$$



u_D is sampled

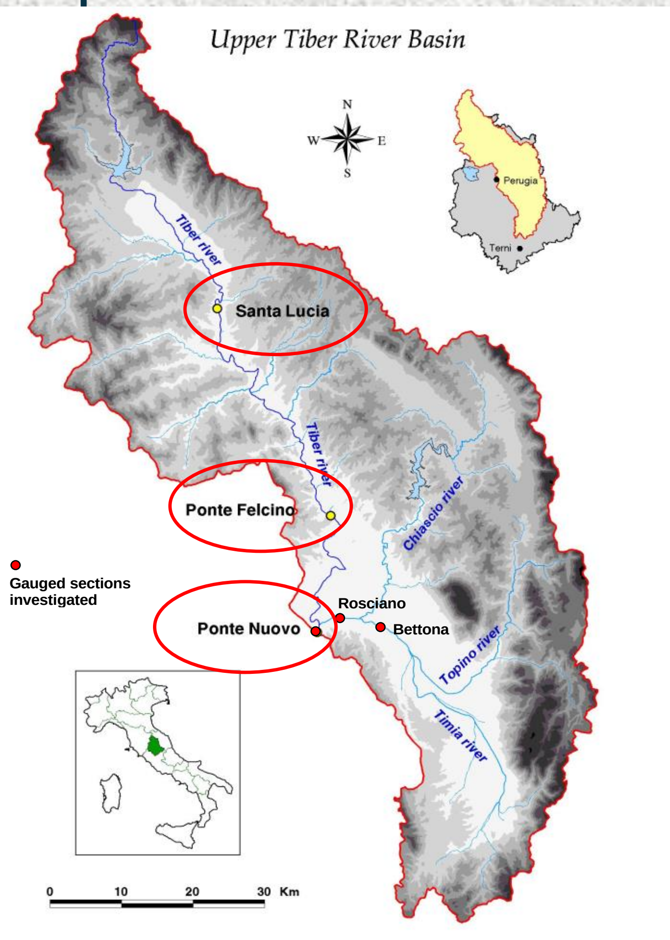
$$u_{max}=(u_D M)\div\ln\left[1+(e^{M}-1)\frac{1}{1-\frac{h}{D}}\exp\left(1-\frac{1}{1-\frac{h}{D}}\right)\right]$$

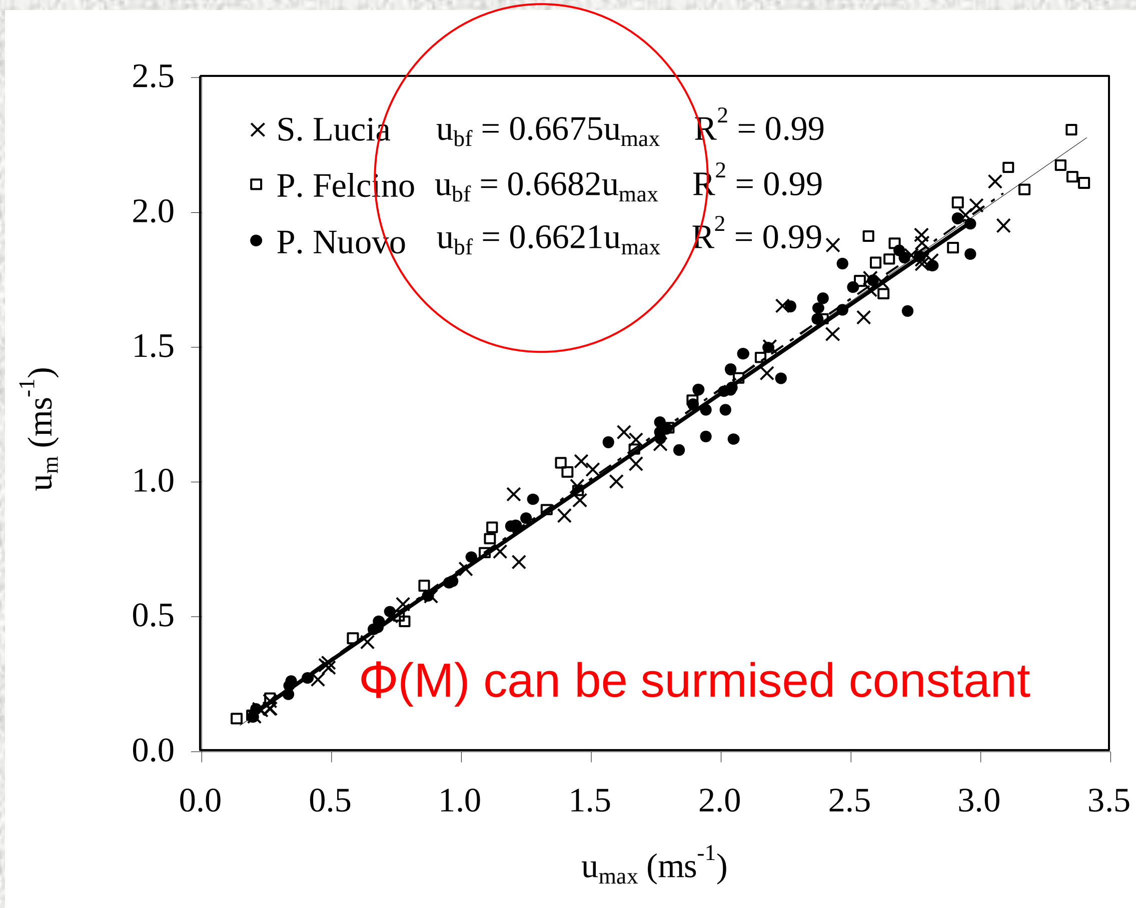
The entropic paramater M:

- is caracteristic of the section
- is estimated through the historical sampled pairs (u_m, u_{max}) by using the linear entropic relation:

$$u_m=\Phi(M)\,u_{max}$$

Accuracy entropic linear relationship



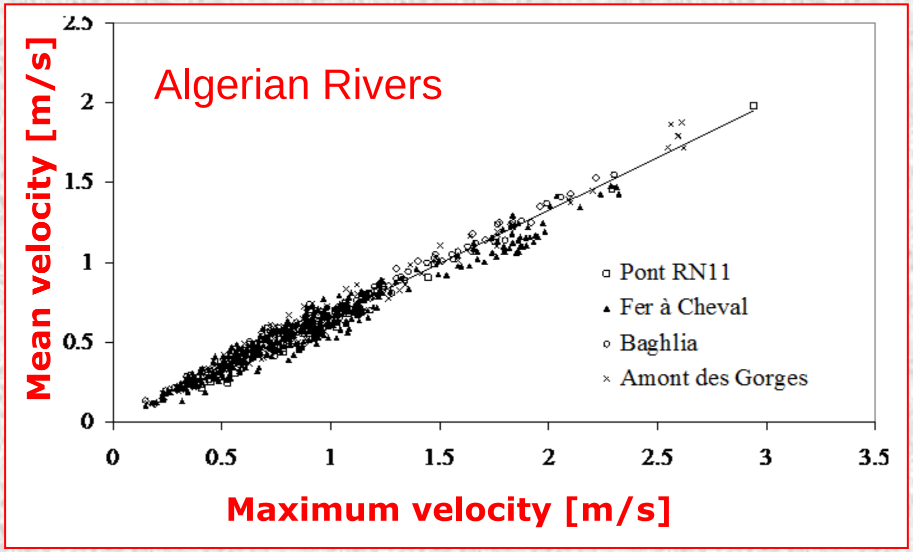


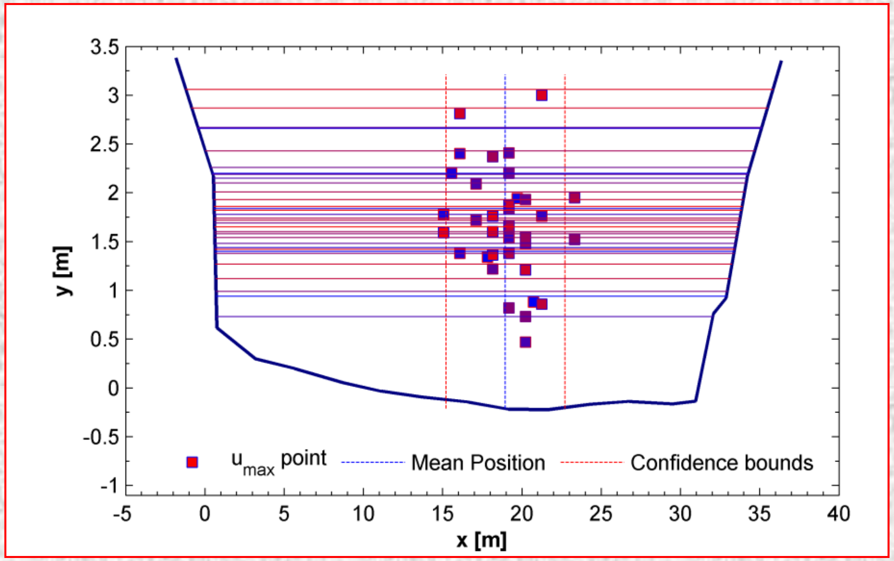
Relation between mean and maximum velocities in the three gauged river sections investigated

Entropic linear relationship

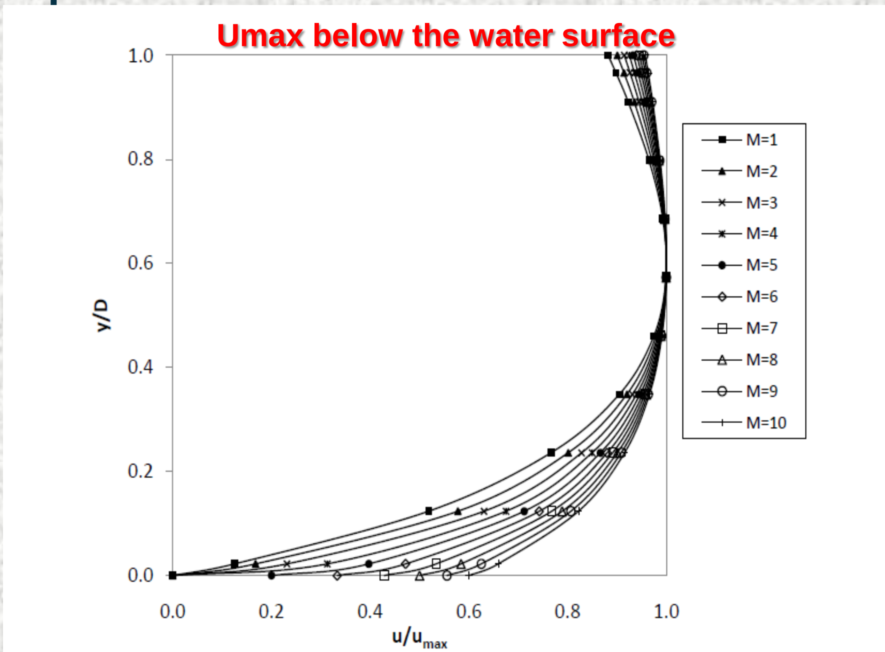
$$\frac{u_m}{u_{\max}} = \Phi(M) = \frac{e^M}{e^M - 1} - \frac{1}{M}$$

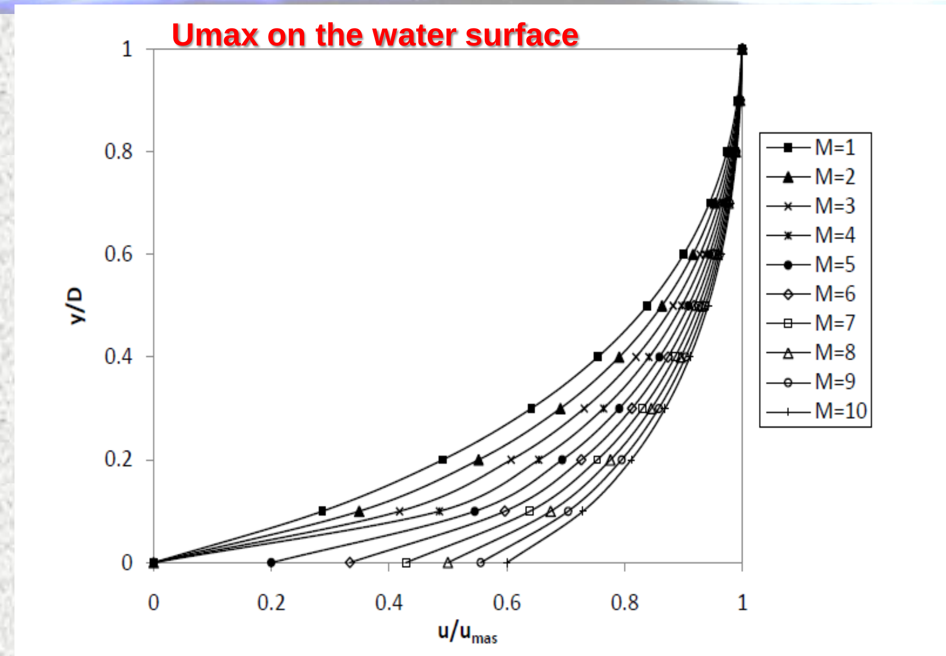
Umax occurs in the same portion of flow area





Physical Meaning of M





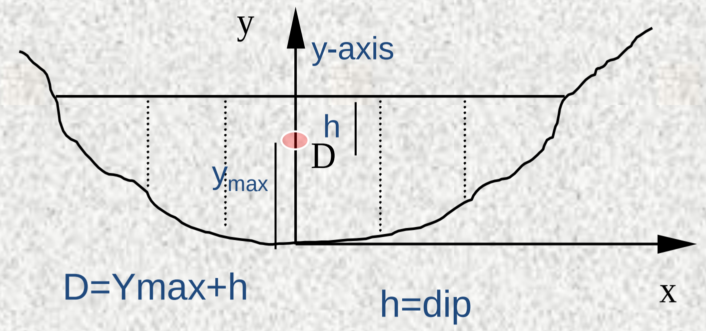
This aspect suggests that parameter *M* can be considered an indicator of the boundary effects on the velocity distribution.

The more low M value, the more warped the profile: high effetcs of banks

Geometric and hydraulic characteristics
Ungauged river site

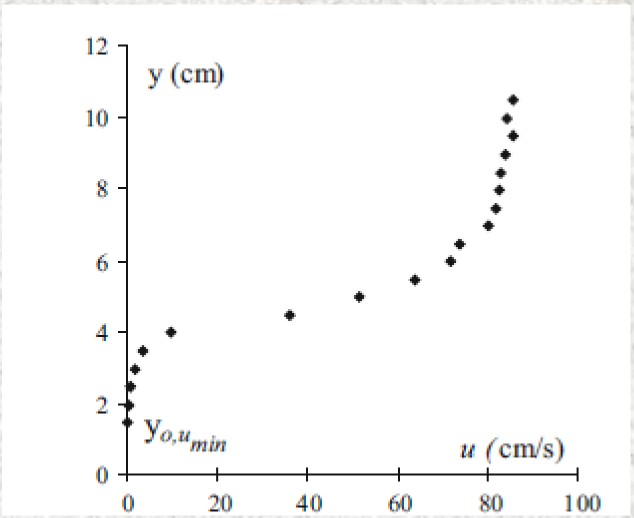
Formulation of the Entropy Parameter Based on Hydraulic and Geometric Characteristics of River Cross Sections
Tommaso Moramarco, M.ASCE[1]; and Vijay P. Singh, F.ASCE[2]
Journal of Hydrologic Engineering, Vol. 15, No. 10, October 1, 2010. ©ASCE

$$\Phi(M) = \frac{\frac{1}{n} R^{1/6} \Big/ \sqrt{g}}{\frac{1}{k}\left[\ln\left(\frac{y_{\max}}{y_o}\right) + \frac{h}{y_{\max}} \ln\left(\frac{h}{D}\right)\right]}$$



For larger rivers

$$\Phi(M) = \frac{\frac{1}{n} R^{1/6} \Big/ \sqrt{g}}{\frac{1}{k}\left[\ln\left(\frac{y_{\max}}{y_o}\right)\right]}$$



Φ(M) doesn't depend on dynamic of flood

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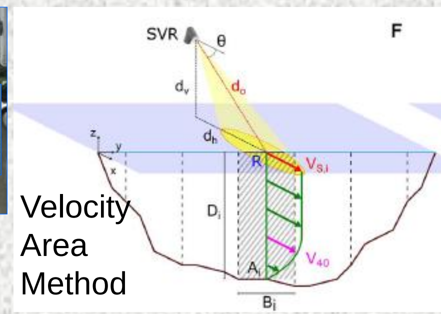
TURNING SURFACE VELOCITY INTO DEPTH-AVERAGED VELOCITY

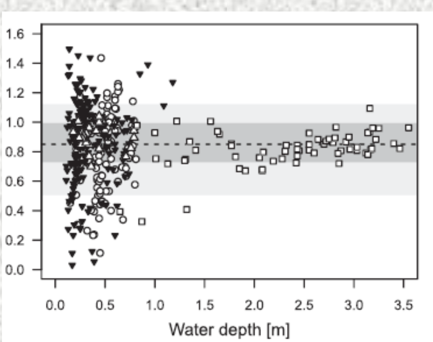
water
Article
From Surface Flow Velocity Measurements to Discharge Assessment by the Entropy Theory
Tommaso Moramarco *, Silvia Barbetta and Angelica Tarpanelli



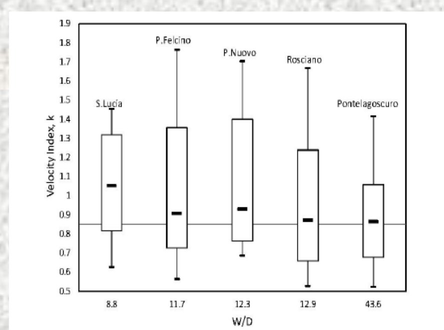
Velocity Index Method

$$\frac{u_{m_{vert}}(xi)}{u_{surf}(xi)} = Vel_{ind} = 0.85$$

(Creutin, et al. JoH, 2003)

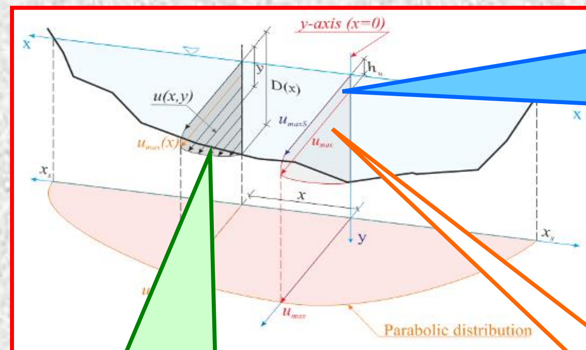


(Welber, et al. WRR, 2016)



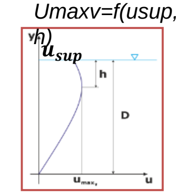
(Moramarco, et al. Water, 2017)

Entropy Method



Surface Velocity Radar

Umaxv=f(usup, h)



2D Entropy velocity distribution :

$$u = \frac{u_{max_v}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{D-y}{D-h}\exp\left(1 - \frac{D-y}{D-h}\right)\right]$$

(Moramarco et al., JHydrolE, 2004)

$$u_{maxv}(x_i) = \frac{u_{sup}(x_i, D(x_i))}{\frac{1}{M}ln[1 + (e^M - 1)\delta(x_i)e^{1-\delta(x_i)}]}$$

$$\delta(x_i) = \frac{D(x_i)}{D(x_i) - h(x_i)} = Dip$$

$$\frac{u_m}{u_{max}} = \Phi(M) = \frac{e^M}{e^M - 1} - \frac{1}{M}$$

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Entropy-based Method to estimate the dip

$$u(x_i, y) = \frac{u_{\max v}(x_i)}{M} \ln\left[1 + \left(e^M - 1\right)\frac{y}{D(x_i) - h(x_i)} \exp\left(1 - \frac{y}{D(x_i) - h(x_i)}\right)\right]$$

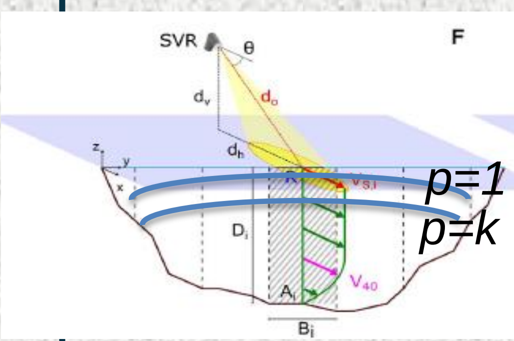
$$u_{maxv}(x_i) = \frac{u_{sur}(x_i, D(x_i))}{\frac{1}{M} ln[1 + (e^M - 1)\delta(x_i) e^{1-\delta(x_i)}]}$$

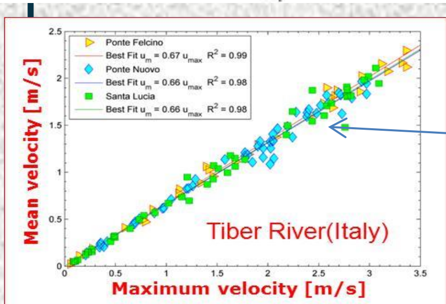
$$dip = \delta(x_i) = 1 + 1.3 e^{-x_i/D(x_i)}$$

Yang et al., J HydrE, (2004)

$\delta'_p(x_i) = a_p + \delta(x_i)$ (secondary currents)

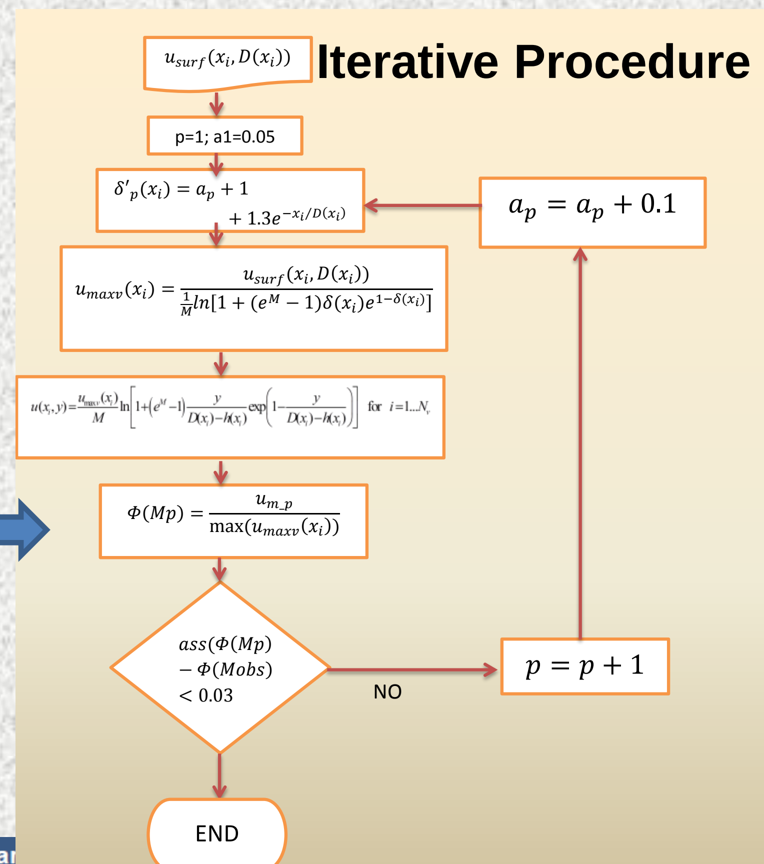
a_p =***dip at y-axis*** *estimated by iterative procedure (p)*





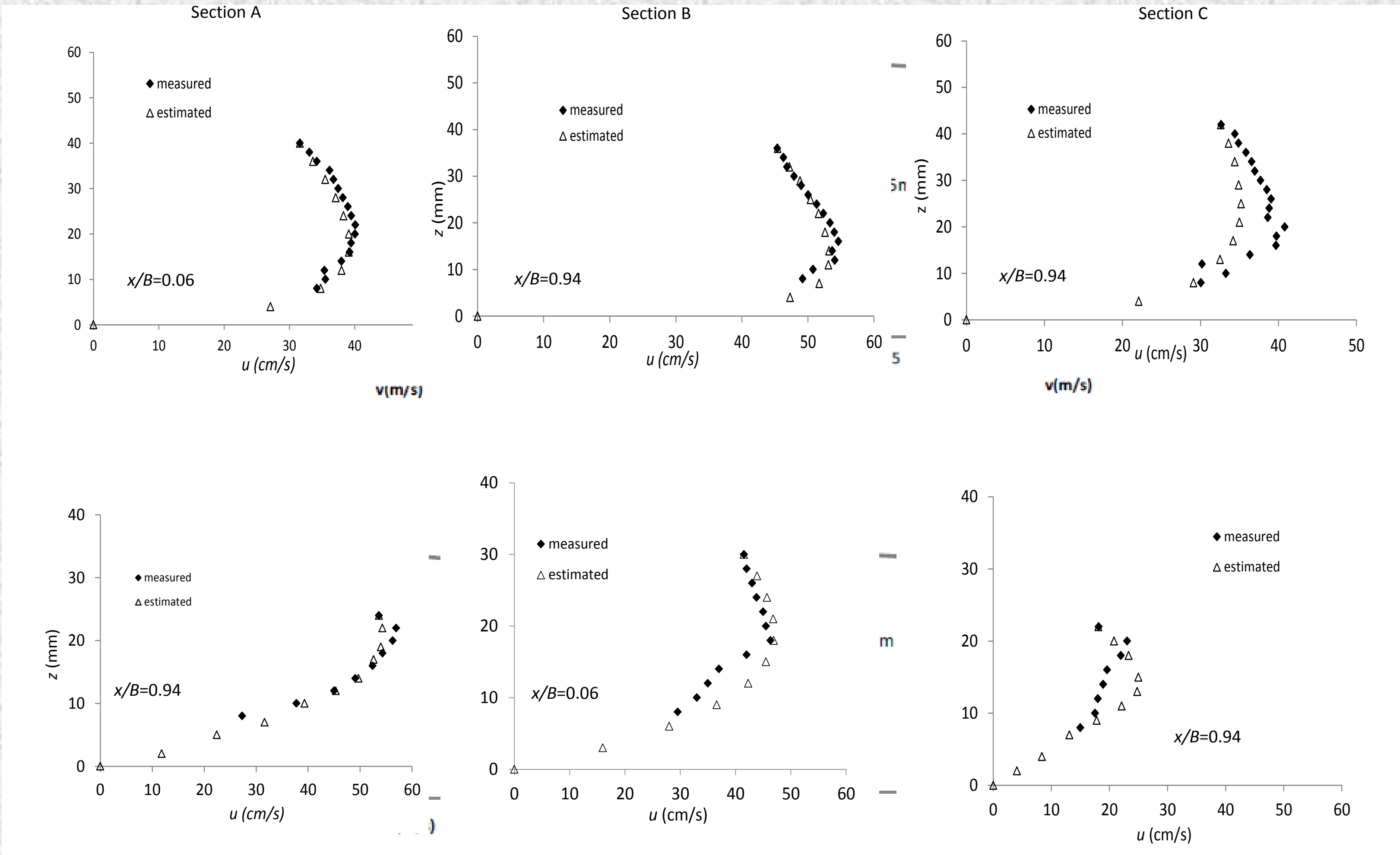
Iterative Procedure

1. Initial dip
2. Entropy profiles by vsurf
3. Umax estimate
4. Um estimate
5. Computation of Phi_com(M)
6. Comparison with Phi_oss(M)
7. Update dip



TURNING SURFACE VELOCITY INTO DEPTH-AVERAGED VELOCITY

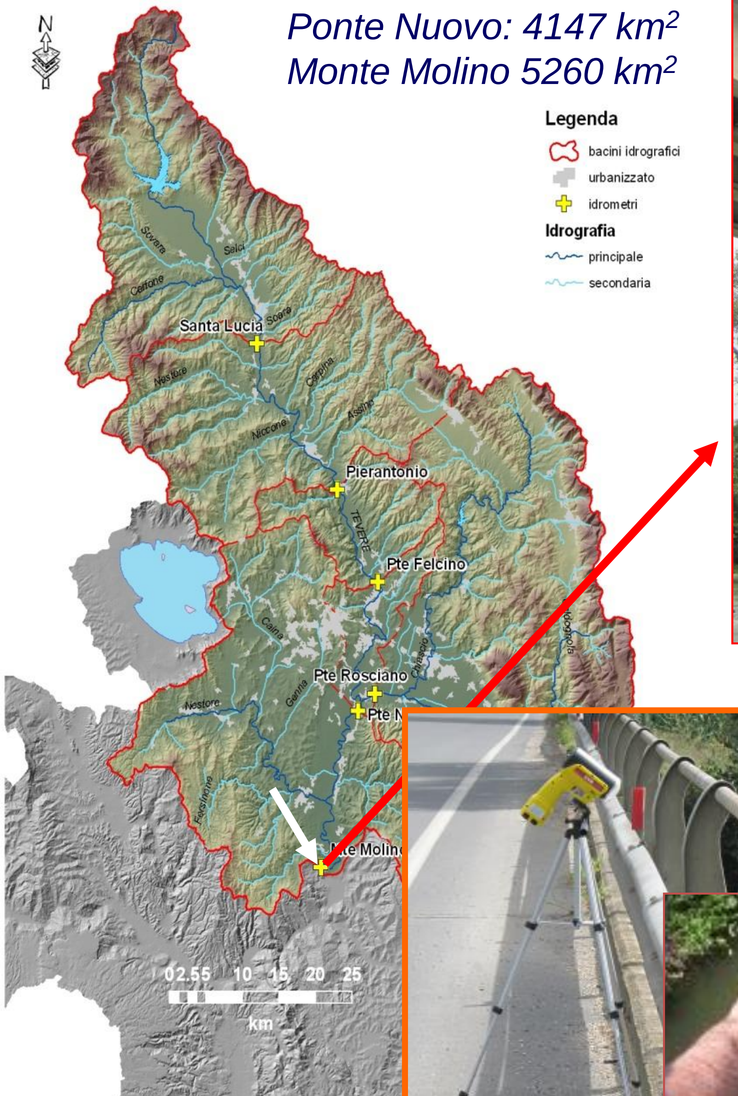
Comparison of velocity profiles and sampled velocity points



Ponte Nuovo field data **Laboratory data**

Maximum Surface Velocity Monitoring by Radar

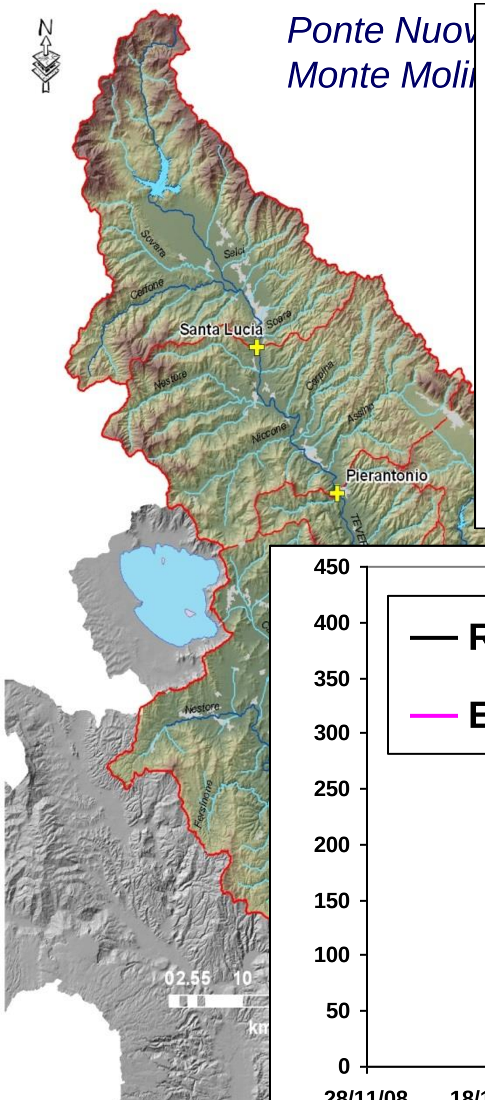
Pierantonio: 1800 km^2
Ponte Nuovo: 4147 km^2
Monte Molino 5260 km^2

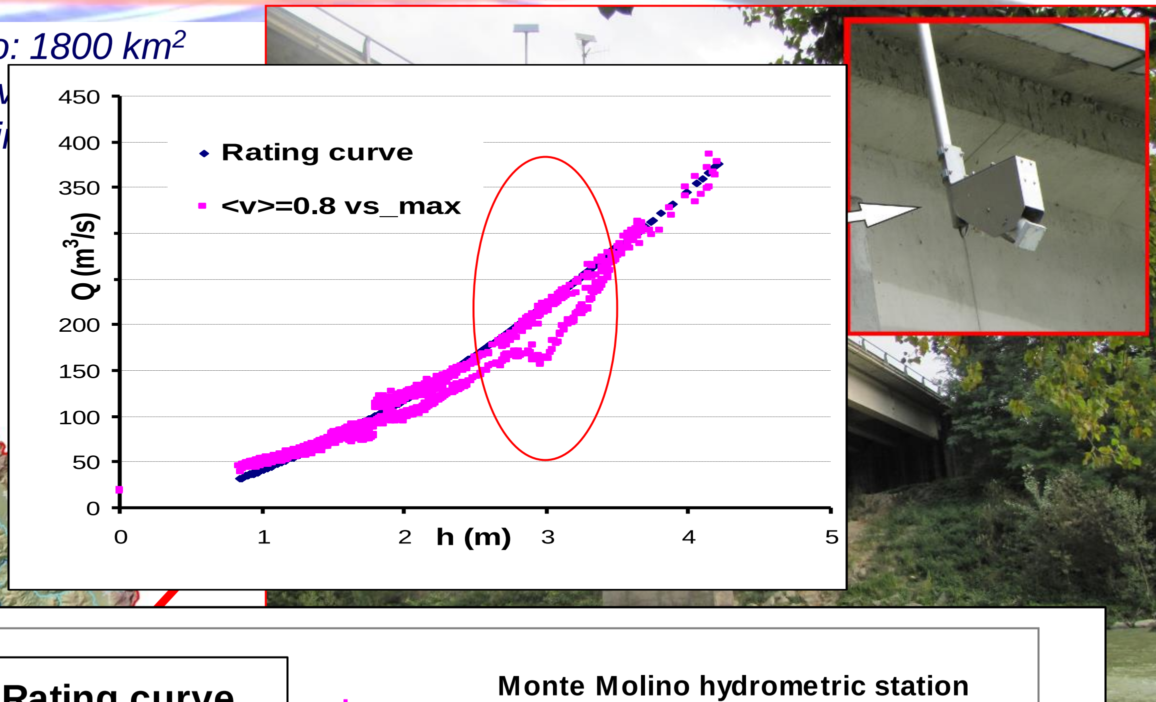


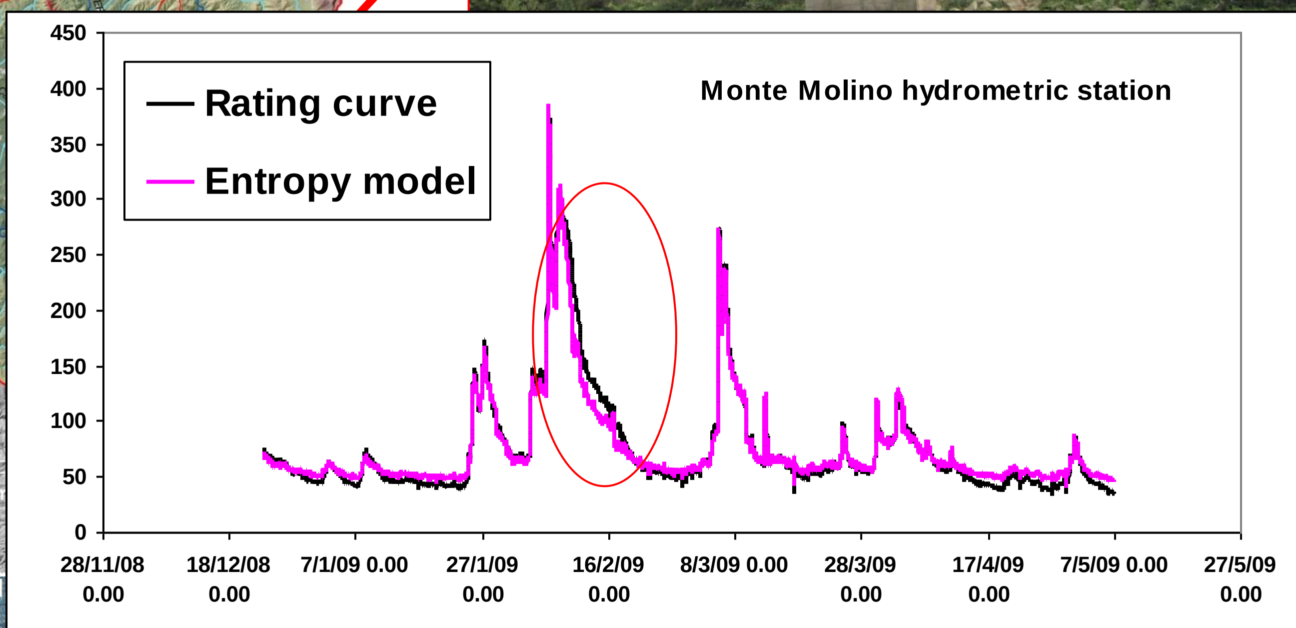
$$u_{max} = (u_D M) \div \ln\left[1 + (e^M - 1)\frac{1}{1-\frac{h}{D}}\exp\left(1 - \frac{1}{1-\frac{h}{D}}\right)\right]$$

Maximum Surface Velocity Monitoring by Radar

Pierantonio: 1800 km²
Ponte Nuov
Monte Moli

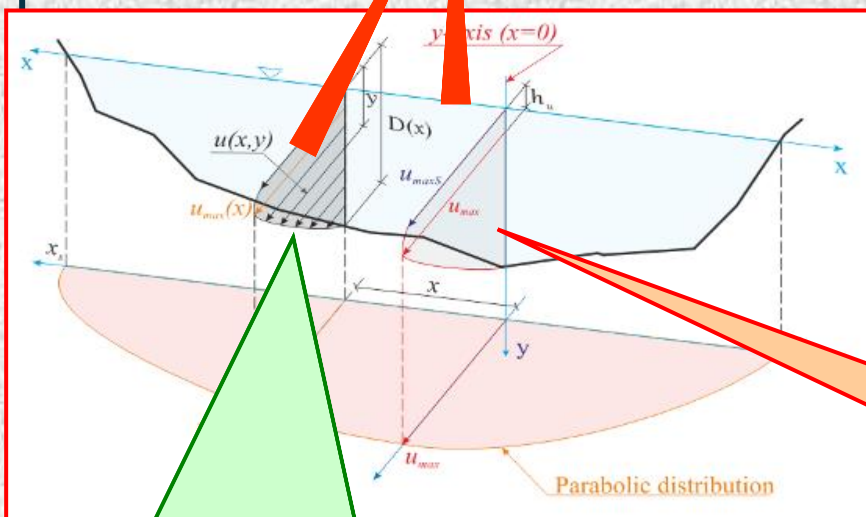






A prototype of radar-drone system for measuring the surface flow velocity at river sites and discharge estimation (SWARMNET Project - MIUR)

U_S WSL



Recently, a growing interest towards the use of Unmanned Aerial Vehicle (UAV) for topographic applications is observed and considering their capability UAV may be of a considerable interest for the hydrological monitoring and in particular for streamflow measurements.
Specifically, UAV may give information in terms of Us and WSL of priority to estimate discharge by Entropy model.

Two-dimensional velocity distribution (Moramarco et al. 2004):

$$u = \frac{u_{\max_v}}{M} \ln\left[1 + \left(e^M - 1\right)\frac{D-y}{D-h}\exp\left(1 - \frac{D-y}{D-h}\right)\right]$$

u_{max} estimation:

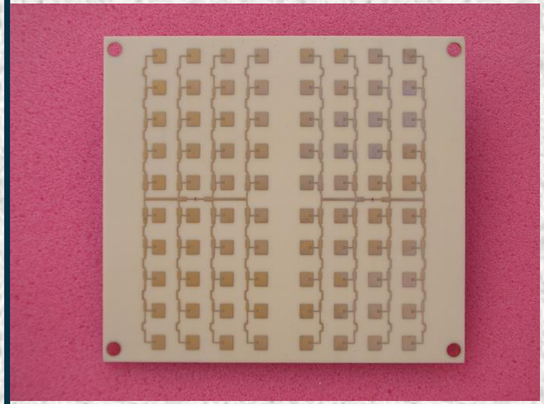
$$u_{\max} = \frac{u_{\max_v}}{\frac{1}{M}\ln\left[1 + \left(e^M - 1\right)\frac{D}{D-h}\exp\left(1 - \frac{D}{D-h}\right)\right]}$$

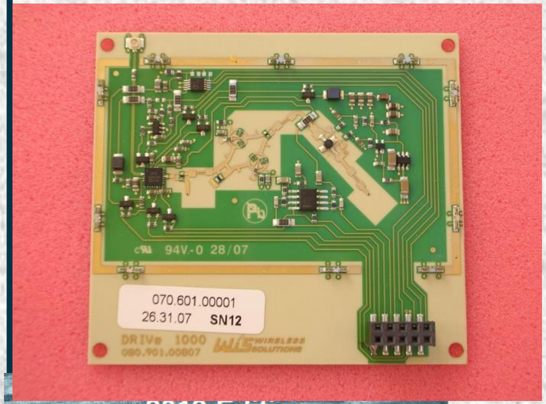
U_S: Surface flow velocity

WSL: Water Surface Level

A prototype of radar-drone system for measuring the surface flow velocity at river sites and discharge estimation

24 GHz Doppler Radar Sensor





The goal is to test a lightweight radar sensor built to be mounted onboard of Drone

- Sensitivity: 160 Hz of Doppler shift for 1 m/s of target relative velocity
- Range: about 20 m for a 1 m/s river speed
- DC current consumption: about 27 mA at 12 V supply
- Mass: **less than 200 g**
- Size: about 200 cubic centimeters (two 10 cm side boards one atop the other)

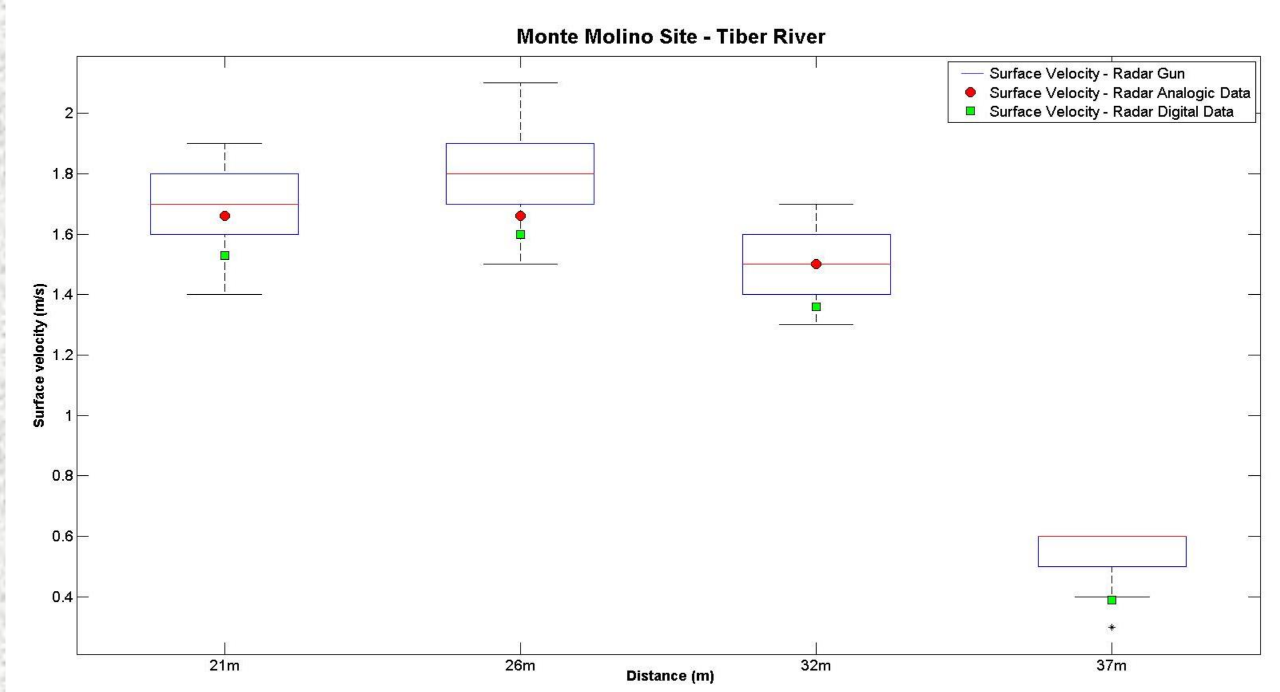
Decatur SVR Radar - Experimental Radar Sensor Comparison

A campaign of flow measurement has been done along the Tiber River (Italy) at hydrometric site at Monte Molino gauged site (5100 km^2).
For that, the Experimental Radar Sensor measurements have been compared with the ones carried out by the Surface Velocity Radar DECATUR used as benchmark.

SVR. When the trigger is in the ON position, the SVR begins measuring the surface velocity and the average velocity over the last 10 seconds is given. SVR updates the velocity every 5 sec. After 60 seconds, SVR has completed ten separate 5-second batches of velocity measurements. The display indicates the average of these measurements.

A prototype of radar-drone system for measuring the surface flow velocity at river sites and discharge estimation

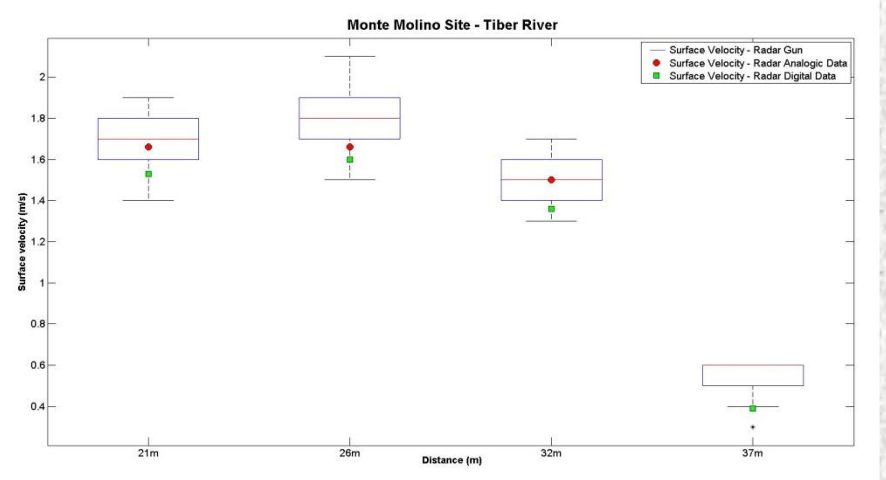
Decatur SVR Radar - Experimental Radar Sensor Comparison

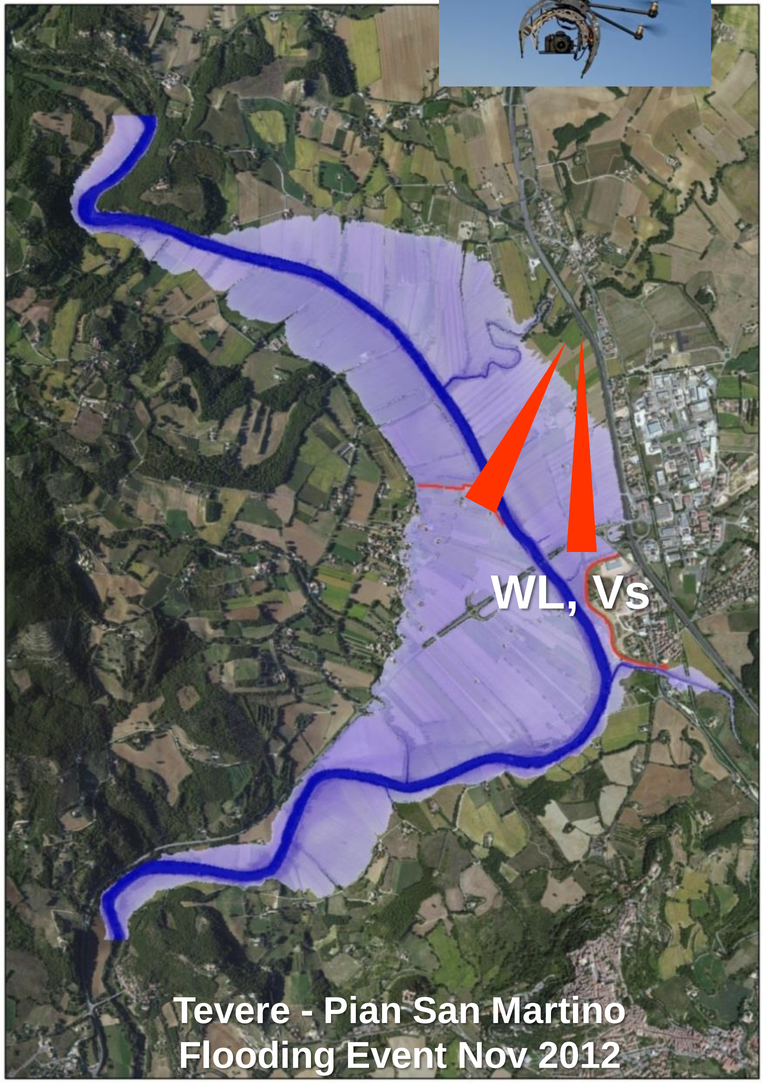


Boxplot with whiskers from minimum to maximum of 10 average velocities by SVR along with Analogic and Digital by Experimental Radar Sensor measurement.

DRONE: Experimental Radar Sensor

Calibration 2D Hydraulic Model





Hydrometric Site Configurations

I. Hydrometric river site with unknown rating curve
Jones Formula (Henderson, 1966), Fenton (Fenton, 1999), Marchi (Marchi, 1976)

II. Equipped river reach with rating curve known at one of ends with significant lateral flow
Rainfall-runoff modeling, RCM (Moramarco et al. 2005)

III. Equipped River reach with level observations only
Dyrac (Dottori et al., 2009), MAST (Aricò et al., 2009), ***VPMS (Perumal et al., WRR, 2007; 2010)***

I. Hydrometric river site with unknown rating curve

Hydrol. Earth Syst. Sci., 15, 2979–2994, 2011
www.hydrol-earth-syst-sci.net/15/2979/2011/
doi:10.5194/hess-15-2979-2011

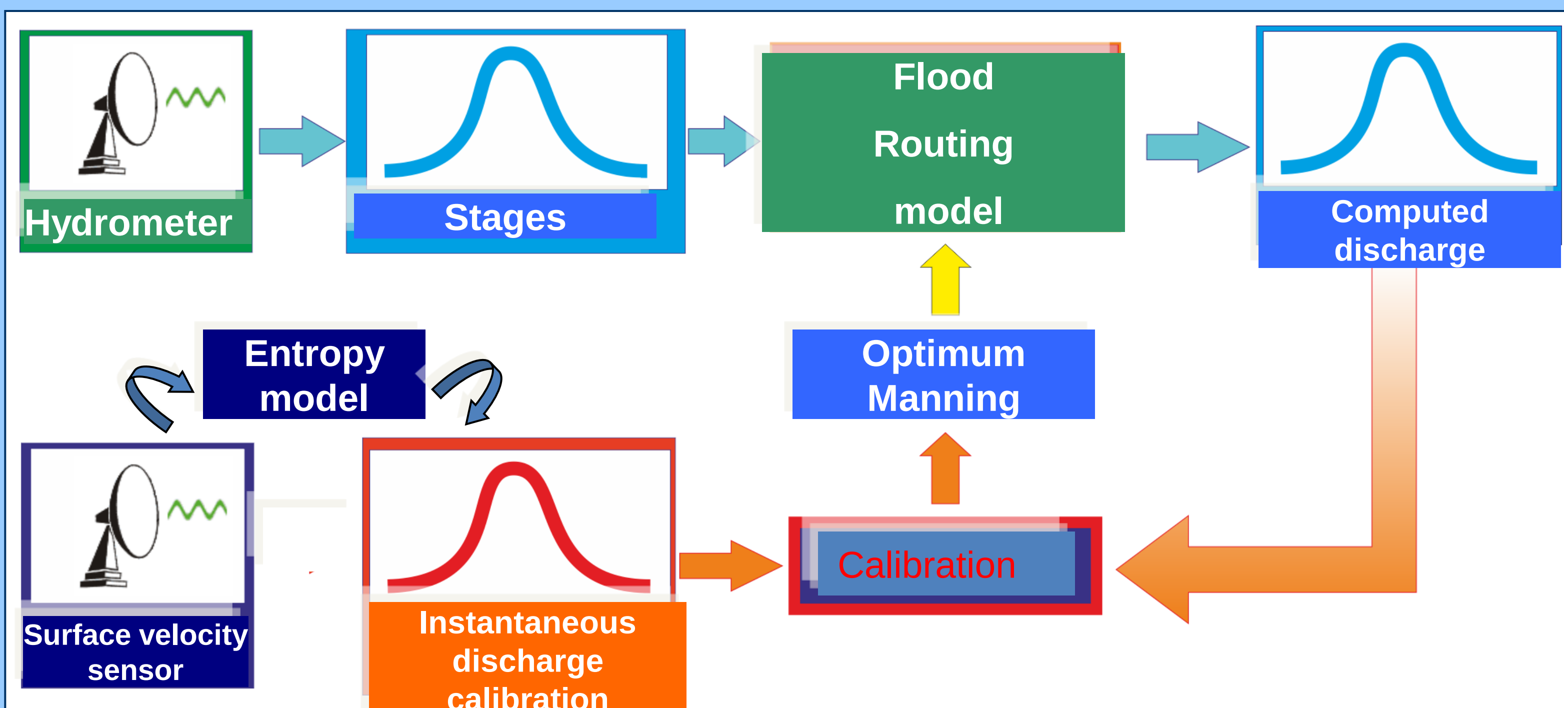
Hydrology and Earth System Sciences

Discharge estimation combining flow routing and occasional measurements of velocity

G. Corato[1], T. Moramarco[1], and T. Tucciarelli[2]

Discharge monitoring in near real time by coupling hydraulic and entropy model and using remote observations

Method



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Hydrology and Earth System Sciences

Discharge estimation combining flow routing and occasional measurements of velocity

G. Corato[1], T. Moramarco[1], and T. Tucciarelli[2]

Coupling stage routing modelling and entropy approach to discharge assessment

$$\frac{\partial A}{\partial t} + \frac{\partial q}{\partial x} = 0$$

$$\frac{\partial H}{\partial x} = -\frac{n^2 q|q|}{A^2 R^{4/3}}$$

Diffusive form of Saint Venant Equation:

$$\frac{\partial H}{\partial t} - \frac{1}{T}\frac{\partial}{\partial x}\left(\frac{R^{2/3} A}{n} \frac{\frac{\partial H}{\partial x}}{\sqrt{\left|\frac{\partial H}{\partial x}\right|}} \right) = 0$$

H: Hydraulic head; R: Hydraulic radius; A: Flow area;

n: Manning’s roughness; T: channel width

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Hydrology and Earth System Sciences

Discharge estimation combining flow routing and occasional measurements of velocity

G. Corato[1], T. Moramarco[1], and T. Tucciarelli[2]

Boundary conditions

Upstream: Observed Stages

$h(0,t) = h_u(t)$ → Water level driven

Downstream: Zero Diffusion

$$\left.\frac{\partial h}{\partial x}\right|_{x=L} = 0 \quad \text{or} \quad \left.\frac{\partial^2 h}{\partial x^2}\right|_{x=L} = 0$$

Manning Calibration

Hydrol. Earth Syst. Sci., 15, 2979–2994, 2011
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doi:10.5194/hess-15-2979-2011

Hydrology and Earth System Sciences

Discharge estimation combining flow routing and occasional measurements of velocity

G. Corato[1], T. Moramarco[1], and T. Tucciarelli[2]

1) Assign n value

2) Compute q(t,n) by model

3) Measure surface vel at time *t*

4) Compute q(t) by Entropy

5) Manning calibration

Manning Calibration

Hydrol. Earth Syst. Sci., 15, 2979–2994, 2011
www.hydrol-earth-syst-sci.net/15/2979/2011/
doi:10.5194/hess-15-2979-2011

Hydrology and Earth System Sciences

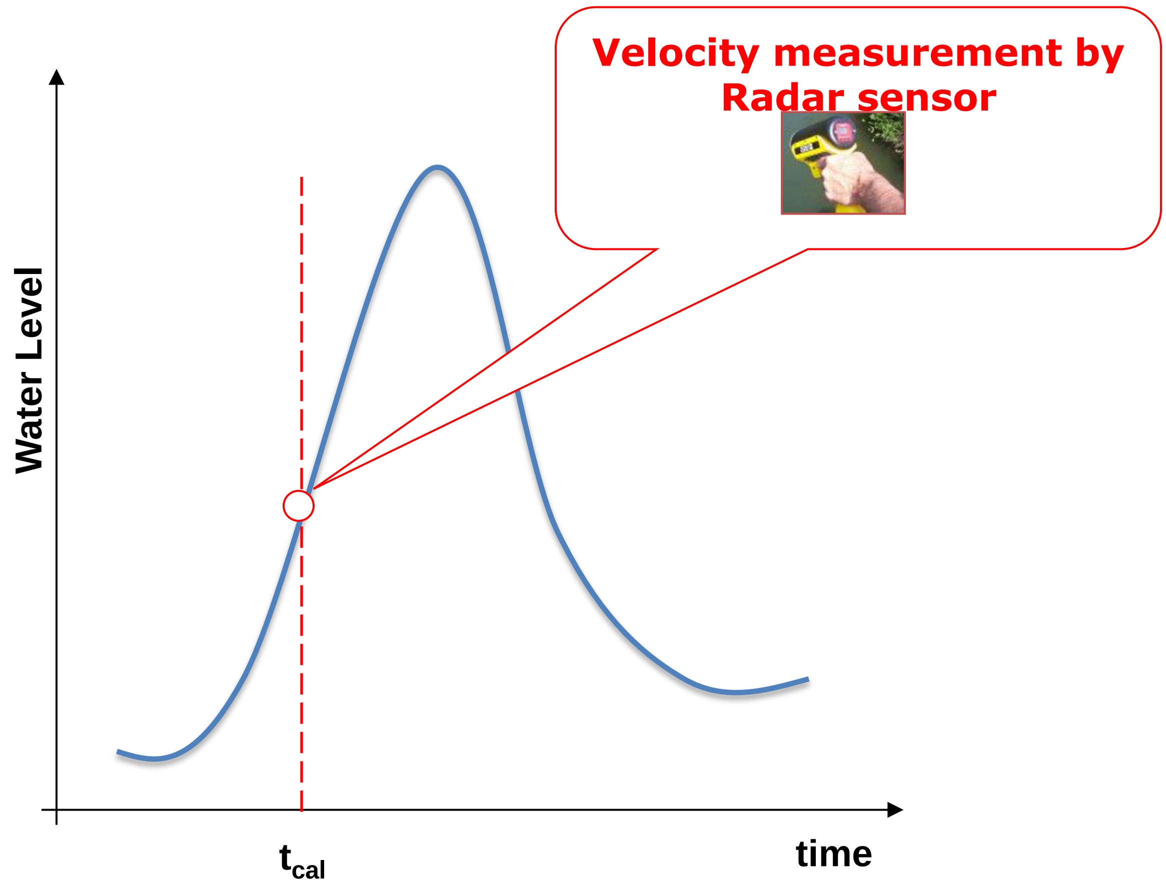
Discharge estimation combining flow routing and occasional measurements of velocity

G. Corato[1], T. Moramarco[1], and T. Tucciarelli[2]

Manning coefficent was determined minimizing the follow objective function:

$$Err(n) = \left| \frac{q_{comp}(t_{cal}, n) - q_{obs}(t_{cal})}{q_{obs}(t_{cal})} \right|$$

where $q_{comp}(t_{cal},n)$ is the computed discharge at the instant t_{cal} in which measurement is carried out, while q_{obs} is the "observed" discharge by using the instantaneous surface velocity measure of basis to apply the entropy model.


Velocity measurement by Radar sensor
Water Level
t_{cal}
time

Pierantonio

Evento	Q_p [m³/s]	t_{ph}[h]	h_p [h]	DT [h]
Dec 1996	380.53	22.5	4.74	49.5
Apr 1997	429.44	32.5	5.07	74.5
Nov 1997	308.17	18.5	4.22	45
Feb 1999	427.93	21.5	5.06	59.5
Dec 2000	565.89	74	5.92	100
Nov 2005	779.03	30.5	7.1	64

Ponte Nuovo

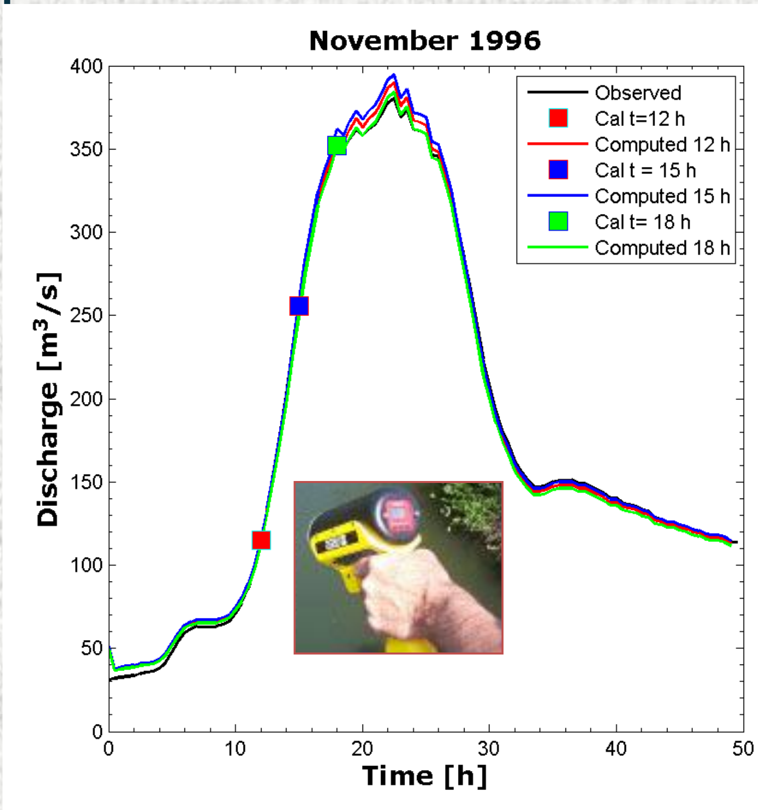
event	Q_p [m³/s]	t_{ph} [h]	h_p [m]	DT [h]
Nov 2005	1073.20	[illegible]	[illegible]	[illegible]
Dec 2005	804.23	[illegible]	[illegible]	[illegible]
Dec 2008	874.73	[illegible]	[illegible]	[illegible]

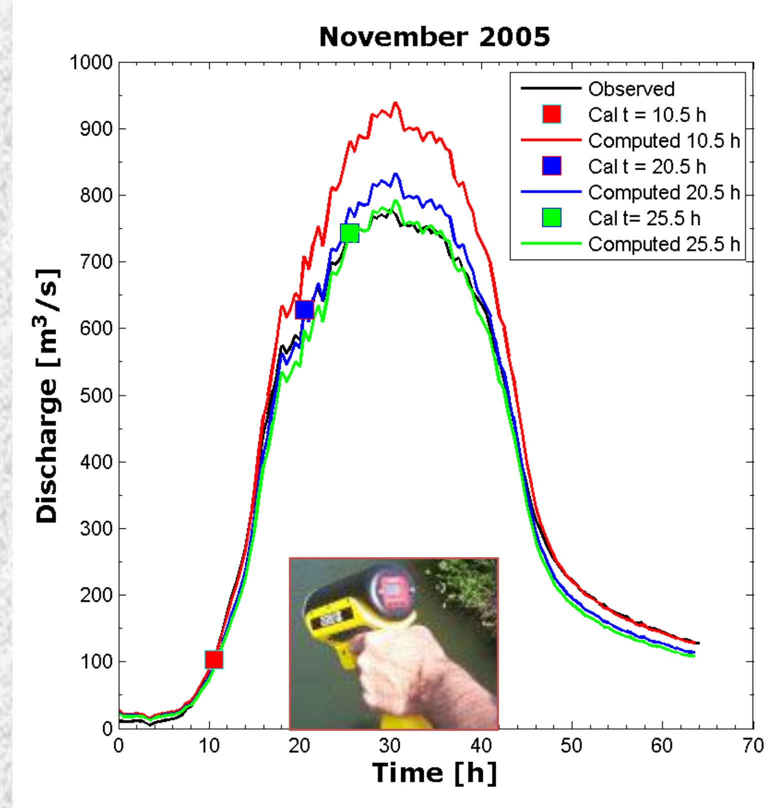
Monte Molino

evento	Q_p [m³/s]
Dec 2010	995.1
Jan 2010	1105.2

Test case 1: Pierantonio

Discharge Estimation Results





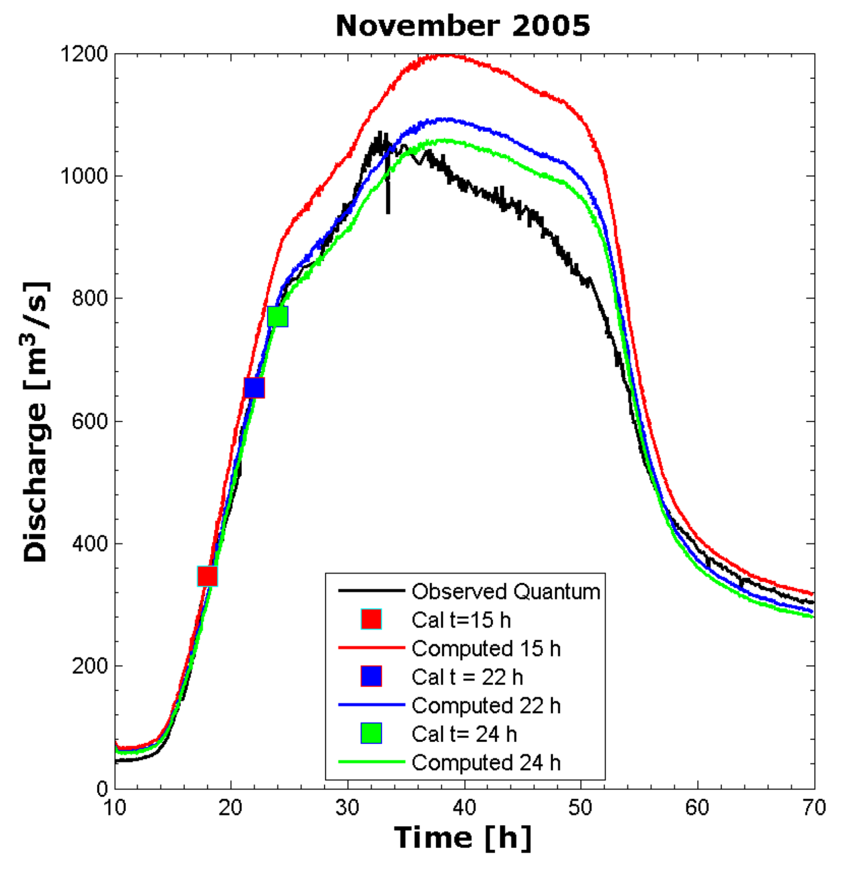
Cal. Time [h]	12	15	18
Man [$sm^{-1/3}$]	0.051	0.050	0.051
Q_{max} err [%]	2.39	3.70	0.90

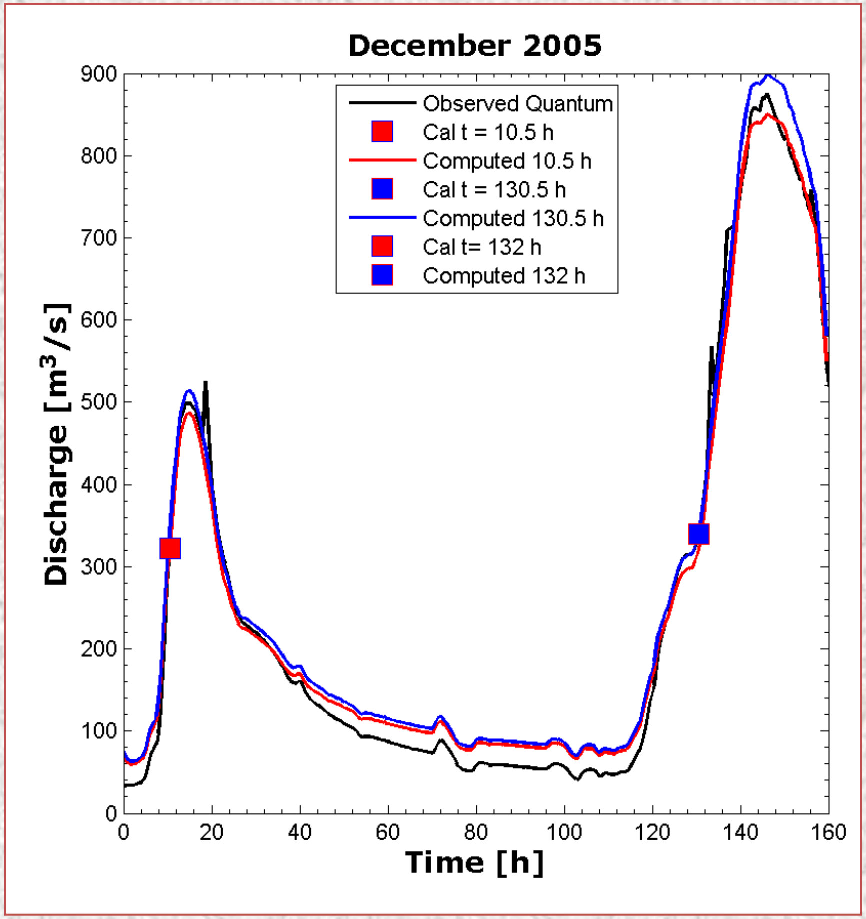
Cal. Time [h]	10.5	20.5	25.5
Man [$sm^{-1/3}$]	0.051	0.058	0.061
Q_{max} err [%]	20.60	6.92	1.66

Case Study: Tiber River

Test case 2: Ponte Nuovo

Discharge Estimation Results



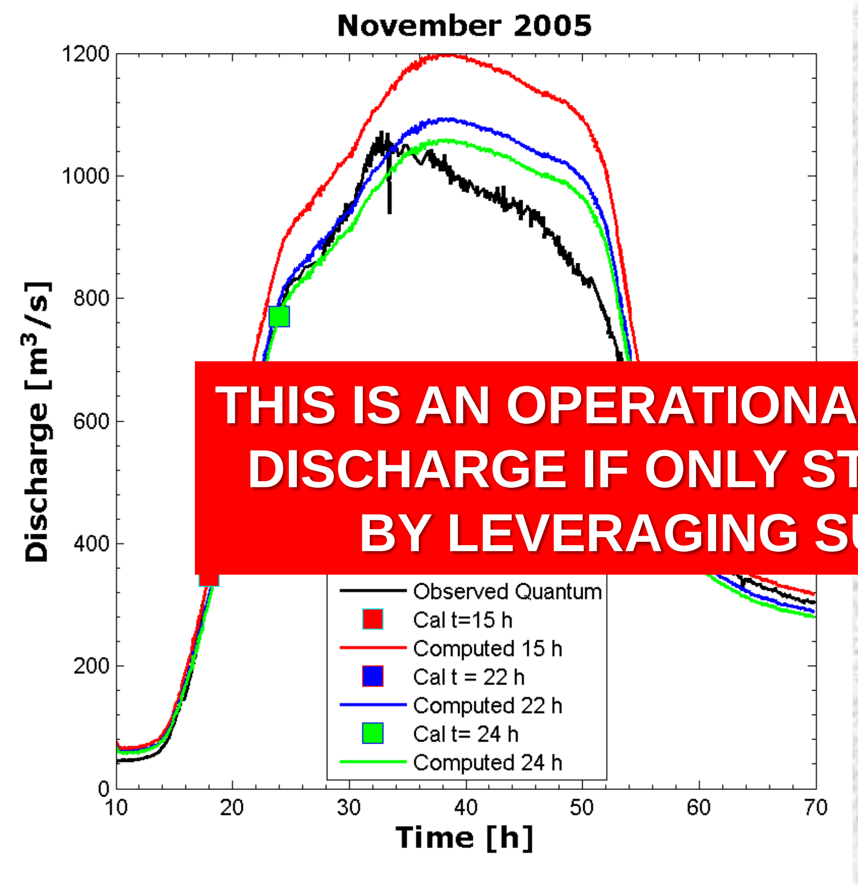


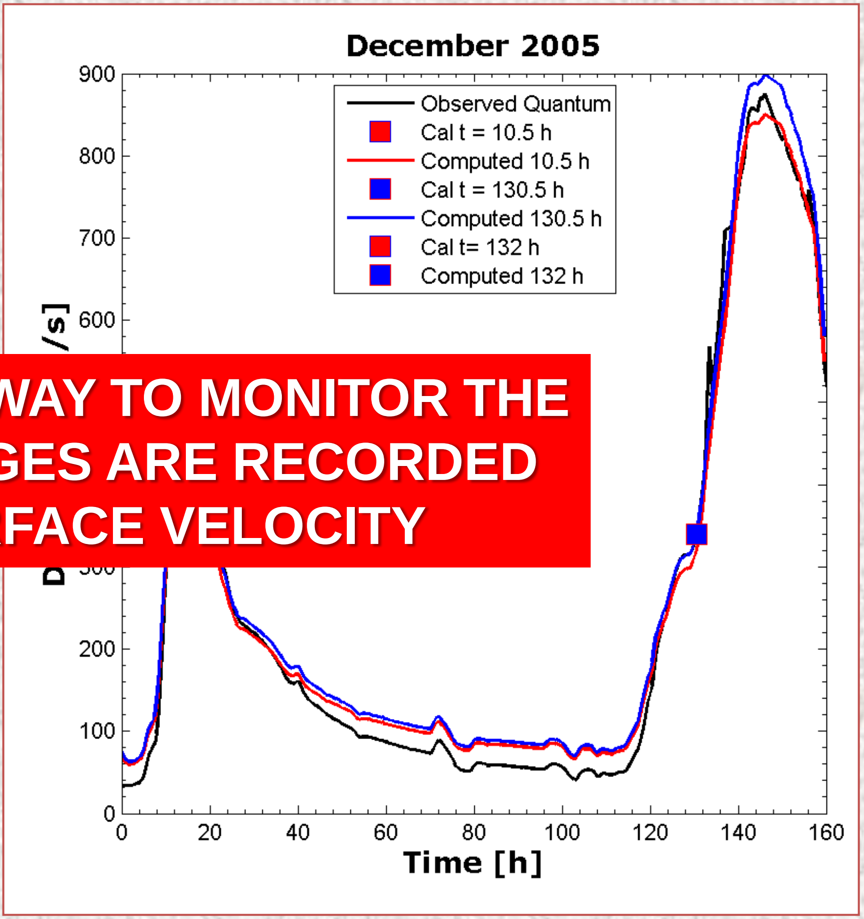
Cal. Time [h]	15	22	24
Man [$sm^{-1/3}$]	0.04	0.044	0.045
Q_{max} err [%]	11.7	1.85	-1.36

Cal. Time [h]	10.5	130.5
Man [$sm^{-1/3}$]	0.045	0.043
Q_{max} err [%]	-2.8	2.8

Test case 2: Ponte Nuovo

Discharge Estimation Results



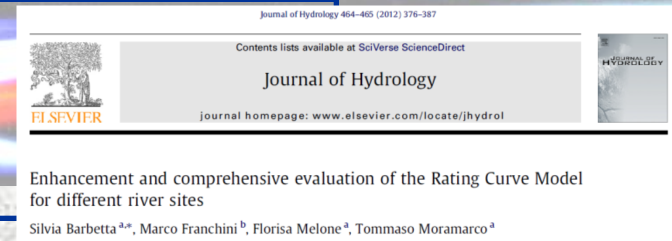


THIS IS AN OPERATIONAL WAY TO MONITOR THE DISCHARGE IF ONLY STAGES ARE RECORDED BY LEVERAGING SURFACE VELOCITY

Cal. Time [h]	15	22	24
Man [$sm^{-1/3}$]	0.04	0.044	0.045
Q_{max} err [%]	11.7	1.85	-1.36

Cal. Time [h]	10.5	130.5
Man [$sm^{-1/3}$]	0.045	0.043
Q_{max} err [%]	-2.8	2.8

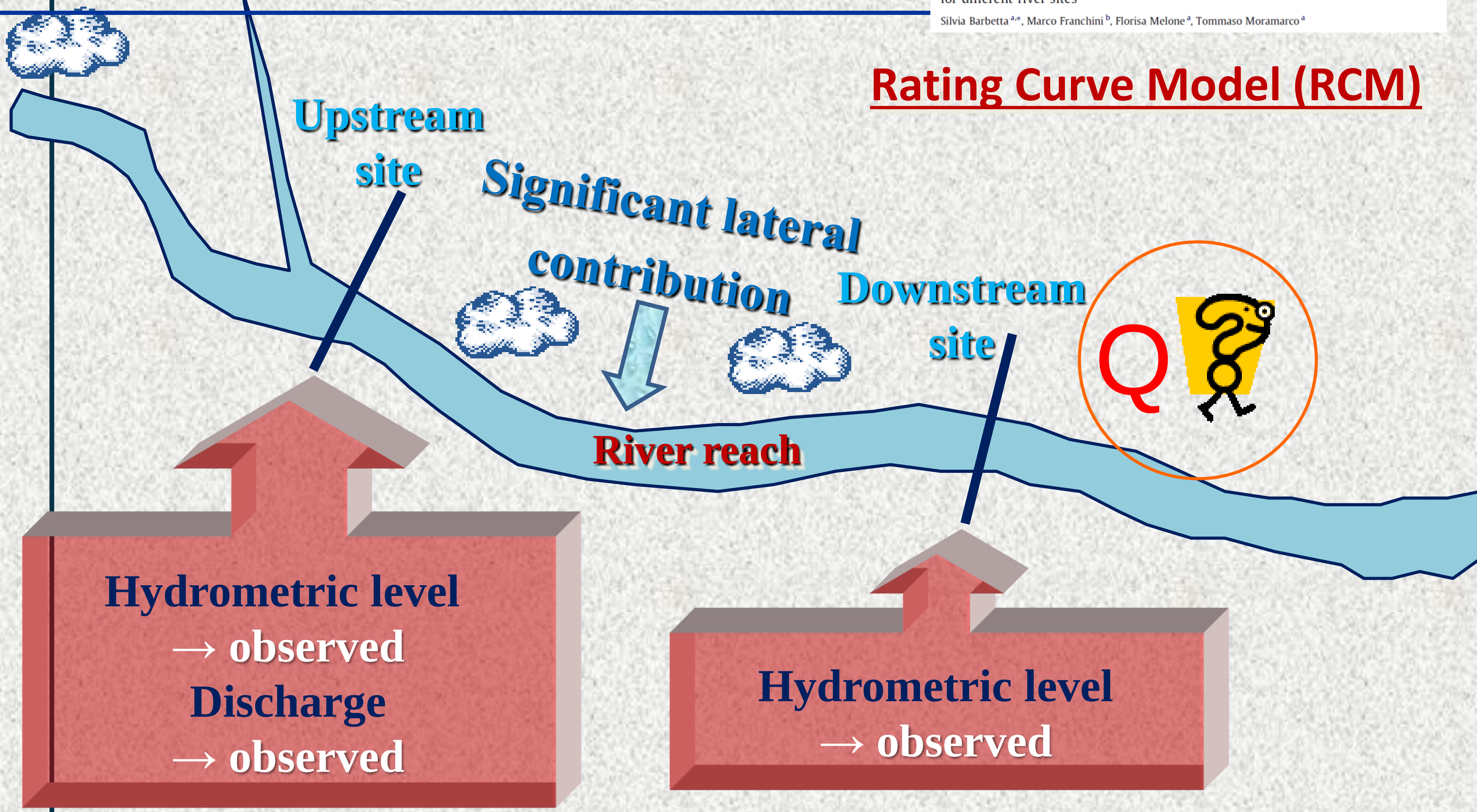
II. Equipped river reach with rating curve known at one of ends


Journal of Hydrology 464–465 (2012) 376–387
Contents lists available at SciVerse ScienceDirect
Journal of Hydrology
journal homepage: www.elsevier.com/locate/jhydrol

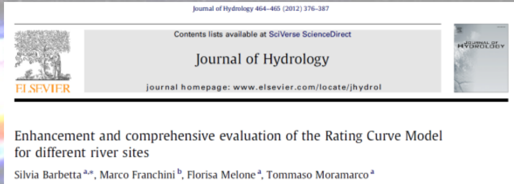
Enhancement and comprehensive evaluation of the Rating Curve Model for different river sites

Silvia Barbetta [a,*], Marco Franchini [b], Florisa Melone [a], Tommaso Moramarco [a]

Rating Curve Model (RCM)



II. Equipped river reach with rating curve known at one of ends with significant lateral flow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Enhancement and comprehensive evaluation of the Rating Curve Model for different river sites

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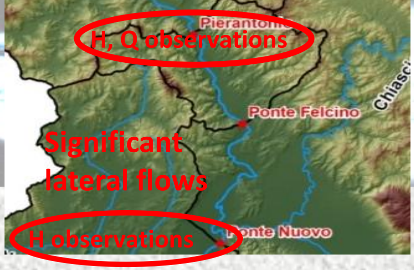


The Rating Curve Model (RCM)

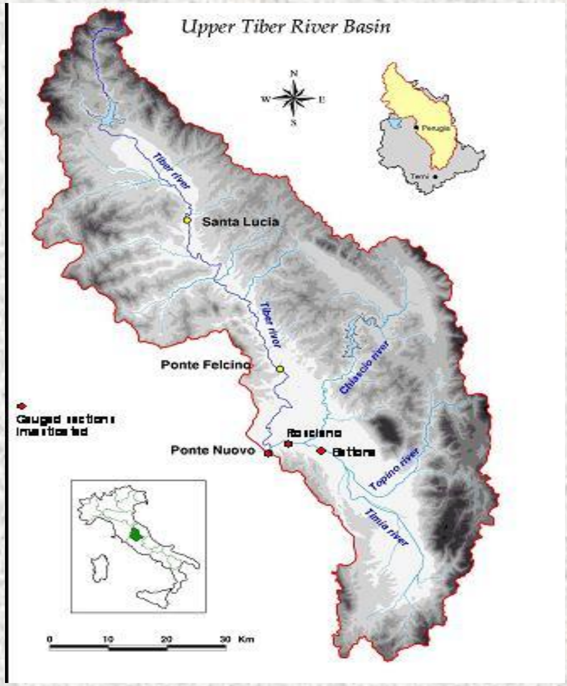
$$\bar{u} = \Phi(M)u_{max}$$

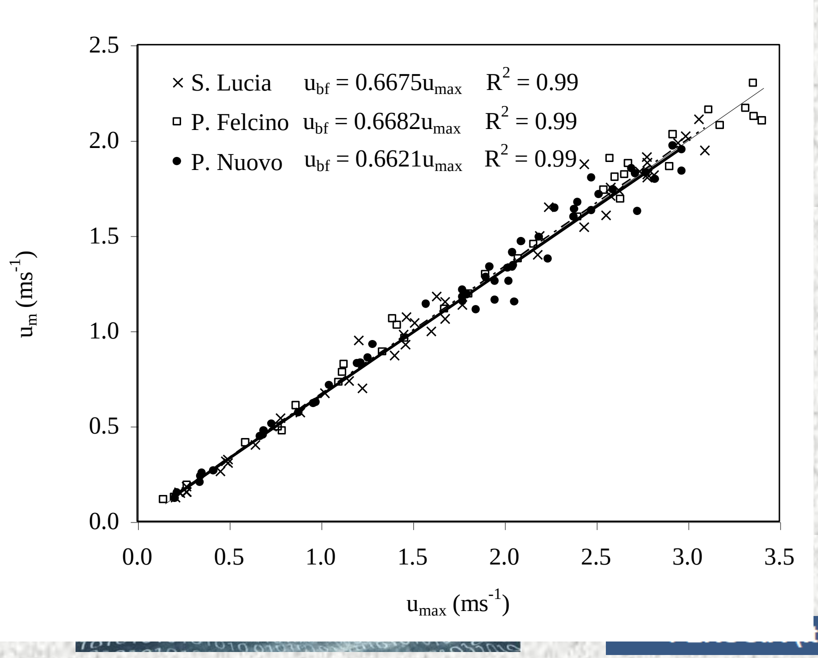
$$\Phi(M) = \left(\frac{e^M}{e^M - 1} - \frac{1}{M} \right)$$

$\bar{u}$ **mean velocity**

u_{max} **maximum velocity**

M **dimensionless entropy parameter**





$\Phi(M)$ almost constant along a reach

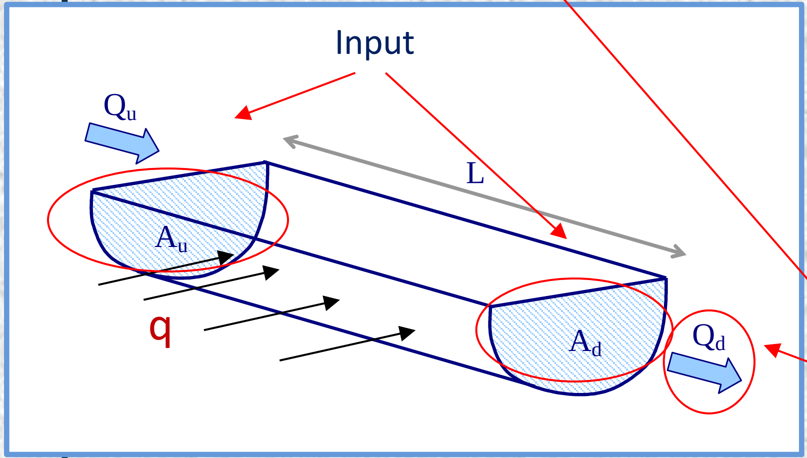
$$\frac{\bar{u}_u}{u_{max,u}} \cong \frac{\bar{u}_d}{u_{max,d}}$$

$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t - T_L)} Q_u(t - T_L) + \beta$$

RCM model: mathematical basis

The RCM model is a simple method for reconstructing the discharge hydrograph at a river site where only the stage is monitored and the discharge is recorded at another section (rating curve assessment for ungauged sites) allowing for significant lateral inflows assessment:

$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t - T_L)} Q_u(t - T_L) + \beta = \alpha X + \beta$$



Q_d, Q_u = *downstream and upstream discharges*

A_d, A_u = *downstream and upstream cross section flow areas*

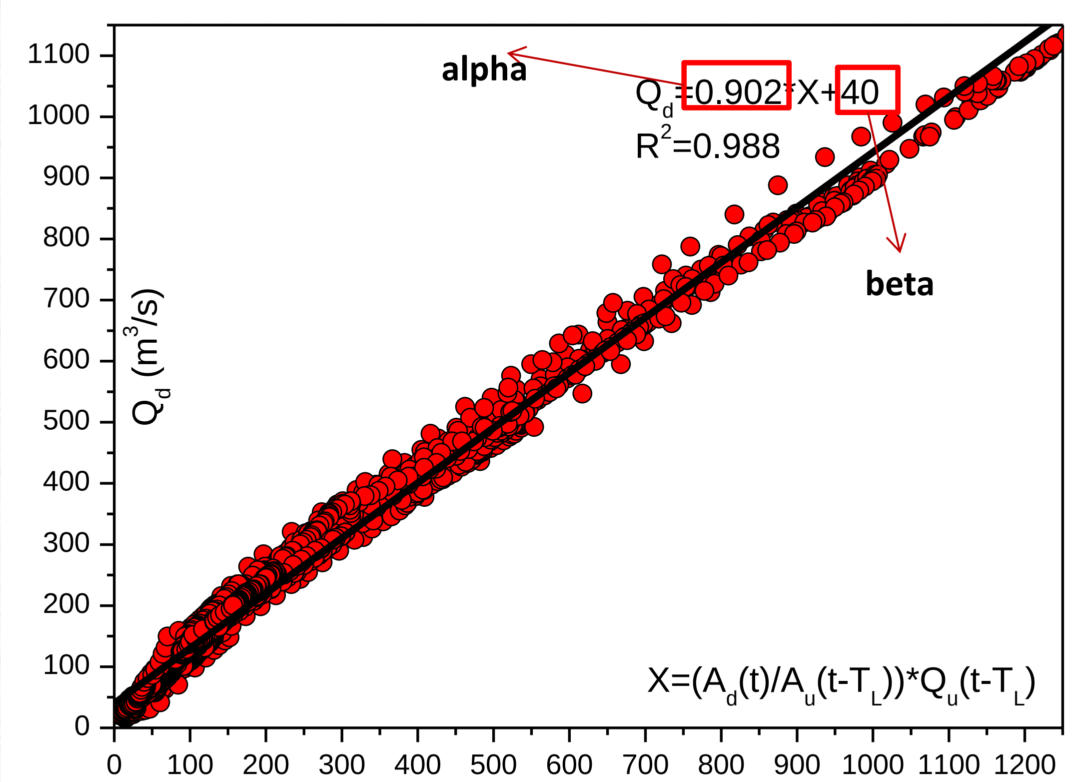
T_L = *wave travel time*

α *and* β = *parameters*

RCM model: mathematical basis

$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t - T_L)} Q_u(t - T_L) + \beta = \alpha X + \beta$$

X_{obs}

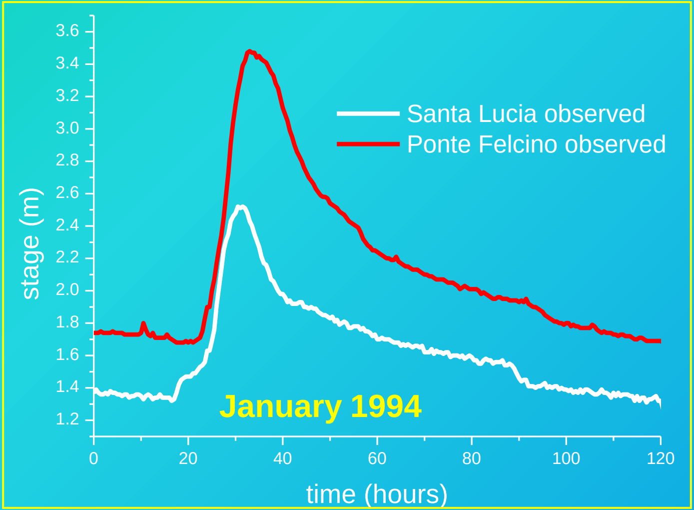


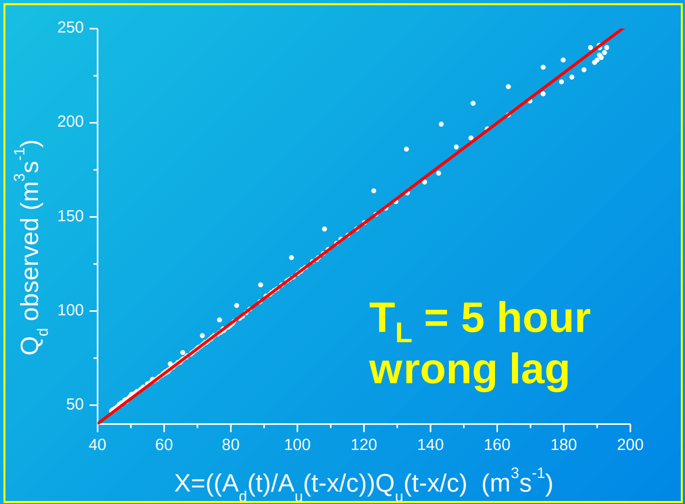
The RCM model identifies a linear relationship between the downstream discharge, Q_d, and the quantity X depending only on the flow areas and on the upstream discharge.

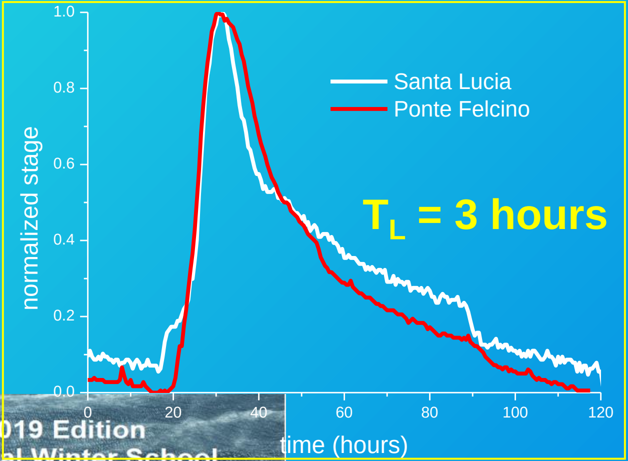
Parameters: α, β, TL

RCM model: parameters assessment

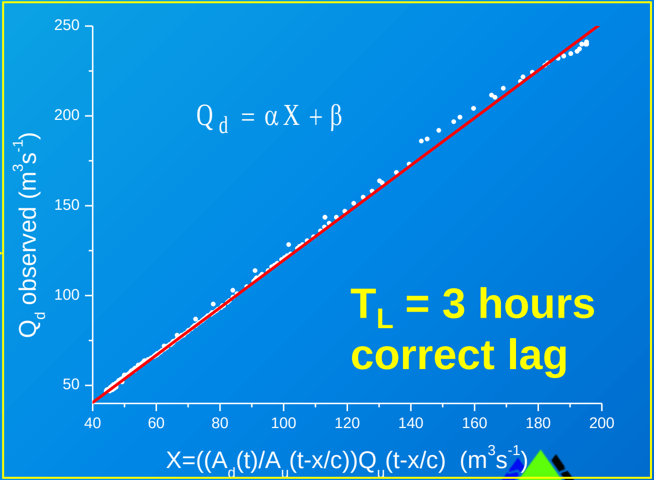
Wave travel time, T_L



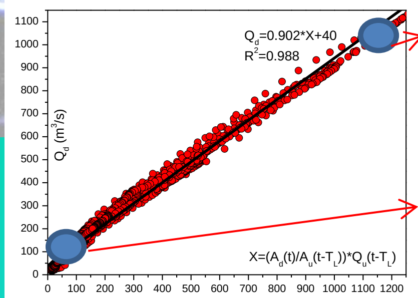




$$h^*(t) = \frac{h(t) - h^b}{h^p - h^b}$$



RCM model: α and β assessment



$$1)\ Q_d(t_p)=\alpha\frac{A_d(t_p)}{A_u(t_p-T_L)}Q_u(t_p-T_L)+\beta=\alpha X+\beta$$

$$2)\ Q_b(tb)=\alpha\frac{A_b(t_b)}{A_u(t_b-T_L)}Q_u(t_b-T_L)+\beta=\alpha X+\beta$$

To estimate α and β, **peak flow conditions, Qd(tp)** and **the baseflow, Qb(tb),** have to be assessed:

Unknown Quantities

$$\alpha=\frac{Q_d(t_p)-Q_d(t_b)}{\left[\frac{A_d(t_p)}{A_u(t_p-T_L)}Q_u(t_p-T_L)-\frac{A_d(t_b)}{A_u(t_b-T_L)}Q_u(t_b-T_L)\right]}$$

$$\beta=Q_d(t_b)-\alpha\frac{A_d(t_b)}{A_u(t_b-T_L)}Q_u(t_b-T_L)$$

Observed Quantities

t_b = time when baseflow occurs at the downstream section

t_p = time when peak stage occurs at the downstream section

RCM model: parameters assessment

- The baseflow, $Q_d(t_b)$, is easily computed if wading measurements for low stages can be carried out. Otherwise, assuming for the downstream section the mean velocity observed at the upstream one, $Q_d(t_b)$ can be computed as the product between the upstream mean velocity at time (t_b-T_L) and the downstream flow area $A_d(t_b)$. The value of baseflow is here assumed known.

Upstream (Q, h) → Downstream (h)

- The downstream peak discharge, $Q_d(t_p)$, can be estimated as:

$$Q_d(t_p) = \left(Q_u(t_p - T_L) - Q^*\right) + q_p L$$

$$Q^* = \frac{K}{(L/T_L)^3} Q_u^p \left| \frac{Q_1 + Q_{-1} - 2Q_u^p}{(\Delta t^*)^2} \right|$$

Q^* = attenuation due to flood routing along the reach of length L (Price formula, 1973)

q_p = lateral inflow per unit channel length during the time interval $(t_p-T_L;\ t_p)$ assessed through a physically based simplified approach based on the continuity equation:

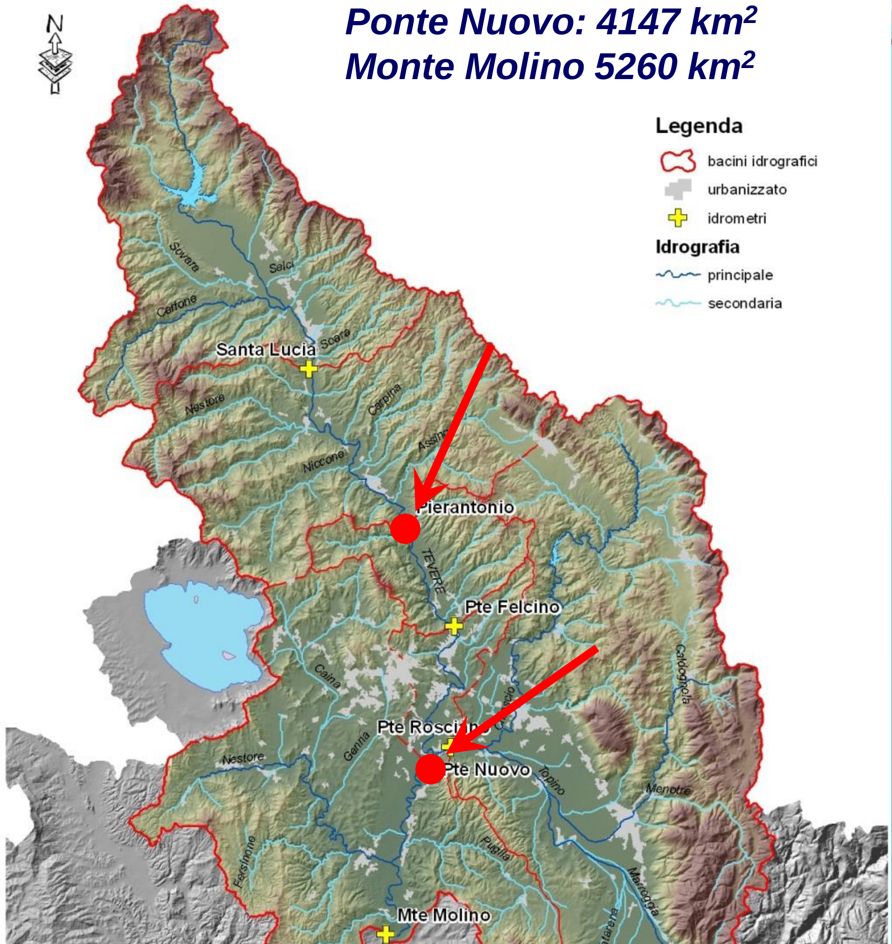
$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \Rightarrow \begin{cases} \dfrac{dA}{dt} = q \\ \dfrac{dx}{dt} = c = L/T_L \end{cases} \Rightarrow \frac{A_d(t_p) - A_u(t_p - T_L)}{T_L} = q_p$$

Tiber river reach – unsteady flow effects

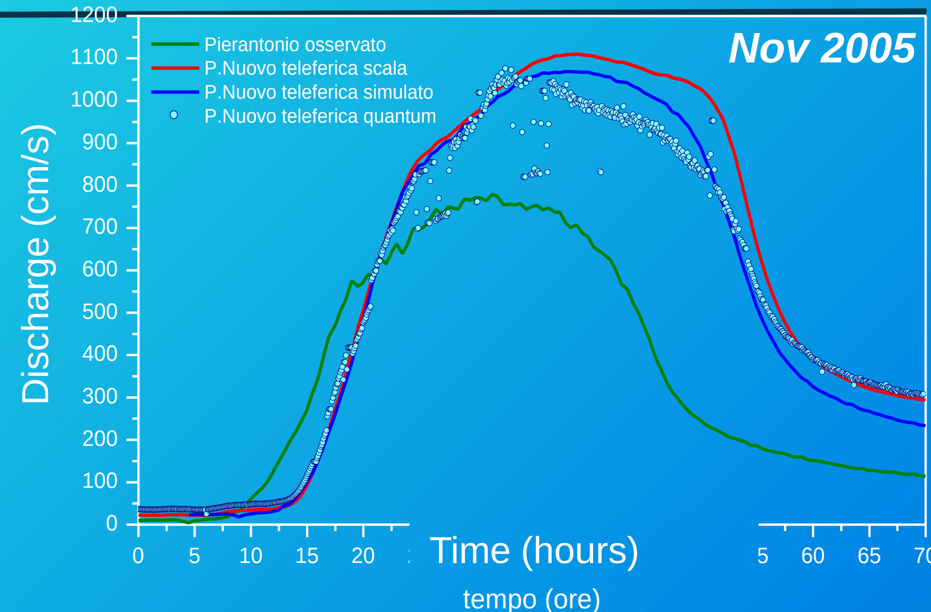
To test the model capability to represent the unsteady flow effects the experimental data recorded by an ultrasonic flowmeter at the hydrometric section of Ponte Nuovo was considered as benchmark.

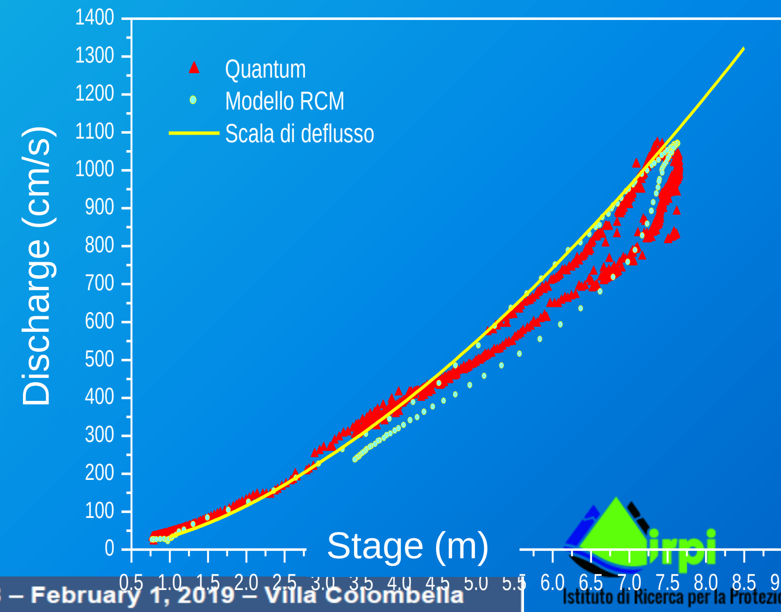
RCM: Case Studies

Pierantonio: 1800 km²
Ponte Nuovo: 4147 km²
Monte Molino 5260 km²

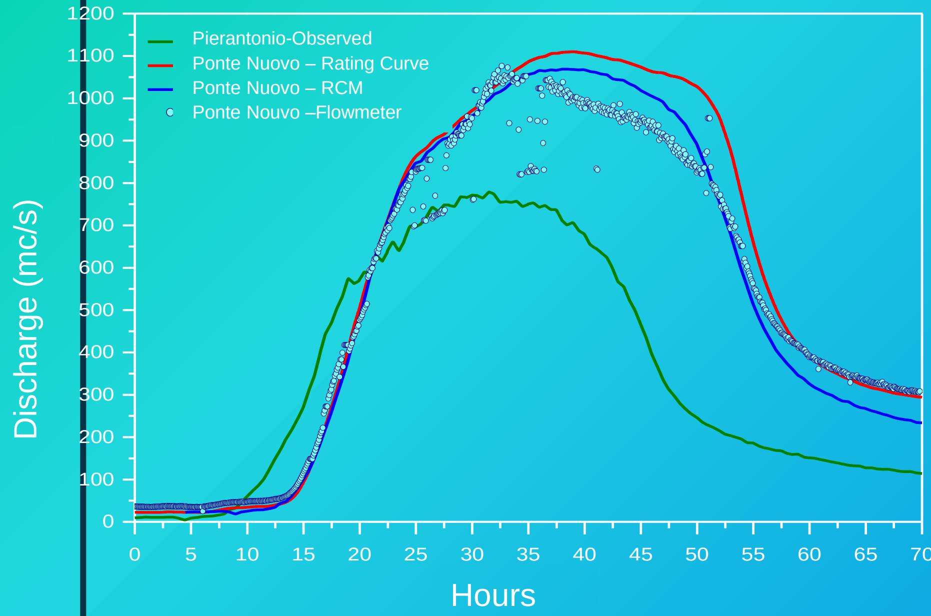


Section	A_b [km²]	A_{int} [km²]	L [km]
Pierantonio	1805	2340	40
Ponte Nuovo	4145		

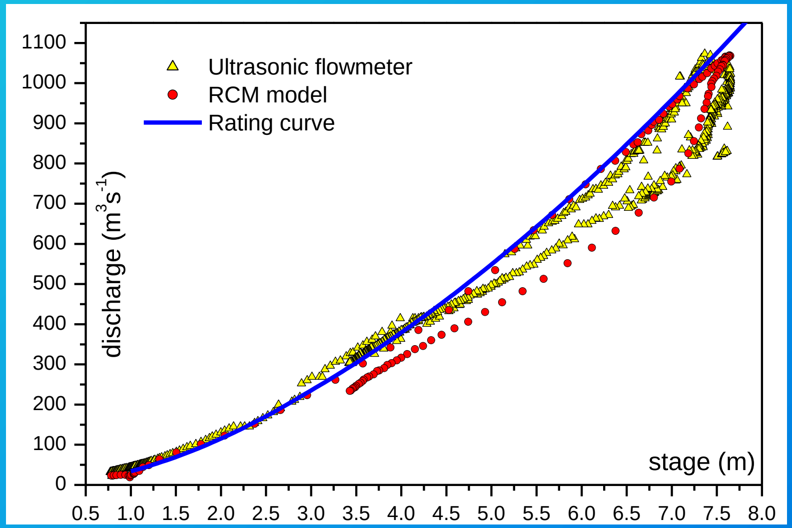


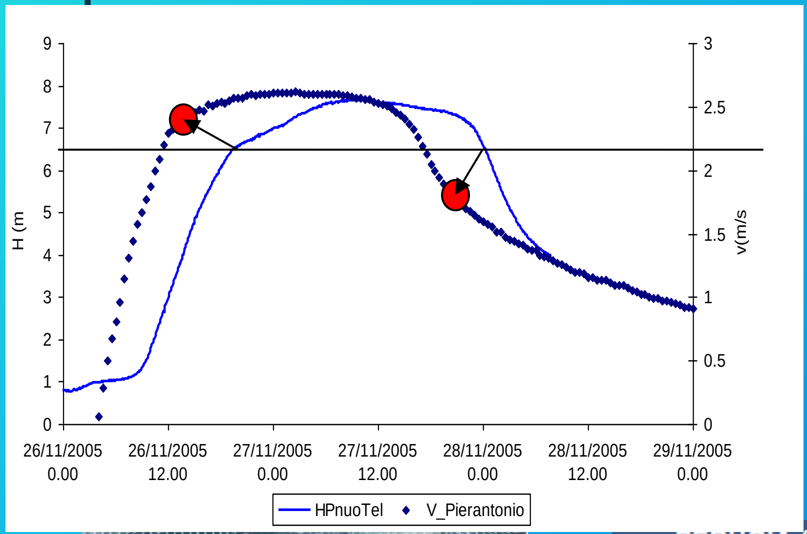


Tiber river reach – Flood Event on 25-27 November 2005



$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t - T_L)} Q_u(t - T_L) + \beta$$





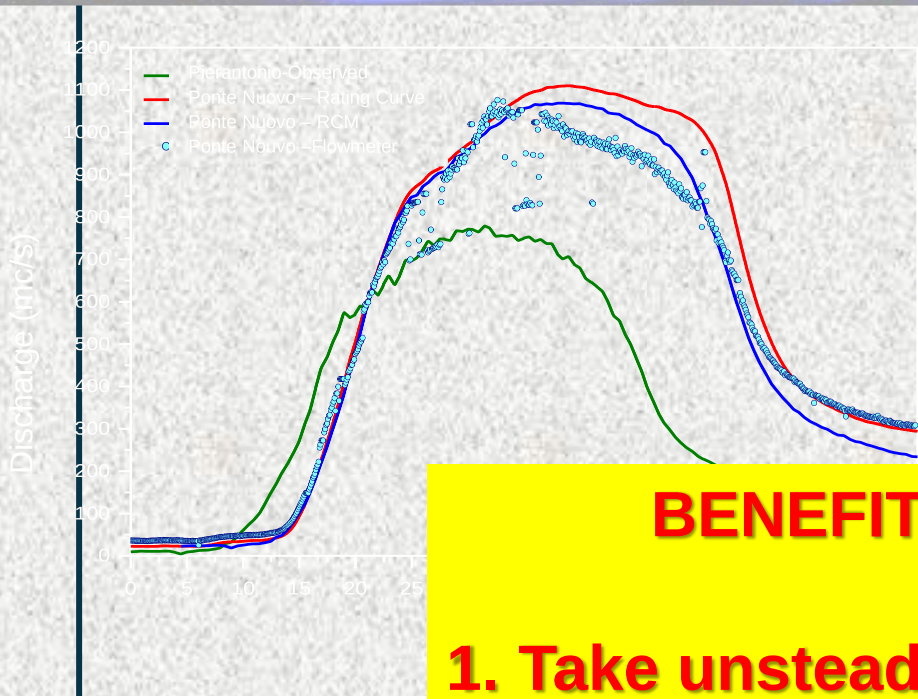
At the same Downstream Stage, i.e., $A_d(t)$

Upstream Rising limb

Upstream Recession limb

$Q_u(t_1-T_L)/A_u(t-T_L) \neq Q_u(t_2-T_L)/A_u(t-T_L)$

Tiber river reach – Flood Event on 25-27 November 2005



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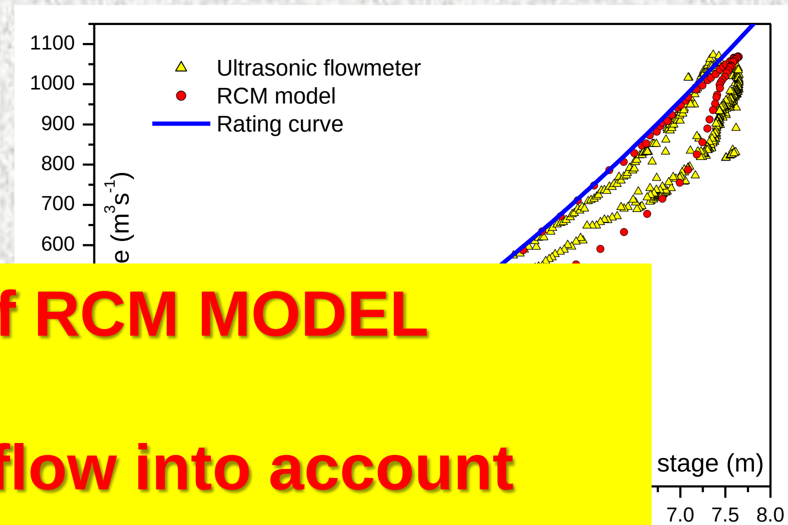
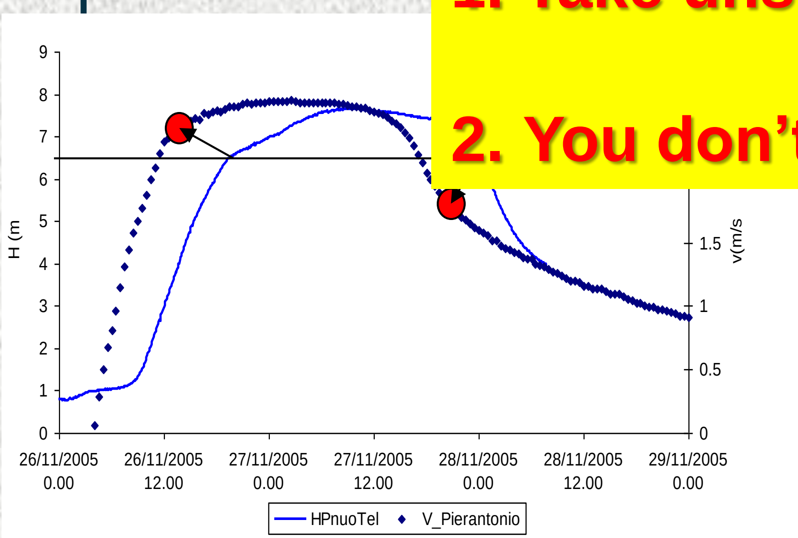




BENEFIT of RCM MODEL

1. Take unsteady flow into account

2. You don't need rainfall data

...i.e.,

$A_d(t)$

Upstream Rising limb

Upstream Recession limb

$Q_u(t_1-T_L)/A_u(t-T_L) \neq Q_u(t_2-T_L)/A_u(t-T_L)$

Discharge Monitoring by Satellite

The SWOT and SENTINEL missions:
River monitoring at global scale

Water Surface Elevation

(ALTIMETER)

Water Surface Velocity

(MODIS - MERIS)

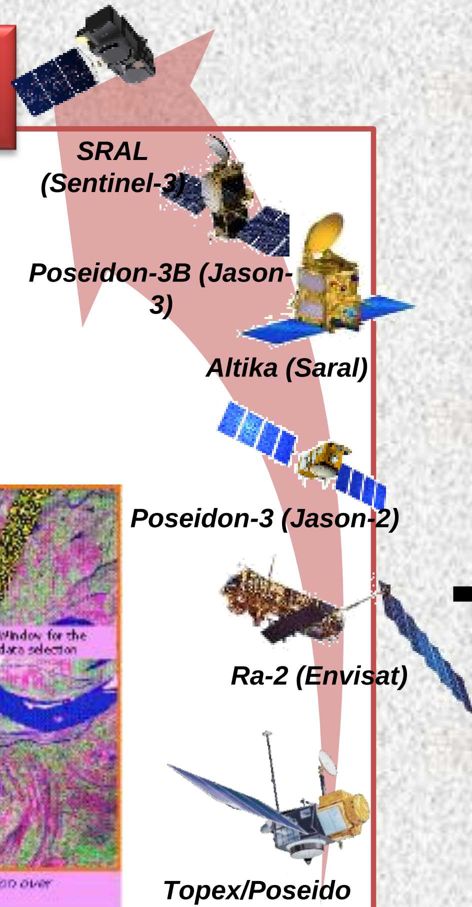
Discharge Assessment

RIVER DISCHARGE FROM SATELLITE OBSERVATIONS

RADAR ALTIMETER

Temporal resolution:

10-35 days



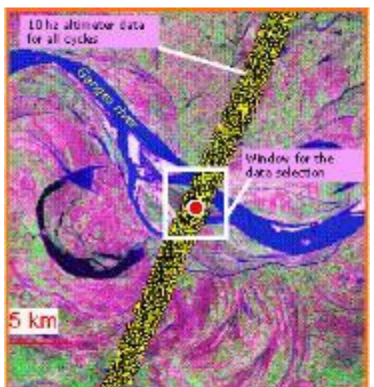
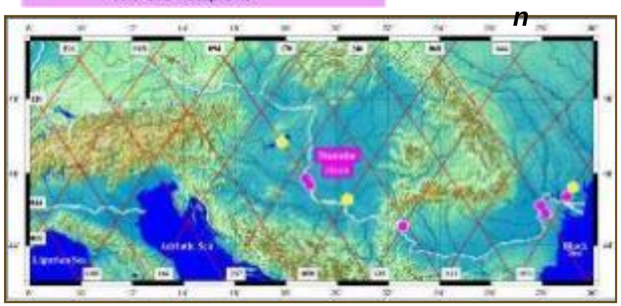


Figure 1 : Concept of virtual station over rivers and floodplains

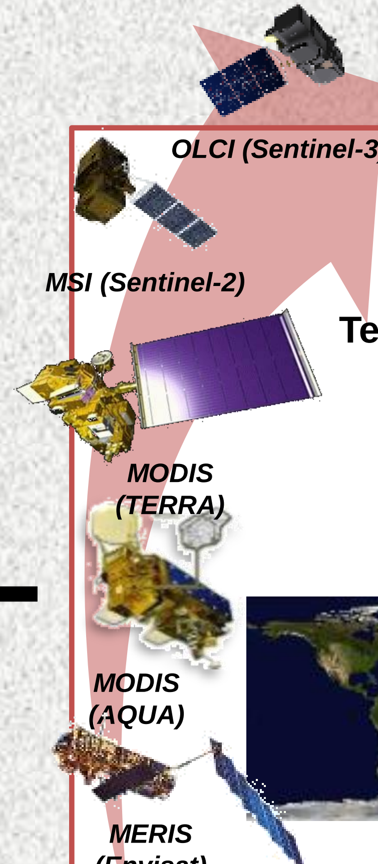


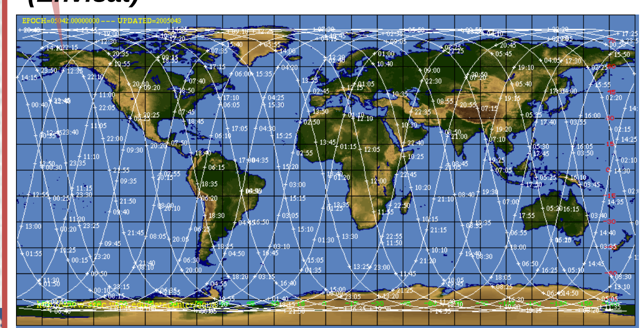
+

RADIOMETER

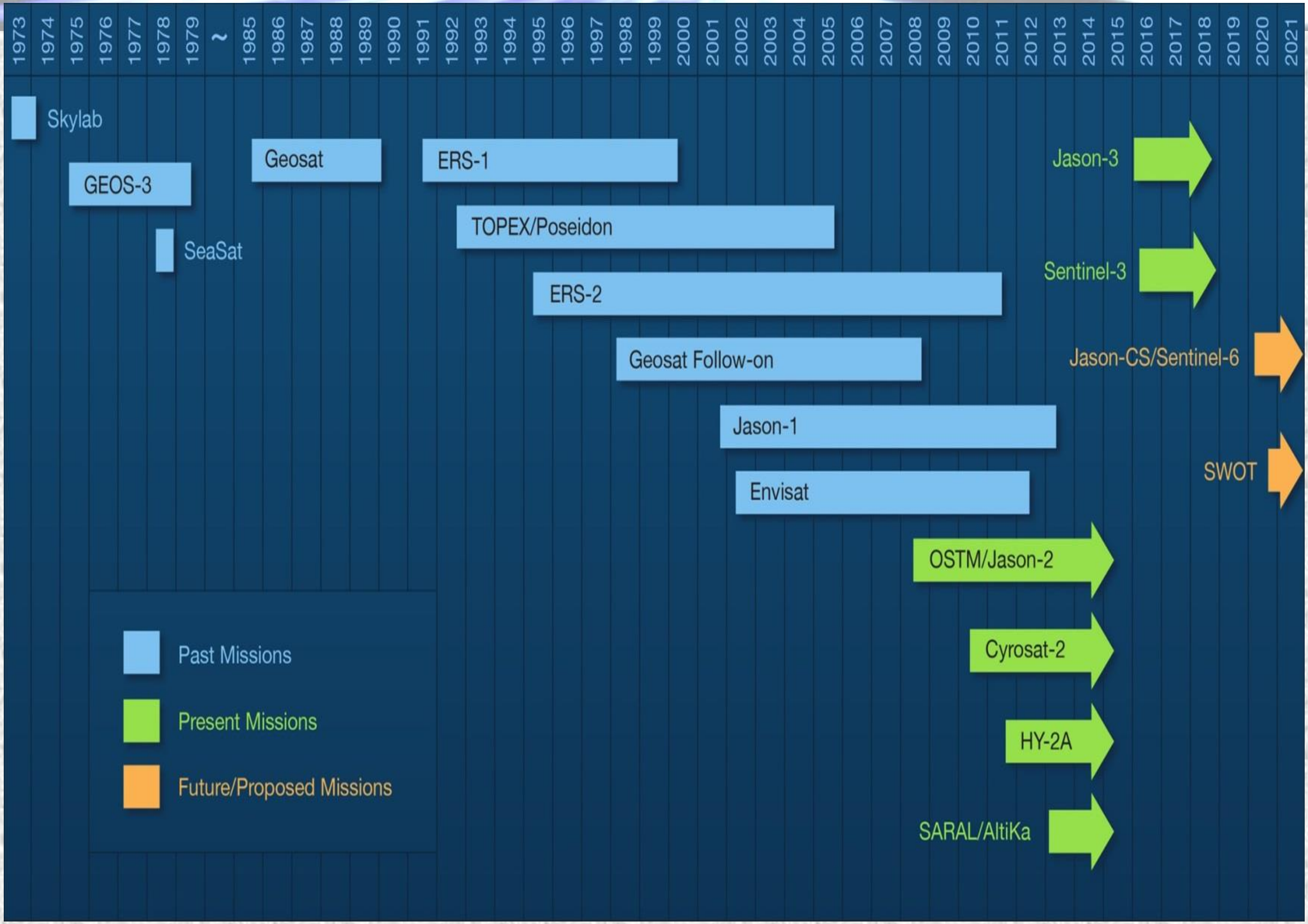
Spatial resolution: 250-350 m

Temporal resolution: 1-10 days

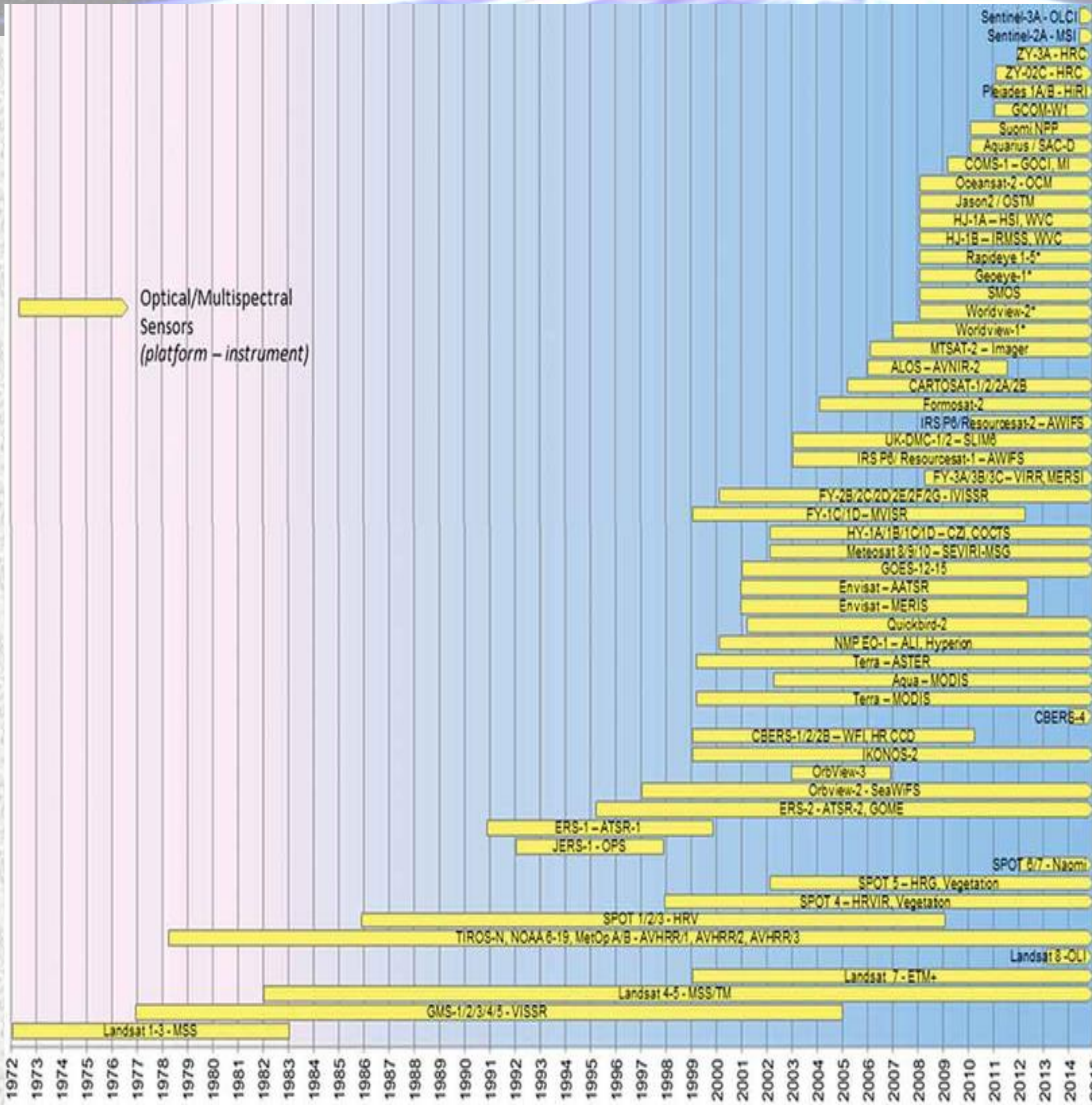




Radar altimetry missions



Optical and multispectral sensors



Vis/NIR

Spatial resolution: 10-350 m

Temporal resolution:

1-10 days

Istituto di Ricerca per la Protezione Idrogeologica

II. Equipped river reach with rating curve known at one of ends

RCM (Moramarco et al. 2005)

Hydrometric Monitoring

Upstream site

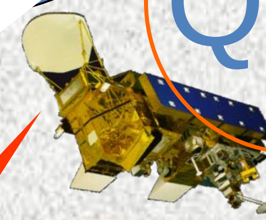
Significant lateral contribution

...tream site

...n

Modis (R...

Q ?



Altimetry Radar
ERS-2
ENVISAT

Hydrometric le...
→ obse...
Dis...
...d

Hydrometric level
→ observed

Short period

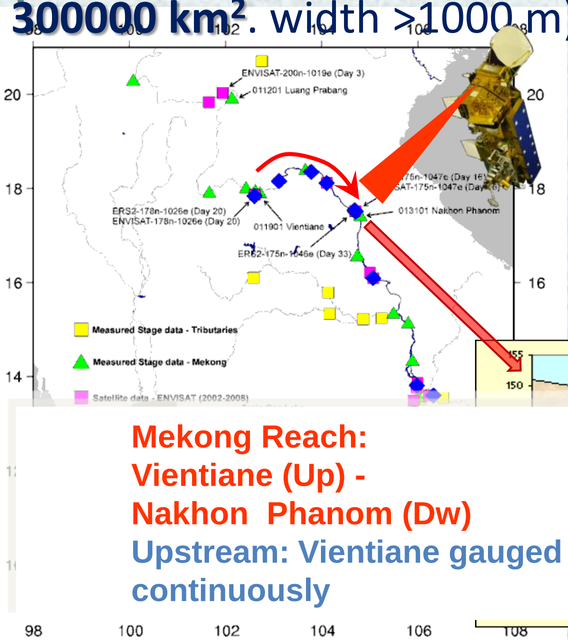
Discharge Monitoring by Satellite

BENEFIT USING ALTIMETRY PRODUCT

Relating Qu– WL(Alt) downstream

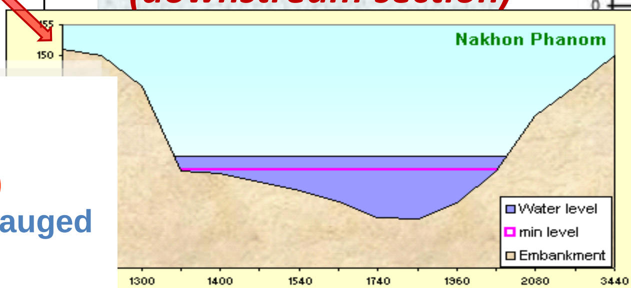
Birkinshaw et al. (2010) used altimetry water levels on the Mekong River (Southeastern Asia) as input data for a simple model, proposed by Moramarco & Singh (2001) and enhanced by Moramarco et al. (2005), named as **Rating Curve Model** (RCM) **Without using rainfall data**

Mekong River: reach bounded by two gauged sections (**400 km**; intermediate drainage area **300000 km²**. width >1000 m)

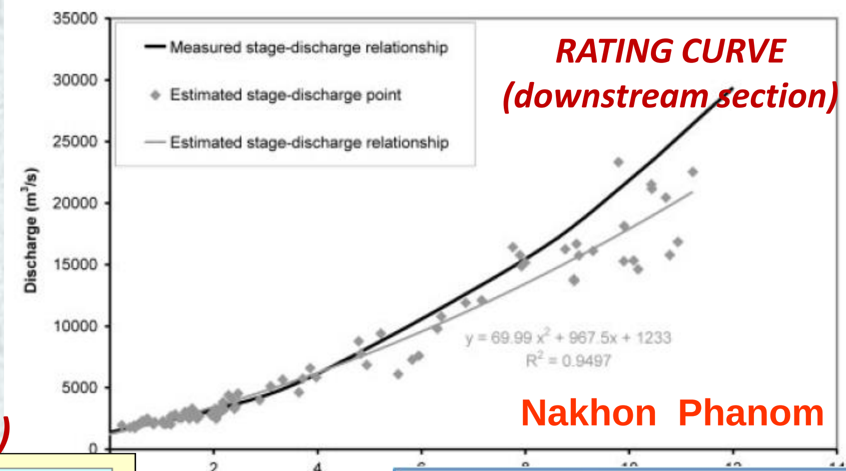


Mekong Reach:
Vientiane (Up) -
Nakhon Phanom (Dw)
Upstream: Vientiane gauged continuously

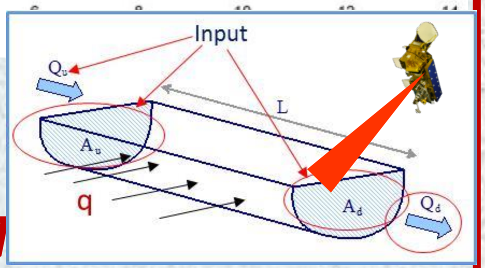
ALTIMETRY LEVEL (downstream section)



RATING CURVE (downstream section)



RCM



Birkinshaw, S.J., O'Donnell, G.M., Moore, P., Kilsby, C.G., Fowler H.J., & Berry, P.A.M. Using satellite altimetry data to augment flow estimation techniques on the Mekong River, Hydrol. Process., 2010, 24, 3811-3825

BENEFIT USING ALTIMETRY PRODUCT

Relating Qu– WL(Alt) downstream

Birkinshaw et al. (2010) used altimetry water levels on the Mekong River (Southeastern A... ...sed by Moramarco & Si... ...l. (2005), named as **Ratin...**

$$Q_d(t)=\alpha\frac{A_d(t)}{A_u(t-T_L)}Q_u(t-T_L)+\beta=\alpha X+\beta$$

Without using rainfall data

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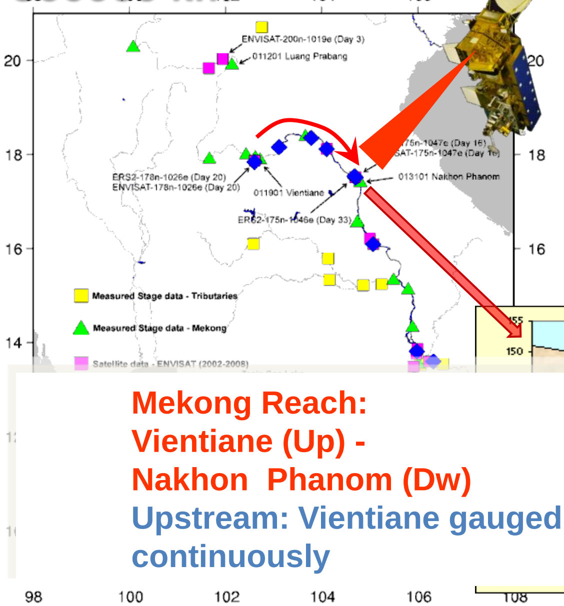
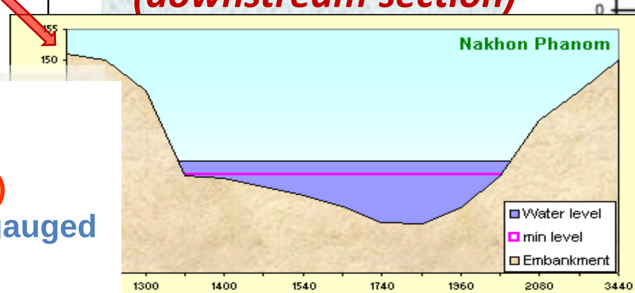
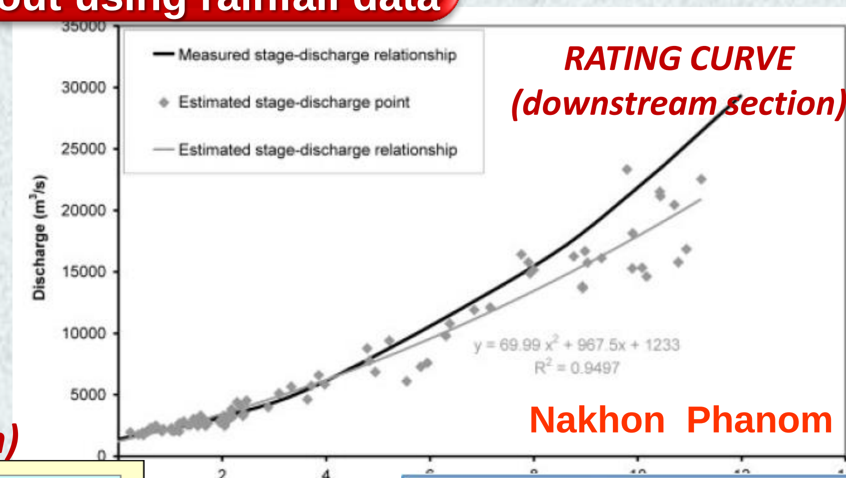


Mekong Reach:
Vientiane (Up) -
Nakhon Phanom (Dw)
Upstream: Vientiane gauged continuously

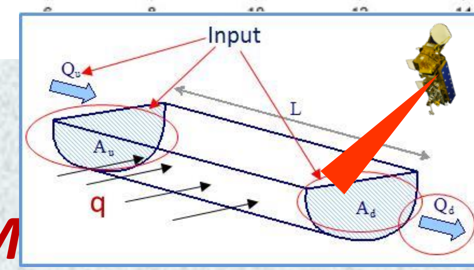
ALTIMETRY LEVEL (downstream section)



RATING CURVE (downstream section)



RCM



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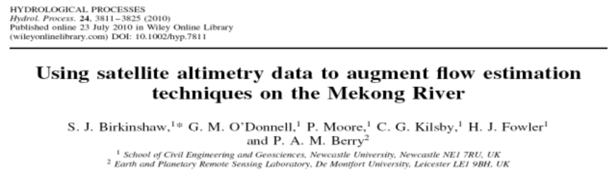

HYDROLOGICAL PROCESSES
Hydrol. Process. 24, 3811–3825 (2010)
Published online 23 July 2010 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.7811

Using satellite altimetry data to augment flow estimation techniques on the Mekong River

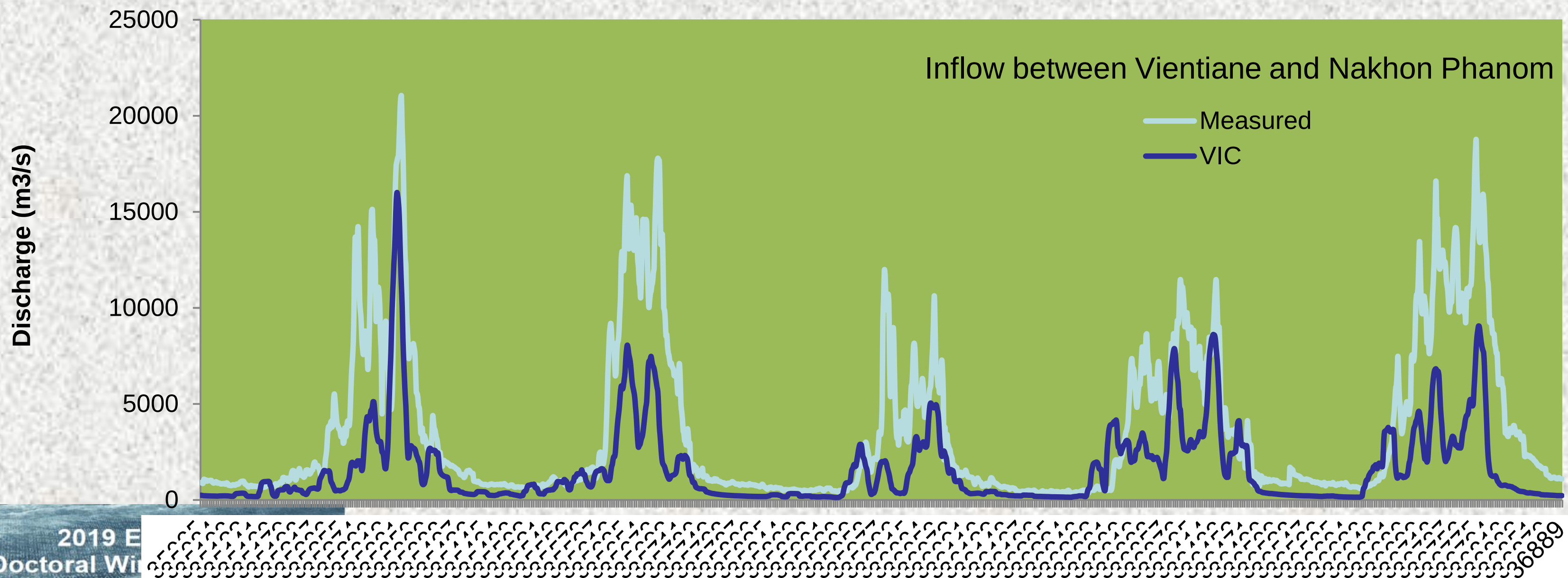
S. J. Birkinshaw,[1*] G. M. O'Donnell,[1] P. Moore,[1] C. G. Kilsby,[1] H. J. Fowler[1] and P. A. M. Berry[2]
[1] School of Civil Engineering and Geosciences, Newcastle University, Newcastle NE1 7RU, UK
[2] Earth and Planetary Remote Sensing Laboratory, De Montfort University, Leicester LE1 9BH, UK

Without altimetry:

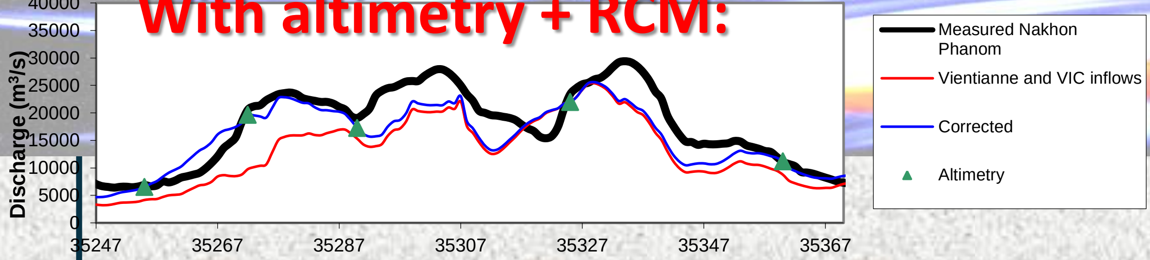
Discharge at Nakhon Phanom equal discharge at Vientiane three days earlier complemented by lateral inflows from a macro-scale hydrologic model

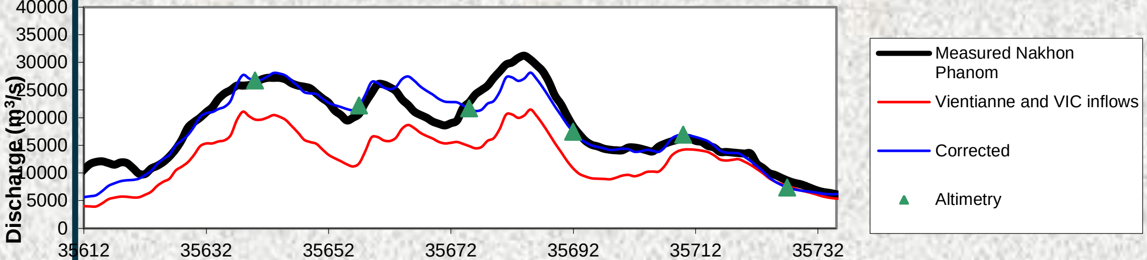
Variable Infiltration Capacity (VIC) model (Liang *et al.*, 1994) run for Mekong basin 1979 - 2000 (Costa-Cabral *et al.* 2008).

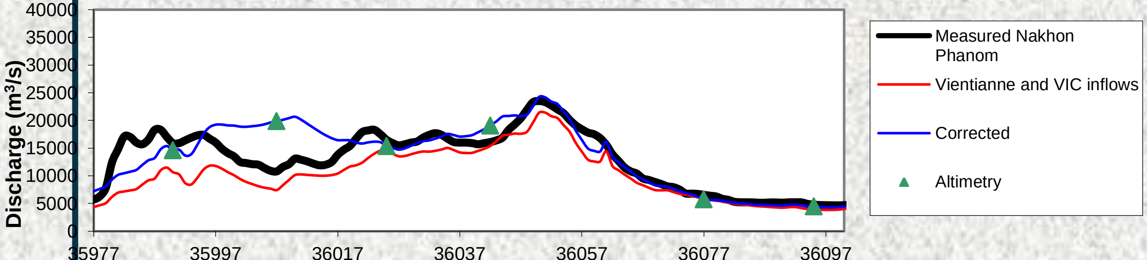
$$Q_{NP-UG}^{t} = Q_{V}^{t-3} + Q_{VIC}^{t}$$

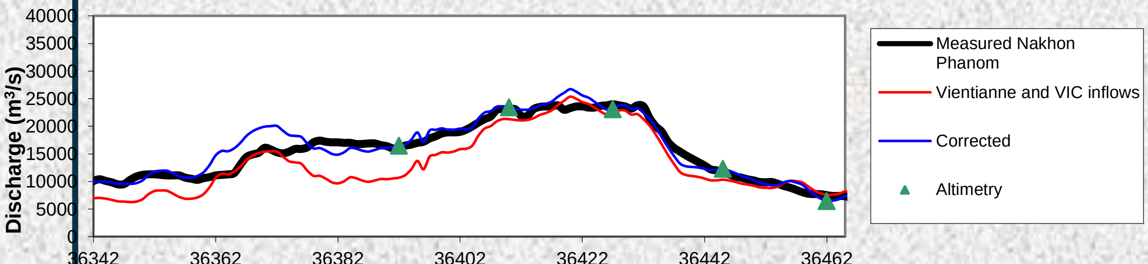


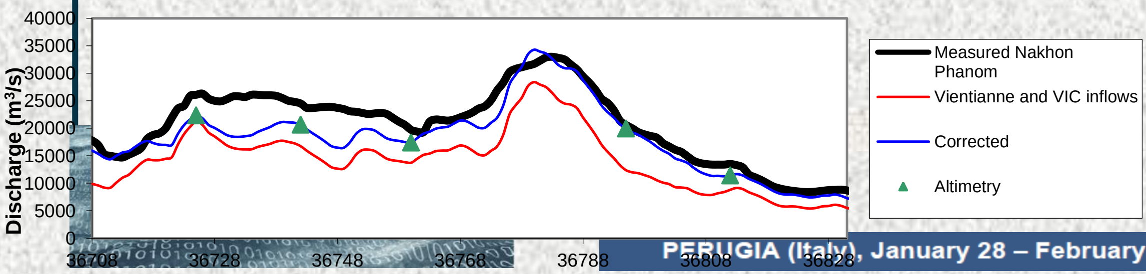
With altimetry + RCM:

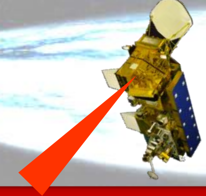












$$Q_d(t)=\alpha\frac{A_d(t)}{A_u(t-T_L)}Q_u(t-T_L)+\beta=\alpha X+\beta$$

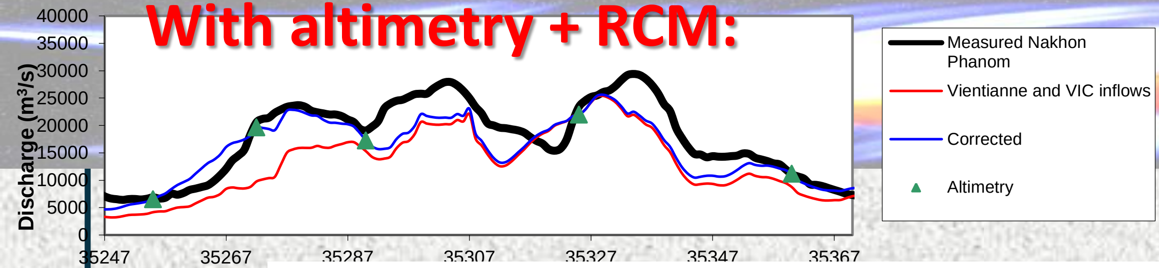
Ungauged site scenario: measured, predicted, altimetric corrected and altimetry data at Nakhon Phanom 1996-2000.

R^2 without altimetry data: 0.823
R^2 with altimetry data: 0.947

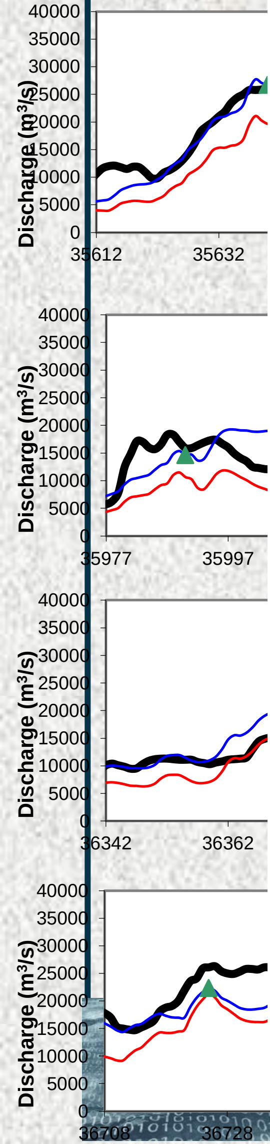
RMSE w/out altimetry data: 3271
RMSE with altimetry data: 1795

(m³/s)

With altimetry + RCM:



$$Q_d(t) = \alpha \frac{A_d(t)}{A_u(t - T_L)} Q_u(t - T_L) + \beta = \alpha X + \beta$$



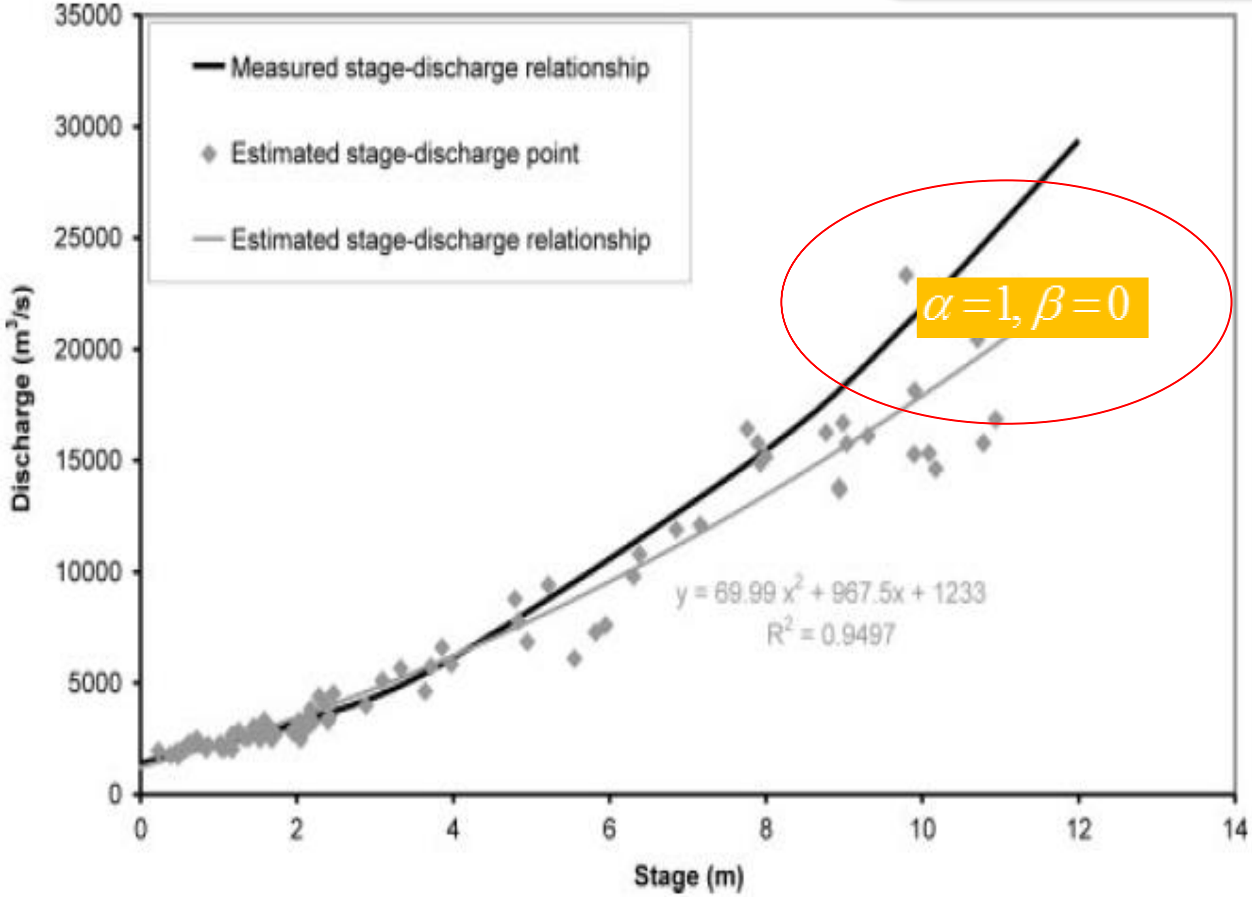
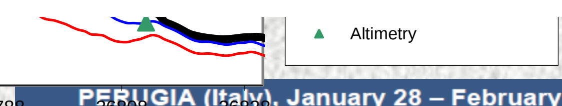


Figure 13. Estimated stage–discharge relationship at NP



measured,

data at

000.

0.823

0.947

: 3271

1795

Remote Sens. **2013**, *5*, 4145-4162; doi:10.3390/rs5094145

OPEN ACCESS

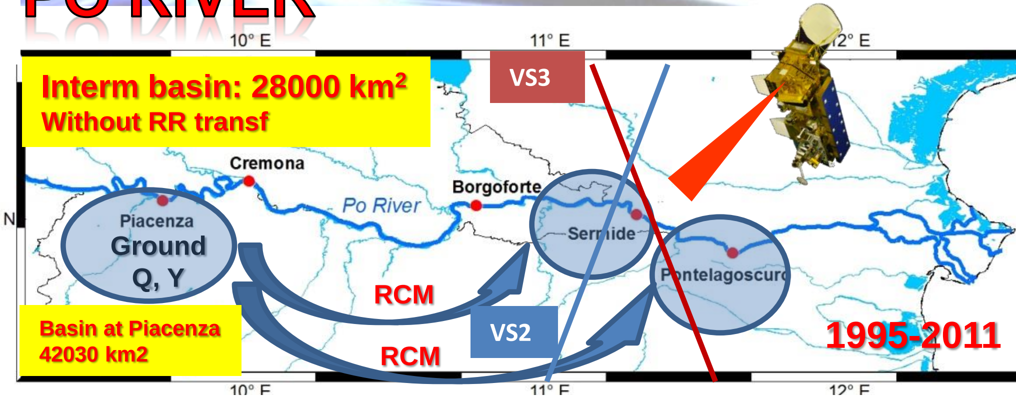
Remote Sensing

River Discharge Estimation by Using Altimetry Data and Simplified Flood Routing Modeling

Angelica Tarpanelli *, Silvia Barbetta, Luca Brocca and Tommaso Moramarco

BENEFIT USING ALTIMETRY PRODUCT

PO RIVER



Empirical discharge formulation (Bjerklie, 2003 JoH)

$$Q = c_1 \cdot W^a \cdot Y^b \cdot S^d$$

Discharge; Surface top width; Depth of the equivalent rectangular section; channel slope

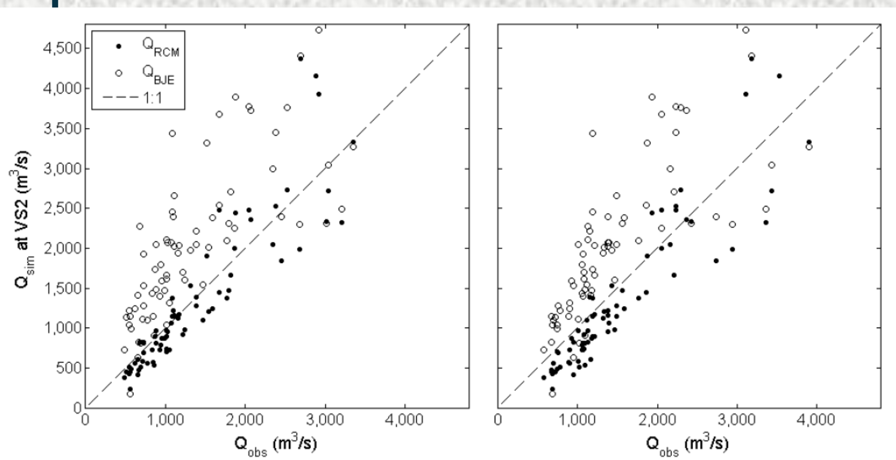
$$Q_{BJE} = 7.22 \cdot W^{1.02} \cdot Y^{1.74} \cdot S^{0.35}$$

Parameters calibrated and validated using 1012 discharge measurements in 102 rivers in the United States and New Zealand

Bjerklie, D.M., Dingman, S.L., Vorosmarty, C.J., Bolster, C.H., Congalton, R.G., 2003. Evaluating the potential for measuring river discharge from space. *Journal of Hydrology*, 278,

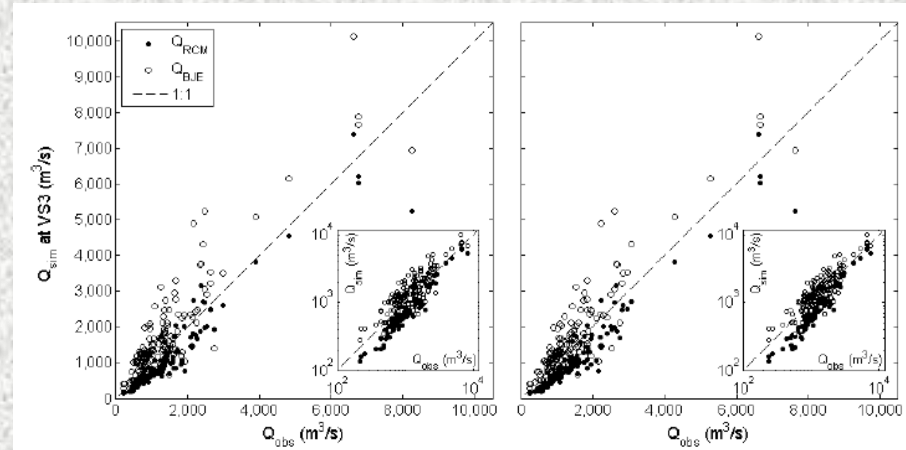
Pontelagoscuro

Satellite	RCM RMSE ($m^3 \cdot s^{-1}$)	RCM RRMSE (%)	RCM NS (-)	RCM RE (%)	BJ03 RMSE ($m^3 \cdot s^{-1}$)	BJ03 RRMSE (%)	BJ03 NS (-)	BJ03 RE (%)
VS2 (ERS-2)	405	26.9	0.73	−12.1	834	55.3	−0.14	3.3
VS3 (ERS-2 and ENVISAT)	497	33.3	0.82	25.8	670	44.9	0.66	0.6
VS3 (ERS-2)	526	31.2	0.82	−22.3	794	47.0	0.60	21.3
VS3 (ENVISAT)	467	35.7	0.80	−30.1	527	40.3	0.74	19.8



Sermide

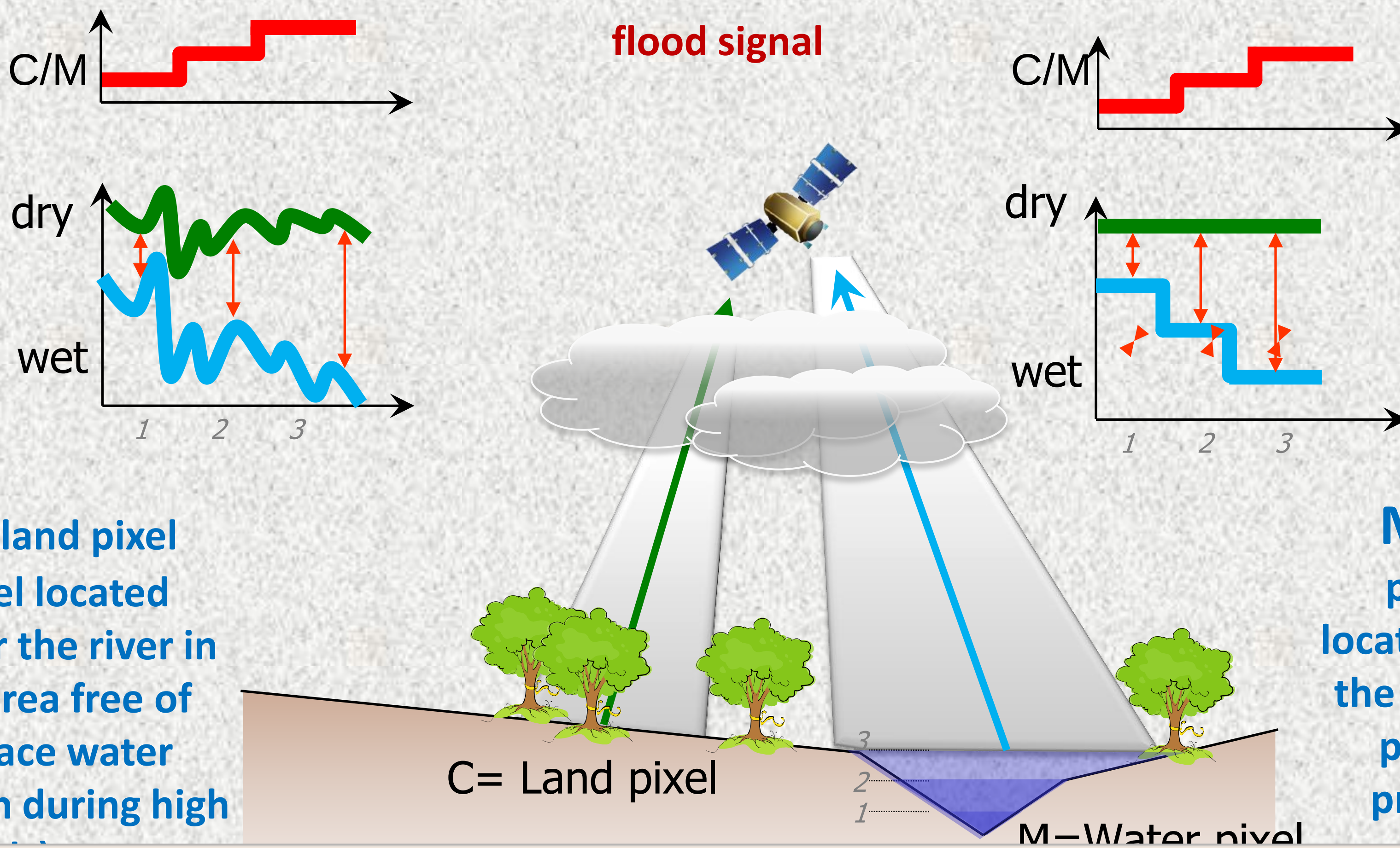
Pontelagoscuro



Sermide

Pontelagoscuro

Flow velocity: estimation by using MODIS data



C = land pixel (pixel located near the river in an area free of surface water even during high flow...)

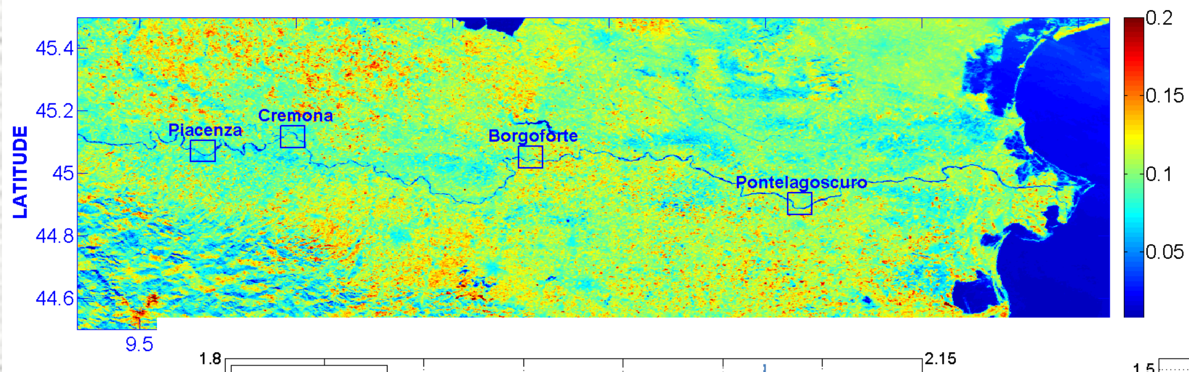
M = water pixel (pixel located within the river with permanent presence of water)

C/M increases with the presence of water and, hence, of discharge

BENEFIT USING RADIOMETER PRODUCTS

PO RIVER BASIN

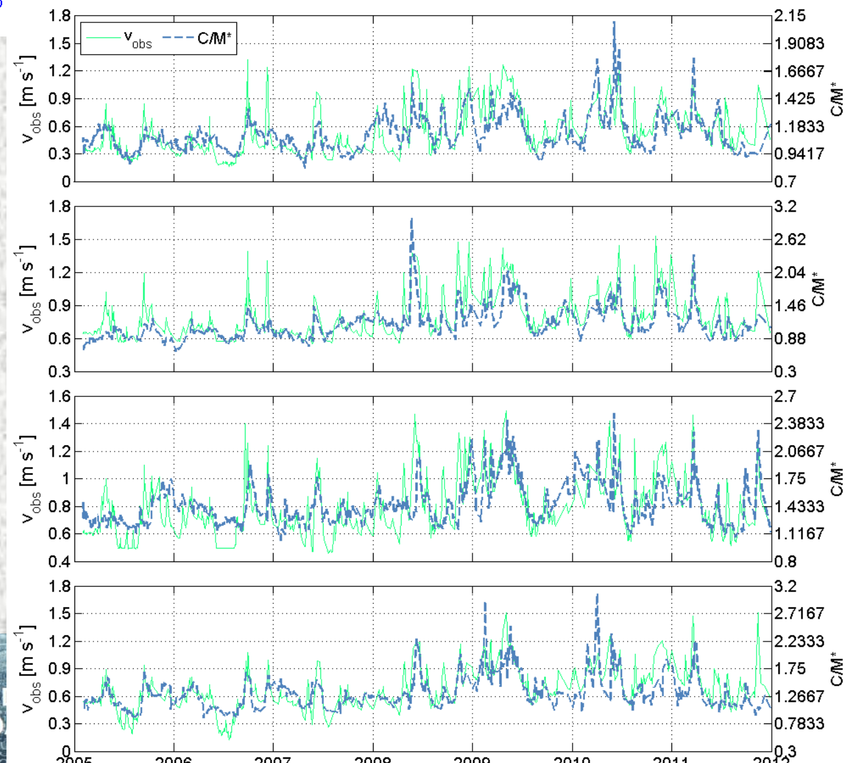
AQUA- MODIS Reflectance value of Channel 2 (10-Feb-2005 10:10)

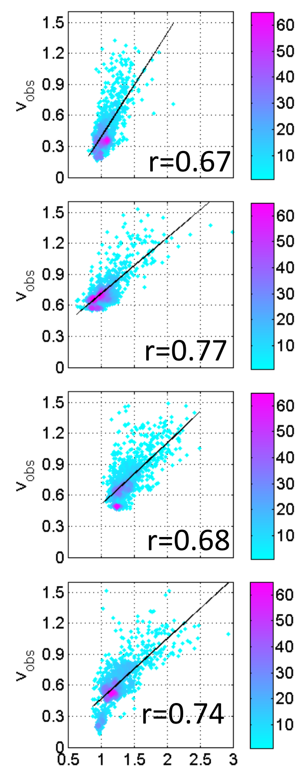


Remote Sensing of Environment 136 (2013) 47–55
Contents lists available at SciVerse ScienceDirect
Remote Sensing of Environment
journal homepage: www.elsevier.com/locate/rse

Toward the estimation of river discharge variations using MODIS data in ungauged basins

Angelica Tarpanelli [a,*], Luca Brocca [a], Teodosio Lacava [b], Florisa Melone [a], Tommaso Moramarco [a], Mariapia Faruolo [b], Nicola Pergola [b], Valerio Tramutoli [c]





Piacenza

Cremona

Borgoforte

Pontelagoscuro

mbella

Istituto di Ricerca per la Protezione Idrogeologica

BENEFIT USING RADIOMETER PRODUCTS

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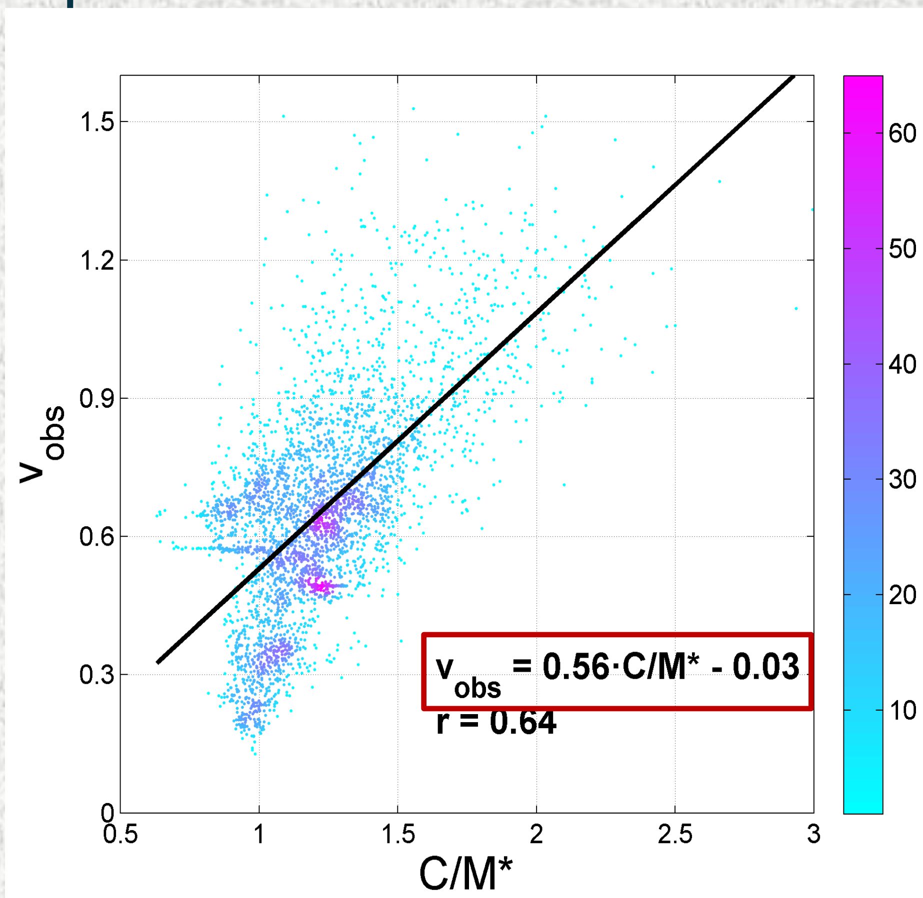
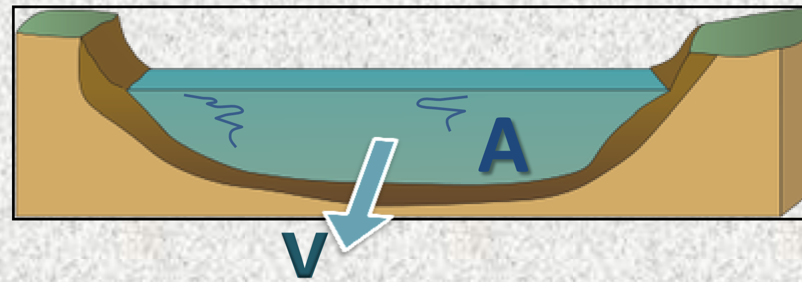
PO RIVER BASIN

Identification of a regional relationship between C/M* and v





$$Q = v \cdot A$$

$$A = f(h)$$

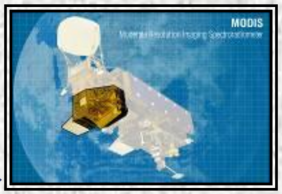
1) h in-situ with actual river section

2) h altimetry with actual river section

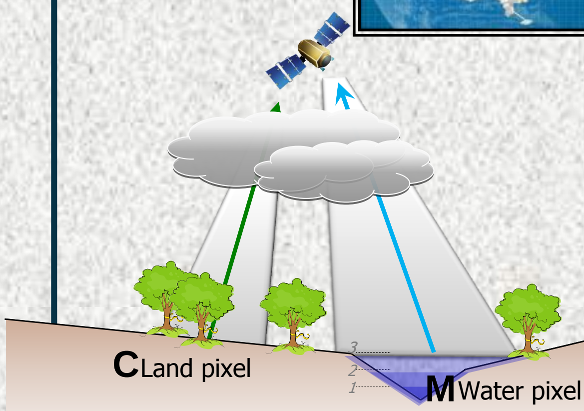
3) h altimetry with Entropy river section

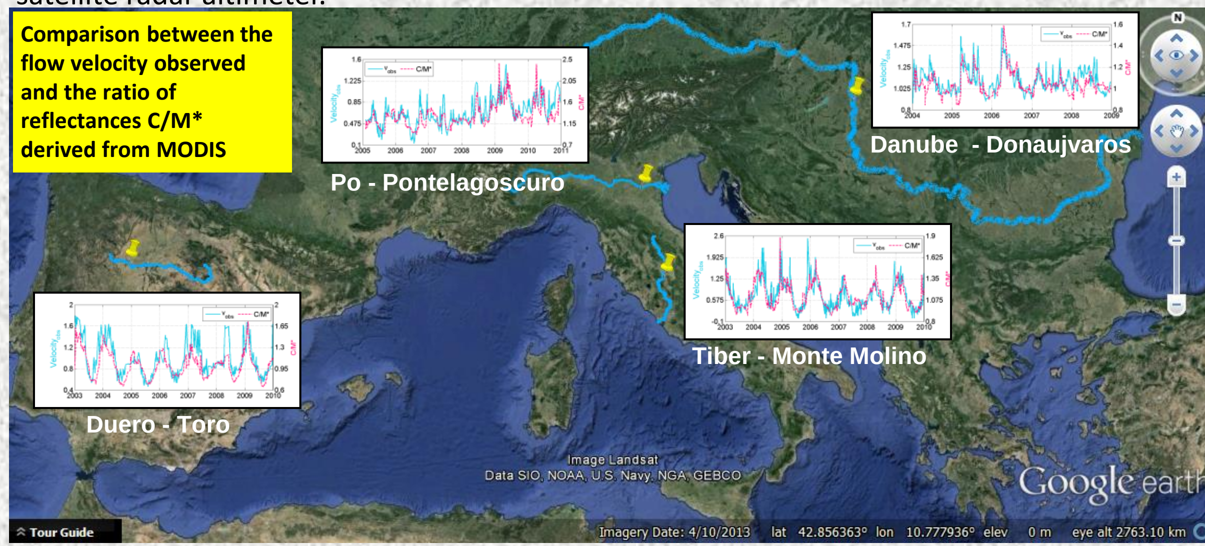
Remote sensing of river discharge

MODIS (MODerate resolution Imaging Spectroradiometer)

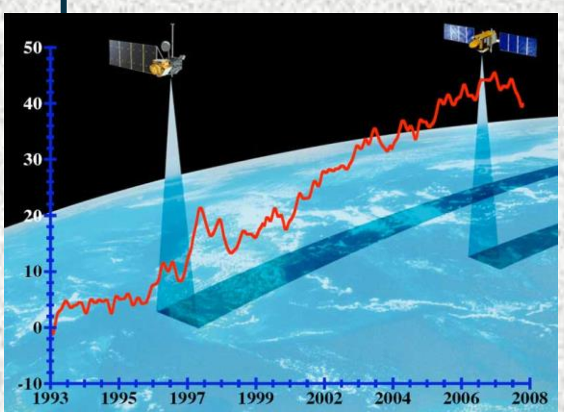


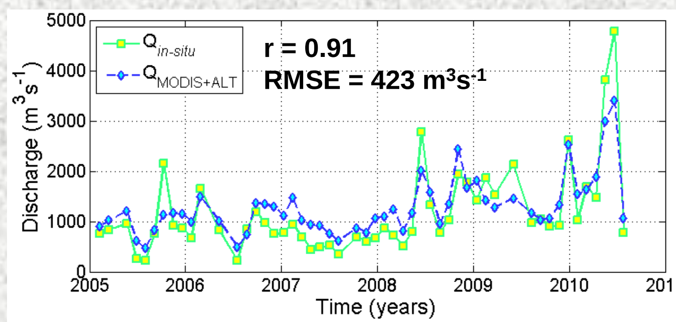
A methodology for river discharge estimation in ungauged sites by using remote sensing data is developed. The discharge is assessed as the product of the flow velocity, derived from MODIS, and the flow area, calculated as a function of the water level derived from the satellite radar altimeter.





Radar Altimetry





Comparison between the discharge observed at Pontelagoscuro and the one derived by remote sensing.

The approach is tested in some European rivers and the agreement with the observed discharge is fairly satisfactory with errors of about 35%.

Tarpanelli, A., Brocca, L., Melone, et al. (2013). Toward the estimation of river discharge variations using MODIS data in ungauged basins. Remote Sensing of Environment, 136, 47-55.

Tarpanelli, A., Brocca, L., Barbetta, M., Faruolo, M., Lacava, T., Moramarco, T. (2014). Coupling MODIS and radar altimetry data for discharge estimation in poorly gauged river basin. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, in press.


Bathymetry Known
Ground Observations
DISCHARGE
Estimation
Satellite Observations
ALTIMETER
MODIS
Moderate Resolution Imaging
Spectro-Radiometer
Bathymetry Unknown


Contents lists available at SciVerse ScienceDirect
Journal of Hydrology
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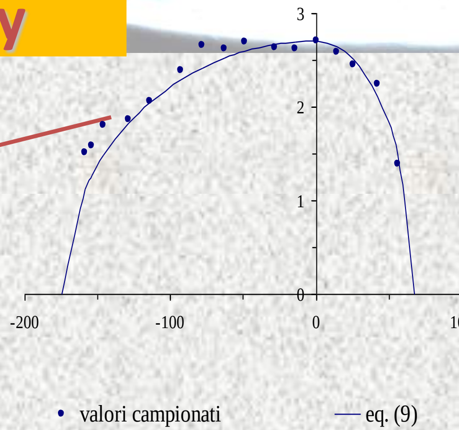
An entropy-based method for determining the flow depth distribution in natural channels

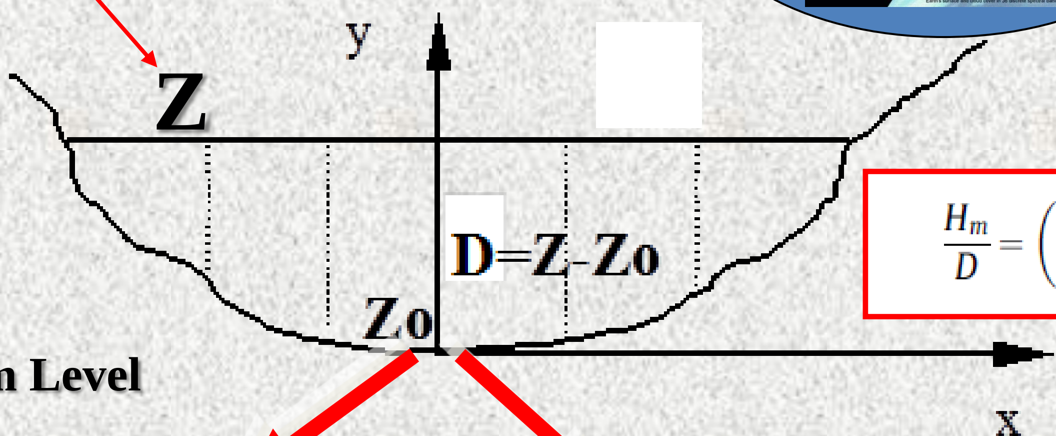
Tommaso Moramarco [a,*], Giovanni Corato [b], Florisa Melone [a], Vijay P. Singh [c,d]

Entropic Model for Unknown Bathymetry



Satellite Observations

$$h(x) = \frac{D}{W} \ln\left[\frac{e^W - 1}{u_{\max S}} u_s(x) + 1\right]$$



$$\frac{H_m}{D} = \left(\frac{e^W}{e^W - 1} - \frac{1}{W}\right) = \Theta(W)$$

Zo Channel Bottom Level

1) Zo Known

2) Zo Unknown

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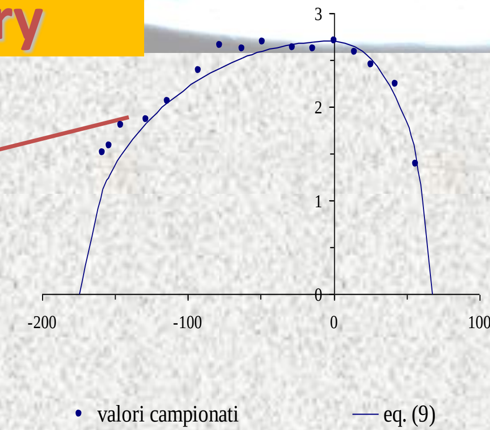

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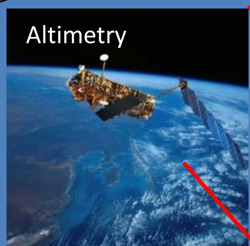
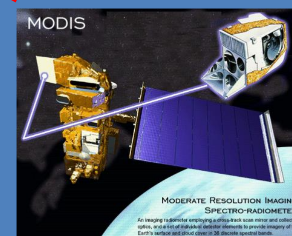
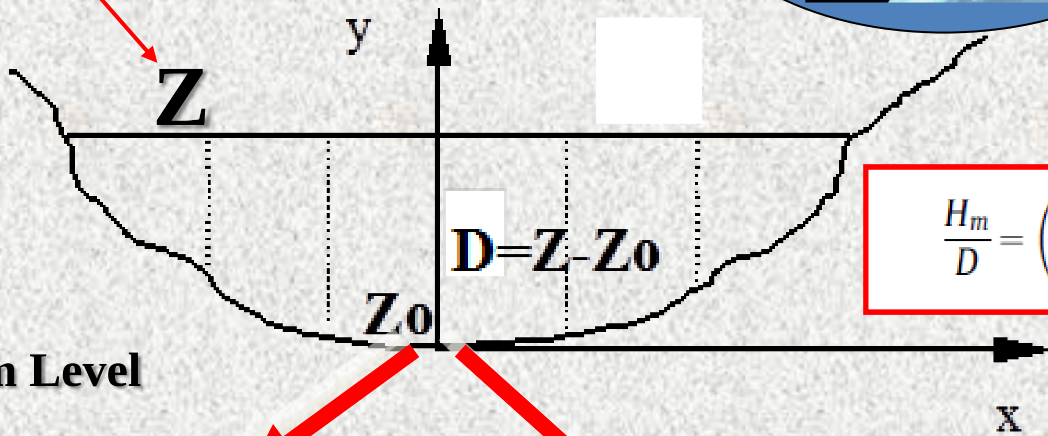
Satellite Observations







$$\frac{H_m}{D} = \left(\frac{e^{W}}{e^{W}-1} - \frac{1}{W}\right) = \Theta(W)$$

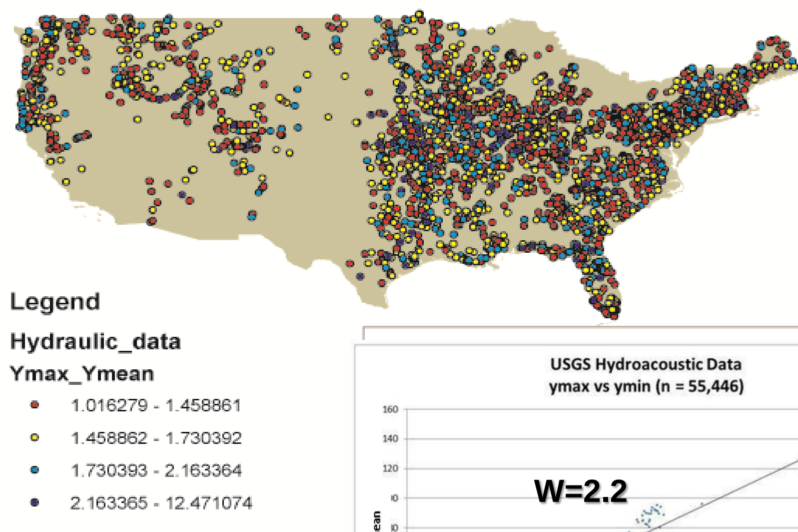
Z_0 Channel Bottom Level

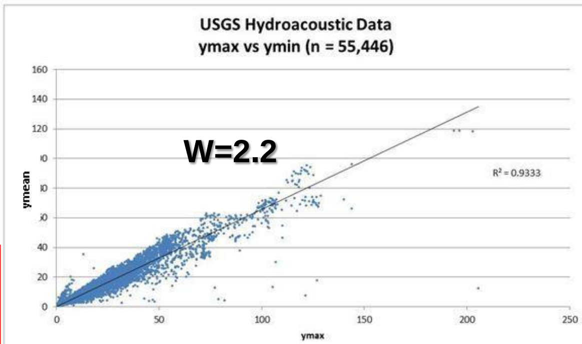
1) Zo Known

2) Zo Unknown

SWOT Project (USGS – IRD(Fr) - IRPI – WS(Ca))
USGS Discharge Measurement Data

N = 17224	stream_wdth	xsec_area	mean_vel	max_vel	mean_depth	max_depth	meas_q	Ymax/Ymean	Vmax/Vmean	W/Ymean
MEAN	403.40	7083.58	2.41	6.19	9.18	13.76	23146.25	1.56	3.02	51.77
MAX	8580.00	340000.00	10.80	76.75	95.20	143.95	1435932.57	16.28	73.10	608.03
MIN	100.00	88.47	0.50	0.50	0.84	1.31	61.48	1.00	1.00	5.37
STDEV	511.64	21814.56	1.48	4.23	9.50	14.03	86793.35	0.33	2.76	42.89
CV	1.27	3.08	0.61	0.68	1.03	1.02	3.75	0.21	0.91	0.83





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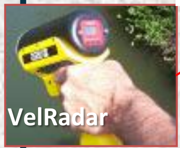
Entropic Model for Bathymetry

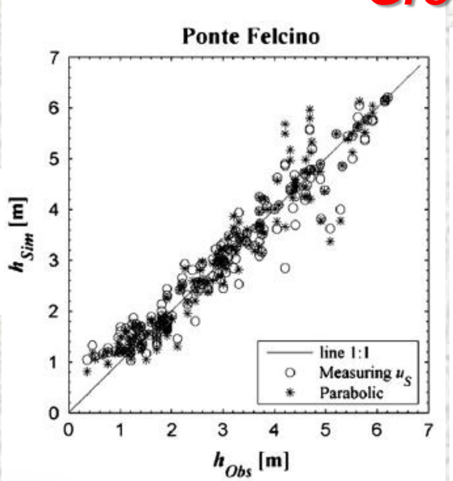
Zo (Channel Bottom Level) - Known

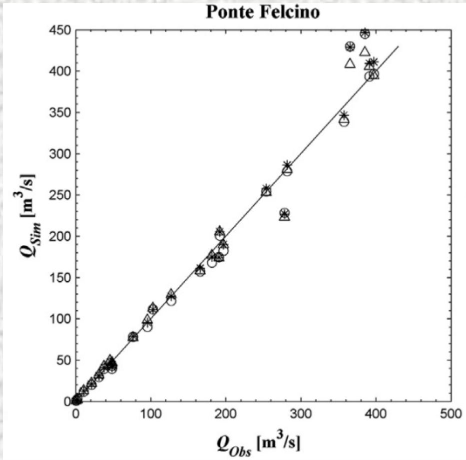
Ground Data

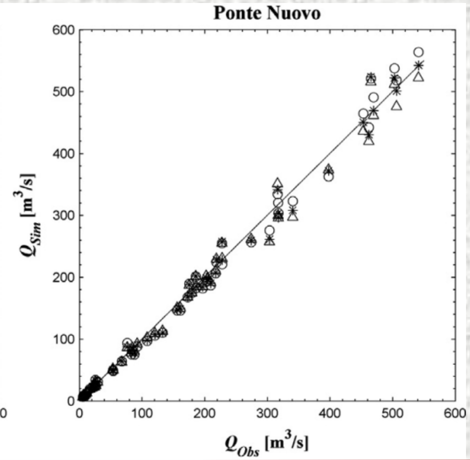
+



$$h(x) = \frac{D}{W} ln\left[\frac{e^W - 1}{u_{max\,S}} u_s(x) + 1\right]$$





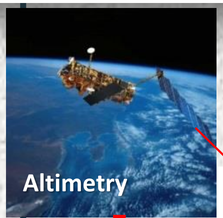


IEEE JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING 1

Coupling MODIS and Radar Altimetry Data for Discharge Estimation in Poorly Gauged River Basins

Angelica Tarpanelli, Luca Brocca, Silvia Barbetta, Mariapia Faruolo, Teodosio Lacava, Member, IEEE, and Tommaso Moramarco

Satellite Observations



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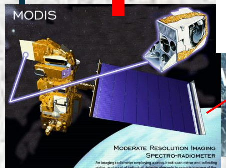
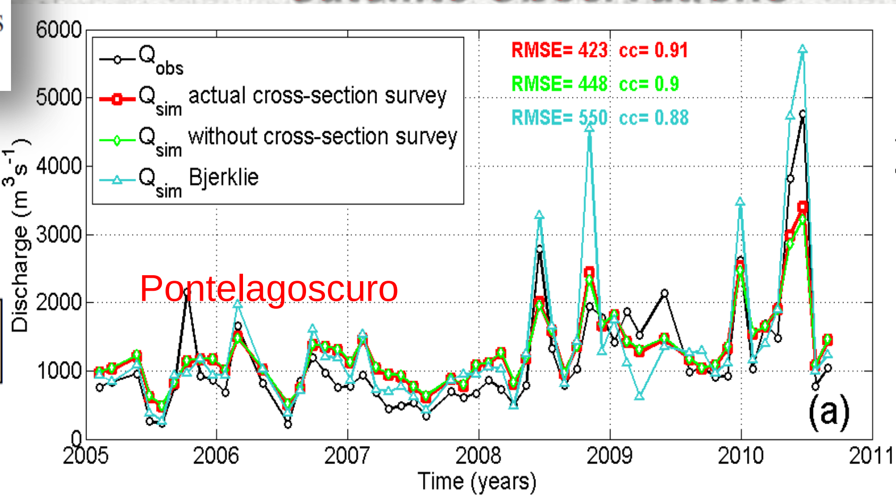
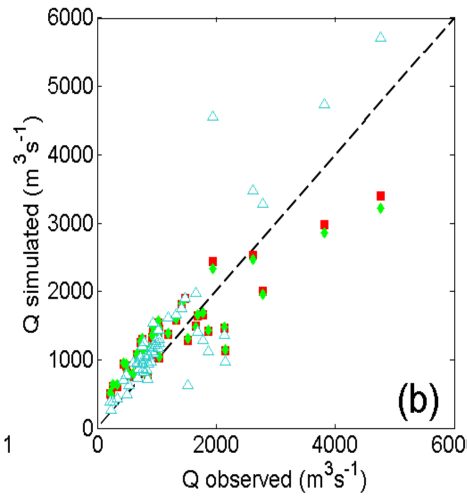


$$h(x) = \frac{D}{W} ln\left[\frac{e^W - 1}{u_{max\,S}} u_s(x) + 1\right]$$

Winter School HYDROLOGY





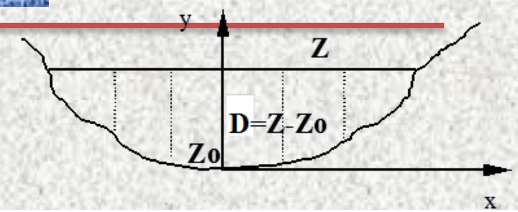
River Bathymetry Estimate and Discharge Assessment from Remote Sensing

Tommaso Moramarco[1] Silvia Barbetta[1] David M. Bjerklie[2] John W. Fulton[3] and Angelica Tarpanelli[1]

WRR under review

Entropic Model for Bathymetry

Zo (Channel Bottom Level) - Unknown



Target: Estimate max flow depth, D

Ground (Radar)

Modis

$$u_{\max|oss} = \frac{\sqrt{g D_m S_f}}{k} ln\left(\frac{1}{\exp(-aD_m)}\right) = \frac{u_{oss}}{\phi(M)}$$

(Moramarco and Singh, JHE, 2010)

K (von Karman=0.41)

$\phi(M)$ Entropy = 0.65

a: parameter. *yo=exp(-aDm): location v=0*

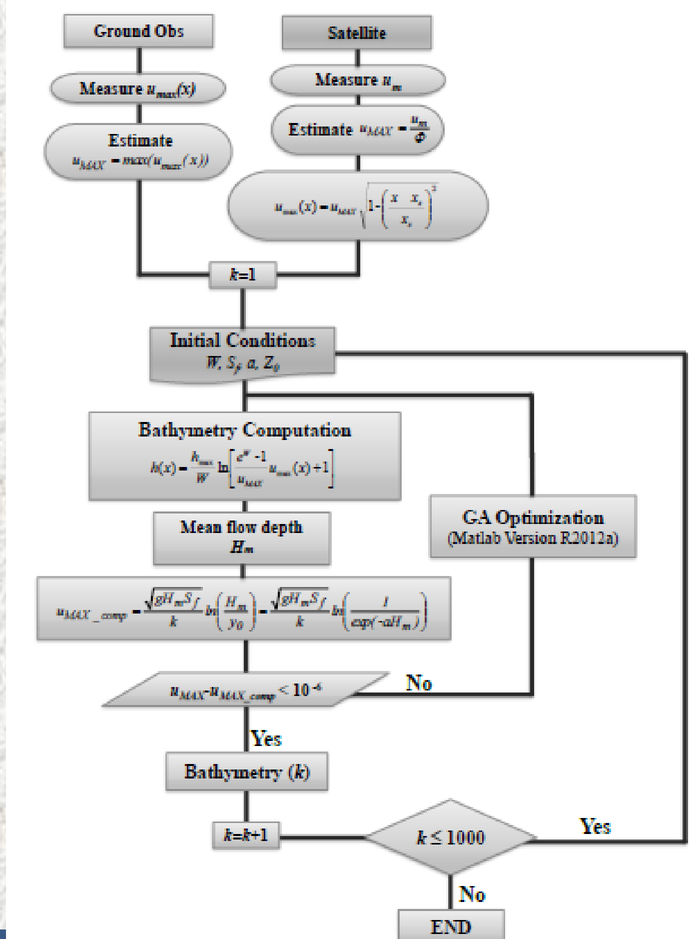
Sf: hydraulic gradient

Dm: Mean flow depth by Entropy law F(W,*Z0*)

$$h(x) = \frac{D}{W} ln\left[\frac{e^{W}-1}{u_{\max S}} u_s(x) + 1\right]$$

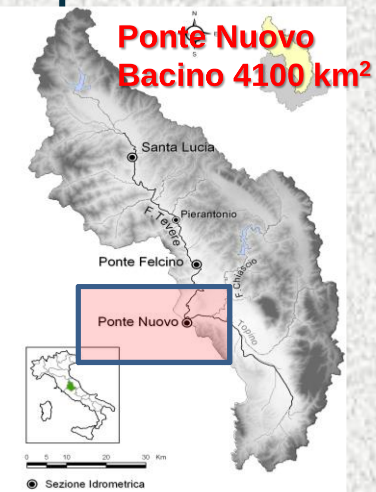
Parameter Estimation (a, Sf, W, Zo)

GA solver (Matlab Ver 2012a)



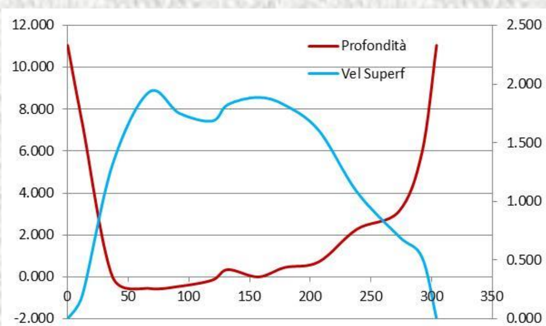
Zo Unknown

Ponte Nuovo
Bacino 4100 km^2



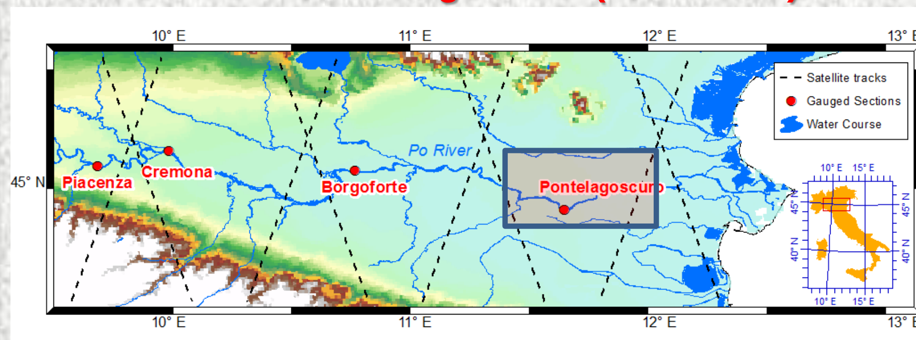
8 velocity measurements
Ponte Nuovo

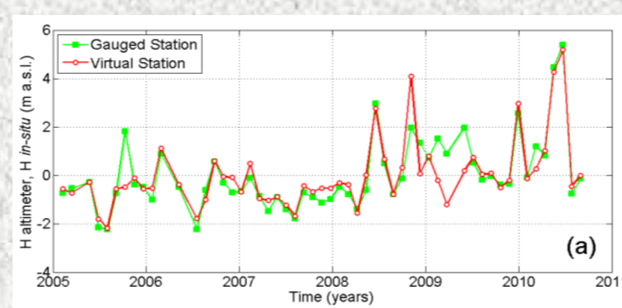
7 velocity measurements
Pontelagoscuro

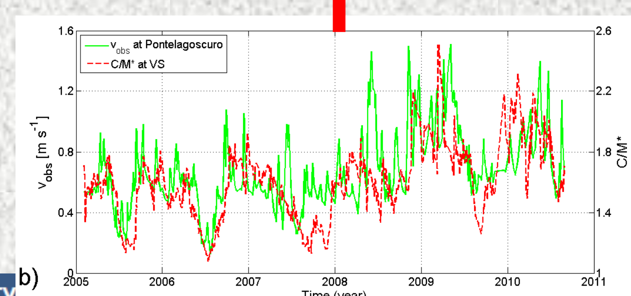


MODIS 2002-2010
Envisat 2002-2010

Pontelagoscuro (70000 km^2)





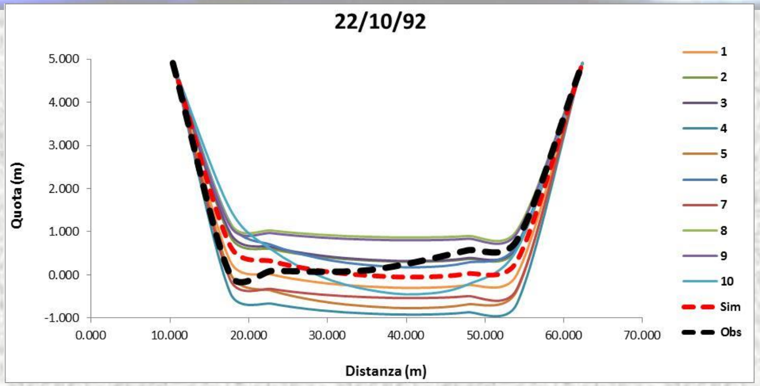


Range of parameters

$W=2.1$ (USGS)	Pnuovo e Pontelagoscuro
$1.2<W_{ini}=7.5<15$	Pnuovo e Pontelagoscuro
$0.001<Sf_{ini}=2\times10^{-3}<0.003$	Pnuovo
$0.0001<Sf_{ini}=2\times10^{-4}<0.0003$	Pontelagoscuro
$0.5<a(yo)_{ini}=0.75<1$	Pnuovo e Pontelagoscuro
$-10< Z0_{ini} = H_{alt}/2<H_{alt} -1$	Pnuovo e Pontelagoscuro

Sensitivity to Initial Conditions

10 random realizations – Average Cross-Section



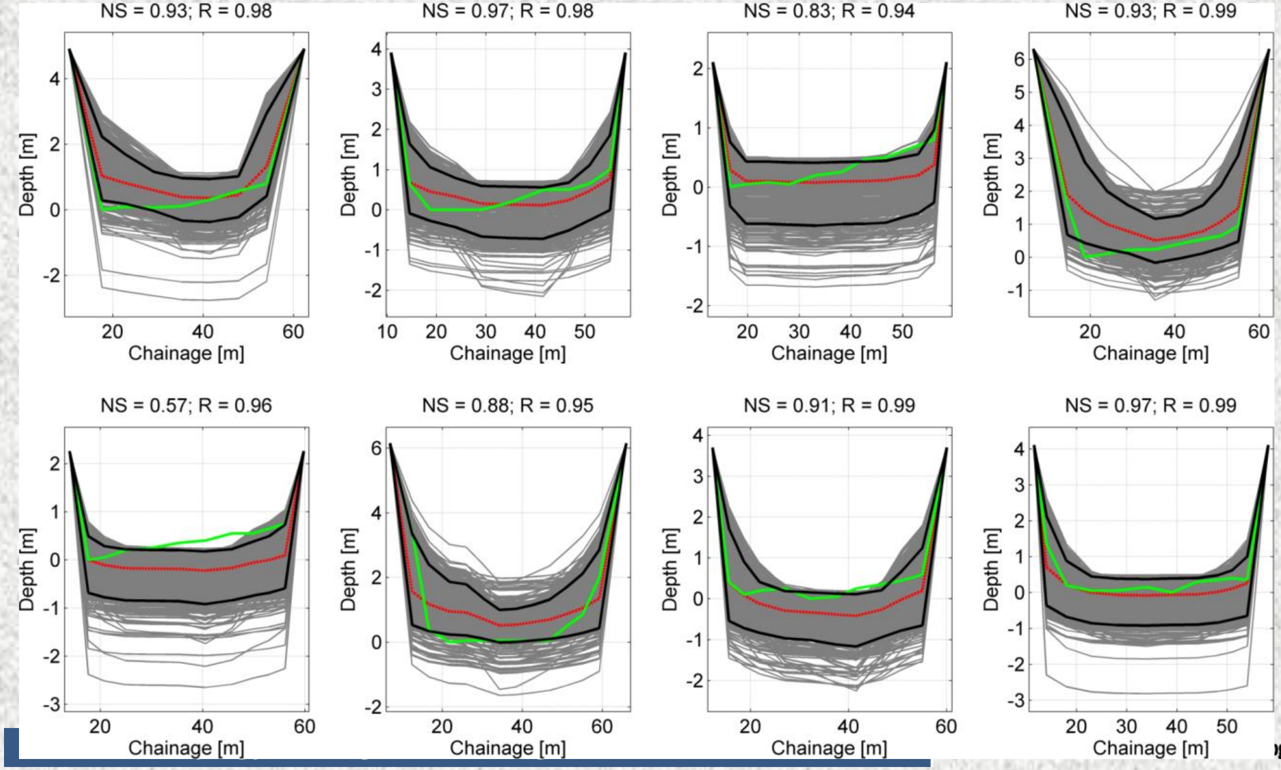
Field Data

RESULTS

1000 realizations

Ponte Nuovo

Vsup-obs;



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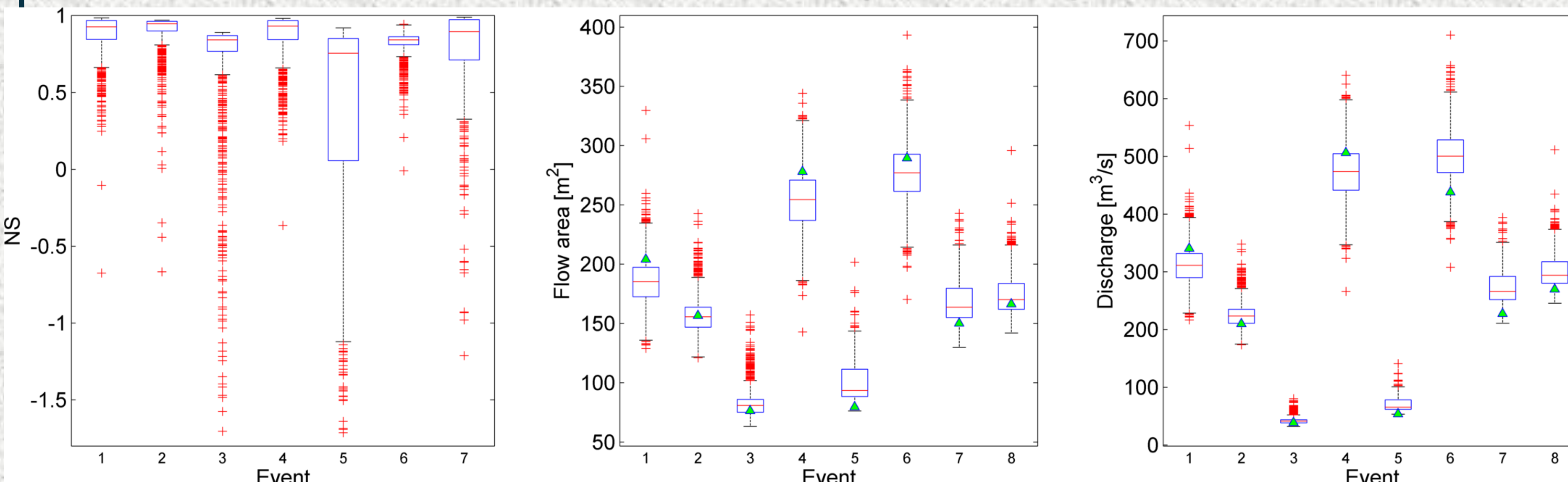
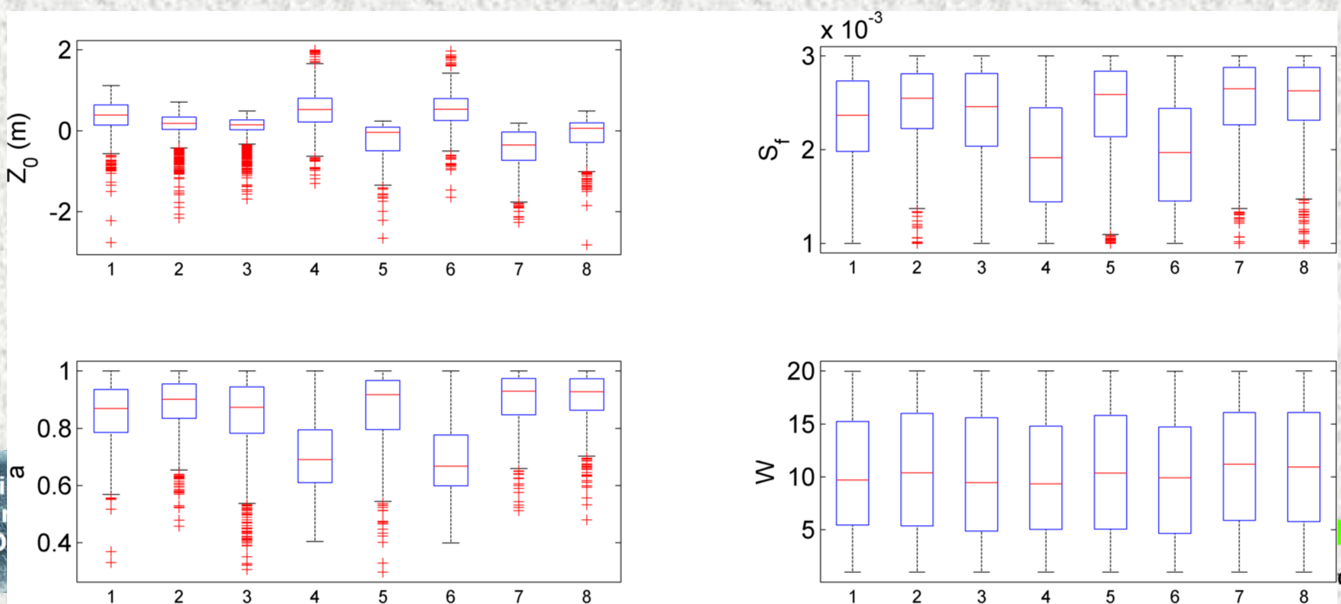
Doctoral Winter School
DATA RICH HYDROLOGY

RESULTS (Field Data)

1000 realizations

Ponte Nuovo (4100 km2)



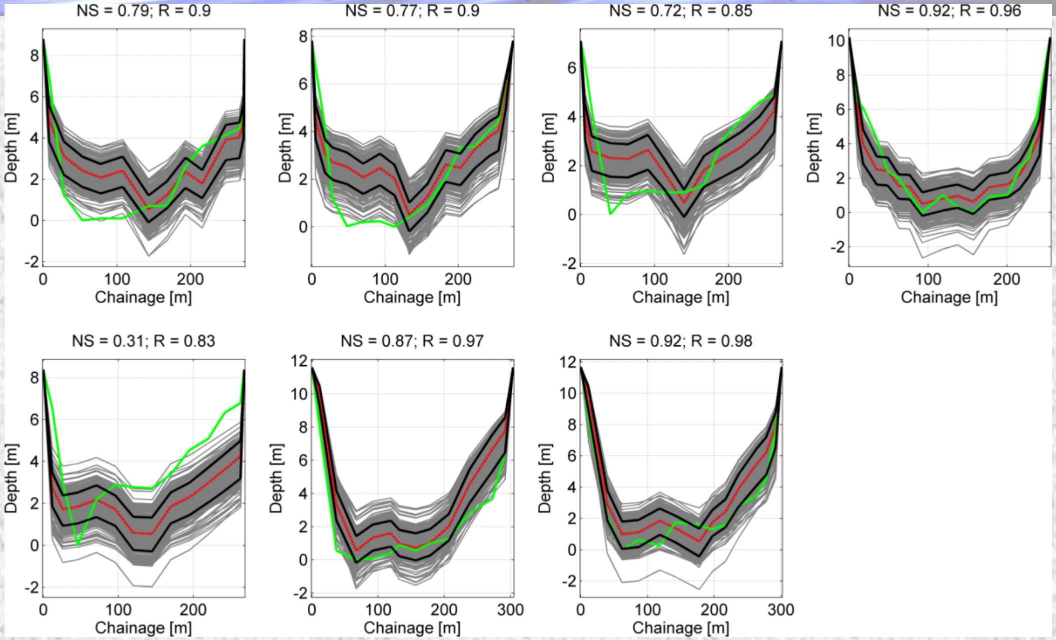


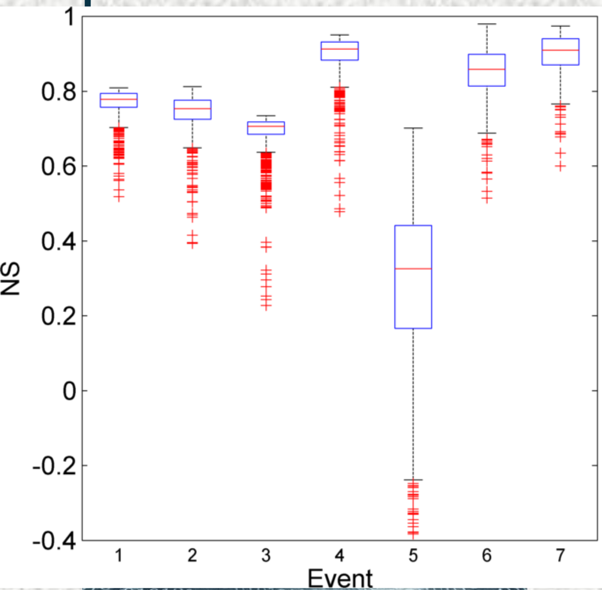
2019 Editi
Doctoral Winter
DATA RICH HYD

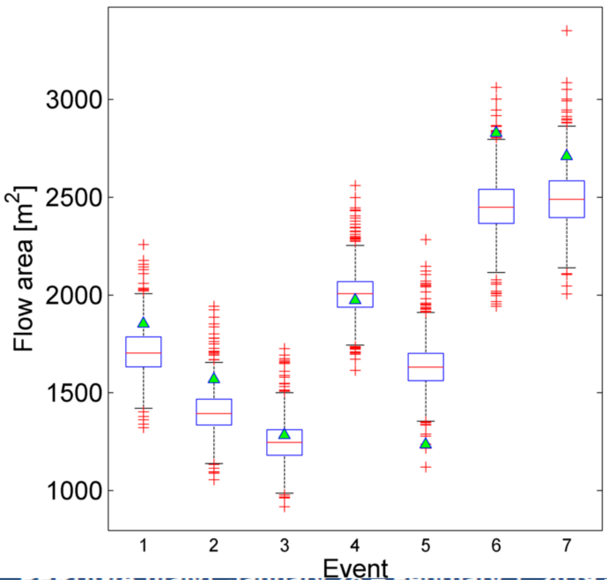
rpi
ca per la Protezione Idrogeologica

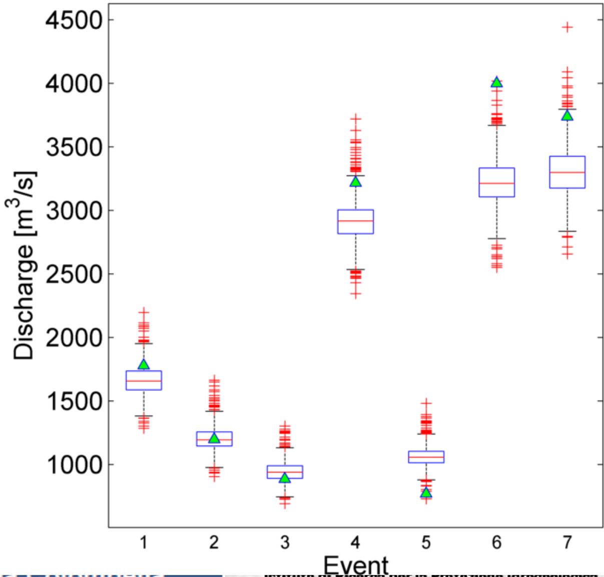
RESULTS (Field Data)

1000 realizations **Pontelagoscuro (70000 km2)**





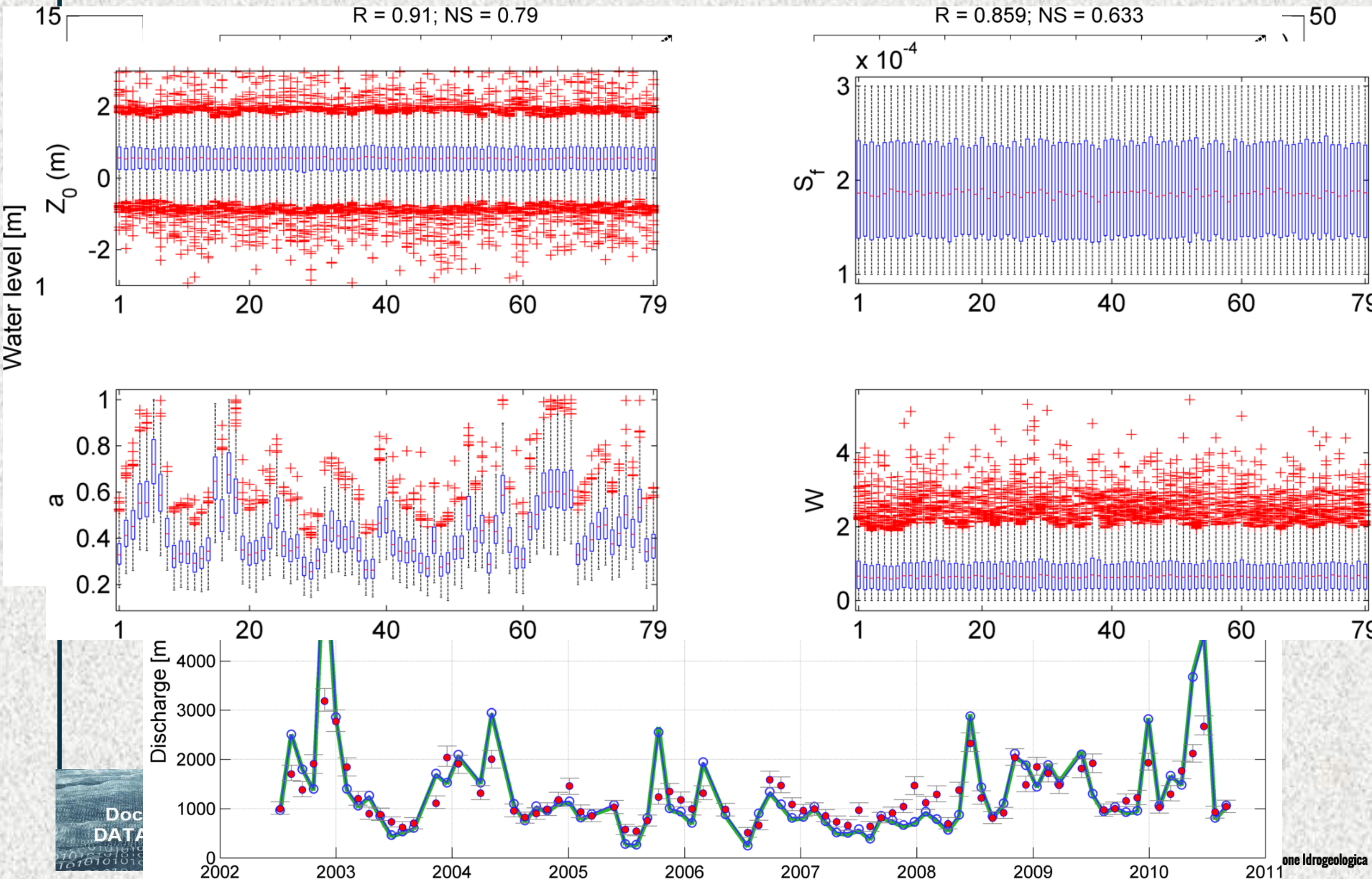




RESULTS (Satellite Observations)

1000 realizations

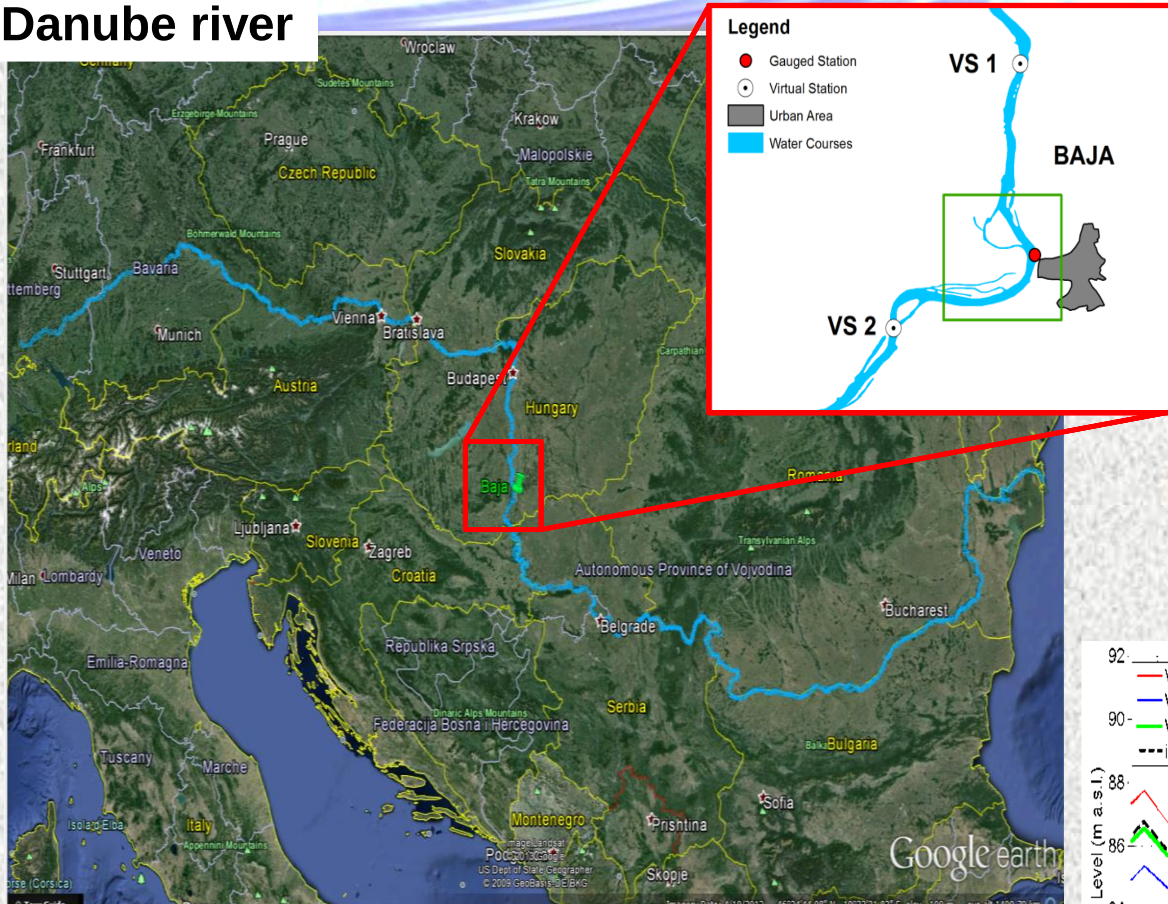
Pontelagoscuro



one Idrogeologica

MODIS + Altimeter

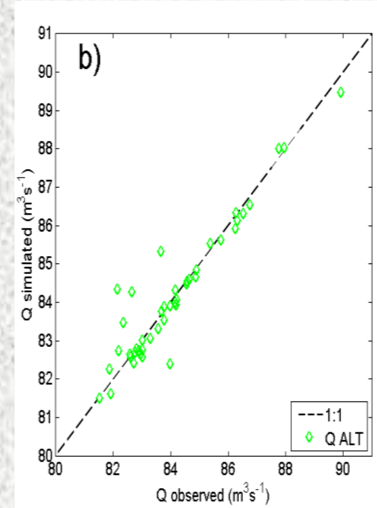
Danube river

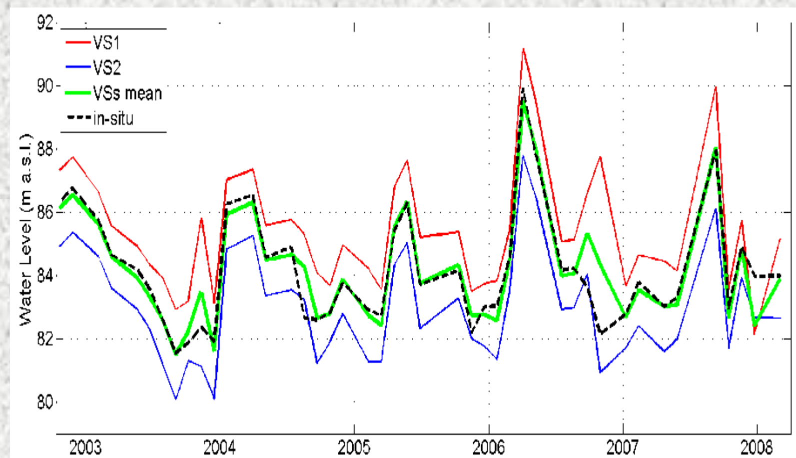


r=0.94

R^2=0.89

NS=0.88



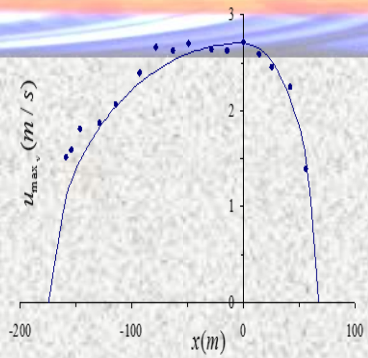


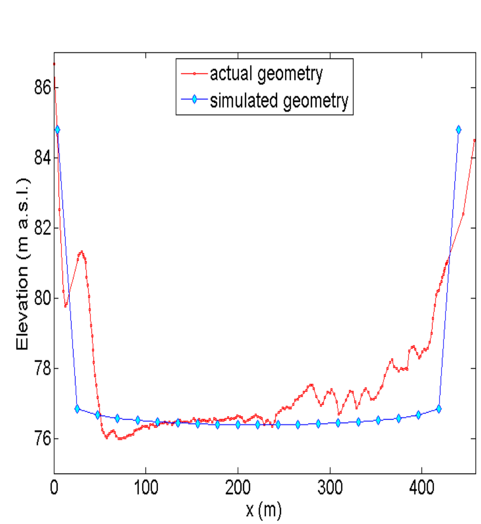
SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

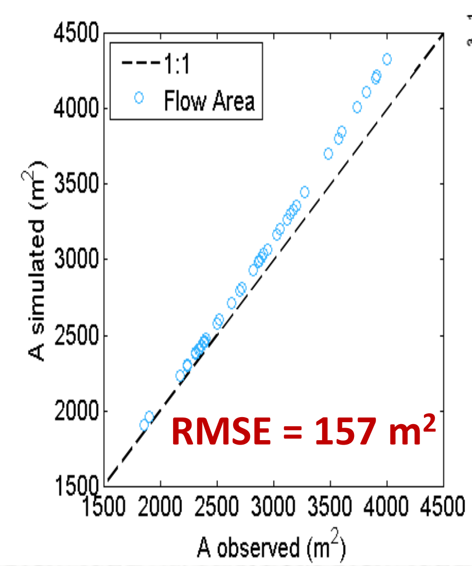
MODIS + Altimeter

Danube river

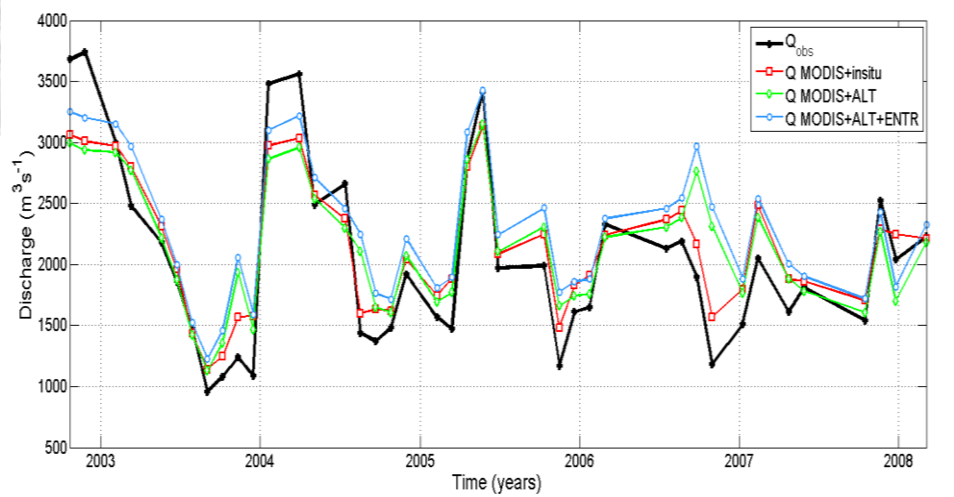
In the case of unknown geometry the entropy model for bathymetry (Moramarco et al., 2013, JoH) can be used.







Qsim (MODIS + altimetry) vs Qobs (Baja)



Q errors	RMSE (m^3s^{-1})	r
$Q_{MODIS+insitu}$	296	0.96
$Q_{MODIS+ALT+Bathymetry\ Survey}$	397	0.88
$Q_{MODIS+ALT+ENTR}$	441	0.88

Conclusions

- The entropy theory may be conveniently adopted to estimate discharge at river site by leveraging ground and satellite observations in terms of stage and maximum surface velocity
- The analysis has shown the potential of entropy model to estimating the discharge in river sites even in absence of bathymetry
- The capability of Radiometers (MODIS, MERIS) to estimate mean flow velocity can be employed together with Altimeter for discharge assessment. These aspects may be of particular interest for Sentinel 3 and SWOT missions for which significant improvements are expected in terms of vertical accuracy and spatial and temporal resolution.

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-Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) Coupling MODIS and radar altimetry data for discharge estimation in poorly *in Applied Earth Observations and Remote Sensing,*

THANK YOU