Hungarian Space Office

SZENT ISTVÁN UNIVERSITY

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→ 7th ADVANCED TRAINING COURSE ON LAND REMOTE SENSING

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RIVER DISCHARGE AND LAKE VOLUME VARIATION USING RADAR ALTIMETRY AND IMAGING SENSORS

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Research Institute for Geo-Hydrological Protection
National Research Council

Summary

- ***Satellite data: Radar altimetry***
  - ***Principles***
  - ***Missions and technologies***
  - ***Applications***
  - ***Data access and toolboxes***

- ***Satellite data: Optical and multispectral sensors***
  - ***Missions and technologies***
  - ***Data access***

- ***Hydrological Applications***
  - ***River Discharge (from altimetry, from multispectral sensors, from multi-mission)***
  - ***Lake Volume variation (from multi-mission)***

Summary

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- *Satellite data: Optical and multispectral sensors*
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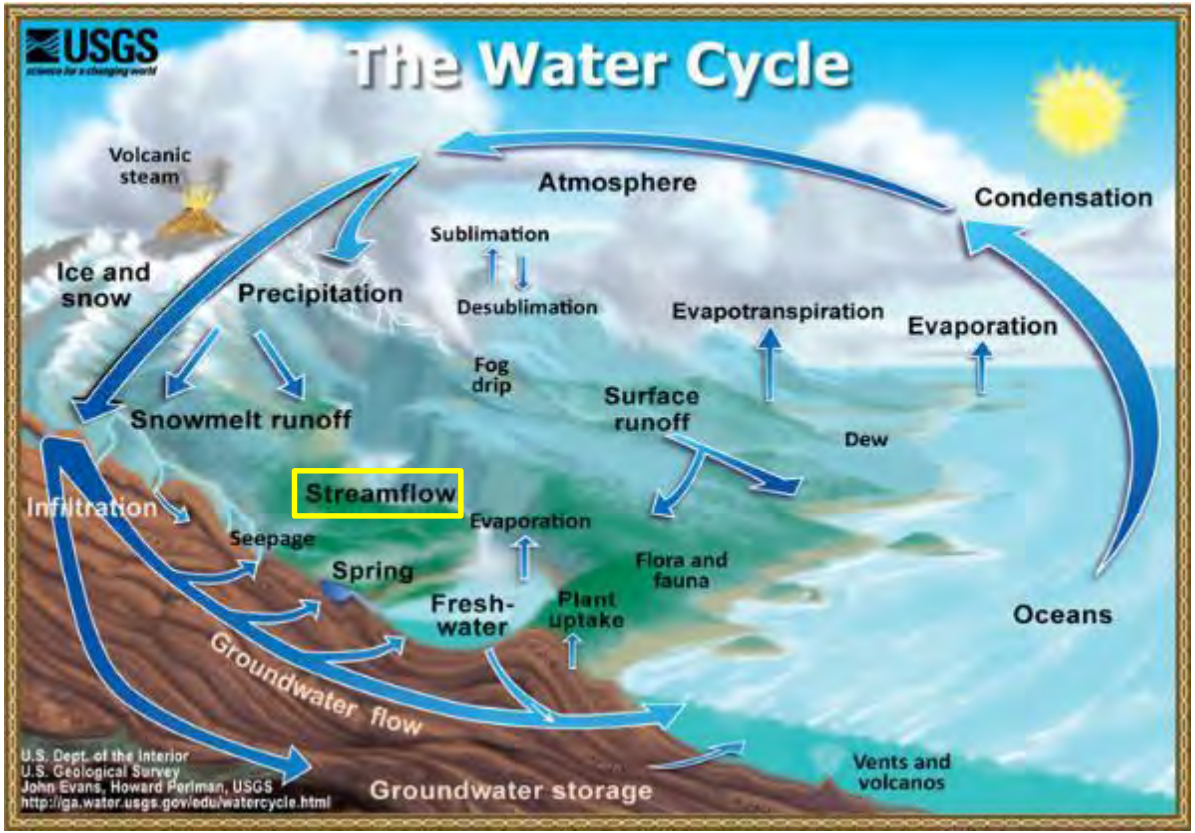
- ***Hydrological Applications***
  - ***River Discharge (from altimetry, from multispectral sensors, from multi-mission)***
  - *Lake Volume variation (from multi-mission)*

River Discharge Definition and Measurements

River discharge is one of ECVs selected by GCOS as an important variable in driving the climate system.

- Key variable in the water cycle
- Essential for water resources management (floods and droughts)
- Necessary for the flood prediction (hydraulic risk)
- Help for identifying and adapting potential effects of climate change.
- Important for the reduction of the ocean salinity and the thermohaline circulation.

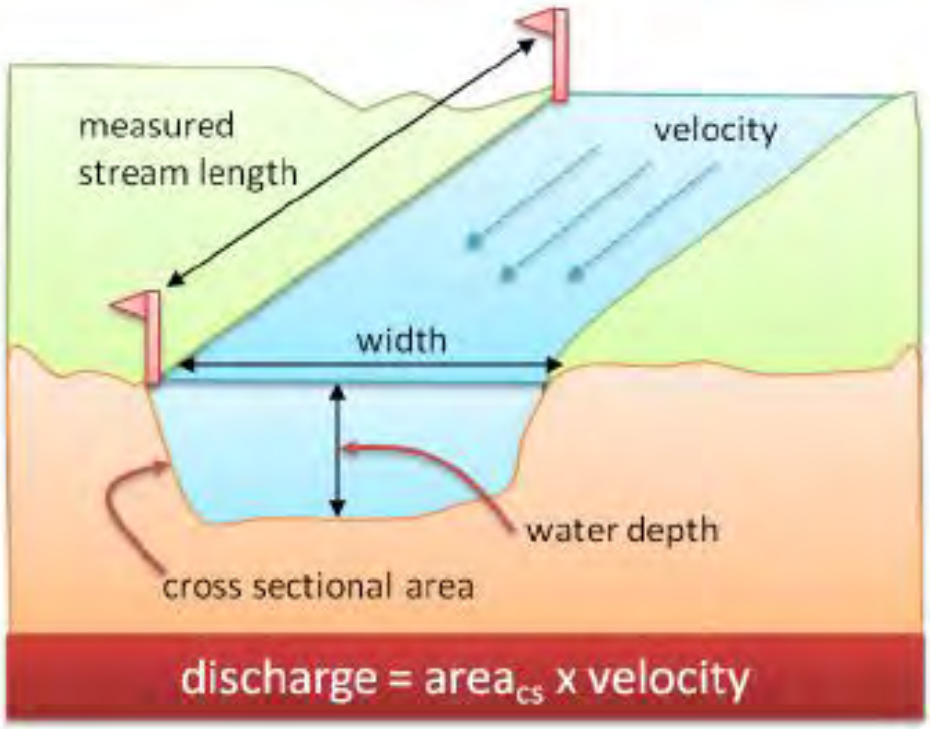


River Discharge Definition and Measurements

- **River discharge** is defined as the volume of water flowing through a river channel cross-section per unit of time.

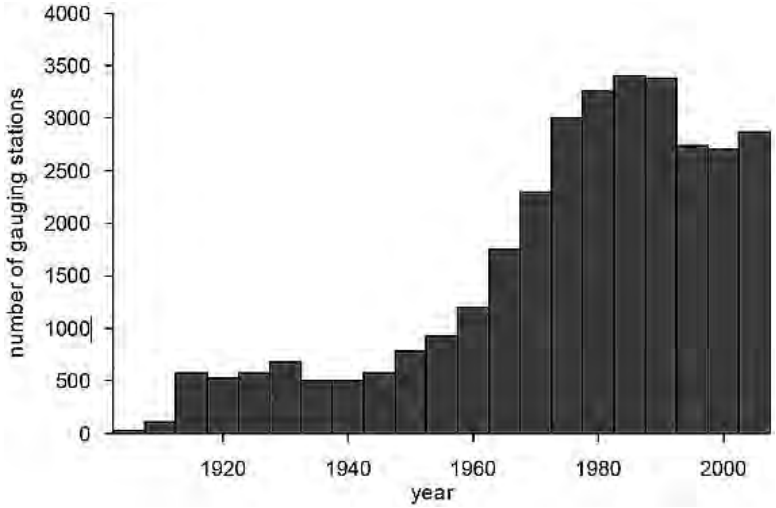
- It can also be expressed as the flow velocity times the cross-sectional flow area.

- Its estimation **is not direct** and, traditionally, it consists of in-situ measurements of water **flow velocity vertical profiles and depth**, at different measuring points across the river and the **water level**.

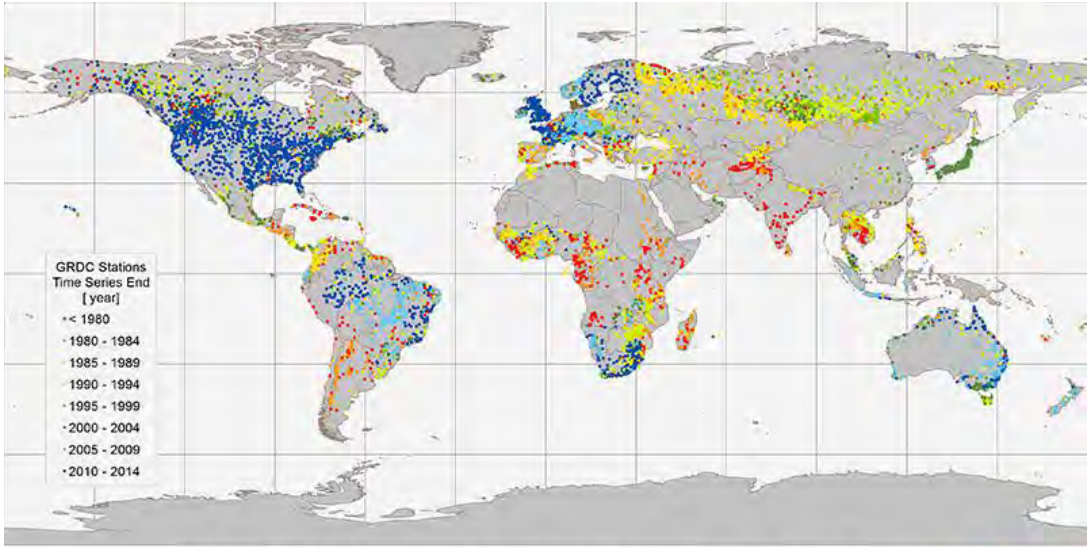


River Discharge Monitoring Network

- Not representative of the global water flow
- High costs of installation and maintenance
- Not uniformly distributed in the world
- Inaccessibility of many remote areas
- Problems of data sharing among neighbouring countries
- Reduction of hydrometric stations



Mishra and Coulibaly, 2009 Reviews of Geophysics



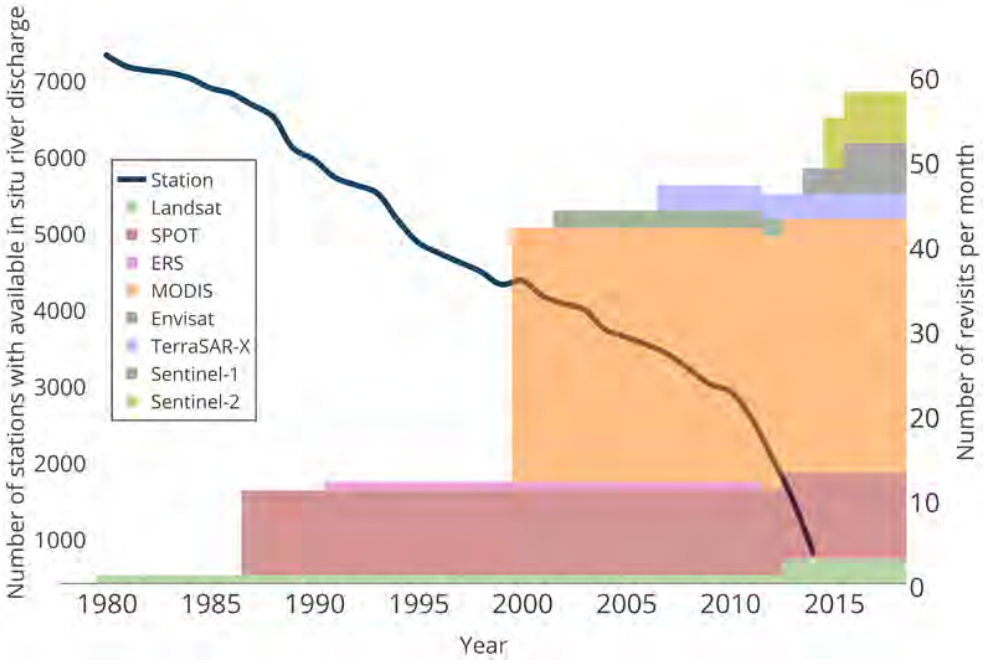
8962 stations with monthly data discharge data, including data derived from daily data (Status: 20 December 2013)
Koblenz: Global Runoff Data Centre, 2014.

River Discharge Monitoring Network

Decline in the number of stations with available in-situ river discharge according to Global Runoff Data Center (GRDC)

and

increase of satellite observations during last three decades



(Elmi, 2015)

River Discharge from remote sensing

The estimation of river discharge by satellite data is carried out through the use of

- radar altimetry
- passive microwave and optical sensors

The availability of new sources of data motivates the development of new procedures for river discharge estimation adapting the traditional approaches to the use of remote sensing technologies.

Generally, the approaches for the river discharge estimation are based on hydraulic laws, that we will classify in two types:

- hydraulic models
- rating curves (either for Altimetry or for optical sensors)

SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from radar altimetry

The water level measurements provided by radar altimetry in the continental environment represent a valid support for hydraulic modeling. Approaches can vary from employing of simple to complex hydraulic models, going from steady uniform flow to unsteady flow.

Complex hydraulic models *(unsteady flow)*

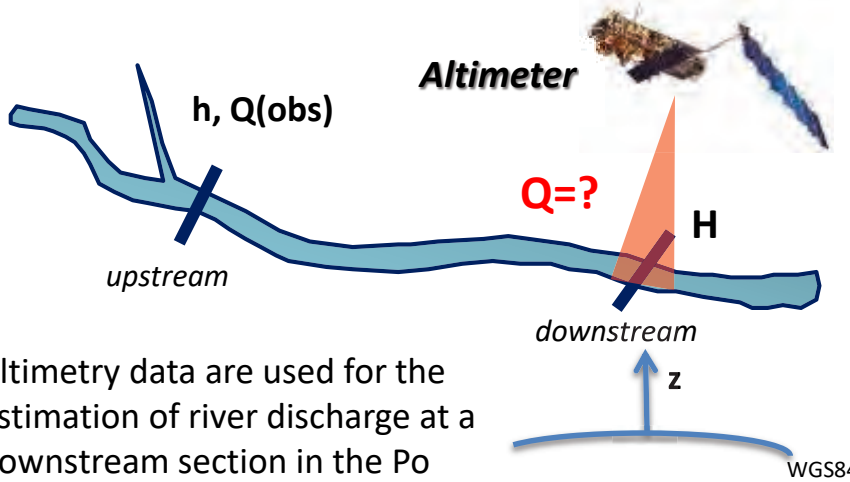
Simple hydraulic model *(steady flow)*

Simplest hydraulic model *(steady, uniform flow)*

SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

River Discharge from radar altimetry

Tarpanelli A., Barbetta S., Brocca L., Moramarco T. (2013) River discharge estimation by using altimetry data and simplified flood routing modeling. *Remote Sensing, 5*(9), 4145-4162.



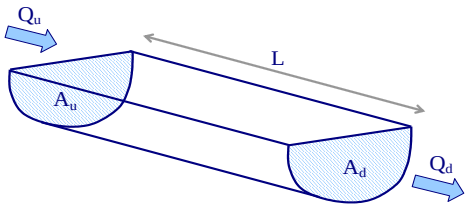
Altimetry data are used for the estimation of river discharge at a downstream section in the Po river.

SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

Two **simple hydraulic models** have been used:

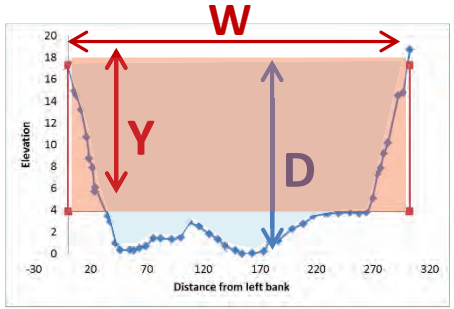
1) RCM (Moramarco et al., 2001, J. Hydrol. Eng)

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



Q = discharge
T_L = wave travel time
A = mean flow area
t = time
α, β = parameters
u = upstream
d = downstream

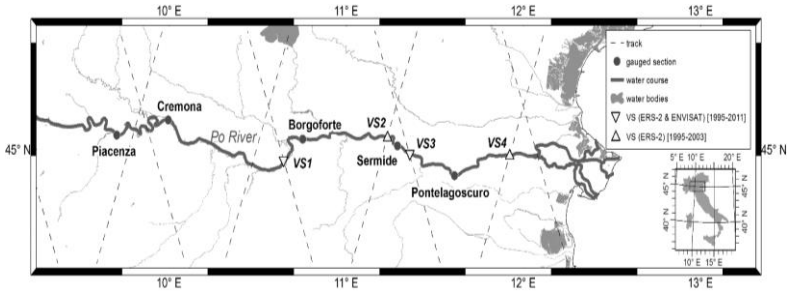
2) BJE (Bjerklie et al., 2003, J. Hydrol)

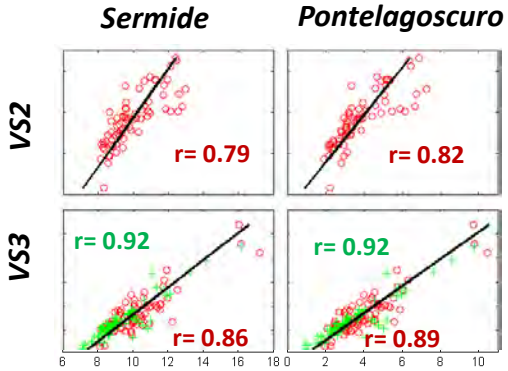


$$Q = 7.22 \cdot W^{1.02} \cdot Y^{1.74} \cdot S^{0.35}$$

W = mean width
Y = mean height
S = slope

River Discharge from radar altimetry



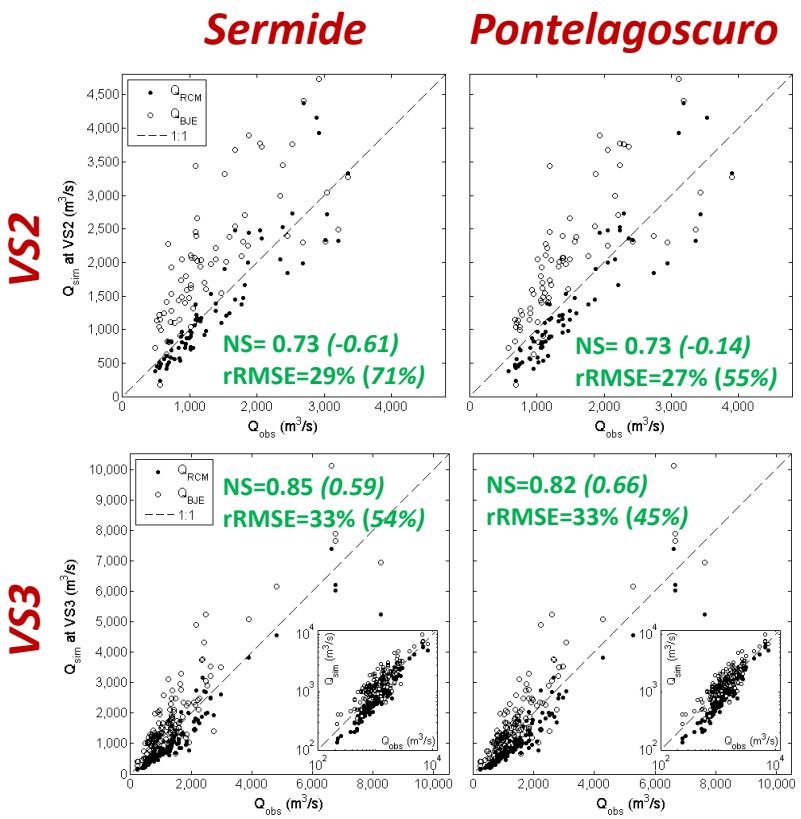


*Comparison in terms of **water level** between VS2 and VS3 (from ERS-2 and ENVISAT) with in situ stations*

*Comparison in terms of **simulated discharge**:*

RCM: Moramarco et al., 2001

BJE: Bjerklie et al., 2003

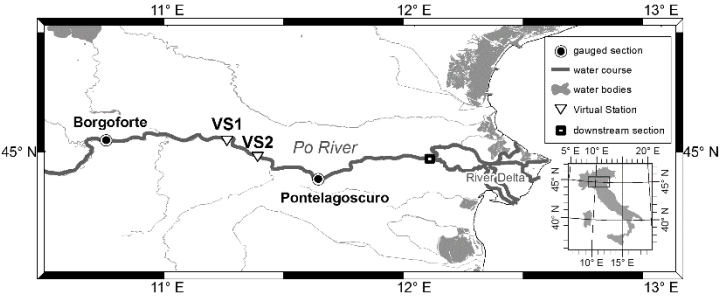


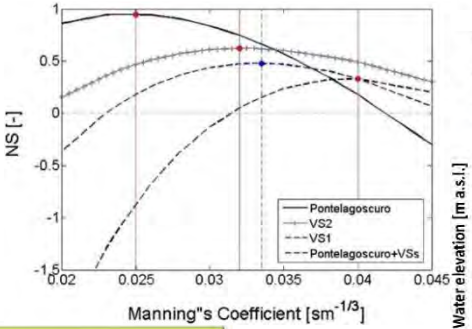
SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

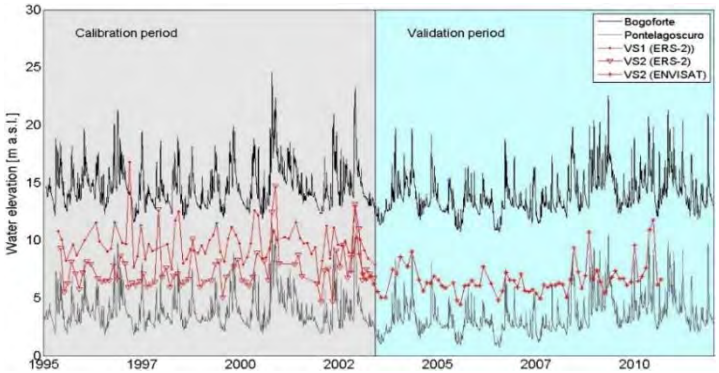
River Discharge from radar altimetry

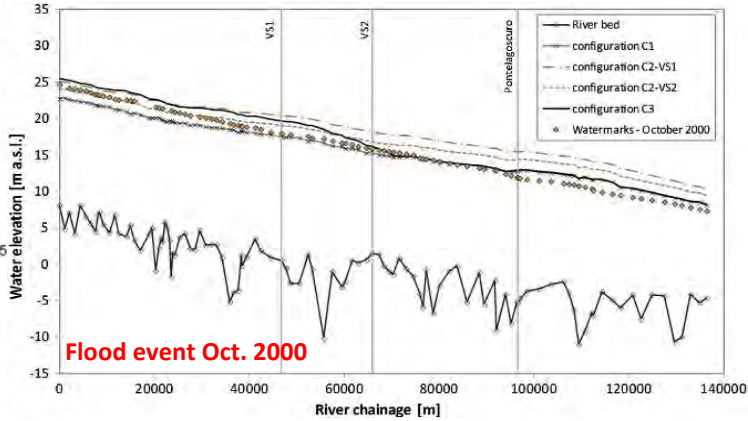
Domeneghetti A., Tarpanelli A., Brocca L., Barbetta S., Moramarco T., Castellarin A., Brath A. (2014) The use of remote sensing-derived water surface data for hydraulic model calibration. *Remote Sensing of Environment*, 149, 130-141.

Altimetry data could be efficiently used to calibrate the friction coefficient that describes the roughness conditions along the main channel of a quasi-2D dimensional hydraulic model (HEC-RAS). The integration of the satellite datasets with traditional in-situ observations fosters the trustworthiness and reliability of the hydraulic model.









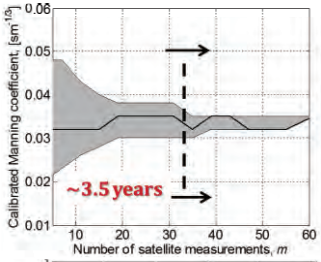
SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

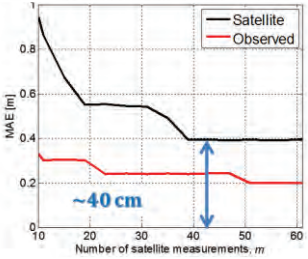
River Discharge from radar altimetry

Domeneghetti et al., Hydraulic model calibration by using satellite altimetry: comparison of different products, in preparation.

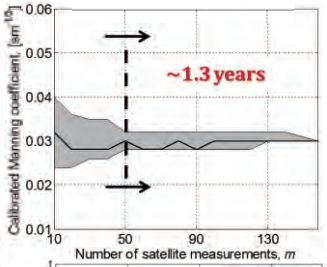
We also investigated the performance and the accuracy of different satellite altimetry products.

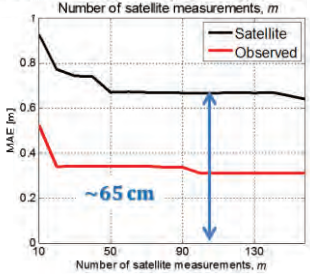
ENVISAT (track 22)



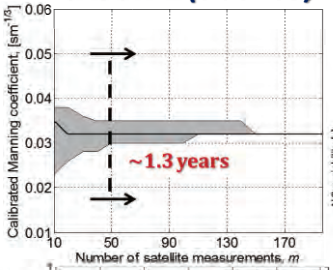


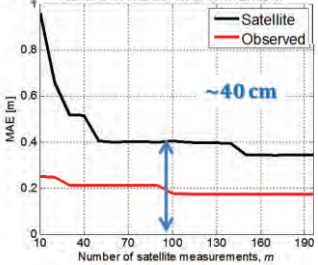
T/P (track 85)

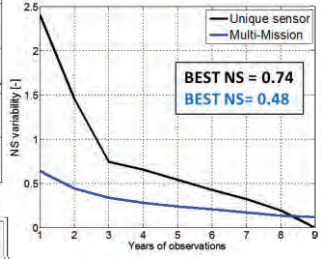


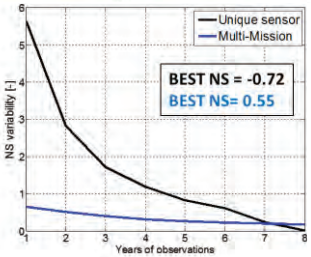


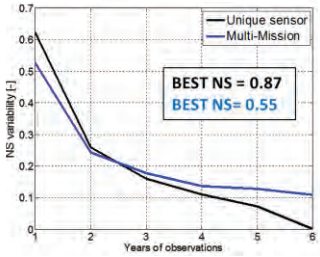
JASON-2 (track 85)

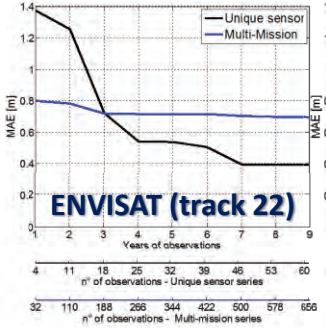




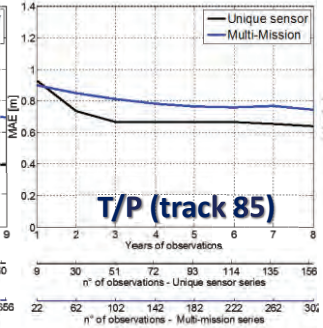




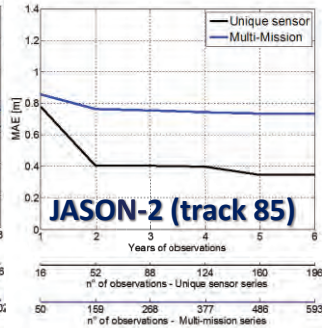




ENVISAT (track 22)



T/P (track 85)



JASON-2 (track 85)

SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

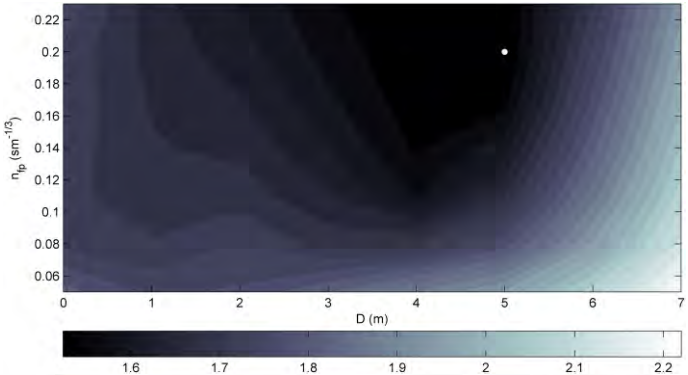
River Discharge from radar altimetry

Yan K., Tarpanelli A., Balint G., Moramarco T., Di Baldassarre G. (2014) Exploring the potential of radar altimetry and SRTM Topography to Support Flood Propagation Modeling: the **Danube Case Study**. *Journal of Hydrologic Engineering* 20(2).

Radar altimetry along with SRTM topography is used in supporting **flood level predictions** in data-poor areas. 2-D hydraulic model (LISFLOOD-FP) is calibrated (in terms of roughness coefficient and depth of the section), by using the water level of the 2006 flood event and validated with the 2007 flood event.

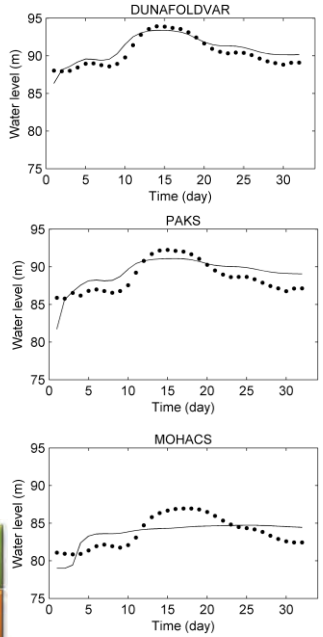
Calibration:

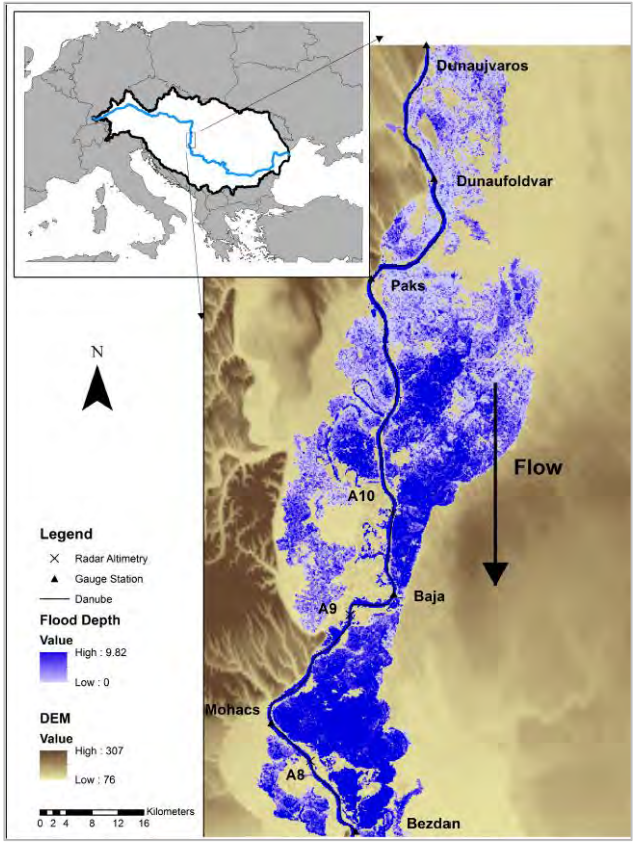
2006 FLOOD EVENT



Validation:

2007 FLOOD EVENT

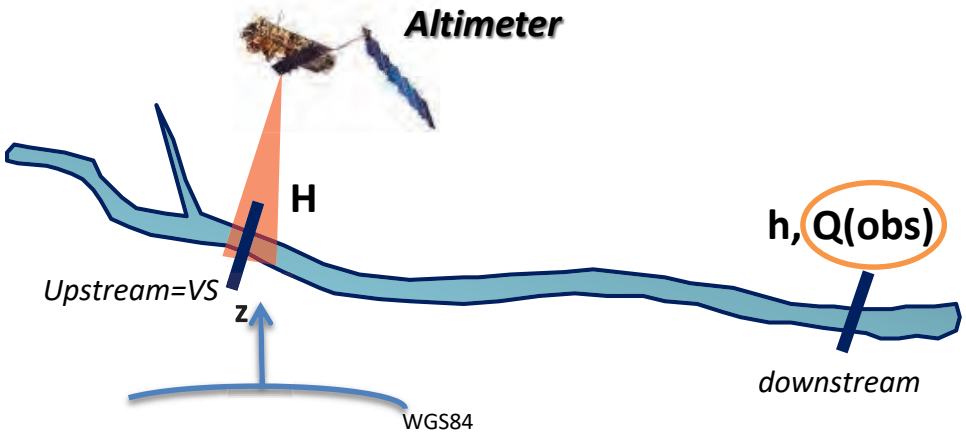




SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

River Discharge from radar altimetry

The **rating curve** is a functional law linking the water stage to the discharge. In the majority of the studies, a rating curve is developed considering the water level retrieved by satellite altimetry and the discharge observed to the nearest ground sections.

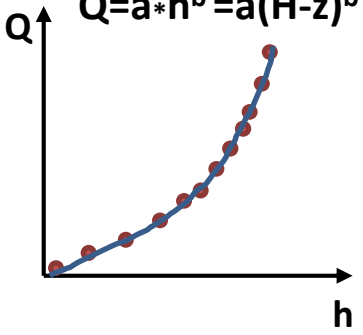


LARGE RIVERS	SAT	STUDY
Ob'	T/P	Kouraev et al. 2004, RSE
Amazon	T/P	Zakharova et al. 2006, CRG
Brahmaputra	T/P	Papa et al. 2010, JGR
Ganga	ERS-2	
Brahmaputra	JASON-2	Papa et al. 2012, JGR
Ganga		
Chad	T/P	Coe et Birkett, 2004, WRR
Zambesi	ENVISAT	Michailovsky et al. 2012, HESS

H is river surface height above WGS84

z is height of the river bottom above WGS84

$$Q = a * h^b = a(H-z)^b$$

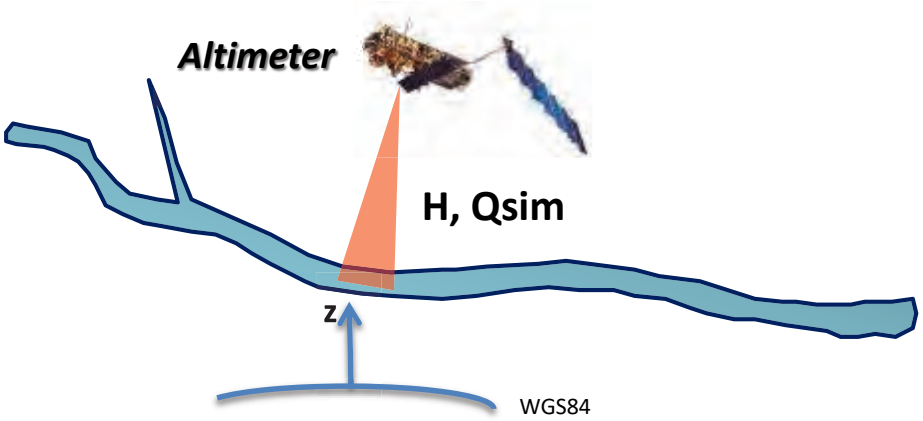


SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from radar altimetry

The **rating curve** is a functional law linking the water stage to the discharge. In the majority of the studies, a rating curve is developed considering the water level retrieved by satellite altimetry and the discharge observed to the nearest ground sections.

If in-situ discharges are not available, the water level is linked to the discharge simulated through rainfall-runoff models (taking in account other variables as rainfall, soil moisture, etc.).

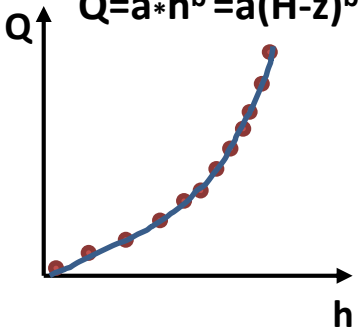


RIVERS	SAT	STUDY
Negro	T/P ENVISAT	Leon et al. 2006, JoH
Branco	ENVISAT	Getirana et al. 2009, JoH
Branco	ENVISAT	Getirana et al. 2013, JoH
Amazon	ENVISAT JASON-2	Paris et al. 2016, WRR

H is river surface height above WGS84

z is height of the river bottom above WGS84

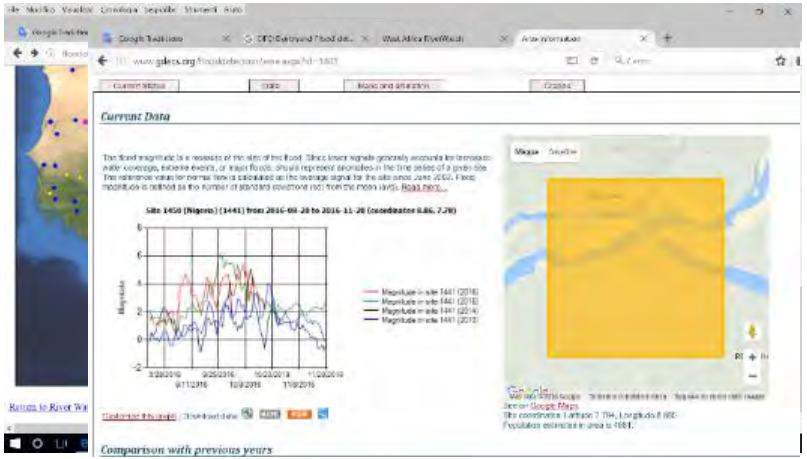
$$Q=a*h^b=a(H-z)^b$$



SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

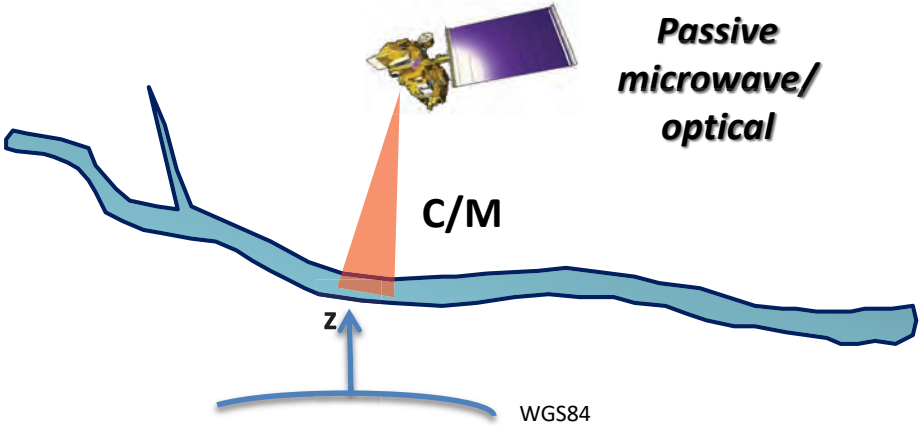
River Discharge from imaging sensors

Extending the concept of **rating curve**, a functional law can be expressed between the discharge and the signal derived by passive microwave or optical sensors.

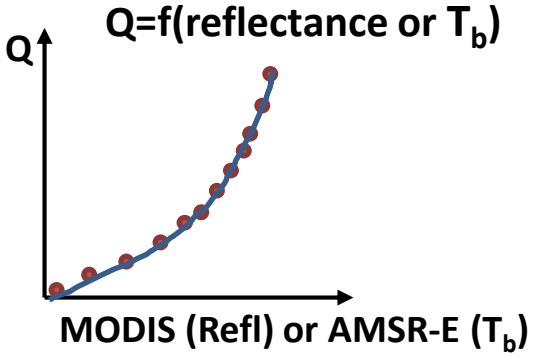


Global Flood Detection System – DFO

http://www.dartmouth.edu/~floods



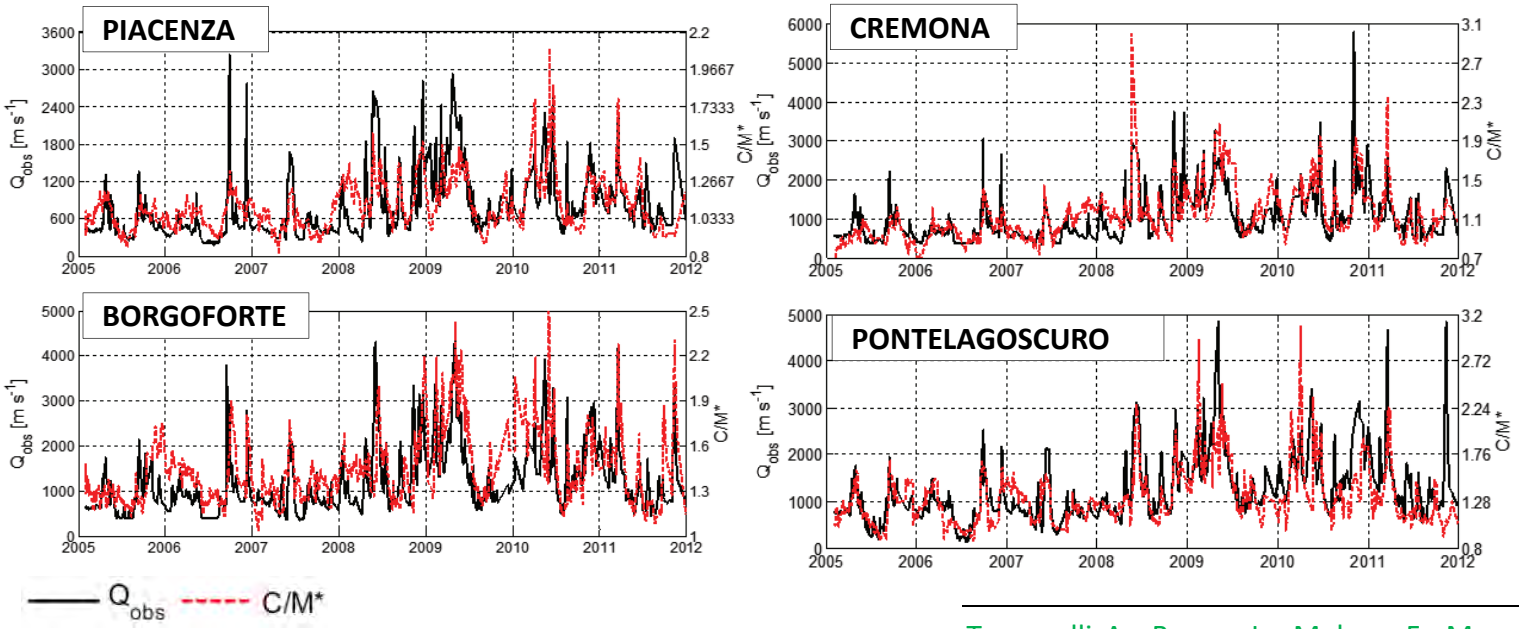
Tb is the brightness temperature



SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

River Discharge from imaging sensors

PO RIVER (ITALY)



Coefficient of correlation

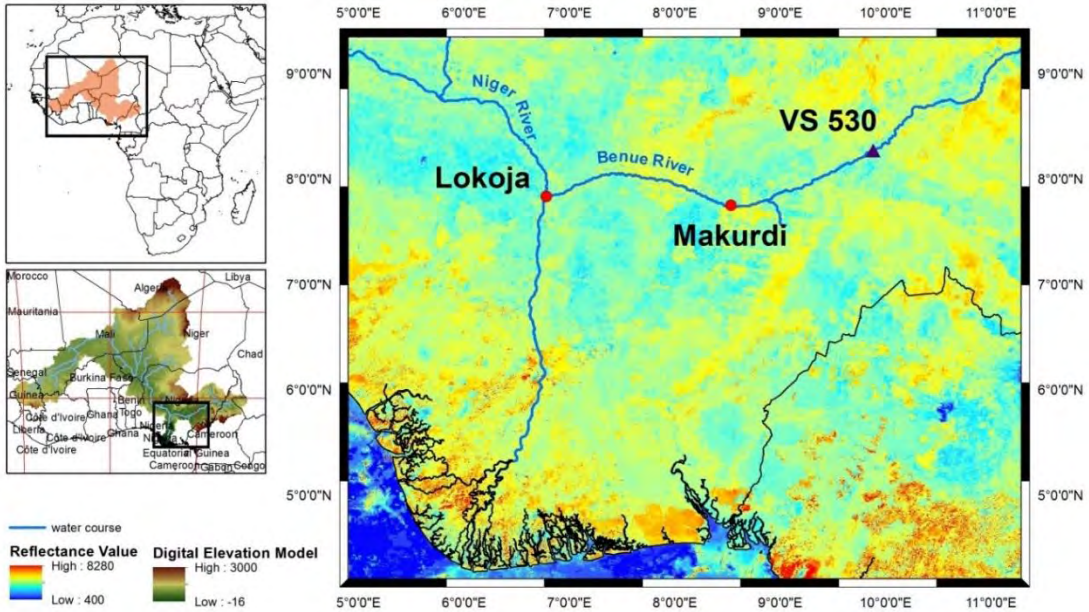
Piacenza	**R = 0.65**
Cremona	**R = 0.75**
Borgoforte	**R = 0.66**
Pontelagoscuro	**R = 0.73**

SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

Tarpanelli A., Brocca L., Melone F., Moramarco T., Lacava T., Faruolo M., Pergola N., Tramutoli V. (2013) Toward the estimation of river discharge variations using MODIS data in ungauged basins. *Remote Sensing of Environment*, 136, 47–55.

River Discharge from imaging sensors

NIGER and BENUE RIVERS (NIGERIA)



SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

Tarpanelli A., Amarnath G., Brocca L., Massari C., Moramarco T. (2017). Discharge estimation and forecasting by MODIS and altimetry data in Niger-Benue River. *Remote Sensing of Environment*, 195, 96-106.

River Discharge from imaging sensors

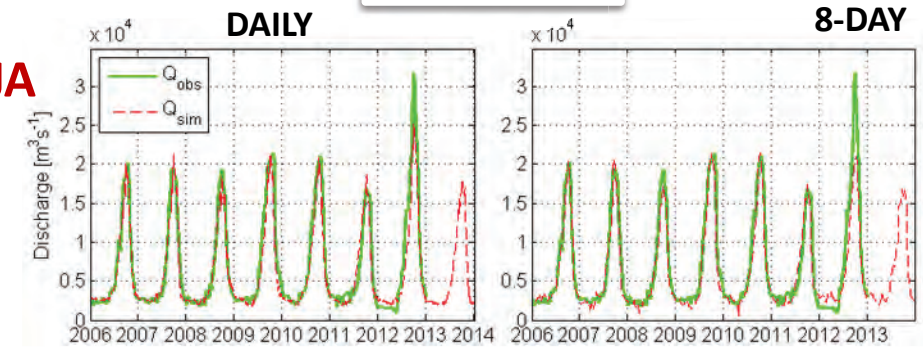
NIGER and BENUE RIVERS (NIGERIA)

ANOMALIES	CORR
LOKOJA (DAILY)	0.72
LOKOJA (8-DAY)	0.69
MAKURDI (DAILY)	0.77
MAKURDI (8-DAY)	0.72

TOTAL DISCHARGE	CORR
LOKOJA (DAILY)	0.99
LOKOJA (8-DAY)	0.98
MAKURDI (DAILY)	0.98
MAKURDI (8-DAY)	0.98

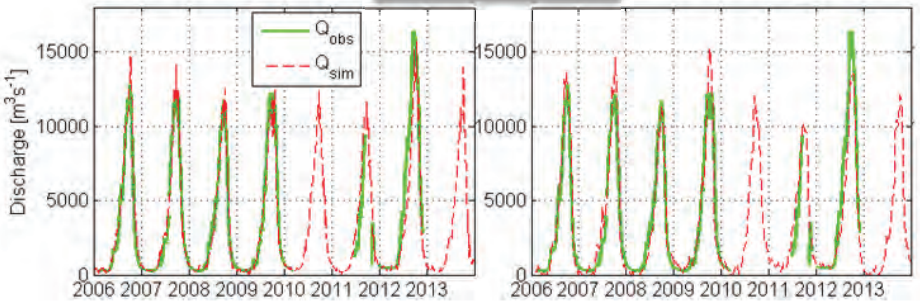
LOKOJA

msc r=0.95



MAKURDI

msc r=0.97



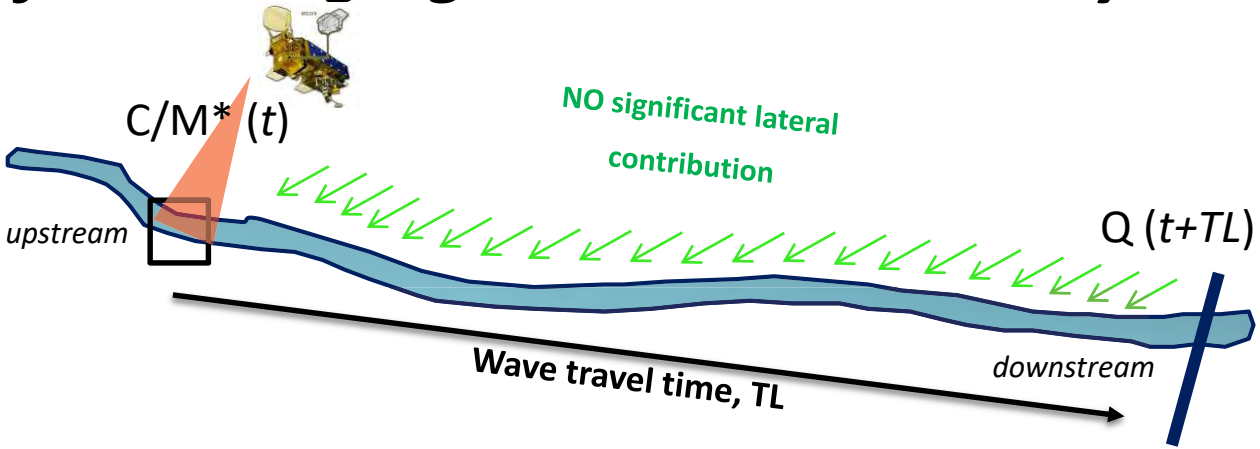
SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

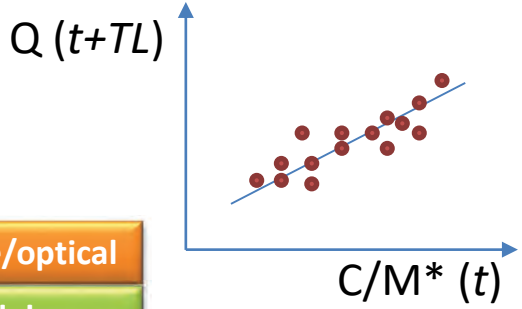
River Discharge from imaging sensors & altimetry

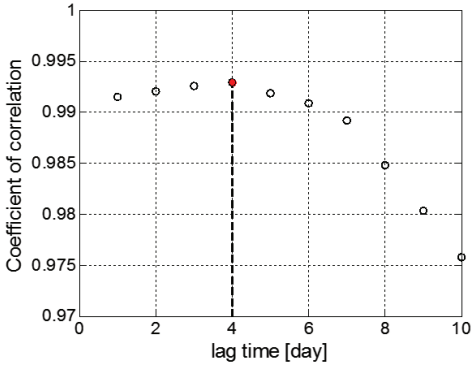
FORECASTED DISCHARGE

The observation acquired some days before at an upstream section is informative of the downstream discharge.

It is plausible to suppose that the discharge at the upstream section is proportional to the one that flows at the gauged station (assuming that the discharge contribution of the intermediate basin is proportional to the contribution at the upstream section). Therefore, by using the information acquired by satellite at an upstream section, the river discharge at downstream section with a forecast of some days (equal to the wave travel time) can be assessed.

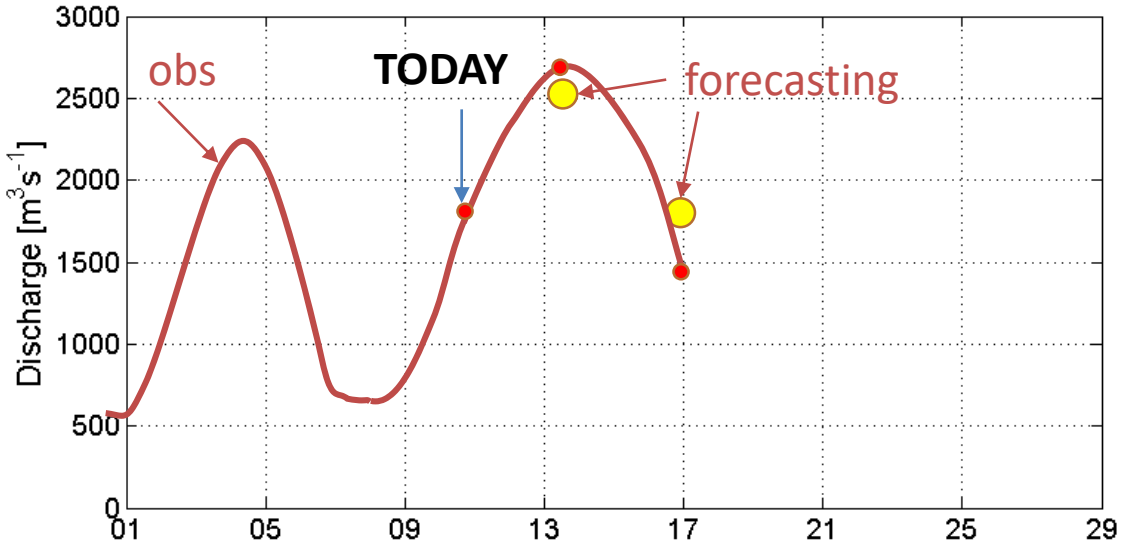






SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from imaging sensors & altimetry



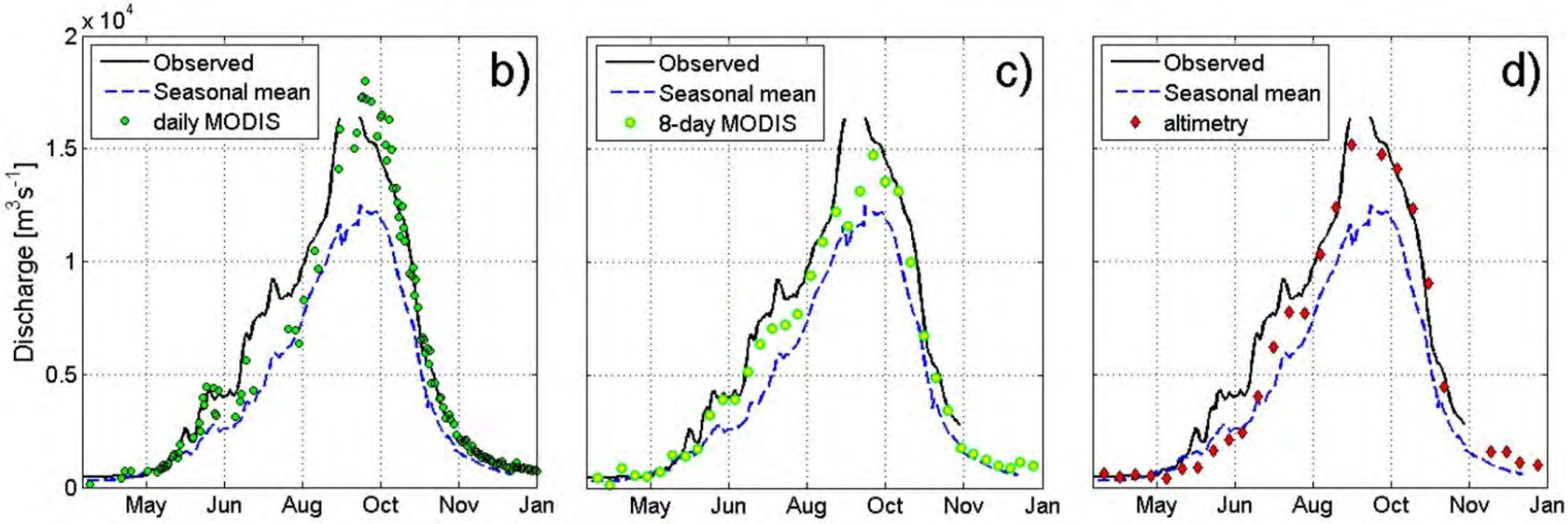
$$PC = 1 - \frac{\sum_1^T \left(Q_{obs}^t - Q_{sim}^t\right)^2}{\sum_1^T \left(Q_{obs}^t - Q_{obs}^{t-TL}\right)^2}$$

Persistent coefficient, PC compares the prediction of the forecast model with the one obtained by the no-model by assuming that the forecast coincides with the most recent observed value.

PC = 0 ÷ 1

SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

River Discharge from imaging sensors & altimetry



SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

Product	r	PC	N°	PC (2012)
ALTIMETRY	0.965	0.59	40	0.55
DAILY (AQUA)	0.991	0.53	854	0.55
8-DAY (AQUA)	0.988	0.83	237	0.10

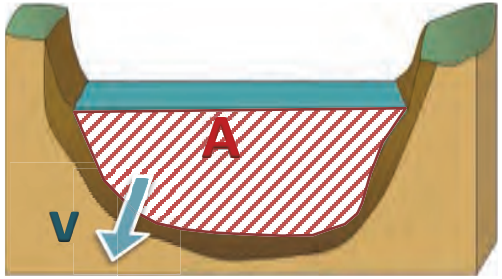
River Discharge from imaging sensors & altimetry

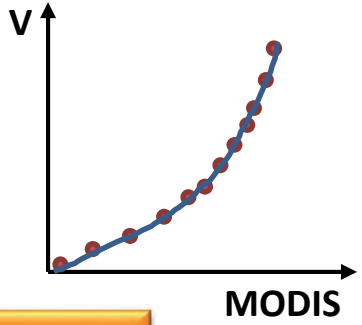
The discharge is inferred as the product of the mean flow velocity by the flow area. The flow velocity is derived by imaging sensors (MODIS, MERIS, etc.) images, whereas the flow area is estimated considering the water levels derived by radar altimetry data and the cross section geometry that can be known from bathymetry surveys. If we don't know the geometry of the cross section different approaches can be used for its estimation.

$$Q = v \cdot A$$

Flow velocity derived by multispectral/ optical sensors

Flow Area





A=f(water level, geometry)

derived by radar altimetry observation

Known (Topographic survey)

unknown

(Moramarco et al., 2013 – Journal of Hydrology)

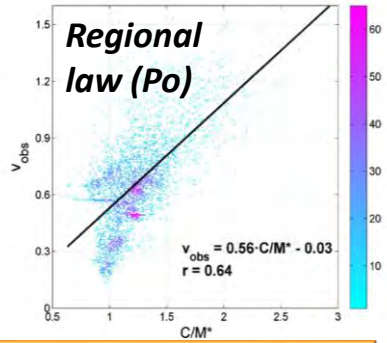
SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

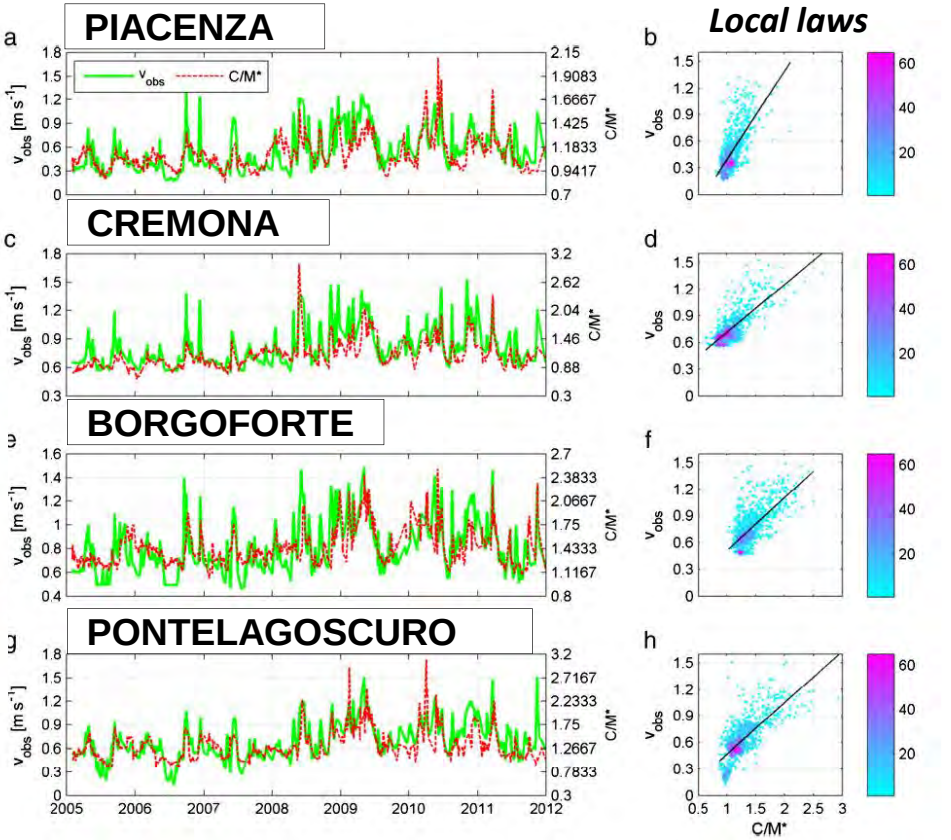
River Discharge from imaging sensors & altimetry

Tarpanelli A., Brocca L., Melone F., Moramarco T., Lacava T., Faruolo M., Pergola N., Tramutoli V. (2013) Toward the estimation of river discharge variations using MODIS data in ungauged basins. *Remote Sensing of Environment*, 136, 47–55.

As for the discharge, also the flow velocity can be estimated by the signal derived by imaging data (i.e. MODIS). Local laws link the reflectance values with in-situ velocity. If all the data are joined together, regional law can be derived to estimate flow velocity by satellites information.

	Local low		Regional law	
	RMSE	NS	RMSE	NS
Piacenza	0.17	0.45	0.21	0.2
Cremona	0.11	0.59	0.22	−0.46
Borgoforte	0.15	0.46	0.15	0.46
Pontelagoscuro	0.16	0.55	0.16	0.49

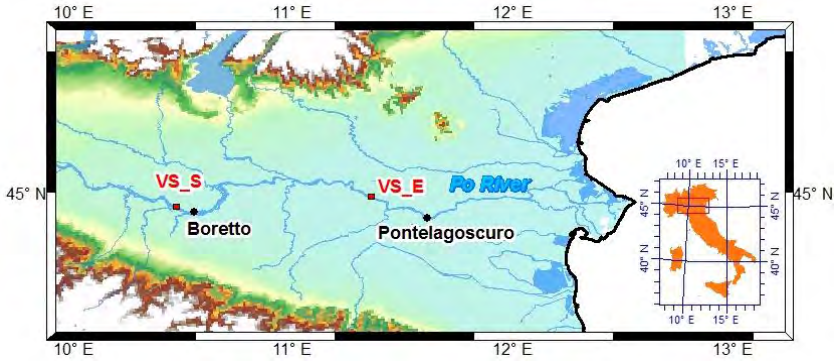




SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from imaging sensors & altimetry

Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) 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*, 8(1), 141-148.

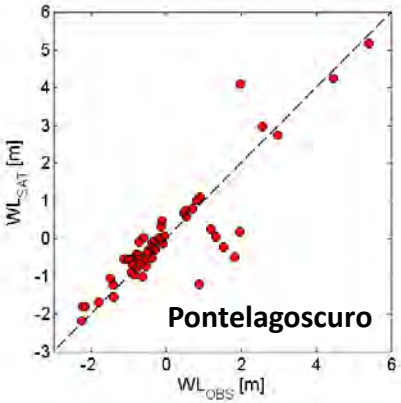


We selected two virtual stations where the satellites ENVISAT and SARAL overpass the river. The water level time series derived by altimetry are compared with the ones observed at the gauging stations of Boretto and Pontelagoscuro.

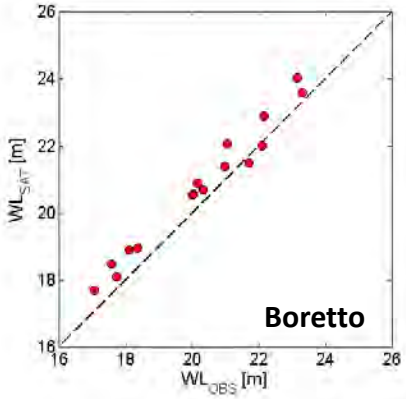
SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

WATER LEVEL COMPARISON

ENVISAT WL derived by "river&Lake" website



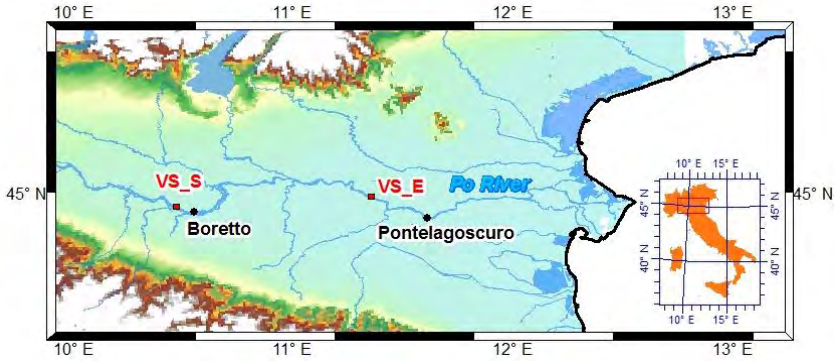
SARAL/Altika derived by "Hydroweb" website



WL ERRORS	ENVISAT vs PONTELAGOSCURO	SARAL vs BORETTO
R	0.89	0.99
RMSE [m]	0.70	0.61
RRMSE [%]	15	3

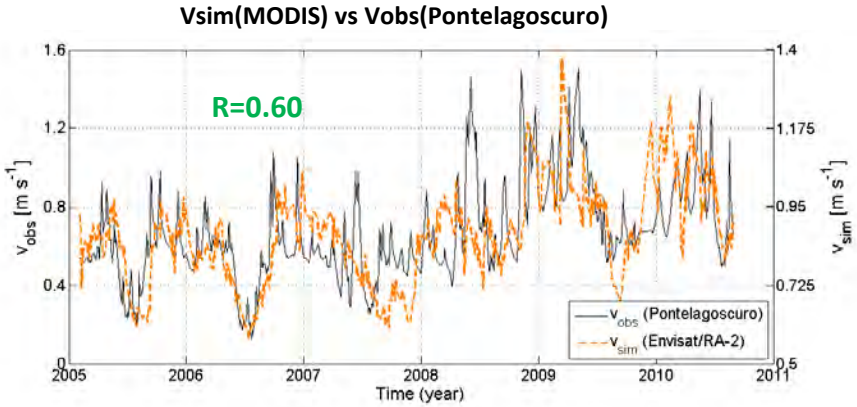
River Discharge from imaging sensors & altimetry

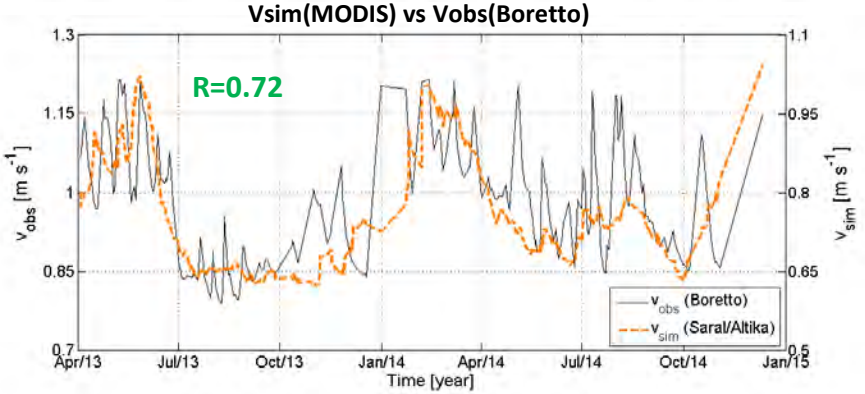
Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) Coupling MODIS and radar altimetry data for discharge estimation in poorly gauged river basin. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8(1), 141-148.



In correspondence of the altimetry track, we selected the MODIS images to derive the mean flow velocity (by using the regional law). The estimated velocity are compared with the ones observed at the gauging stations of Boretto and Pontelagoscuro.

SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

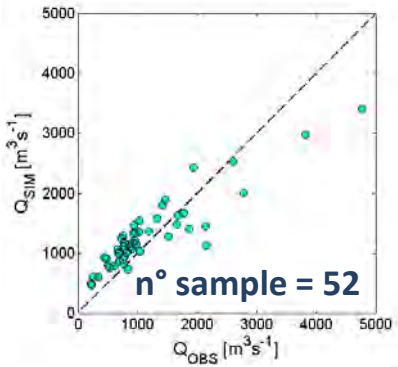


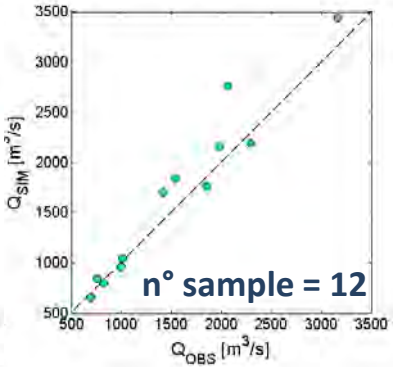


River Discharge from imaging sensors & altimetry

Tarpanelli A., Brocca L., Barbetta S., Faruolo M., Lacava T., Moramarco T. (2015) 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*, 8(1), 141-148.

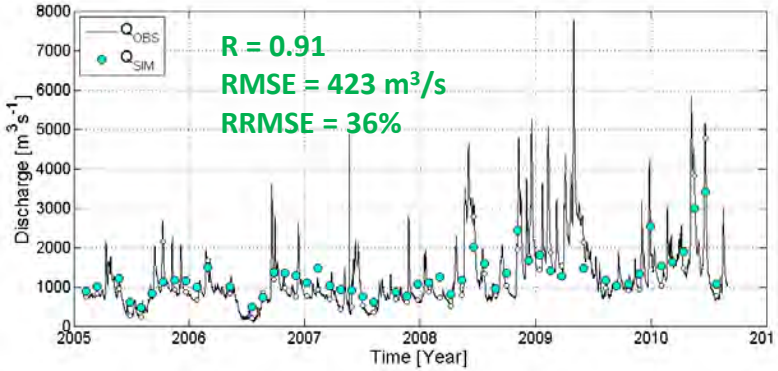
Supposed known the cross section, the river discharge is calculated as the product between flow velocity (from MODIS) and flow area (derived by altimetry water level).



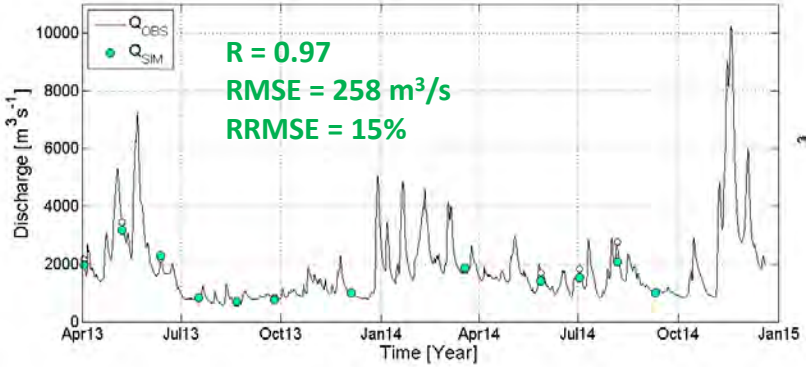


SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

Envisat + MODIS vs Pontelagoscuro



Saral + MODIS vs Boretto



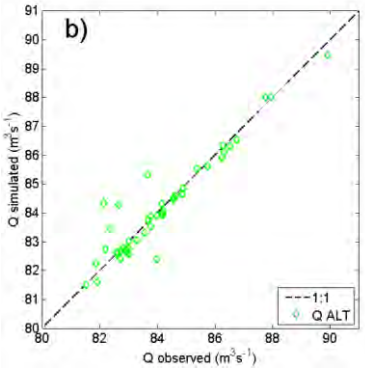
River Discharge from imaging sensors & altimetry

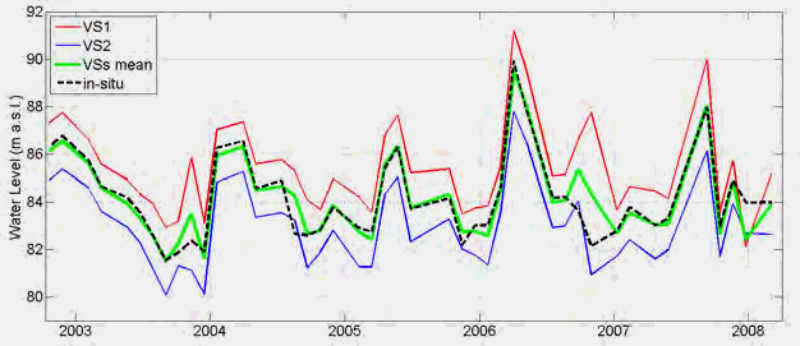
Danube river

r=0.94

R^2=0.89

NS=0.88



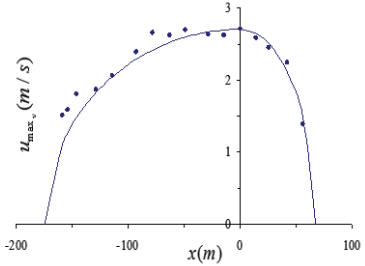


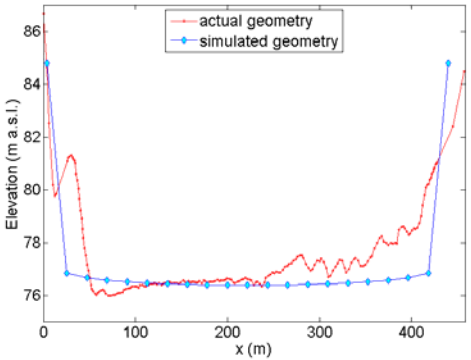
SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

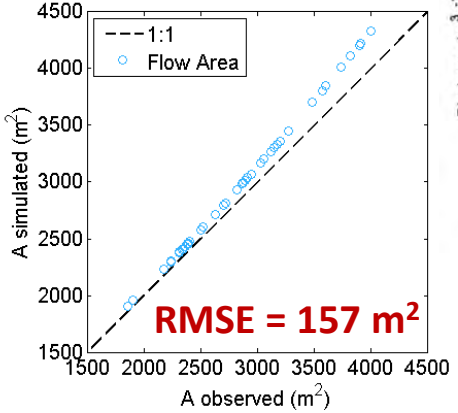
River Discharge from imaging sensors & altimetry

Danube river

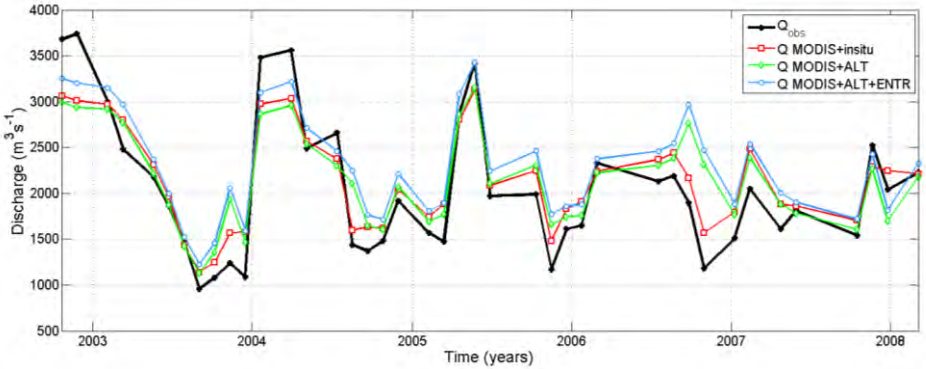
In the case of known geometry the entropy model for bathymetry (Moramarco et al., 2013, JoH) can be used.







Qsim (MODIS + altimetry) vs Qobs (Baja)

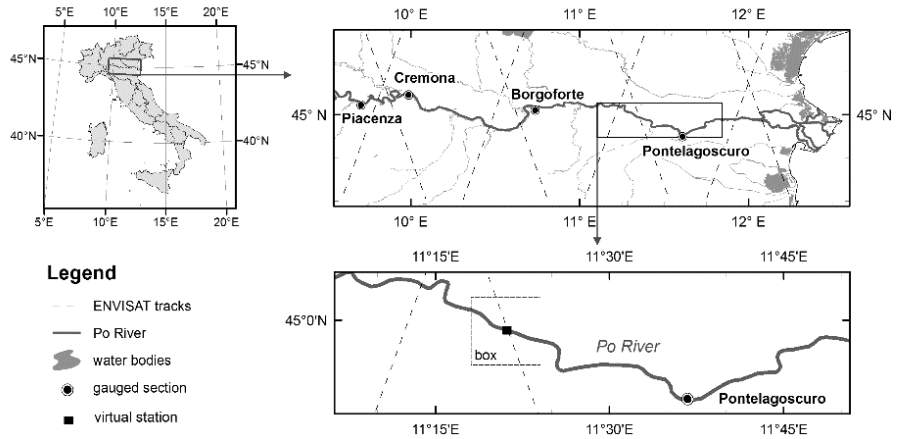


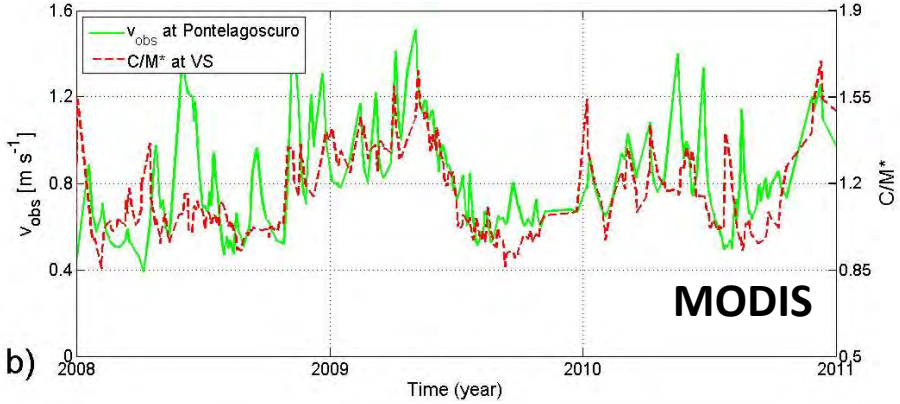
Q errors	RMSE (m^3s^{-1})	r
$Q_{MODIS+insitu}$	296	0.96
$Q_{MODIS+ALT+Bathymetry\ Survey}$	397	0.88
$Q_{MODIS+ALT+ENTR}$	441	0.88

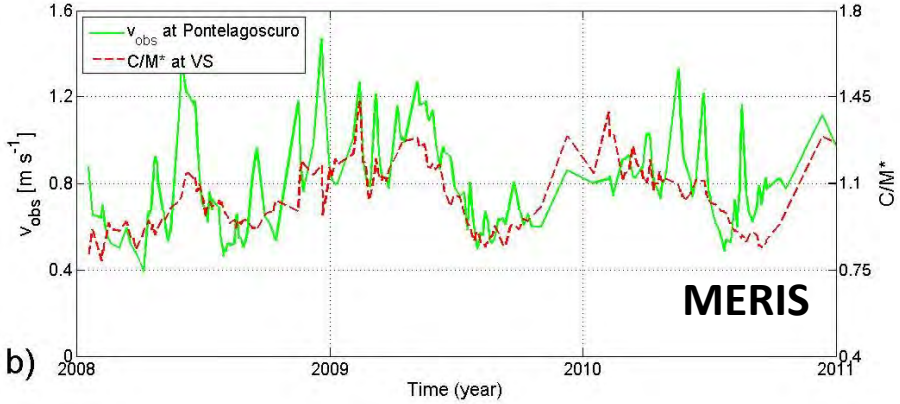
SENSORS	Altimeter	Passive microwave/optical
APPROACHES	Rating curve	Hydraulic models

River Discharge from imaging sensors & altimetry

Po river







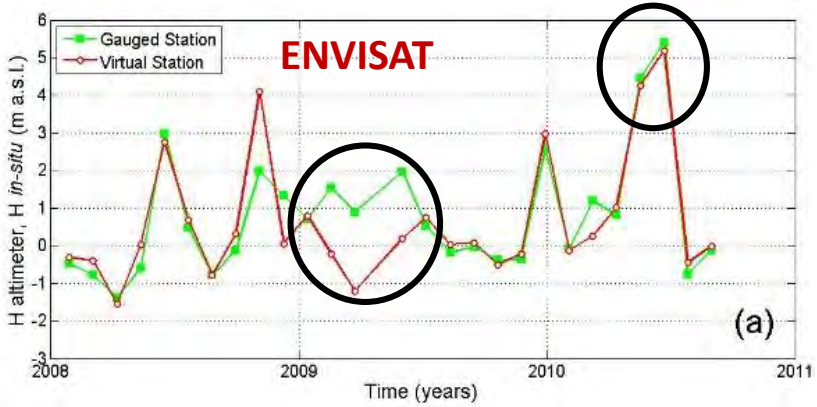
Another example is shown with MERIS data, in a comparison with MODIS for the estimation of river velocity at the gauging station of Pontelagoscuro and for the same period of three years.

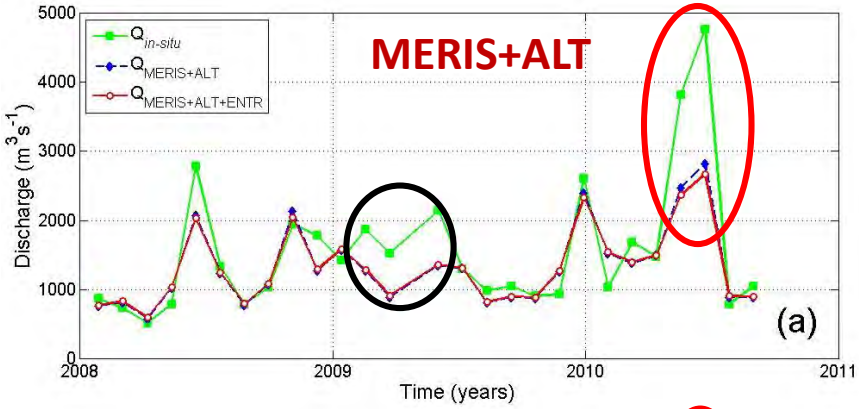
SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

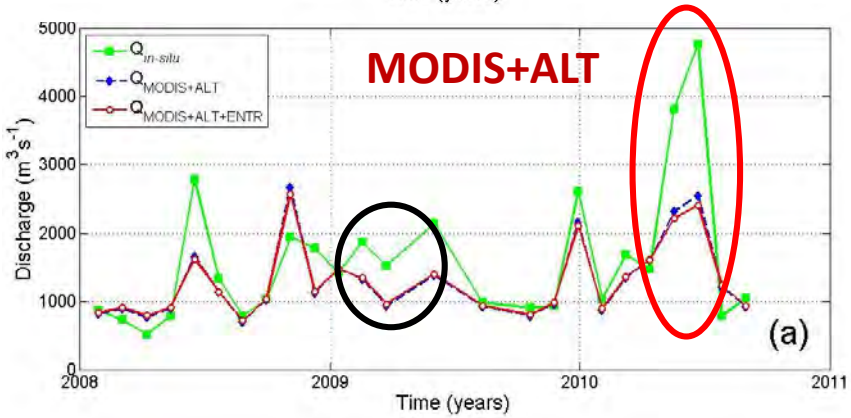
River Discharge from imaging sensors & altimetry

Po river

In terms of discharge, some peak values are underestimated with respect to the observed ones and this is due to both the sensors, altimetry and MODIS (or MERIS).







SENSORS	**Altimeter**	**Passive microwave/optical**
APPROACHES	**Rating curve**	**Hydraulic models**

Summary

- *Satellite data: Radar altimetry*
  - *Principles*
  - *Missions and technologies*
  - *Applications*
  - *Data access and toolboxes*

- *Satellite data: Optical and multispectral sensors*
  - *Missions and technologies*
  - *Data access*

- ***Hydrological Applications***
  - *River Discharge (from altimetry, from multispectral sensors, from multi-mission)*
  - ***Lake Volume variation (from multi-mission)***

Lake volume variation (from multi mission)

20 Years of River and Lake Monitoring from Multi-Mission Satellite Radar Altimetry

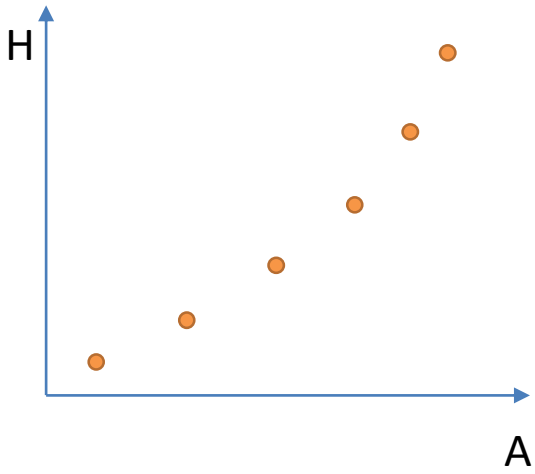
Philippa A.M. Berry [1], Richard G. Smith [1]
Mark K. Salloway[1], Monika Quessou[1],
Jérôme Benveniste [2]

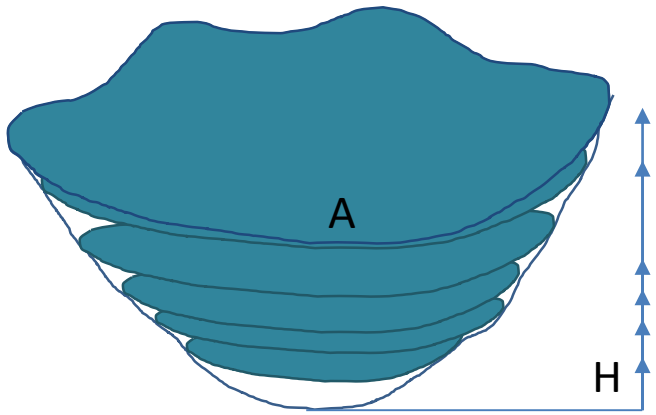
1. EAPRS Lab, De Montfort University
2. ESA ESRIN

Lake volume variation (from multi mission)

Lake volume estimation is only possible using bathymetry, but it is available only for a small number of lakes. Nevertheless, volume variation can be calculated for all lakes.
From satellite it is possible to estimate the water surface elevation, H, from altimetry and surface area, A, from imaging sensors or SAR.
The volume can be deduced from the observable function A(H) relating the surface area of a lake to a specific water level through this integration:

$$V(H) = \int_0^H A(H')dH'$$



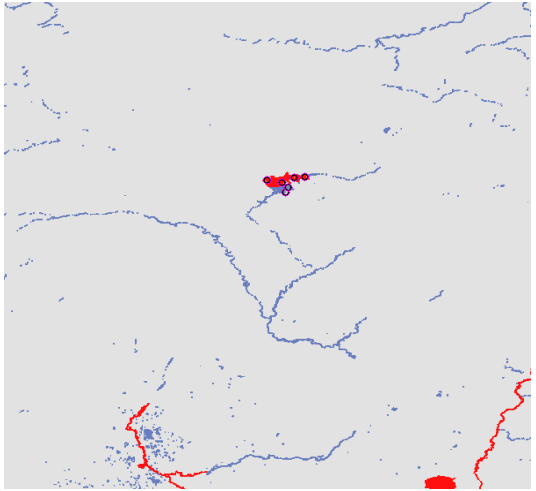


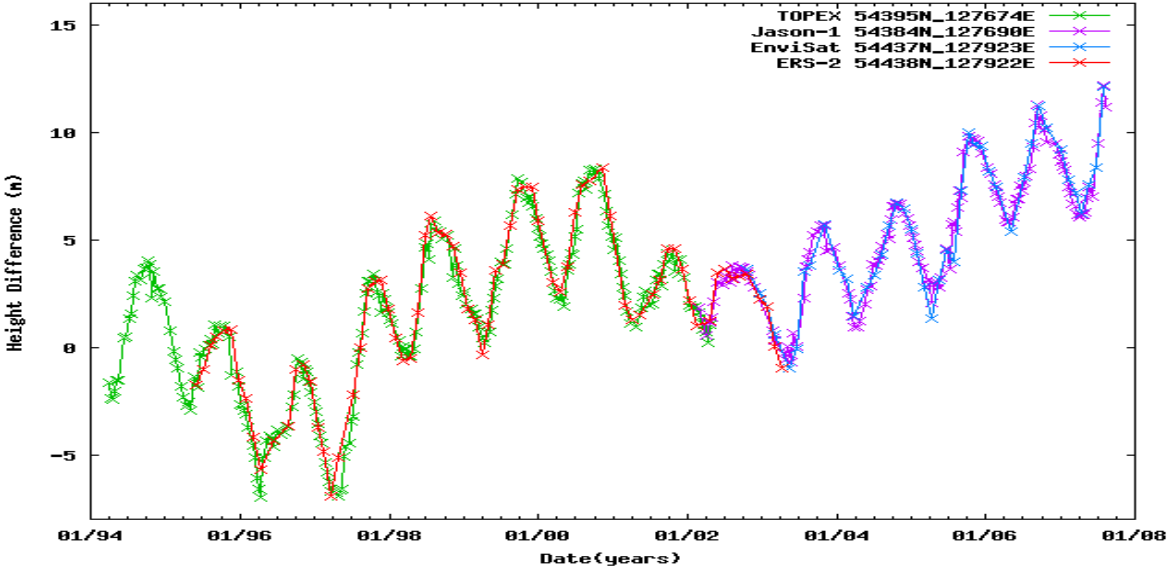
Monitoring H and A from satellite observations, the relationship can be continuously use to monitor water bodies.

Lake volume variation (from multi mission)

Zeyskoye Vodokhranilishche

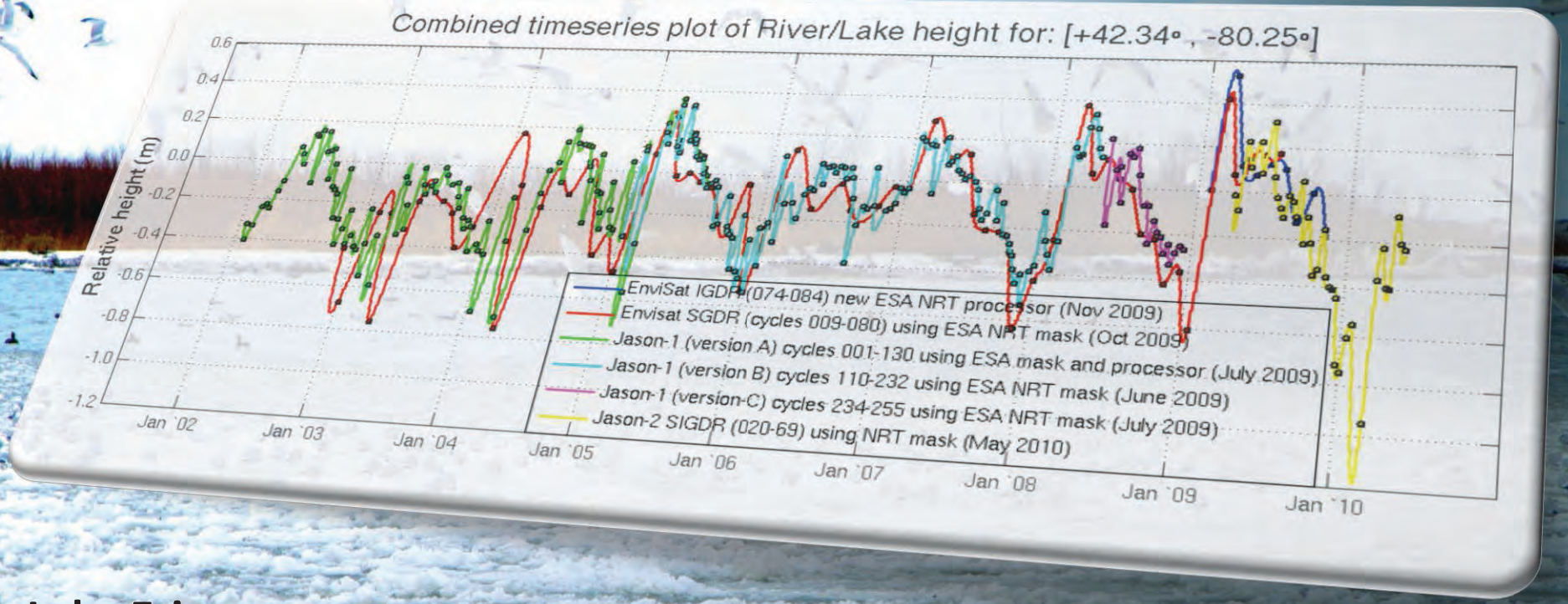
Reservoir Zeyskoye Vodokhranilishche, Russia, water level with 12 year combined time-series derived from retracked ERS-2, EnviSat, TOPEX and Jason-1 waveform data.





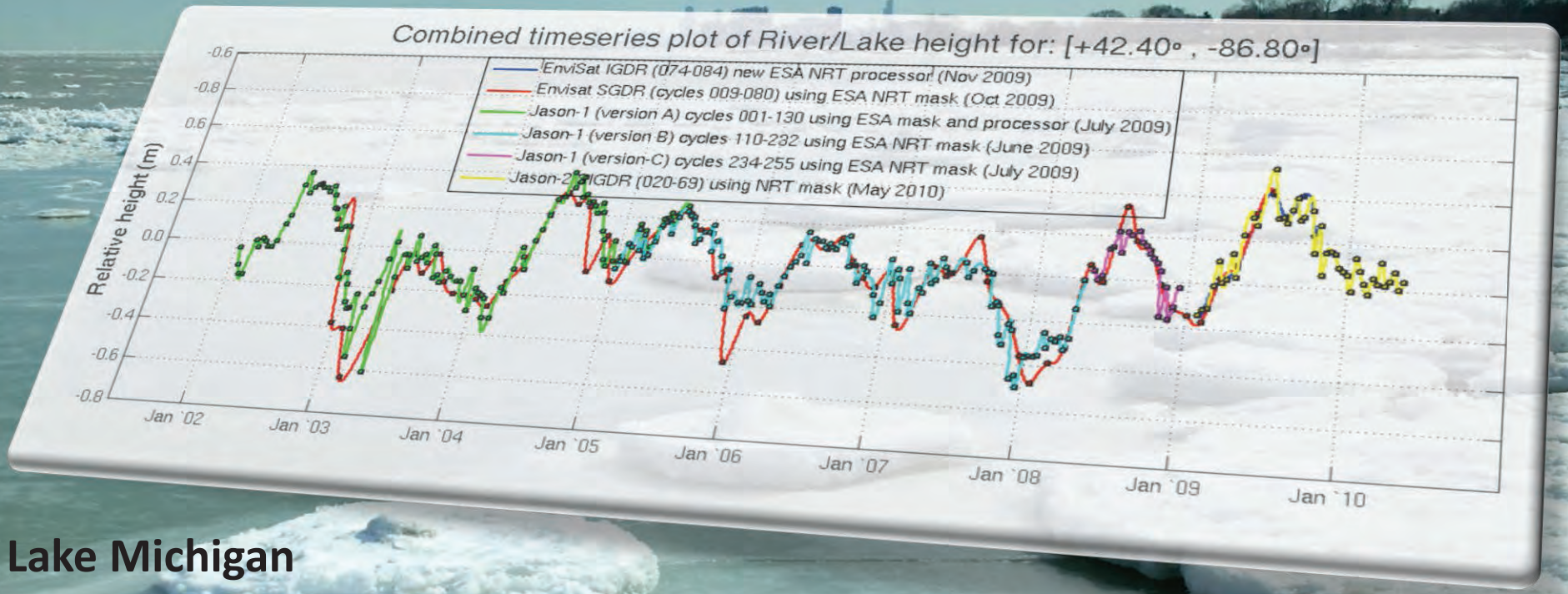
- Excellent agreement is achieved over this fairly complex target.
- Note the very good data from Jason-1 over this reservoir.

Lake volume variation (from multi mission)



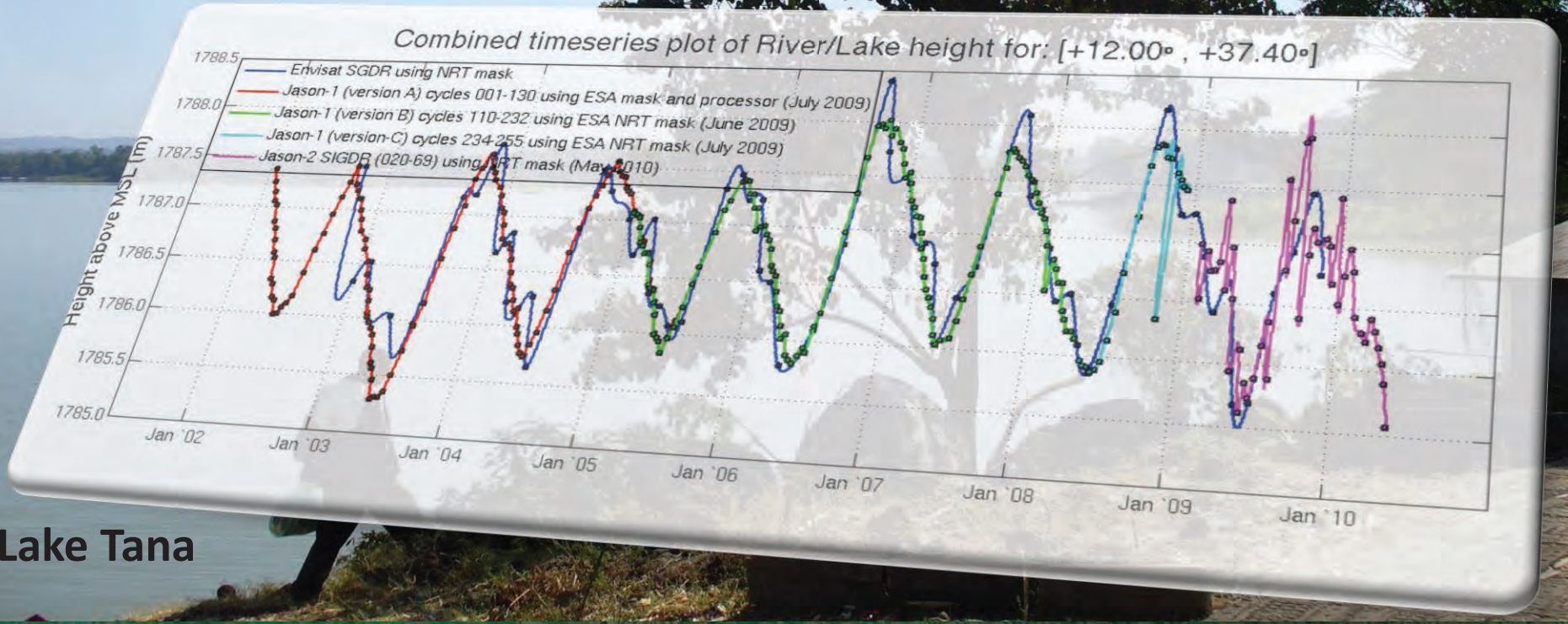
Lake Erie

Lake volume variation (from multi mission)



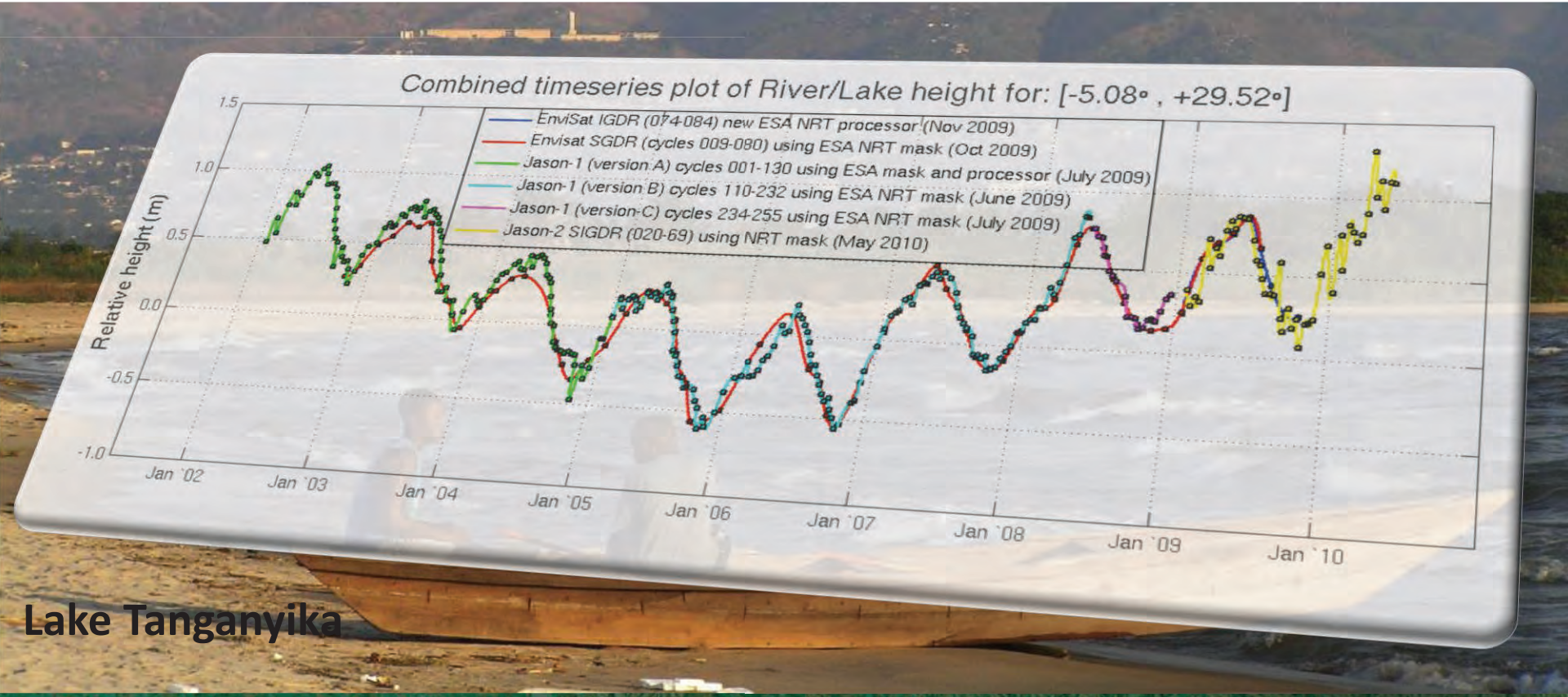
Lake Michigan

Lake volume variation (from multi mission)



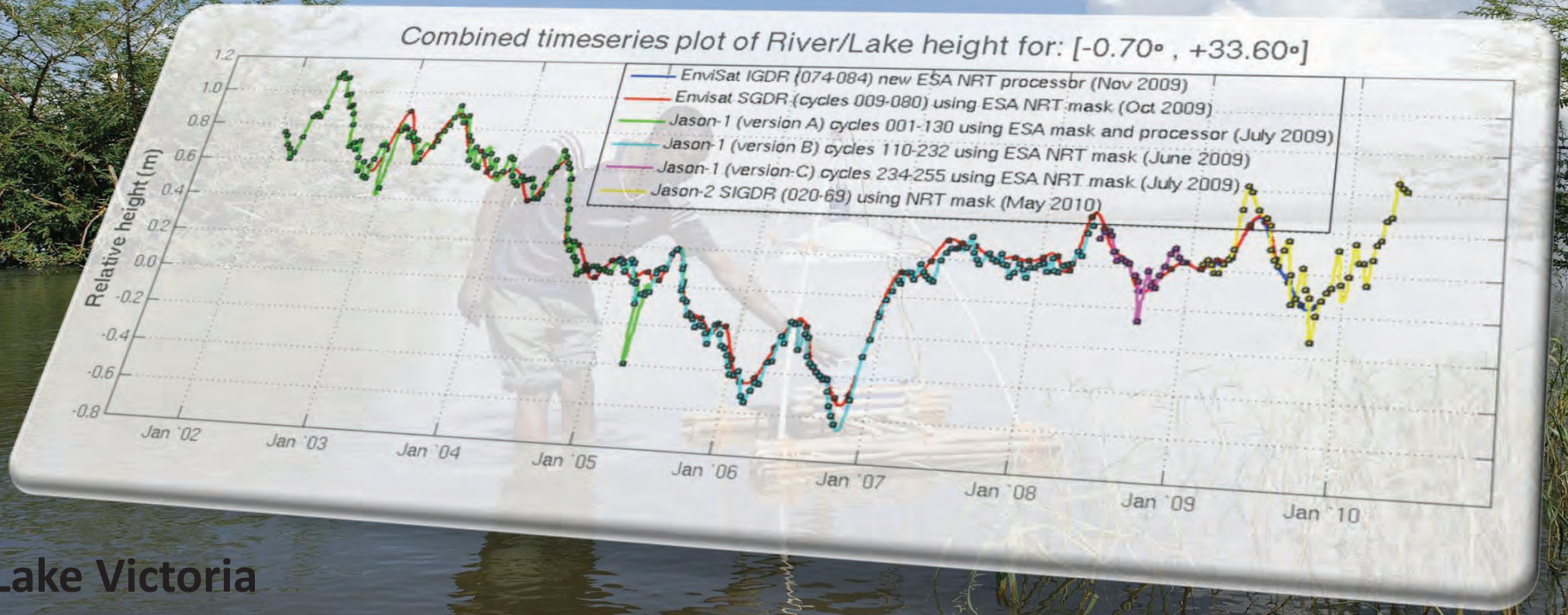
Lake Tana

Lake volume variation (from multi mission)



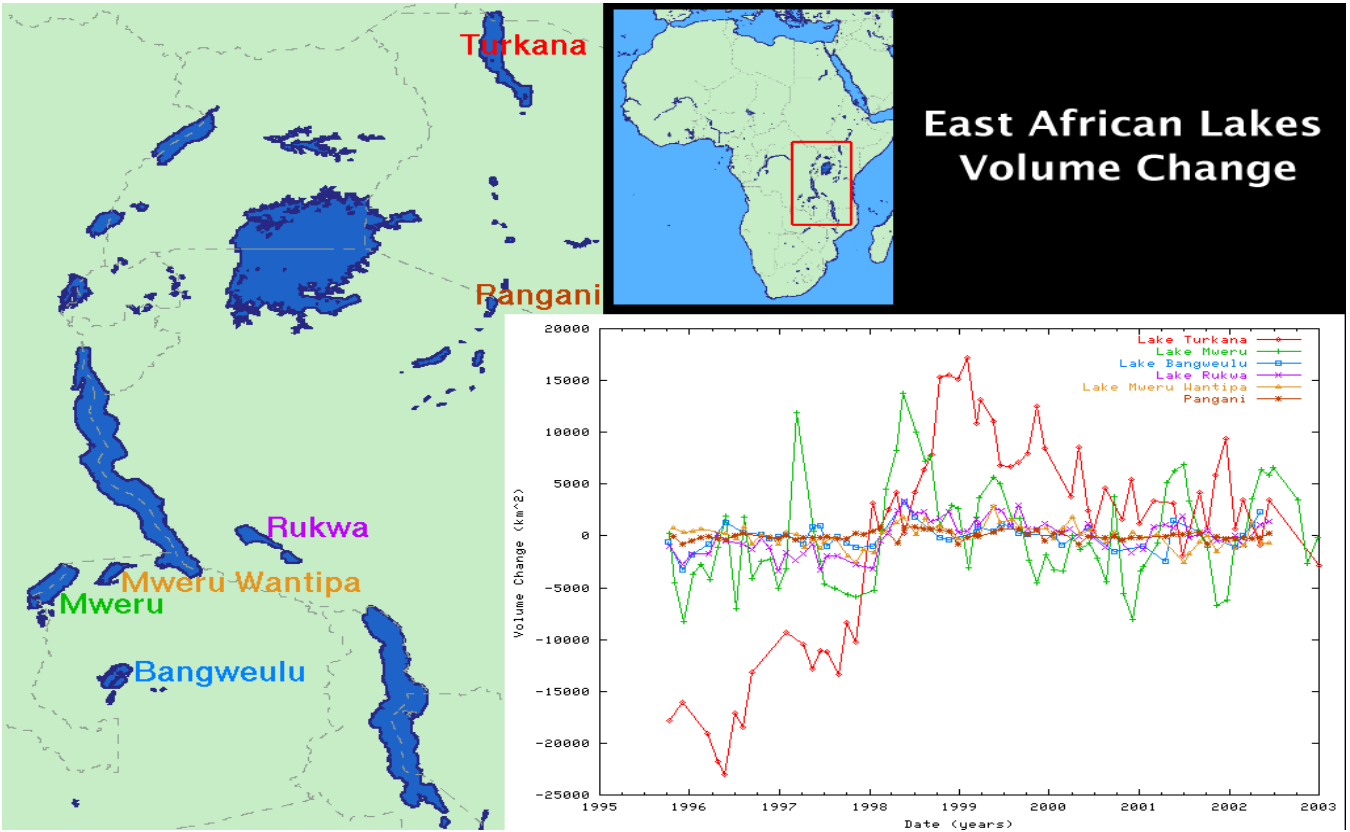
Lake Tanganyika

Lake volume variation (from multi mission)

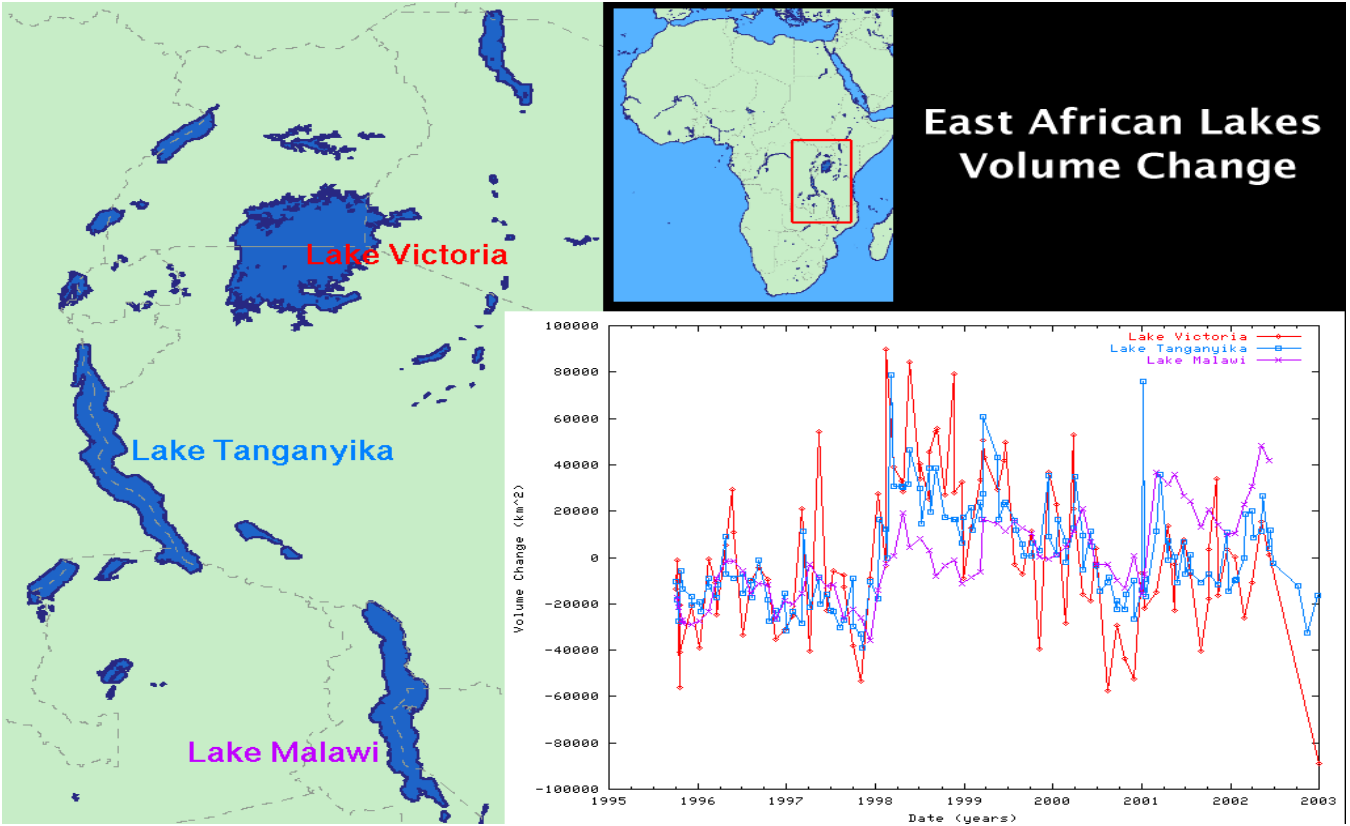


Lake Victoria

Lake volume variation (from multi mission)



Lake volume variation (from multi mission)



Thank you for your attention

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