Impacts of the assimilation of remote sensing soil moisture products into a continuous distributed hydrological model

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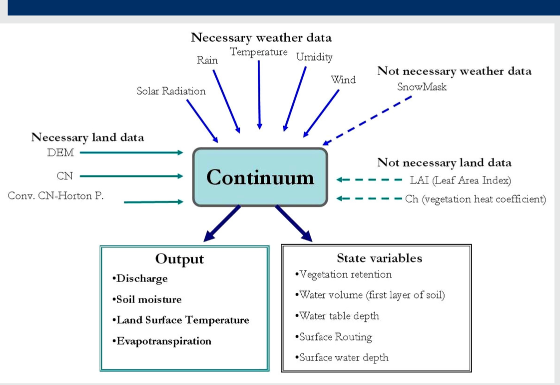
Abstract

Soil moisture is a key variable for many scientific applications such as climate modelling, water management and operational forecasting of flood, landslide, weather, drought. In particular a correct estimation of soil water content can highly affect the improvement of the accuracy of flood predictions. This variable can be monitored using in situ data, but local measurements are expensive, time consuming and hard to spatialize. Consequently remote sensing can offer a chance to provide good space-time estimates of several hydrological variables and then improve hydrological model performances. The goal of this work is to test the effects of the assimilation of satellite soil moisture on the hydrological cycle. Among the currently available different satellite platforms, four soil moisture products, from both the ASCAT scatterometer and the SMOS radiometer, have been assimilated into a continuous hydrological model using a Nudging scheme. Three soil moisture products are from ASCAT and are provided by the EUMETSAT's H-SAF (Satellite Application Facility on Support to Operational Hydrology and Water Management) project; while for SMOS the reprocessed Level 2 soil moisture product has been considered. The model has been applied to a test basin (area about 800 km²) located in Northern Italy for the period July 2012 – June 2013. The experiments have been carried out for all the above-mentioned satellite-derived measurements and the impacts on the model discharge predictions and the other hydrological variables have been tested.

Continuum model



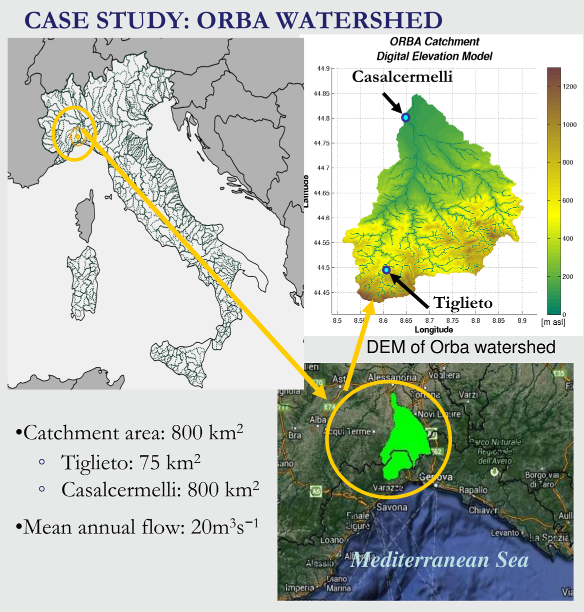
Conceptual scheme of Continuum model

Continuum is a complete and fully distributed model that allows to simulate the main hydrological processes with a simple but robust processes schematization (Silvestro et al., 2013).

MAIN CHARACTERISTICS:

- Complete description of Hydrological Cycle
  - Schematization of vegetation interception and water table
  - Tank schematization of overland and channel flows
- Mass Balance and Energy Balance completely solved
- River network derived from a DEM
- It can be calibrated using only satellite data (e.g. surface temperature or soil moisture).
- Model suitable for application in data scarce environments

CASE STUDY: ORBA WATERSHED



DEM of Orba watershed

- Catchment area: 800 km²
  - Tiglieto: 75 km²
  - Casalcermelli: 800 km²
- Mean annual flow: $20 m^3s^{-1}$

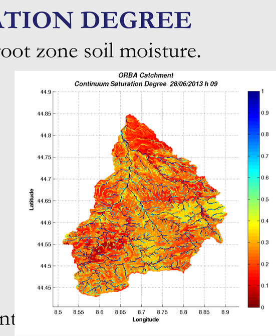
Continuum SATURATION DEGREE

Index related to the dynamics of root zone soil moisture.

$$SD = \frac{V(t)}{V_{max}}$$

V= Actual water volume
V_{max}= Max soil retention capacity (derived from CN)

Time frequency: Hourly map
Spatial coverage: single catchment
Resolution: 100 m
Unit of measurement: [-]



Example of Saturation Degree map on Orba catchment

The model source code is open and can be requested to: http://www.cimafoundation.org/cima-foundation/continuum/

Satellite soil moisture products

•H-SAF SM OBS 1 - H07 → SWI

Large-scale surface soil moisture (SSM)

Time frequency: 2 maps per day
Spatial coverage: 1000 km swaths covering the globe
Resolution: 25 km
Unit of measurement: [-]

•H-SAF SM OBS 2 - H08 → SWI

Small-scale surface soil moisture (SSM)

Time frequency: 2 maps per day
Spatial coverage: 1000 km swaths crossing the H-SAF area
Resolution: 1 km
Unit of measurement: [-]

•H-SAF SM DAS 2 - H14 → SMI level 2

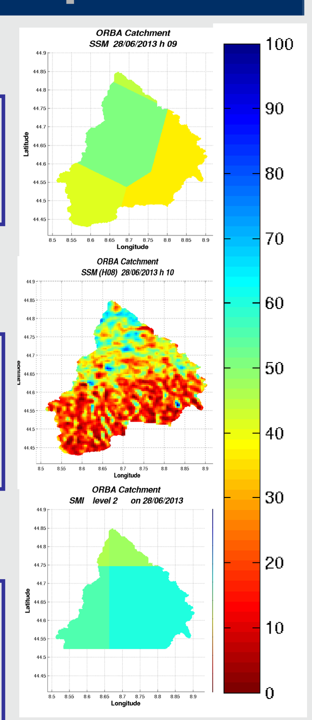
Profile Soil Moisture Index (SMI) in the root zone

Time frequency: Daily map (at 00.00)
Spatial coverage: Globe
Horizontal resolution: 25 km
Vertical resolution: 4 layers (0-7 cm, **7-28 cm**, 28-100 cm, 100-289 cm)
Unit of measurement: [-]

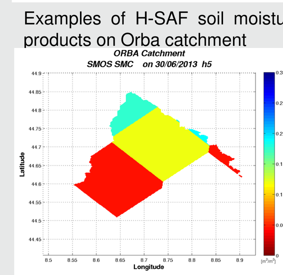
•SMOS, level 2 → SMC

Volumetric soil moisture content (SMC)

Time frequency: 2 maps per day, (revisit time 3 days)
Spatial coverage: 600 km swath covering the globe
Resolution: 43 km in average, 35 km (centre of field of view)
Unit of measurement: $[m^3/m^3]$



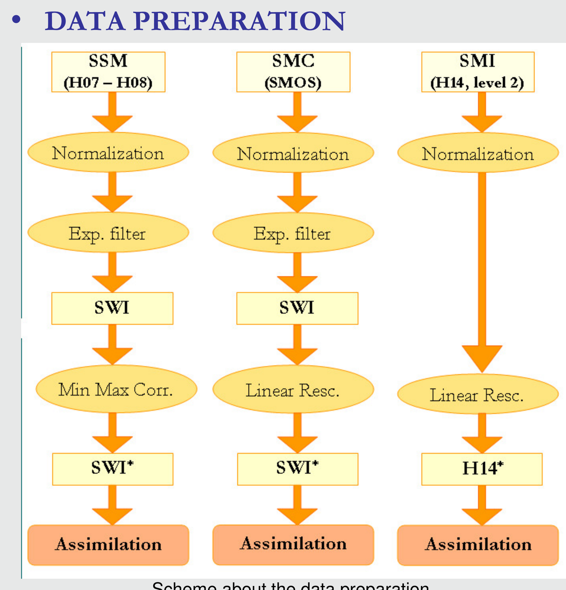
Examples of H-SAF soil moisture products on Orba catchment



Example of SMOS soil moisture product on Orba catchment

Assimilation experiments

- **DATA PREPARATION**



Scheme about the data preparation

- Satellite soil moisture data firstly **regridded** to Continuum grid using **nearest neighbour method**
- For H07 and H08 only the **mornig passes** were assimilated into the model
- Discarded H07 data with quality flag > 15
- Discarded SMOS data with DQX>0.045 and RFI>1%

•Normalization: $SAT_{norm} = \frac{SAT - \min(SAT)}{\max(SAT) - \min(SAT)}$

•Exponetial filter (H07, H08 and SMOS)

The exponential filter (SWI), proposed by Wagner et al. (1999), is a method to retrieve profile soil moisture values from surface ones.(Stroud, 1999; Albergel et al., 2008)

•Rescaling

- Linear Rescaling (H14 and SMOS) $SAT^* = \frac{SAT - \mu(SAT)}{\sigma(SAT)} \cdot \sigma(SD_{mod}) + \mu(SD_{mod})$
- Min Max correction (H07 and H08) $SAT^* = \frac{SAT - \min(SAT)}{[\max(SAT) - \min(SAT)]} \cdot [\max(SD_{mod}) - \min(SD_{mod})] + \min(SD_{mod})$

- **NUDGING TECHNIQUE**

X^+_{mod}= **Assimilated** variable
X^-_{mod}= **Modeled** variable
X_{obs}= **Observed** variable (SWI* or H14*)

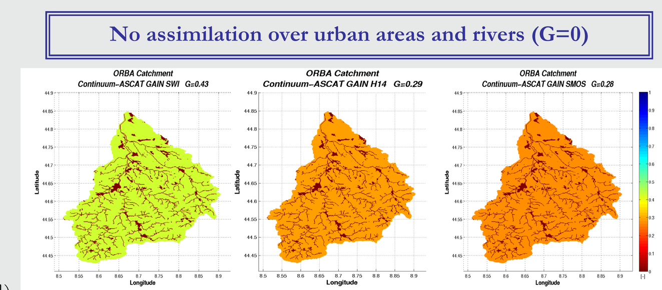
G = **Gain** matrix → $G = \frac{RMSD_{mod}}{RMSD_{mod} + RMSD_{obs}}$

$RMSD_{mod}$ = Root Mean Square Difference of X^-_{mod} = 0.092
$RMSD_{obs}$= Root Mean Square Difference of X_{obs}:

- $RMSD_{H14}$: 0.22 [-] (SOURCE: Albergel validation work preesented during H-SAF meeting in Budapest 2013)
- $RMSD_{SWI,HSAF}$: 0.12 [-] for H07 and H08 (SOURCE: Brocca et al. 2011)
- $RMSD_{SWI,SMOS}$: 0.24 [-] (SOURCE: Albergel et al. 2012)

$$X^+_{mod}(t) = X^-_{mod}(t) + G \cdot [X_{obs}(t) - X^-_{mod}(t)]$$

No assimilation over urban areas and rivers (G=0)



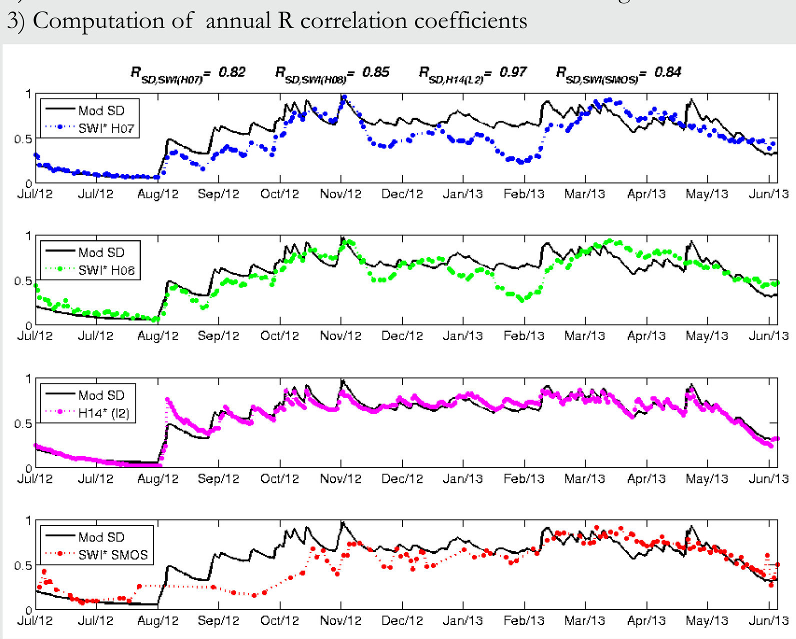
Gain matrix maps for SWI from H07 and H08 (image on the left), H14 (central image) and SWI from SMOS (image on the right)

Results

Average saturation degree comparisons before assimilation experiments

PROCEDURE:

1)Estimation of catchment means for Continuum Sat.Degree and for satellite soil moisture data (H14, SWI from H07, H08 and SMOS)
2) MinMax Correction over H07 and H08 and Linear rescaling over H14 and SMOS data
3) Computation of annual R correlation coefficients



Comparisons of catchment means between modeled saturation degree (black) and satellite derived soil moisture: SWI*,H07 (blue), SWI*,H08 (green) , H14 (magenta) and SWI*,SMOS (red). Correlation coefficients are reported on the top of the figure.

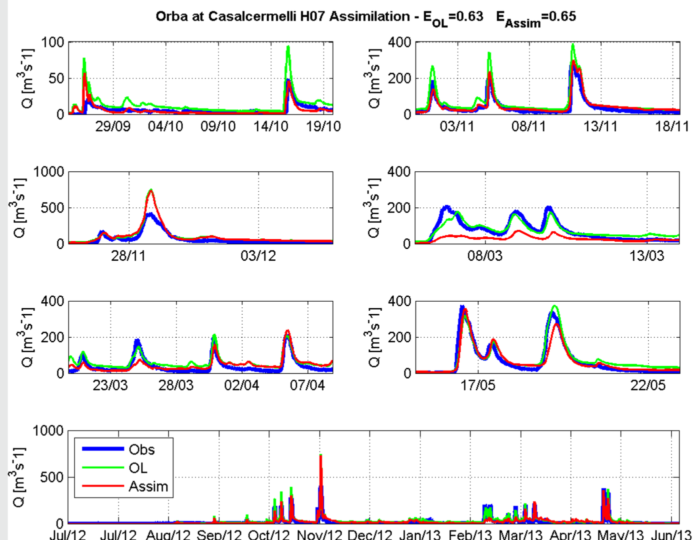
July 2012 - June 2013	# Available Maps	# Expected Maps	Absent maps [%]
H07	185	365	49
H08	202	365	45
H14	365	365	0
SMOS	115	365	69

For each satellite-derived soil moisture data the table reports the available maps, the expected maps and the percentage of absent maps

RESULTS:

- Good annual correlation coefficients (R>0.8) for soil moisture data
- H14 soil moisture temporal trend is very similar to that predicted by the model
- H07 and H08 products observed drier soil moisture conditions in February/March 2013
- Few SMOS data over the catchment (69% of absent maps)

Annual assimilation impacts on discharge



Hydrographs resulting from the assimilations of SWI*,H07 (red lines) compared with those without assimilation (OL) (green lines) and the observed ones (blue lines) from Casalcermelli data station.

Mean Absolute Error

$$MAE = \frac{1}{n}\sum_{i=1}^{n} |Q_{mod,i} - Q_{obs,i}|$$

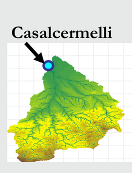
Root Mean Square Error

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (Q_{mod,i} - Q_{obs,i})^2}$$

Nash-Sutcliffe coefficient

$$E = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{mod,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q_{obs}})^2}$$

where:
Q_{si} – simulated values
Q_{oi} – observed value

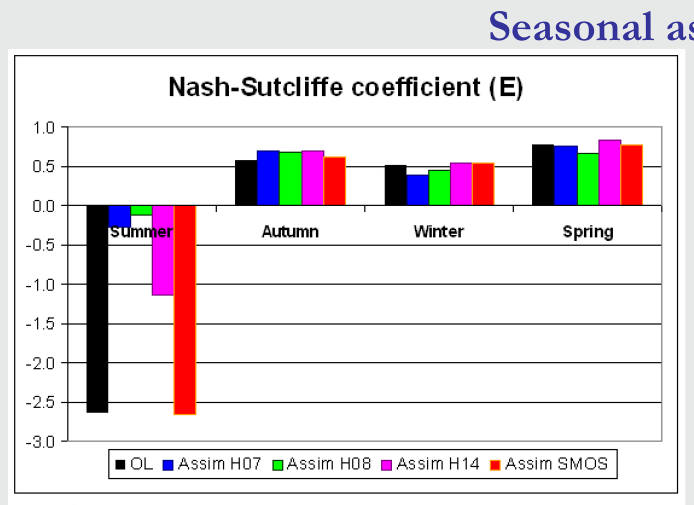


July 2012 - June 2013	MAE	RMSE	E
OL	17.4	25.3	0.63
Assim H07	14.0	24.7	0.65
Assim H08	15.5	25.4	0.63
Assim H14	15.2	22.5	0.71
Assim SMOS	16.9	24.6	0.65

MAE, RMSE and E evaluated in the whole considered period, respect observed values, on the modeled discharges in case of both open loop model and assimilation of soil moisture satellite data

- H07 (SWI) and H14 assimilations improved the efficiency (E) and reduced the errors (MAE and RMSE) on discharge
- H08 didn't improve the model efficiency but reduced the MAE
- SMOS assimilation improved the efficiency and slightly reduced errors in discharge

Seasonal assimilation impacts on discharge predictions



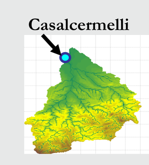
Nash-Sutcliffe coefficients evaluated for each different season, respect observed values, on the modeled discharges in case of both open loop model and assimilation of soil moisture satellite data

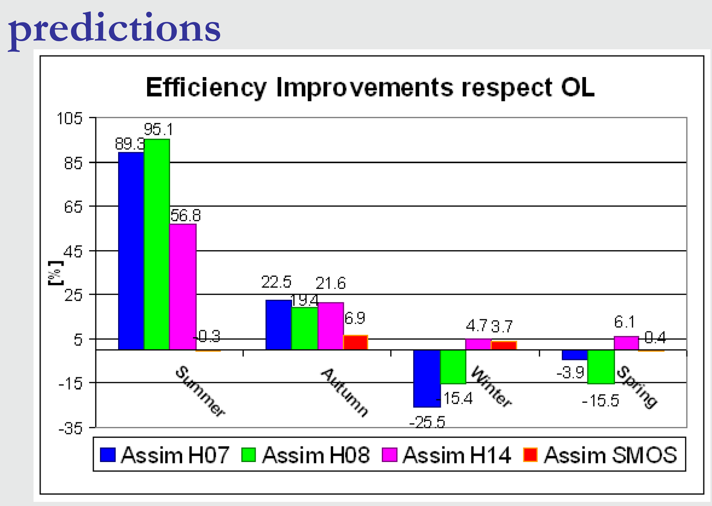
E	Summer	Autumn	Winter	Spring
OL	-2.64	0.57	0.52	0.78
Assim H07	-0.28	0.70	0.39	0.75
Assim H08	-0.13	0.68	0.44	0.66
Assim H14	-1.14	0.69	0.54	0.83
Assim SMOS	-2.65	0.61	0.54	0.78

Nash-Sutcliffe coefficients evaluated for each different season, respect observed values, on the modeled discharges in case of both open loop model and assimilation of soil moisture satellite data

Nash-Sutcliffe coefficient

$$E = 1 - \frac{\sum_{i=1}^{n} (Q_{obs,i} - Q_{mod,i})^2}{\sum_{i=1}^{n} (Q_{obs,i} - \overline{Q_{obs}})^2}$$





Efficiency improvements evaluated for each different season, respect OL efficiency on discharge

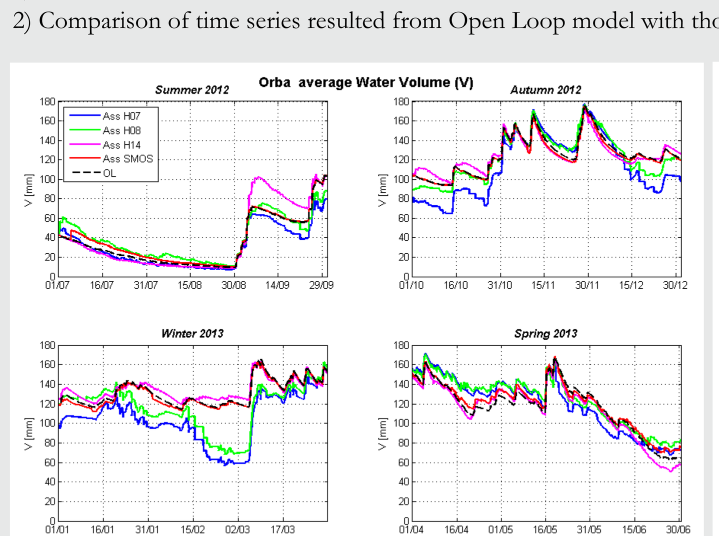
RESULTS:

- Low efficiency values in summer (discharge values were few m^3/s), however the assimilations of H-SAF soil moisture products improved the efficiency respect to the Open Loop simulation from 57 to 95 %
- In autumn the assimilations of all soil moisture products improved the performances of the model, from 7 to 23%
- In winter and spring months assimilations of H07 and H08 reduced the efficiency (problem of ASCAT retrieval in snow and frozen conditions)

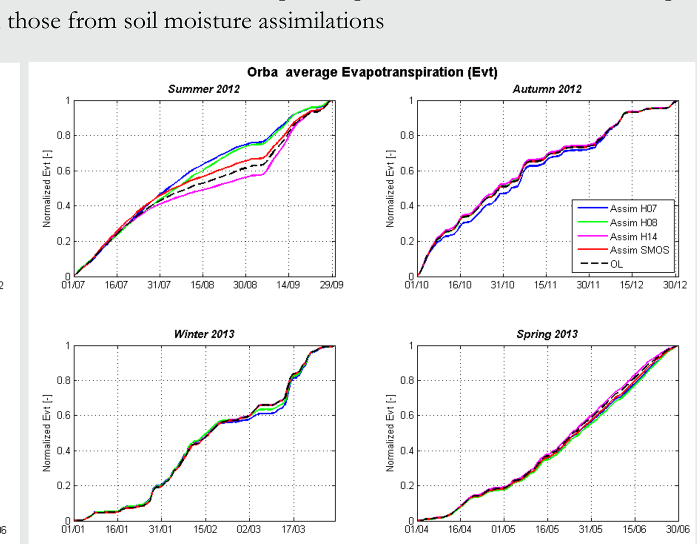
Seasonal assimilation impacts on averaged hydrological variables

PROCEDURE:

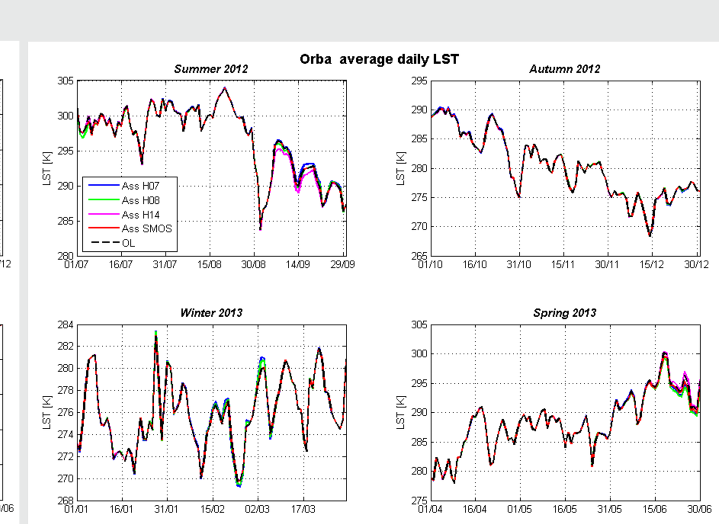
1)Estimation, for each season, of catchment means of modeled Water Volume, normalized Evapotranspiration and Land Surface Temperature
2) Comparison of time series resulted from Open Loop model with those from soil moisture assimilations



Catchment means of modeled water volume in case of Open Loop model (black dashed line) and assimilation of SWI*,H07 (blue), SWI*,H08 (green), H14* (magenta) and SWI*,SMOS (red).



Catchment means of modeled normalized evapotranspiration in case of Open Loop model (black dashed line) and assimilation of SWI*,H07 (blue), SWI*,H08 (green), H14* (magenta) and SWI*,SMOS (red).



Catchment means of modeled land surface temperature in case of Open Loop model (black dashed line) and assimilation of SWI*,H07 (blue), SWI*,H08 (green), H14* (magenta) and SWI*,SMOS (red).

RESULTS:

- Assimilations of satellite-derived soil moisture data didn't affect the land surface temperature (simulated LST values in case of assimilation of soil moisture products are similar to Open Loop ones
- The assimilation of SMOS data lead to slight differences respect to OL run (few SMOS observations over the catchment)
- In autumn, winter and spring there were no significant differences in evapotranspiration values respect to OL run; Assimilation of H07 and H08 increased the evapotranspiration in August 2012 while H14 assimilation reduced it
- Water volume (variable related to soil moisture) presented more differences respect the other two variables: H14 assimilation increased the soil moisture in the month of September; H07 dried the soil in winter and both H07 and H08 observed driest conditions respect OL run in March 2013

Conclusions

- Soil moisture products presented good correlation with Continuum saturation degree. This correlation is lower in winter months where H07 and H08 products observed drier soil moisture conditions in February/March 2013, this is due to ASCAT problems in soil moisture estimation in presence of snow or frozen soil.
- Assimilations of Soil moisture products improved the performances, in terms of discharge, of Continuum model. In general all the assimilation improved the Nash-Sutcliffe coefficient and reduced errors on streamflow.
- SMOS gave slight improvement to the model due to few observations maps over the catchment
- In summer H-SAF soil moisture assimilations improved a lot the efficiency, respect to Open Loop run
- In autumn all soil moisture assimilations gave a good contribution in the simulation of discharge.

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