HYDROLOGICAL MODEL FOR RETRIEVING SUBSIDENCE VELOCITY FROM GPS DATA: APPLICATION TO PO DELTA AREA

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Introduction. Suitable estimation of the land subsidence is crucial in deltas and coastal areas, where the climate variability effects (e.g., frequent and intense rain storms, peaks in river discharge and sea level fluctuations), coupled with natural or anthropogenic land sinking, represent serious factors of inundation risk. Nowadays, continuous GNSS (Global Navigation Satellite Systems) networks have become precision monitoring tools of the ground displacement. Many site-position time series exhibit a linear trend plus seasonal oscillations of annual and semi-annual periods. These periodic variations may be due to the joint contributions of surface mass redistribution (atmosphere, ocean, snow and soil moisture), frequently masked by the superposition of several correlated or uncorrelated noise sources (Bock and Melgar, 2016). These signals have to be recognised and properly modelled in order to estimate the vertical ground lowering. Several authors investigate the seasonal component by using the "peering approach", which is based on the comparison between the joint contribution of established individual geophysical sources (not removed during the data processing phase) and the observed seasonal variations (Dong *et al.*, 2002). This approach allows to quantify influence, distribution and magnitude of the individual sources and to understand the main processes affecting the geodetic time series. Differently from this approach, we propose a procedure based on two steps: multi-disciplinary and multi-methodological comparative analyses are first performed for selecting the physical mechanism (individual source) that better explain the seasonal signals clearly exhibited by the GPS (Global Positioning System) time series. Then, a physically-based model is used for enhancing the extraction of the geodetic trend and thus estimating the geodetic velocity without seasonal oscillations.

The proposed approach is applied to the Codigoro Area, for the time span ranging from 2009 to 2017. Codigoro is located in the southern part of the Po Delta – Northern Italy (Fig. 1), an area historically affected by both anthropogenic (Bondesan and Simeoni, 1983) and natural

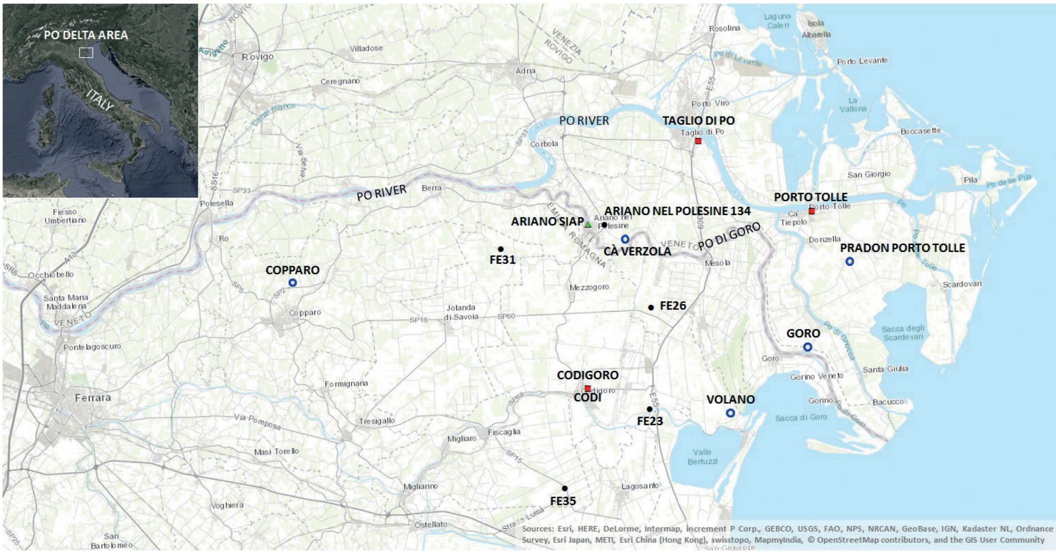

Fig. 1 - Po Delta area and data sites: continuous GPS (red square), pluviometric (blue circles), piezometric (black points) and hydrometric stations (green triangle).

subsidence (Teatini *et al.*, 2011; Carminati *et al.*, 2006) and influenced by climatic changes (Simeoni and Corbau, 2009).

The multi-methodological analysis consisted of histogram analysis of cumulative and mean annual values, centered moving average, cross wavelet transform and wavelet transform coherence analyses (Grinsted *et al.*, 2004), which have deepened the understanding of the relationship between ground surface and water system (rain-, river- and ground-water) and unveiling the important role of the hydrological load in driving the seasonal effects. Then, as it concerns the second step of the proposed procedure, a physically-based modelling of the hydrological surface loading (http://loading.u-strasbg.fr/displacements.php) has been chosen that relies on the Modern-Era Retrospective analysis for Research and Applications (MERRA2) (Gelaro *et al.*, 2017) and Global Land Data Assimilation System (GLDAS) (Rodell *et al.*, 2004). Once the seasonal oscillations have been modelled, the geodetic velocity has been calculated within a time period of interseismic deformation (2012-2016), considering both original data and data residuated by the simulated periodic components.

Data analysis. All data used in this work are available on open source websites and refer to 11 stations of the Po Delta area (see Fig. 1): ground level (CODI), Po River hydrometric level (Ariano SIAP), piezometric levels (Ariano del Polesine 134, FE35, FE31 and FE23 and Cà Verzola) and rainfall data (Copparo, Volano, Goro and Pradon Porto Tolle). CODI station is located at Codigoro, near Po di Volano River, and belongs to the GPS network of Nevada Geodetic Laboratory (MAGNET). CODI is placed on the roof of a one-floor building whose foundations do not exceed 2 m of depth and lay on 15 m of deltaic and littoral sediments of the last prograding sequences. The daily series clearly exhibit non-tidal loading effects (i.e. atmospheric pressure, ocean bottom pressure and hydrological loading).

Meanwhile, the 6-months moving average points out the presence of a clear annual signal with variable amplitude, the 12-months centered moving average applied on the whole data set reveals a gentle lowering trend plus a quite regular narrow oscillation characterised by an inter-annual period (~ 2 years). The wavelet transform confirms the presence of these two stronger power peaks at about 1-year and 2.1-years period both in the geodetic time series and also in the hydrometric level of Po di Goro River. Moreover, at these scales, the two analysed signals share a common spectral power with a phase difference of about 180°, suggesting that a loading

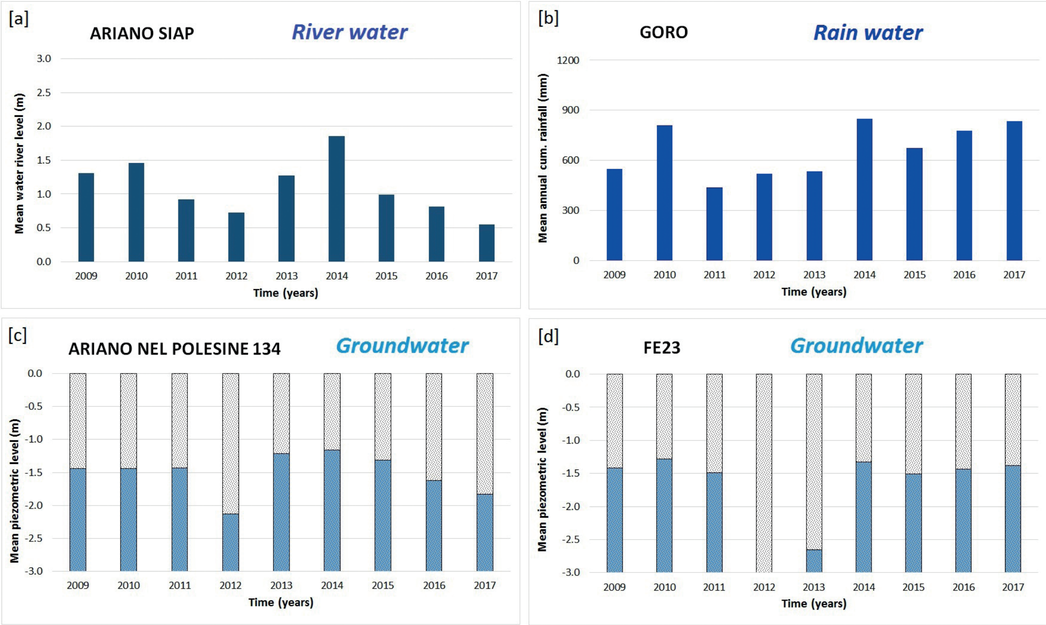

Fig. 2 - Mean annual values histograms of: (a) hydrometric level of Po di Goro River; (b) cumulative rainfall at Goro station; (c) and (d) piezometric levels at Ariano del Polesine 134 and FE23, respectively.

mechanism is involved. Such a kind of correlation has been already observed in the central part of the Po Delta, in particular in Taglio di Po and Porto Tolle areas (Vitagliano *et al.*, 2017). As expected, the analyses of the time evolution of the mean annual and annual cumulative values have shown some correlations among hydrometric level, rainfall and groundwater levels. In particular, the relative Po di Goro river level measured at Ariano SIAP station, reaches maximum mean annual value in 2009-2010 and 2013-2014, while lower values during 2011-2012 and 2015-2017 (Fig. 2a). The mean annual cumulative rainfalls measured at Goro station show maximum values in 2009-2010 and 2014-2017 and lower values in 2011-2013 (Fig. 2b). The groundwater levels of the shallower unconfined aquifer and the floating porous lens depend by both water river and rainfalls. In fact, Piezometer 134 (Fig. 2c), which is close to the Po di Goro, better correlates with the river hydrometric level (Fig. 2a), while Piezometer FE23 (Fig. 2d), close to Po di Volano river, shows higher similarities with the local rainfalls (Fig. 2b). The former piezometer exhibits a groundwater level that reaches minimum depth in 2012 and a depth-decreasing from 2015 to 2017, while the latter piezometer shows lower groundwater levels only in 2012-2013.

Modelling and discussion. Our analyses aim to identify the most reliable physically-based modelling for simulating the periodic components and estimating the geodetic trend from residual ground displacement. In particular, useful information have been derived from the piezometric data. FE23, located near Codigoro area, shows annual groundwater fluctuations within the soil sequence (up to 3 m below the ground level, b.g.l.) that better correlate with the local rainfall at Goro station (Figs. 2b and 2d). Conversely, the piezometer located close to the Po di Goro River (Ariano del Polesine 134) exhibits groundwater annual values that mainly correlate with the river stage (Figs. 2a and 2c). Thus, the infiltration of rainwater in the soil sequence seems to be more active far from the river. Since the GPS antenna is far from Po and Po di Goro Rivers, and it is fixed to a building characterised by shallow foundations (up to 2 m b.g.l.), it may be heavily influenced by water infiltration processes, as it occurs in FE23 site. Its oscillations may be due to the hydrological loading depending on rainfall, soil moisture

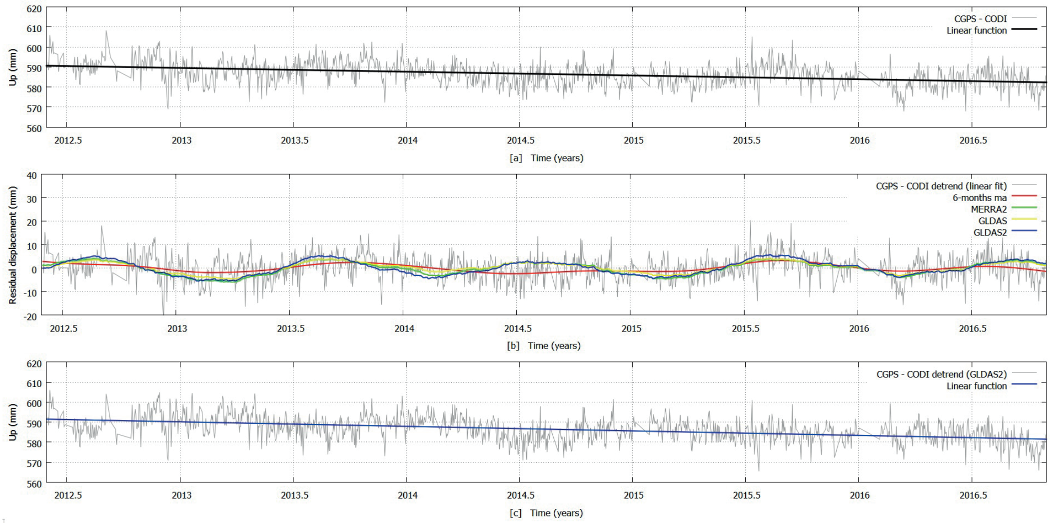

Fig. 3 - CODI time series: a) original data and linear fit; b) residual data after linear de-trending and fits by using moving average (red line) and physically-based models (light-green, green and brown lines); c) fitting of the final linear trend. See the text for details.

and canopy water. In order to verify this hypothesis, we compute the ground displacement due to the hydrological loading using MERRA2 (Gelaro *et al*., 2017) and GLDAS (Rodell *et al*., 2004) models. Even if these models do not account for surface water, including rivers, and deep groundwater processes, they simulate the mass transfer at Earth's surface and other environmental parameters by integrating satellite- and ground-based observations into land surface models through data assimilation techniques.

With respect to the modelling results, Fig. 3a depicts the original continuous GPS time series from June 2012 to October 2016 (inter-seismic deformation time span) and its linear trend, calculated on the basis of a linear fit analysis. This fit, which indicates a mean subsidence rate of -1.9 +/- 0.1 mm/yr, has been used to preliminarily de-trend the original signal (Fig. 3b). In Fig. 3b the de-trended series is compared with the 6-months centered moving average and the hydrological modelling results. MERRA2, GLDAS/Noah v1.0 and GLDAS/Noah v2.1 models well fit the residual data and their results slightly differ due to some modelling basic conditions (e.g. spatial resolution, land surface model, layer geometry, etc.). All the models simulate periodicities at 6-months, 1- and 2-years with amplitudes ranging 6-10 mm. Although the standard statistical analysis (moving average) is able to detect the seasonal periodicities as well as the physically-based models, it underestimates the amplitude (Fig. 3b). An example of the linear fitting, after periodic trend removal with the best fitting model (GLDAS2), is shown in Fig. 3c. In this case, the most reliable mean subsidence velocity is -2.3 +/- 0.12 mm/yr.

The used hydrological models have been also applied to other two GPS stations located very close to the Po River (i.e, Taglio di Po and Porto Tolle in Fig. 1). Since a single model mesh covers the entire Delta (spatial resolution: 0.5° x 0.625° for MERRA2 and 0.25° for GLDAS), the periodic oscillations simulated in these sites are very similar to the one obtained in Codigoro area. As expected, due to the Po River loading, the computed oscillations therein do not match the observations as other processes are not accounted by the modelling (e.g. surface water loading and ground settlements due to the river).

In conclusion, the inter-annual (1- 2 years) variability observed in the hydro-meteorological data and due to weather and climatic processes, strongly influences the groundwater trend within the soil canopy and affects the large-scale oscillations visible in the geodetic data at CODI station. Moreover, the hydrological modelling confirms that far from the main river course, shallow processes, such as runoff, evapo-transpiration and shallow infiltration, act at delta scale causing a loading effect on the Earth's surface. This mechanism explains great part of the annual and biennial periodic signals observed in the geodetic data. Significant differences are obtained by using or not the hydrological models for retrieving the subsidence velocity.

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