Estimación desde satélites de la dinámica de área inundada y altura hidrométrica en ríos de la Cuenca del Plata

Salvia, M. [1], Grings, F[1], Barraza, V[1], Perna, P[1], Ferrazzoli, P[2], Karszenbaum, H[1]

[1] Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), Pabellón IAFE, Ciudad Universitaria, Buenos Aires, Argentina.

[2] Tor Vergata University, Ingegneria, DISP, 00133 Rome, Italy.

mercedessalvia@gmail.com

RESUMEN

En la Cuenca del Plata, las inundaciones son un fenómeno recurrente. El río Paraná posee una amplia planicie de inundación, poblada y cultivada, por lo que obtener información sobre el estado hidrológico de la cuenca sistemáticamente es crucial. Es especialmente importante el monitoreo de los ciclos de inundación-sequia de los humedales de las planicies de inundación, que se extienden a lo largo del eje Paraná-Paraguay y tienen intercambios de agua con el río altamente dinámicos, con importantes variaciones anuales e interanuales. Entonces, tanto el área inundada como la altura del agua en la planicie son indicadores importantes del volumen de agua dentro de la planicie. Además, la dinámica de estas variables es indicadora del comportamiento hidrológico global de la planicie. Estimando estas variables sistemáticamente mediante sensores remotos es posible restringir los resultados de modelos de pronóstico hidrológico. En este trabajo presentamos una metodología para estimar área inundada y altura del agua en humedales herbáceos, basado en datos de microondas activas y pasivas y un modelo de emisividad. Comparamos los resultados con datos de altímetros de microondas y estudiamos el comportamiento de la planicie durante las fases de inundación y estiaje mediante el análisis de la relación entre fracción de área inundada y altura del agua en la planicie.

Palabras clave: fracción de área inundada, altura hidrométrica, microondas pasivas, Índice de Polarización, Delta del Paraná

ABSTRACT

Flooding is a major concern in the Plata Basin. In particular, Paraná River has a long and wide floodplain, which has been settled and cultivated. Therefore, providing information about the current state of the basin hydrologic condition in a systematic way is critical to the regional economies and society. Especially, monitoring basin floodplain wetlands flood-drought cycles is extremely important. These ecosystems extend along the Paraná-Paraguay axis and have highly dynamic exchanges of water with the river, presenting important annual and interannual variations. In this context, both floodplain water level and flooded area become relevant proxies for the total water volume inside the floodplain. Moreover, the dynamics of these variables will be a raw indicator of floodplain overall hydrological behavior. Therefore, estimating these variables in a systematic way using remote sensing data, it is possible to constrain the outputs of hydrological forecast models. In this paper, a methodology to retrieve flooded area and water level in herbaceous wetlands, based on active/passive microwave data and an emission model is presented. We compare our results with microwave altimetry data, and analyzed floodplain behavior during flooding and “unflooding” phases by studying the relationship between fraction of flooded area (ff) vs floodplain water level (WL).

Keywords: flooded area fraction, hydrometric water level, passive microwave, Polarization Index, Paraná River Delta.

1 INTRODUCTION

Flooding is of major concern in the Plata Basin. This multinational basin, covering 3.2 million km^2, comprises the Río de la Plata and its main tributaries, the Paraguay, Paraná, and Uruguay rivers. This region is of significant social and economic importance because it is densely populated, and has important agricultural activities (this area, includes the Argentinean ‘‘Pampa Húmeda’’ and is one of the richest agricultural regions in South America). This hydrographic network serves a population of about 70 million providing irreplaceable ecological/hydrological functions, such as mitigating large floods and droughts, recharging aquifers, supporting fish breeding areas and supplying the majority of the high quality fresh water.

The largest flood of the century occurred on the Paraná River in 1983 during a strong ENSO event. For a year and a half after the event, the Paraná flood level was above street level in areas of Santa Fé, Argentina. Economic losses due to floods in Argentina during the 1983, 1992, 1998, 2007 and 2009-2010 episodes exceeded US$1 billion each. Therefore, providing information about the current state of the basin hydrologic condition in a systematic way is critical to the regional economies and society. In particular, it is of extreme importance to monitoring basin floodplain wetlands flood-drought cycles. These ecosystems extend along the Paraná-Paraguay axis and have highly dynamic exchanges of water with the river, presenting important annual and interannual variations.

In this context, both floodplain water level and flooded area become relevant proxies for the total volume of water inside the floodplain. Moreover, the dynamics of these variables will be a raw indicator of floodplain overall hydrological behavior. Therefore, estimating these variables in a systematic way using remote sensing data, it is possible to constrain the outputs of hydrological forecast models. In this paper, a methodology to retrieve flooded area and water level in herbaceous wetlands, based on active/passive microwave data (Prigent et al., 2007; Sippel et al., 1994; Salvia et al., 2011) and an emission model (Ferrazzoli and Guerriero, 1996) is presented. We compare our results with microwave altimetry data (Cretaux et al., 2011), and analyzed floodplain behavior during flooding and “unflooding” phases by studying the relationship between fraction of flooded area (ff) vs floodplain water level (WL).

2 METHODOLOGY

2.1 Study Area

The lower part of Paraná River is subject to strong variations of water level, related to local rain events and the contribution of up-water of Paraná and Paraguay Rivers.

In this paper, we studied the area shown in Fig. 1. It encompasses the Paraná River floodplain, which is topographically lower than its surrounding areas and is covered by a highly heterogeneous wetland with a complex landscape pattern. Nevertheless, at the spatial scale of AMSR-E, this wetland is dominated by lagoons and different communities of herbaceous vegetation in the extended lowlands.

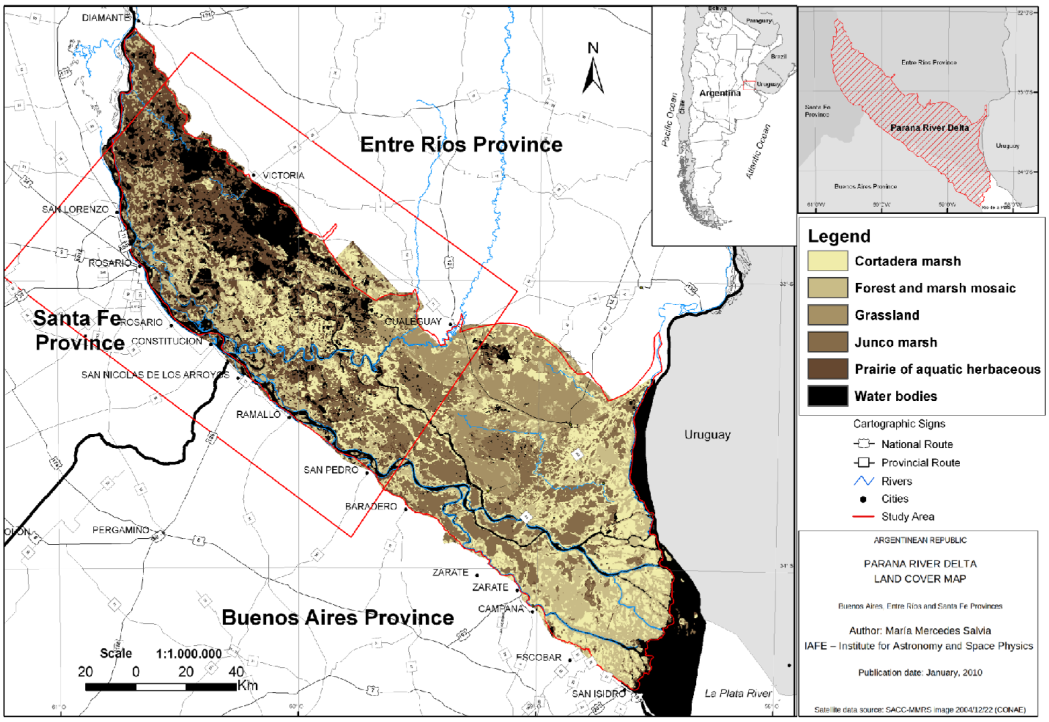

Figure 1 - Paraná River Delta.

2.2 Flooding Event & Available data

In this work two ENSO (El Niño/Southern Oscillation) flooding events are analyzed. In both events Paraná River water level rose above the levee level, flooding an extensive part of Paraná River Delta. To estimate the hydrological condition of this area, we used both active and passive microwave signatures, as well as altimeter data and ancillary data. Details are given in Table 1.

Table 1 - Available data

Sensor	Data used	Dates	Data obtained
AMSR-E (C, X, Ka Bands)	L1B Tb	2007/03 - 2010/09	PI=2*(Tbv-Tbh)/(Tbv+Tbh)
ENVISAT ASAR(C Band)	WSM HH σ^0	2009/08 - 2010/09	Flooded area maps
ALOS PALSAR (L Band)	WB1 HH σ^0	2007/04 - 2007/11	Flooded area maps
ENVISAT altimeter Virtual Stations (LEGOS GOSH team)	134-05 ; 579-04	2007/01 - 2010/10	Water level
Emission model	Ferrazzoli and Guerriero, 1996		
Auxiliary data	Water level in Rosario Port, Land cover map,		

2.3 Estimation of fraction of flooded area and water level inside the floodplain.

Basically, the passive data have been analyzed using the simple model proposed by Sippel et al. (1994). The model has three end-members, that represent the contributions of water, non-flooded land, and inundated floodplain to the total observed polarization index PI_{obs},

$$PI_{obs} = f_w\, PI_w + f_{nf}\, PI_{nf} + f_f\, PI_f \qquad (1) \quad \text{and} \qquad 1 = f_f + f_{nf} + f_w \qquad (2)$$

where PI_{obs} is the PI observed by the radiometer, f_w, f_{nf} and f_f are the fractional areas of open water (rivers and lakes without emergent vegetation), non-flooded land, and seasonally flooded land, respectively, and PI_w, PI_{nf}, and PI_f are the PI values for open water, non-flooded land, and seasonally flooded land.

The algorithm is based on the following hypothesis:

1. The polarization index of water bodies, PI_w, is constant and known (emission model simulations).
2. The fractional area of permanent water bodies is constant and known (land cover map).
3. The polarization index of non-flooded land, PI_{nf}, is constant, shows a unique value for all the non-flooded vegetation types present in the area and can be estimated, in our case from emission models (emission model simulations).
4. The polarization index of flooded land, PI_f, is constant, shows a unique value for all the flooded vegetation types present in the area, has a negligible dependence on flood condition and can be estimated from images. The estimation of this value is a critical part of the algorithm and presents large variations as reported in (Sippel et al, 1994).

Previous work (Salvia et al., 2010) has proven hypothesis 4 not to be valid for our study area, since the increase of water level reduces the height of the vegetation, causing a decrease in emission but an increase in PI.

Since PI_f is one of the key parameters of our algorithm, SAR images were used in conjunction with passive microwave data to estimate PI_f at regular basis. Basically we obtained higher resolution flooding maps by thresholding a change image constructed via image algebra of SAR images at regular intervals. We calculate f_f for our study area from those maps, and use it to estimate PI_f from nearly coincident passive images.

2.4 Comparison with altimetry water level data.

Basically, an orbital altimeter determines the distance between the satellite and the earth surface by emitting a radar pulse towards the surface and measuring its travelling time (Rousmorduc et al., 2009). Besides this basic measurement, all altimeters measure the intensity and waveform of the backscattered signal, so as to infer target characteristics (Rousmorduc et al., 2009). Applications to measure wind speed and wave height using radar altimeters have been developed.

Radar altimeters have been used for years in hydrological applications (Parsons et al, 1994), particularly to measure water level in rivers on specific areas. In order to do this, an open water area of about 1 km^2 is selected, so the backscattering coefficient at nadir is meaningful. With this precaution, altimeter based water height measurements have a precision of ~ 5 cm. (Parsons et al., 1994).

In order to get some insight on the validity our estimations of flooded area fraction and water level, we compared this data from two virtual stations obtained from LEGOS (Laboratoire d'Etudes en Géophisique et Oceanographie Spatiales) GOSH team (Geodesy, Oceanography et Hydrologie from Space).

2.5 Analysis of fraction of flooded area vs water level dynamics

Hydrometric levels provide the best proxy for the temporal variations of flooded area of the floodplains adjacent to the large rivers of South America. While the water in floodplains can originate both by river overflow and by local runoff, it is the river which mostly controls water levels and therefore the flooded area in the adjacent plains (Sippel et al., 1998).

An approach for the study of flooding dynamics is the analysis of the existent relation between water level in a river and flooded area in the adjacent floodplain. Thus, the characteristics of this relation are indicative of the equivalent hydrodynamic behavior of floodplains of an area of the basin. This hydrodynamic behavior describes globally the water movements during flooding events (Fig. 2)

When both river and wetland water level are below levee level (A in Fig. 2), river water level changes has little effect on flooded fraction. When water level reaches levee level (1 in Fig. 2), a small increase in river water level produces a large increase in flooded area fraction. This situation is sketched in Fig. 2 as (B). Then, when river water level reduces to normal values, flooded area fraction remains high, due to poorer drainage conditions (C in Fig. 2). This would implicate that the floodplain is working as a water reservoir, since the water stays inside the floodplain when river water level has descended. This kind of effect is the explanation of the known buffer effect of wetlands. The magnitude of this buffer effect will depend on how much time wetlands can hold the water, and how gradually the discharge is done, being to the same river or to the groundwater. When wetland water is finally drained, the initial condition is reached (A in Fig. 2).

We constructed graphs equivalent to fig 2 for our study area comparing the results obtained on 2.4 with the two closest virtual stations from Hydroweb project (Cretaux et al., 2011; LEGOS GOSH team, 2013).

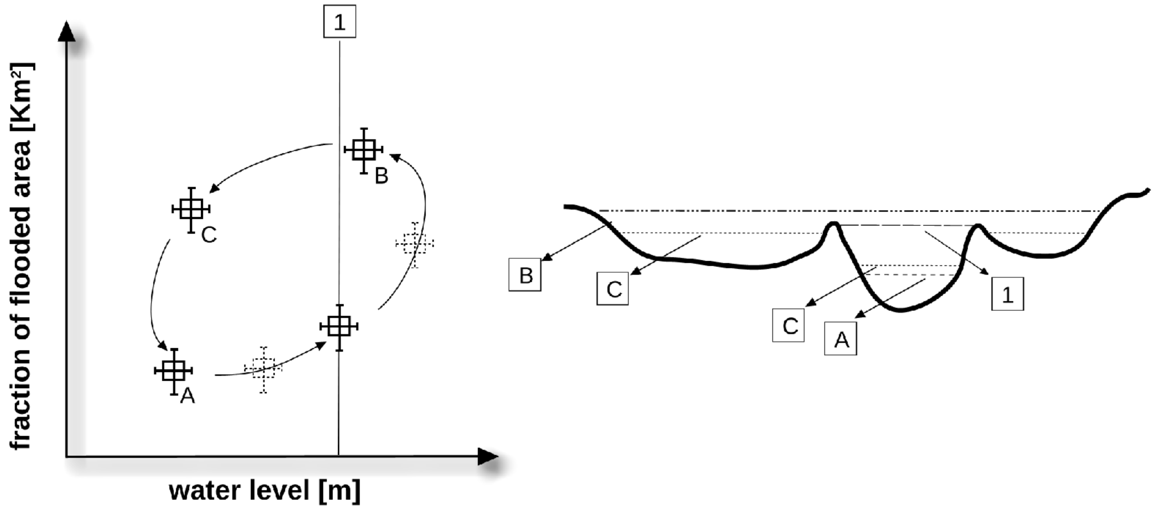

Figure 2 - Schematic of the expected results for the relation flooded area fraction/ hydrometric water level. *Left*: flooded area fraction vs hydrometric water level. *Right*: Equivalent topography schematic resulting from the graph on the left.

3 RESULTS AND DISCUSSION

Both the fraction of flooded area and water level obtained from AMSRE data and the water level obtained from two virtual stations of altimeter data showed similar trends for the both flooding events studied (fig. 3). In the case of water level data, we see that the three remote sensing measurements show a good agreement, but they all show some lag with Rosario port gauge. This could mean that Rosario may be the point of entrance of water to the floodplain, and the lag is the time it takes the water to be distributed throughout the floodplain.

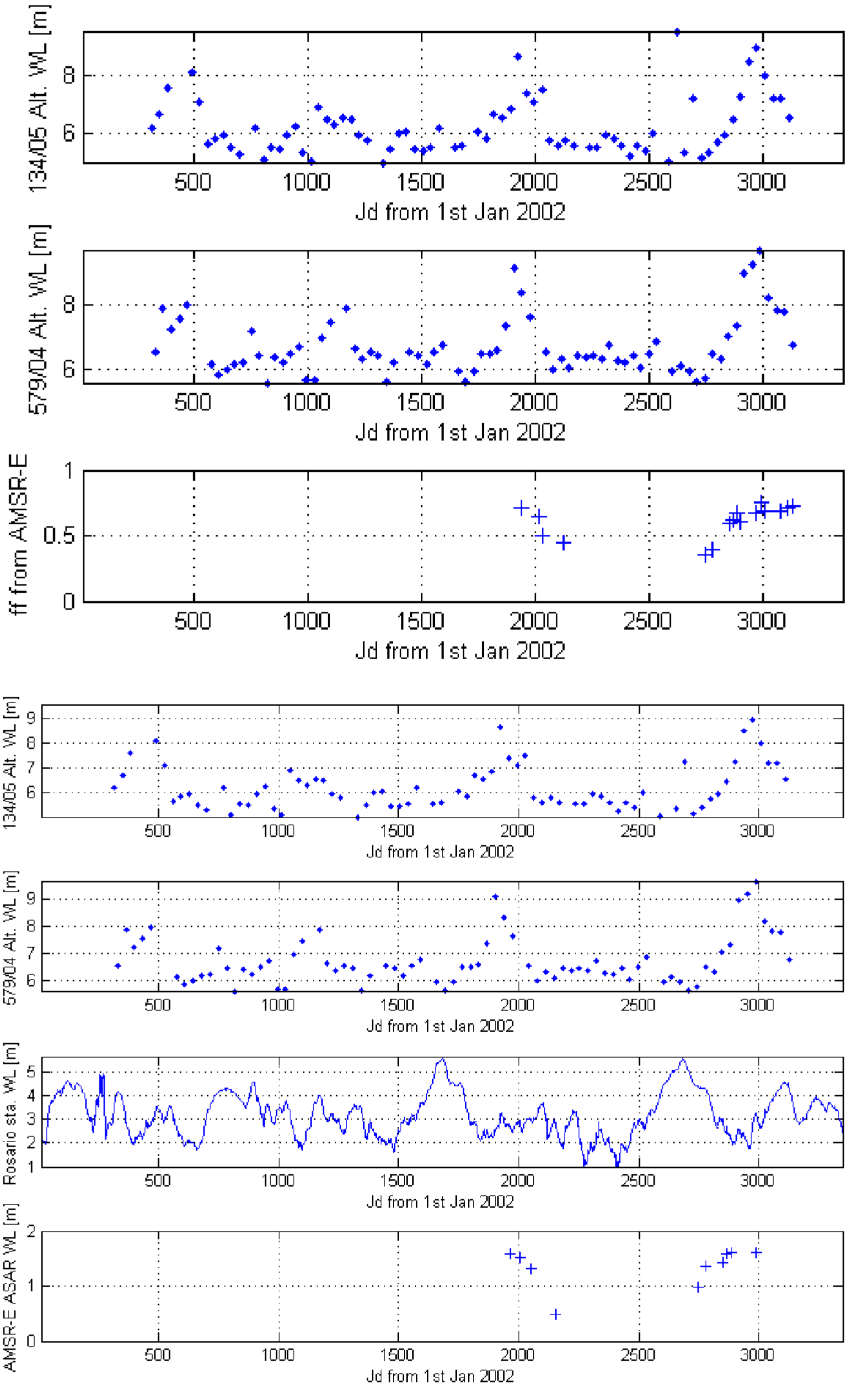

Figure 3 - Comparison between flooded area fraction and water level from passive microwave data and water level from altimeter data. Up: flooded area fraction. Down: water level.

Although figure 3 shows good results, and the altimeter data from both virtual stations seems quite similar, the f_f (AMSRE) vs WL (altimeter) plots show very different temporal trends for the two altimeter virtual stations (Fig4 Up and Down). However, in both cases we see that the first part of the flooding event (water rise) has a different path than the second part (water descent). This effect is called hysteresis and it is responsible for the well known “buffer effect” of wetlands.

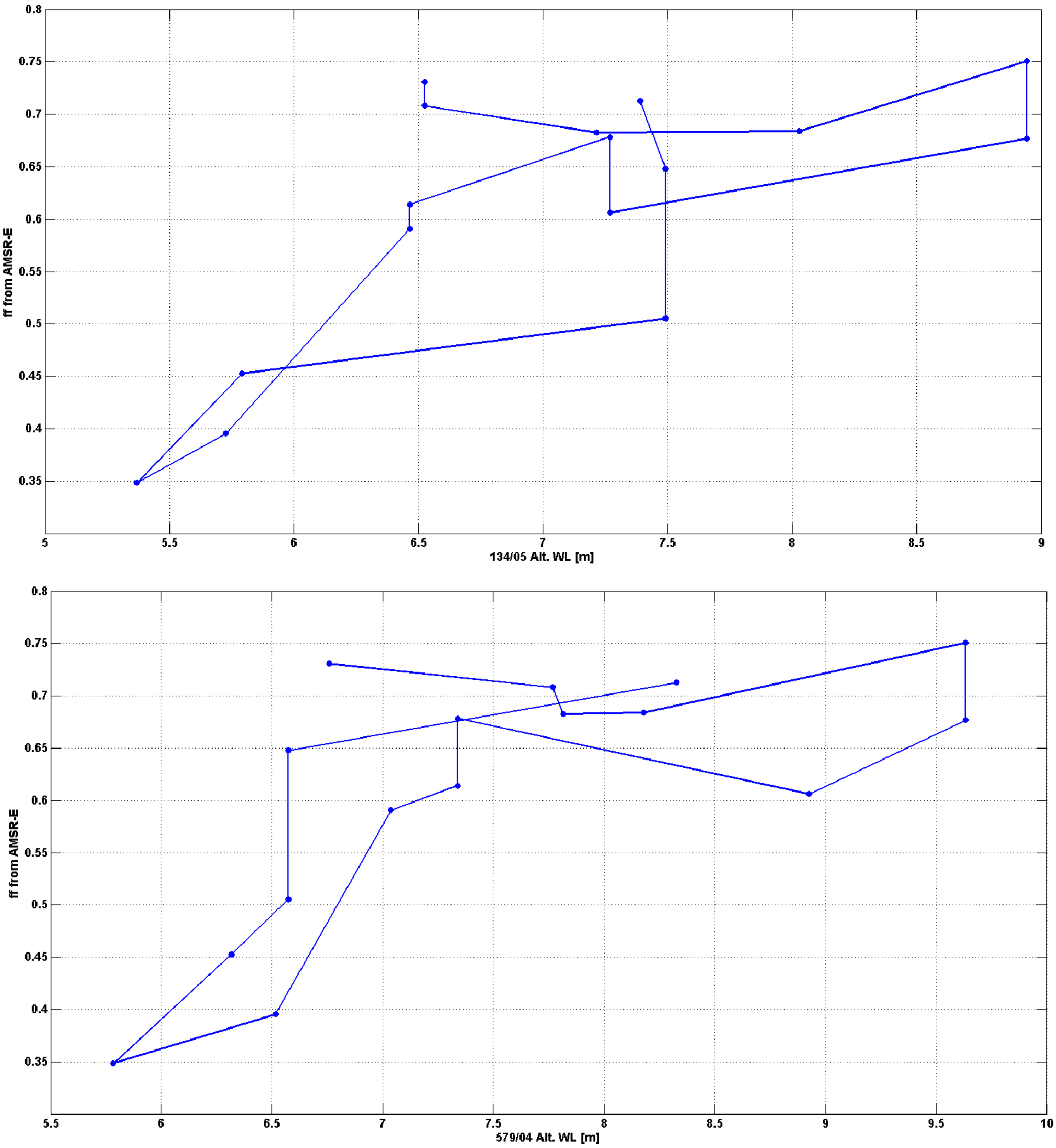

Figure 4 - Schematic of the relation between flooded area fraction and altimeter driven water level. *Up*: Envisat virtual station 134/05. *Down*: Envisat virtual station 579/04. To be compared with the scheme presented in Fig. 2.

One reason for the difference between figures 4a and 4b could be the location of the virtual stations. Even though both stations are located inside the studied area (the area where ff was retrieved) and they are ~20 km apart, there is a road that is built over an embankment between those stations, and may prevent the circulation of water over the floodplain. This would mean that the studied area is not homogeneous in terms of flooding source, and in future analysis the area should be divided into two or more smaller homogeneous areas.

In summary, the approach used on this work allows for the analysis of current hydrological condition in terms of the flooded area vs. water level space, and the posing of different possible future flooding scenarios, which would be useful for flooding forecast and alert.

Acknowledgments

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