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► **To cite this version:**

Theodora Perrou, Anatol Garioud, Asterios Papastergios, Issaak Parcharidis. Flood Hazard Mapping in a Reservoir-regulated River Basin using Sentinel-1 imagery: The Case of Serres Basin.. 11th International Hydrogeological Congress of Greece, Hellenic Committee of Hydrogeology, Oct 2017, Athens, Greece. hal-03189333

HAL Id: hal-03189333

<https://hal.science/hal-03189333>

Submitted on 6 Apr 2021

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FLOOD HAZARD MAPPING IN A RESERVOIR-REGULATED RIVER BASIN USING SENTINEL-1 IMAGERY: THE CASE OF SERRES BASIN

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Keywords: Flood Hazard Mapping; SAR images; Sentinel-1; Strymon River, Kerkini Lake.

Abstract

Flood is a natural disaster and causes loss of life and property destruction. Flood hazard Monitoring and Mapping is of great importance because it represents a significant contribution to risk management. The present study investigated the flood event occurred in 2014-2015 at Serres Basin, a reservoir-regulated river basin, aiming to understand its spatio-temporal dynamic of the flood hazard. Within the Strymon River basin, a transboundary river outflows to Kerkini Lake-reservoir which has the role of regulating water flow to downstream for irrigation purposes and flood protection. For this research, a dataset of Sentinel-1 SAR GRD images was collected and processed covering the period of October 2014 - October 2015. Based on SAR images binary water and non-water products were generated and interpreted. Satellite Earth Observation has proved to be an effective tool for hazard dynamic extension mapping and in combination with hydro-meteorological data can be a significant knowledge in flood disaster management.

1. Introduction

In this study SAR images from ESA's Sentinel-1 satellite have been exploited for monitoring the related water volume changes in the Kerkini Lake-reservoir during the period 2014 – 2015, and at the same time used for flood hazard mapping in the downstream of Strymon River (Serres Basin, Northern Greece) which occurred in the beginning of 2015 (Figure 1).

Kerkini Lake is located in Serres Basin and it is an artificial reservoir on the site of a former lake (Kerkinitis). The Strymon River, a transboundary river and main supplier of the lake, crossing 120 km Greek territory of which 77 km are downstream of the Lake Kerkini. The water level in the lake is controlled by the income of the Strymon River and river's flow downstream is controlled through the Lithotopos dam.

After the dam construction in 1983 the lake is characterized by seasonal changes in the water level with amplitude of about five meters (Jerrentzup, 1992) which helps to decrease the flood hazard and to irrigate the agricultural area in the lower part of Serres Basin, collecting excess runoff during rainy season and make water available during dry season. The efficient management and use of the water stored in these reservoirs have very positive socio-economic impacts on the livelihoods of the local inhabitants. Actually, the lake constitutes a wetland and has an extremely productive ecosystem of international importance (Gerakis et al. 2007, Doulgeris et al., 2008).

Satellite Earth Observations (EO) are a unique source of synoptic information at global scale that can supply regular, detailed updates on the status of hazards on a global, regional, or national basis. The EO can simplify consistent, comparable implementation, monitoring and link hazard to risk. Satellite EO data are a complementary data source to in-situ and collateral data.

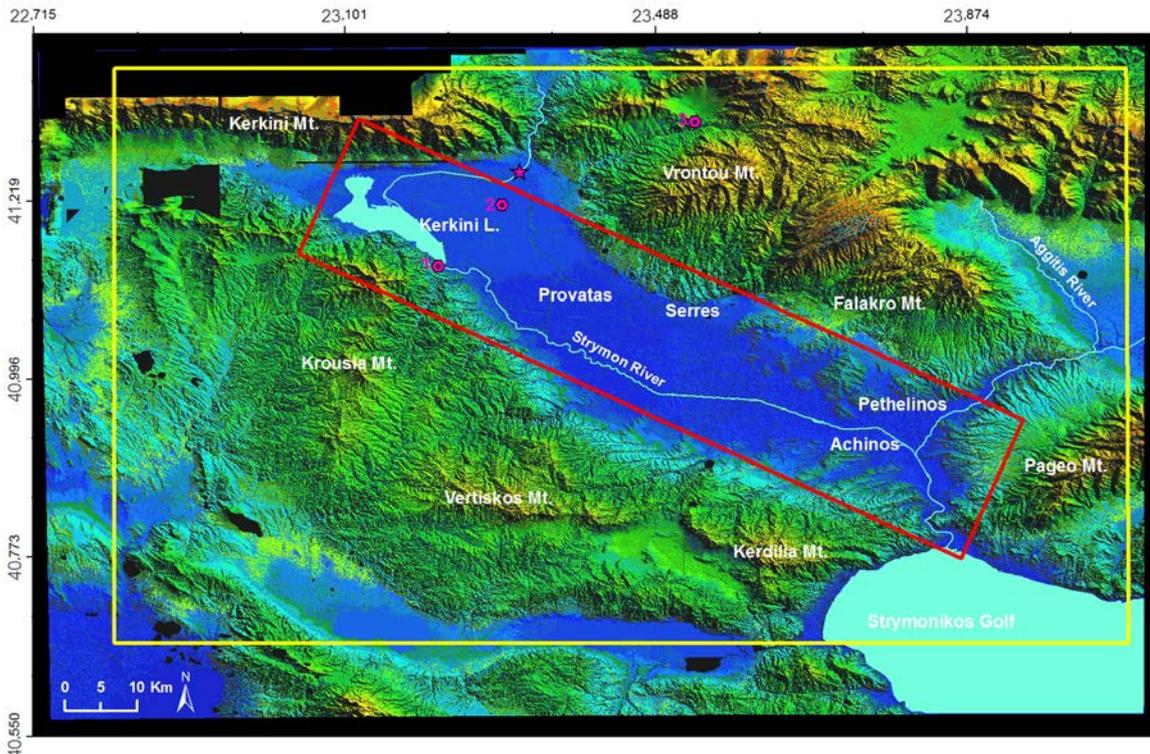


Figure 1. Location map. SAR subset processed image (yellow frame), area included in figures 3, 4 (red frame), meteo-stations (circles) 1: Lithotopos, 2: KoimissiSerron, 3: Achladochori. Location of water level measurement, Faros (star).

Repeatability of observations allows an improved capability to analyse, monitor and forecast the evolution of phenomena, facilitating water resources management. The most common approaches making use of EO for flood mapping are based on Synthetic Aperture Radar (SAR) data. Satellite radar images are most valued for flood detection purposes, because, in contrast to optical data, their recording is independent of sunlight availability and microwave radiance emitted by the SAR sensor, is able to penetrate haze and clouds. The SAR scenes are playing a crucial role in operational services in the case of river flood risk management. Numerous studies from the past (Oberstadler et al., 1997; Pierdicca et al., 2013; Chini et al., 2016; Foumelis, 2017; Nakmuenwai et al., 2017) demonstrated that SAR satellite sensors are especially suitable tools for flood mapping. This is mainly due to their high sensitivity to water surface combined with a capability to provide data day and night, regardless of cloud cover. The flood extent mapping and dynamic monitoring are very important for the calibration and validation of hydraulic models (Horritt, 2006). It can also be used for damage assessment and risk management and can be of great benefit to rescuers during flooding (Corbley, 1999).

The main objective of the current research is, exploiting the Copernicus Sentinel-1 data, the record of a flood event in a reservoir-regulated river basin by monitoring both the spatio-temporal extent and dynamic of the flood occurred on downstream and recording at the same time changes in water amount of the lake. This is achieved by developing retrospective products working from archived EO flood extent to better deliver flood-related information.

2. Background

2.1 *Geological-Geographical settings of the study area*

The basin of Serres is the final recipient of natural water throughout the Strymon's catchment inside and outside Greece (Psilovikos et al., 1994). The present form of river network within the Serres Basin can be considered mainly as natural, with considerable human effect over its form by hydraulics works occurred during last decades. The boundaries of the basin are defined by the following mountains: Kerkini (northern limit) Kerdilia, Krousia, (western limit), Falakro, Lekani and Pageo (south-eastern limit). It has been formed between the Serbo-Macedonian Massif west and the Rhodope Massif east. The total thickness of Neogene and Quaternary sediments at the center of the basin is approximately 4000 m. Considering the Strymon River as a central axis, the basin presents an asymmetry relative to the height distribution; the east-northeast is higher while the west-southwest lower. The long axis has a length of 80 km and NW/NE direction, while the small axis is about 10 km with NE/SW direction (Papafilipou-Pennou, 2004).

The Serres fault zone is responsible for the creation of the current morphological terrain of the area and is considered active (Tranos and Mountrakis, 2004). The principal faults are oriented in NW-SE, NNE-SSW to NE-SW and WNW-WSE to WE directions.

According to Vouvalidis (1994) the Strymon River as well the rest of the hydrographic network in the area was formed during the second phase of Graben evolution (Quaternary up to the beginning of last century). During third period (from the beginning of last century), flood preventing draining and irrigation works have been conducted. This last period is characterized by the creation of a "man-made hydrography".

Changes in bedding, as well as the creation of meandering, were also common. About 63% of the Serres plain, is covered by marshes, lakes, ponds and periodically flooded land, and only 37% of the area was not threatened by floods. The large projects carried out in the area caused the drainage of the ponds and marshes, the rehabilitation of several thousand acres, which were given to local population for cultivation. It is estimated that 62% of the previous lakes and stretches of land have been allocated for agricultural use. Among the improvement projects including the drying of Lake Achinos, were the arrangement of the bed of the Strymon and the remaking of the old lake Kerkinitis known today as Kerkini.

Strymon River flow is man-controlled through the artificial Kerkini Lake and all along the downstream. From the Kerkini Lake to the area of the former lake of Achinos there is a parallel drainage canal which has dimensions of a river and drains several torrents from the north-east slope of the basin. During the irrigation period (May - September) a maximum discharge of 40 m³/s is released downstream the Lake while of the rest of the year a maximum amount of 200 m³/s is allowed in Strymon River downstream the Lake (Doulgeris et al., 2008). The Dam affects the stratification conditions in Strymon River mouth during spring and early summer (April to June) (Syllaios et al., 2010). Furthermore, the silting of the lake with debris from the river Strymon and the deposition in the delta formed by the river at the entrance to Kerkini creates a major problem reducing the total volume of the water. Essentially, the retention of sediment reduces the effective volume so it cannot store much water or even defuse flood benefits. The deposition processes of Kerkini were the major causes of its development into an internationally important wetland and biotope. Kerkini offers development opportunities for scientific research, environmental education, ecotourism, and recreation activities (Psilovikos and Margoni, 2010). Lake Kerkini should be considered as eutrophic with a tendency to become hypertrophic. River inflows greatly affect the reservoir's water volume, nutrients concentration and water's transparency which consequently affects the plankton growth (Kamarianos et al., 1993).

2.2. About active remote sensing sensors and flood mapping

SAR systems emit microwave radiance, and then coherently record the amplitude and phase of the returned signal to produce images of the earth's surface. SAR measurements are regardless of weather conditions and daytime, offering valuable information for flood monitoring. Parameters that affect and determine the response of the radar signal can be summarized to those who depend on (i) the system itself (direction of observation, frequency, wavelength and polarization), (ii) the landscape characteristics and properties (roughness, moisture) and (iii) environmental, climatic and anthropogenic factors (temperature, rain, fog, wind).

One of the major advantages of using SAR images corresponds to the way that the incoming microwave signal interacts with water. The ground, for its part, gives a much greater amount of radar energy due for example to the surface roughness and this generates the high contrast between surfaces: ground and water. Smooth water bodies act as a mirror reflecting surface, the return backscatter signal towards the satellite is low or null and thus water appears black in SAR imagery (Rees, 2001). At the same time, a wind-ruffled surface can give strong backscatter signal larger than the surrounding land. This for example complicates the detection of water surfaces on SAR images for flood applications.

Over the past decades, several studies have used SAR data to map flood bodies with different techniques. Among the many flood extent mapping techniques currently available, commonly used methods are simple visual interpretation (Oberstadler et al., 1997), supervised classification (De Roo et al., 1999; Townsend, 2002, Psomiadis 2016), histogram thresholding (Hostache, 2006; Schumann et al., 2007), and several different multitemporal change detection methods (Bazi et al., 2005). Active contour models based on image statistics have also been used by Bates et al., (1997) and Horritt (1999). Mason et al., (2007) and Pierdicca et al., (2008) proposed a flood extraction algorithm considering both the SAR image and the Digital Elevation Model (DEM) of the region, so that waterlines (instantaneous land-water boundaries) in the outcome flood map are conditioned to be smoothly varying in ground height along the river reach. Pulvirenti et al., (2011) introduced a method that couples segmentation techniques and a SAR backscatter model. On a different note, in another study, Schlaffer et al., (2012) proposed a harmonic analysis of multitemporal ENVISAT Advanced SAR (ASAR) time series to delineate flood events. Additionally, the discrimination of inundated areas can be optimized by selecting the most suitable polarization of the radar waves. Henry et al., (2006) compared the ENVISAT ASAR with the performance of the SAR system on ERS-2 to evaluate the contribution of polarized configurations to flood boundary delineation. The ASAR instrument was activated in the alternating polarization and image modes, providing high-resolution data sets. They observed that HH polarization provides a more suitable discrimination of flooded areas than HV or VV. However, HV improved the existing HH data and proved to be an important contributor to flood detection. VV polarized data was highly influenced by surface roughness conditions.

The availability of new EO products, such as Sentinel-1A & B imagery has the potential to facilitate flood detection and monitoring of surface waters changes which are very dynamic in space and time (Bioresita et al., 2017). The enhanced observational capabilities of C-band Sentinel-1 radar in terms of dualpol acquisition mode, the medium spatial resolution (20m) with a very wide swath (250 km width), the high repeat cycle (temporal resolution of 6 days) could be fruitfully used for a more accurate detection of floodwater especially in vegetated and urban areas.

3. Materials and Methods

3.1 SAR images

A total number of 14 GRD SAR scenes, in descending and one in ascending Interferometric Wide swath (IW) mode, with dual polarization VV and VH, were collected spanning the period from October 2014 to October 2015. Those SAR scenes series were employed to investigate the

multitemporal backscatter properties in the area.

Various image processing techniques were used to delimit areas covered by water from SAR images. These data were processed, analyzed and combined to detect land/ water boundary and then focus on isolation of water bodies and finally to investigate multitemporal backscatter signatures over the study area. To achieve the above task, this study is based on the expected contrast variations between the backscattering signatures of land and water.

The SAR images were first processed using the SNAP version 5.0 ESA's open s/w to improve their characteristics with applying orbit file operator, calibration, speckle filtering, subsided over the area of investigation and were finally terrain corrected using the DEM SAR-simulation method. Binarization was used to separate land from water using the suitable threshold for each image-date. Hazard maps were converted in kmz files and then imported into the Google Earth environment overlapping high resolution optical images in order to better identify the areas affected by the flood phenomenon.

3.2 Hydro-Meteorological data

For the under-investigation period, the mean monthly accumulated precipitation from three meteorological stations (Figure 2) was collected using the interactive map of the National Observatory of Athens/ Institute of Environmental Research and Sustainable Development. We obtained data from the stations Achladochori (41,318 N / 23,536 E), Lithotopos (41,137 N / 23,217 E) and Koimissi Serron (41,214 N / 23,297 E). As shown in Figure 2 the rainfall is spread over the study period. Both the three meteorological stations show a maximum in December 2014 with an accumulated monthly rate about 145 mm. The second maximum value (maximum 100 mm) appears on March, and the third on June continuing the downward trend in rates (maximum 90 mm).

The relative stream flow measurements were collected from a single location, namely Faros area, of the Strymon river (41° 16' 23'' N / 23° 19' 51'' E) about 10 km before river's outlet to the lake Kerkini. Measurements were collected every half an hour and then converted to monthly average. In Figure 2, the mean relative values of Strymon water level are shown for the under investigation period. The most significant change in water level is observed on February, when the level increased to about 265 cm, then the rates trend is apparently downward.

4. Data Processing

4.1 SAR data processing

Processing is based on ESA's Sentinel Application Platform (SNAP) version 5.0 using ESA's Virtual Machine facilities. The orbit state vector accompanying the SAR scenes downloaded from the Copernicus Hub, are generally not very accurate and must be updated with the precise orbit parameters. This refinement provides scene's metadata with accurate satellite position and velocity information. Following orbit file refinement, a subset (Figure 1) of the whole image was created.

After image subsetting, radiometric correction has been applied so that pixel values can be directly related to radar backscatter. Image calibration is essential for quantitative use of the SAR data as the pixel values represent the true radar backscatter of the reflecting surface. In the case of Sentinel-1 data, a calibration vector is included as an annotation allowing conversion of the image intensity values into sigma nought values (σ^0). From this step onward the processing relates to the use of VV polarity. The above mentioned actions are considered as pre-processing steps. In this study the main product was water and non-water binary images. For obtaining the water/non-water products the image binarization technique is applied.

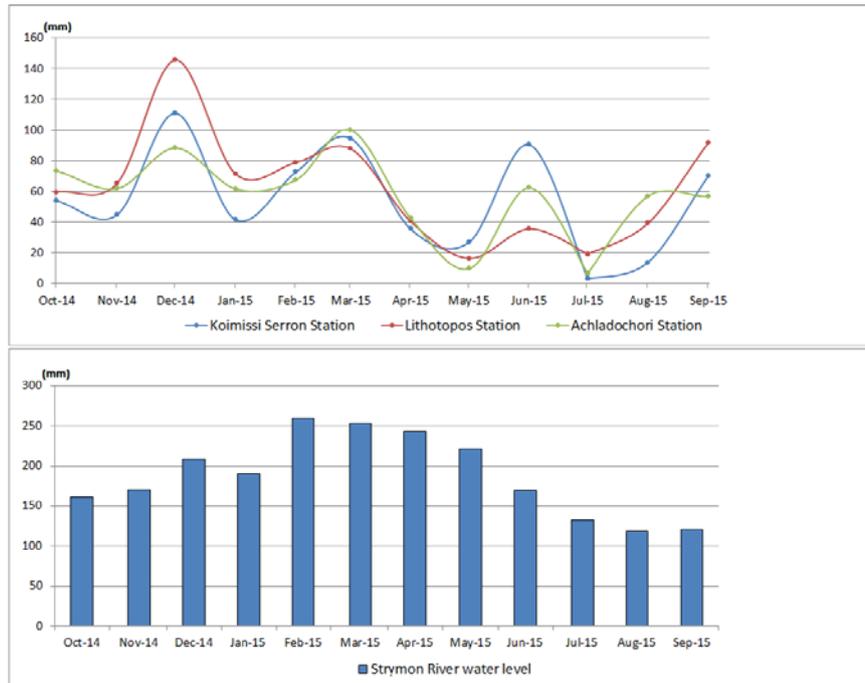


Figure 2. Diagrams of the precipitations (up) and river's water level changes (down).

The first step to separate water from non-water areas, through binarization, is the calculation and selection of a threshold. For this purpose, we have investigated the histogram of the filtered backscatter coefficient. In order to facilitate this investigation a logarithmic display of the histogram is selected. Normally the histograms show two peaks (pixel value frequencies) of a different magnitude of backscattering. Low values of the backscatter corresponded to the water, while high values corresponded to the non-water areas. The aim was to specify the backscatter value separating the two set of pixels (water and non-water). Our goal was to create a new binary image which would be, for example, a value of 255, for water objects, and 0 for land objects. To do this, we use the following Expression:

$$\text{Binary band} = 255 * (\text{Sigma0_VV} < h)$$

Where h is the selected threshold based on the histogram from each amplitude image.

The expression will return the logical value: true (or 1) for values less than the threshold's value, and false (or 0) for higher values. Then we just multiply by 255. The bright areas in the final image represent the water areas and dark ones the non-water. After the above processing steps, the products generated were the subset amplitude images and the water/ non-water binary image for each date as well. The obtained images are in the geometry of the sensor, so it is necessary to re-project them into geographic projection. The scenes were firstly co-registered and stacked collocating the master and slave images into a single reference (master) geometry. As the spatial registration of the imagery is an essential requirement for effective change detection, the RMS value of the polynomial transformation of all pairs was decisively less than a pixel (0.05 of pixel). The Range Doppler orthorectification method (Small and Schubert 2008) was used for geocoding the SAR images from 2D raster radar geometry, considering for this purpose available information in the image's metadata about orbit state, radar timing annotation, slant to ground range conversion parameters in combination with DEM (SRTM 3sec Arc) to derive precise geolocation information. The map projection type of the output images was expressed in WGS84 geographic coordinates.

5. Interpretation-Analysis

Observing the binary water/ non-water images, we discern that the first changes in the surface waters coverage are mainly spotted in December 2014 when compared to October and November of the same year in Lake Kerkini and specifically in the area of the river delta of the lake. Lake level remains stable over the next month of January. On the downstream of the basin, there is a small first indication of water coverage, during January, along with the river in the area between the settlements of Achinos and Pethelinos (Figure 3). The first significant change in the shoreline of the lake, particularly in the north and east part, occurs in February. Downstream, near the area of Achinos-Pethelinos some water coverage southwards and specifically immediately after the convergence of the Rivers Aggitis and Strymon were recorded. Aggitis River drains a small basin to the west of Serres Basin (Figure 3). Beginning of March and while the lake's level does not change significantly, at downstream the flood phenomenon is ongoing both in the area of the old Achinos Lake and further south after the convergence of the two rivers (Figure 3).

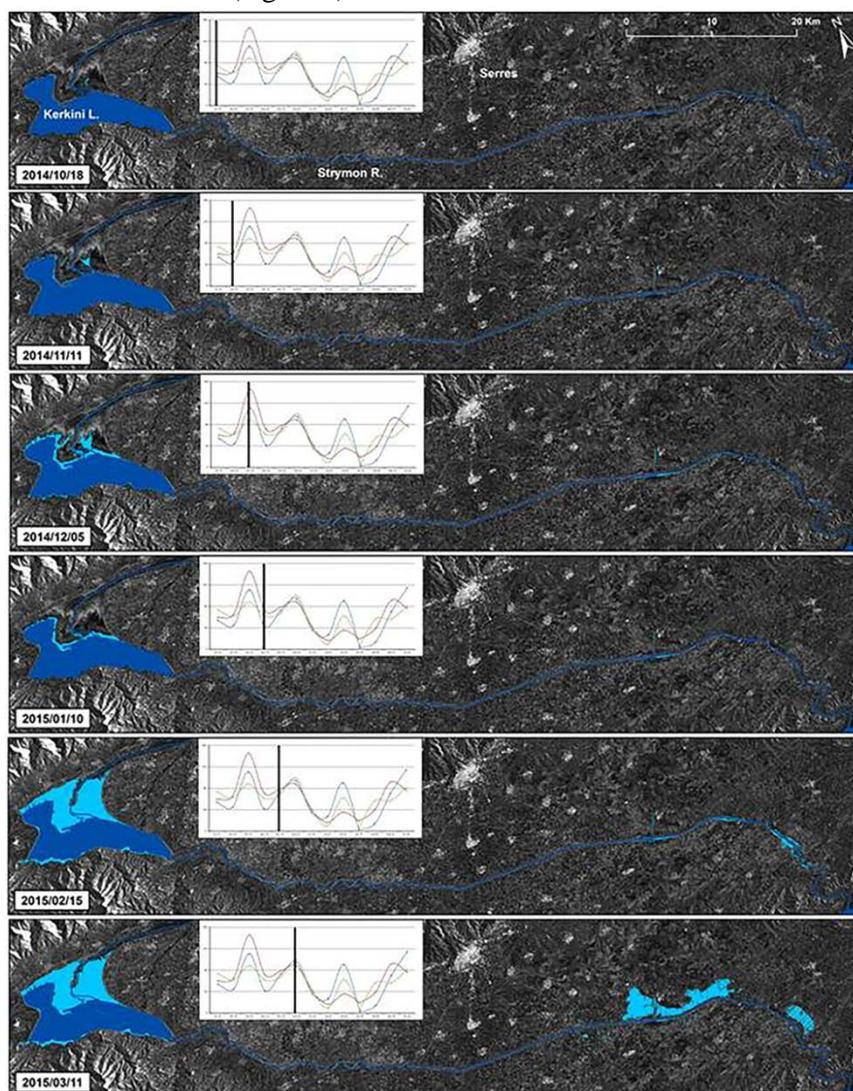


Figure 3. Binary images water/non water from October 2014 to March 2015.

The next month the lake's water level is stable while in the downstream the two flooded areas tend to be unified due to the spatial expansion of the phenomenon (Figure 4). In May (Figure 4), there is a slight change in the lake's level, in fact, it decreases. The most significant change is

observed in the downstream where the southern inundated area is drained while in the area of old Achinos Lake, the standing water is withdrawn partially. Locally standing water areas close to Provatas about 12 km south of the Kerkini Lake and along the River are considered with scepticism, because they could be related to rice crops that are the most common in this area. At this time of the year, the rice fields are in seed period and are filled with water. During the dry period (June, July, August of 2015), the lake's level is constantly shrinking on the north and east coasts, and there is also an accelerated water withdrawal from the flooded areas in the downstream. In September, while the lake's level is now stable, no further indication of land under water is visible (Figure 4).

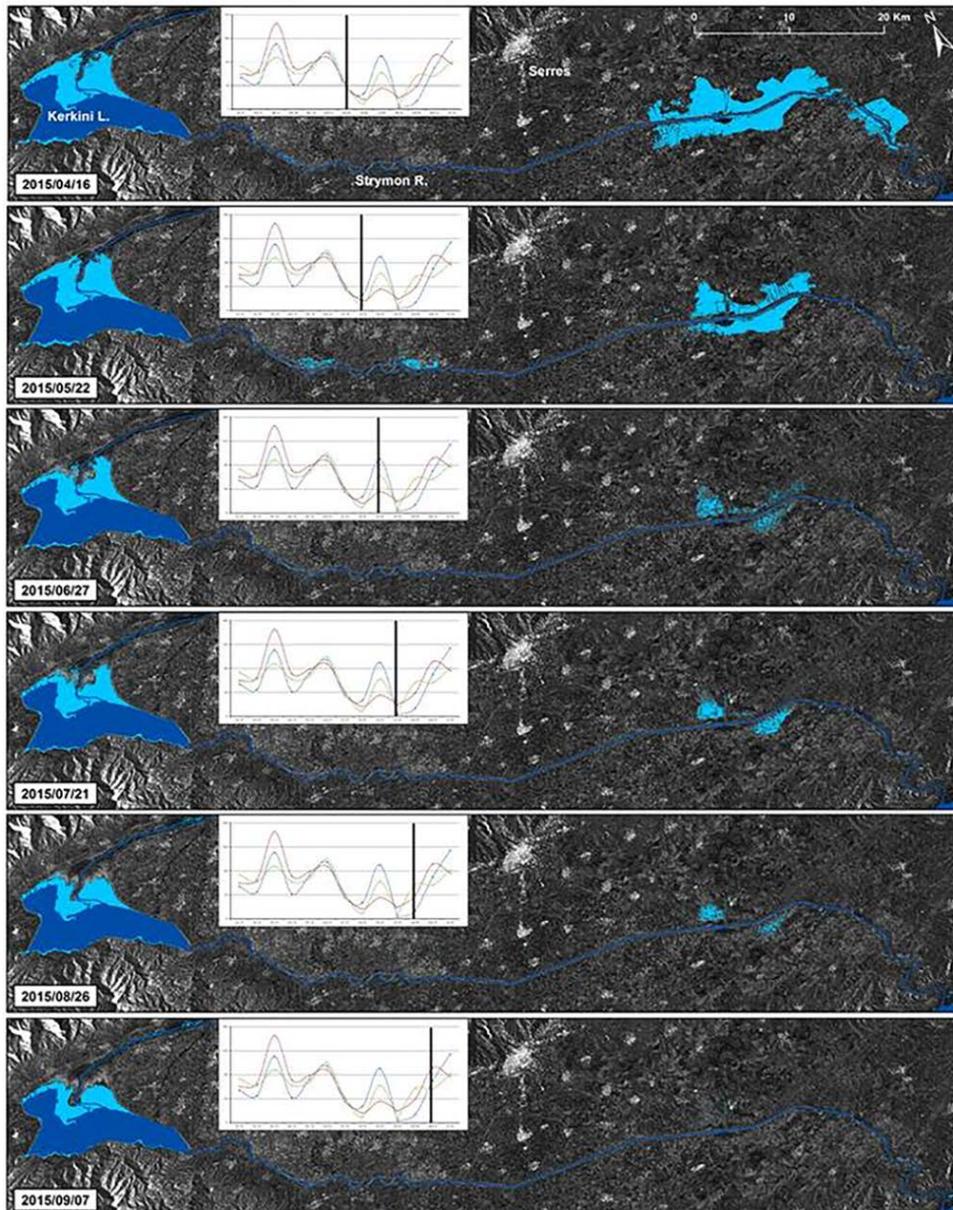


Figure 4. Binary images water/non water from May 2015 to September 2015.

6. Discussion - Conclusions

The main objectives of the current research firstly concern the record of a flood event in a reservoir-regulated river basin located in Serres, by monitoring the dynamic of the flood occurred on downstream in the period 2014-15. While changes in water amount of the Lake Kerkini are recorded at the same time. For both objectives were create retrospective products for

flood extent working with archived EO data and therefore improve flood-related knowledge. Results can be summarized as follows:

- The spatio-temporal mapping of the phenomenon based on SAR imagery has produced excellent hazard maps without any particular obstacles. Without the presence of tree crops or high vegetation and because of the early stage of the development of the crop during the monitoring period, the signal scattering was not affected and thus permits flooded areas detection within agricultural land use. The only issue worth mentioning concerns the fact that for two acquisition dates imagery due to the strong winds that prevailed that days creation of waves in the standing water making thresholds discrimination difficult to define.
- Identification the beginning of March as the start time of the flood event and July as the end of it.
- Identification of the inundated areas in the downstream, specifically the area of the old lake of Achinos and further south immediately after the junction of Strymon river with Aggitis river (Figure5).
- The maximum flood extension takes place in April when the two flooded areas are close to being unified.
- Our SAR based results show that the most vulnerable to flood area is the low topography land of old lake Achinos (Figure5).

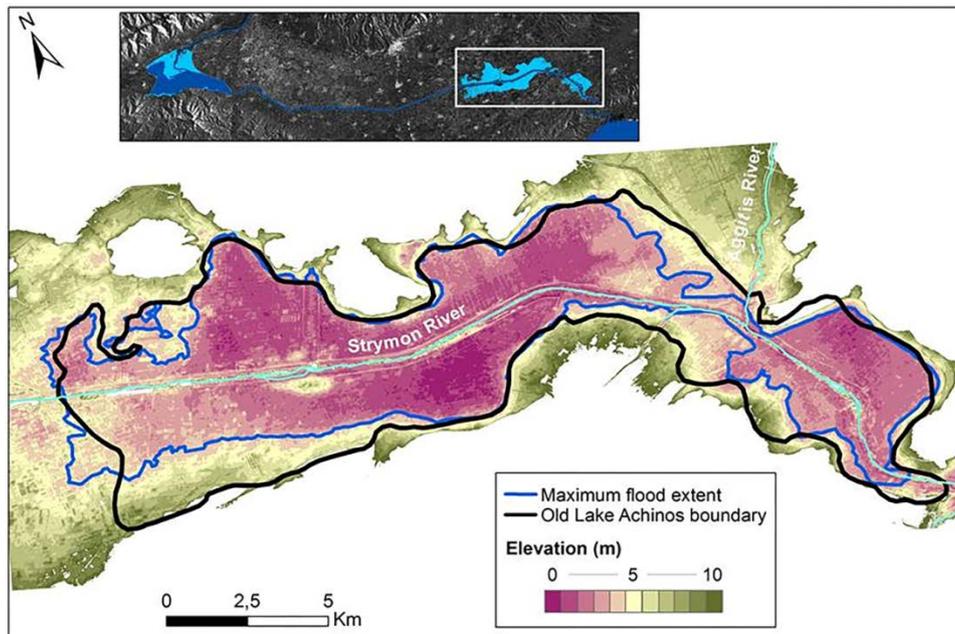


Figure 5. A composition of topography, altitude and maximum inundation in the area of old Achinos Lake

7. Acknowledgments

Authors would like to thank Dr. Francesco Sarti (ESA/ESRIN), Mr. Michael Davis (Lake Kerkini Management Authority) and Mrs Vassiliki Amanatidou (Serres Basin agricultural cooperative).

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