Time Series Synthetic Aperture Radar Interferometry for Ground Deformation Monitoring over a Small Scale Tectonically Active Deltaic Environment (Mornos, Central Greece)

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ABSTRACT
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This study deals with the estimation of subtle ground deformation at millimetric accuracy over the broader area of the Mornos River delta in Central Greece and its spatio-temporal distribution for the period between 1992 and 2009 through Persistent Scatterers Interferometry (PSI). The results showed that the majority of the scatterers, which show subsidence, are located within the delta plain with mean subsidence rates throughout the delta varying between –7.2 and +0.7 mm/y. An attempt is made to highlight the geographic distribution, the amplitude, and the causes of the observed delta plain subsidence. The positive correlation between the thickness of the fine-grained Holocene deltaic deposits and the subsidence rates reveals that the main cause is the natural compaction of sediments. The highest subsidence is observed at Bouka Karahassani village, which corresponds to the area of the most recently abandoned river mouth, which is intensely eroded by marine processes. Apart from the dominance of fine sediments in the study area, subsidence may also be attributed to submarine gravitational mass movements along the steep slopes of the prodelta as well as to the reduction of sediment load after the dam construction in 1979. The NW part of the delta seems to have been affected by aseismic slip along a NE-SW trending normal fault buried beneath the alluvial deposits of the Skala torrent fan.

ADDITIONAL INDEX WORDS: River Deltas, subsidence, Persistent Scatterers Interferometry, Mornos River Delta.

INTRODUCTION
Repeat-pass interferometry is a unique tool for large-scale monitoring (spatially continuous) of surface deformation at a low cost (Massonnet et al., 1993; Zebker et al., 1994). Regardless of the applied differential interferometric method, repeat-pass interferometry is limited by a number of parameters, such as

- large baselines, which lead to low correlation attributable to spectral shift for distributed targets;
- loss of coherence attributable to long temporal separation between acquisitions;
- difficulties to unwrap interferograms with large baseline attributable to low correlation and high fringe rates; and
- atmospheric artifacts attributable to tropospheric water vapor and ionospheric electron density.

The Permanent or Persistent Scatterers Interferometry (PSI) (Ferretti, Prati, and Rocca, 2001; Hanssen, 2005; Werner et al., 2003), a relatively recent development used to overcome the previous limitations, is a technique implemented to calculate fine motions of individual points over wide areas covering mainly urban and semiurban environments (Burgmann et al., 2006; Colesanti et al., 2003; Parcharidis et al., 2006; Raucoules et al., 2008; Salvi et al., 2004; Testini et al., 2005). The technique uses a series of coregistered Synthetic Aperture Radar (SAR) scenes to identify time persistent scatterer (PS) points. The processing is carried out on these persistent points of the SAR images having stable radiometric characteristics. By examining their interferometric phase it is possible to monitor ground stability for an area that is normally characterized by its low coherence. Additionally millimetric target displacement along the line of sight directions can be detected, allowing the measurement of slow terrain motion (Ferretti, Prati, and Rocca, 2001; Hanssen, 2005).

The unique benefit of PS interferometry is its ability to provide both annual average motion rates and deformation histories for the individual targets (Parcharidis et al., 2009).

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River deltas are coastal features developed from the accumulation of sediment near the mouth of rivers. They have been and continue to be the heart of economic developments. They confront the coastal regions with dynamically changing qualitative and quantitative characteristics of the river that feeds them. Pollution, canalization, urbanization, and deforestation within the catchment areas affect the delta environment. The deltas themselves are protected areas and/or are characterized by agricultural activity and in many cases by the existence of urban centers. On tectonically active areas, delta evolution may be influenced by abrupt relative sea level changes attributable mainly to coseismic uplift or subsidence (Barnhardt and Sherrod, 2006).

Land subsidence is a common phenomenon in modern delta plains because of compaction of sediments by consolidation of the dewatered material, compression of the load of the subsequent overburden deposits, and groundwater or oil pumping (Day et al., 1995; Dumont and El-Shabrawy, 2007; Meckel, Ten Brink, and Williams, 2007; Nageswara Rao et al., 2010; Shi et al., 2007; Stanley, 2005). Previous studies on delta rivers based on field data show that deformation features of the hydrographic units are greatly related to hydrogeological properties and ground–water–level variations. An identical hydrographic unit may exhibit different deformation features in different locations, and additionally the hydrogeology in the same location could exhibit different deformation in different periods or seasons (Shi et al., 2008; Wu et al., 2008). Except near coastal areas, land subsidence because of ground-water pumping generally is not a serious hazard if the whole area subsides. The major problems related to subsidence areas are the potential destructive results caused by differential subsidence (Holzer and Pampeyer, 1981).

Several studies were made on land subsidence from various river deltas around the world. Cencini (1998) investigated the subsiding Po delta in Italy, the greater part of which lies below sea level today. Stanley and Warne (1998) described and discussed symptoms of a destruction phase of the Nile delta in Egypt during the past 150 years, triggered by water regulation schemes. A dam completed in 1979 regulates its flow. The Mornos River, about 200 km west of Athens, drains the SE Pindos Mountain and is one of the two existing water resources that supply the greater Athens area with potable water. A dam completed in 1979 regulates its flow. The Mornos delta, a subaerial delta with fan-shaped body (Piper et al., 1990), is located in the NW Gulf of Corinth (Figure 1). The Gulf is an asymmetric rift and one of the most active continental tectonic structures in the Mediterranean area (Armijo et al., 1996; Avallone et al., 2004).

The present paper concerns the application of PSI to detect ground deformation in the Mornos delta for the period 1992–2009. The objective of the study is three-fold: (i) detect spatial-temporal deformation of the delta, (ii) distinguish between deformation attributable to natural delta sediment compaction and deformation induced by human activities, and (iii) investigate the existence of differential vertical subsidence in the delta area caused by buried fault zones and submarine mass movements.

Data and Methodology

In this study SAR and Advanced SAR (ASAR) scenes from ERS-1,2 and ENVISAT satellites, respectively, were used. In total 71 Single Look Complex (SLC) scenes in descending orbits, VV polarization, and operating in C-band (track:279, 704,
frame:2835) were used. From them 42 were acquired from ERS covering the time period 1992–2001, and 29 were from Envisat (ERS-like mode) covering the time period 2002–09. Moreover, a Digital Elevation Model (DEM) produced by the Shuttle Radar Topography Mission was used with approximate spatial resolution of 90 m. Finally, precise orbit vectors were ingested in processing to enhance the accuracy of the satellite’s orbit and estimate the initial interferometric baselines. Specifically, for ERS scenes, orbit data from DELFT Institute (NL) for Earth-Oriented Space Research (DEOS) (Scharoo and Visser, 1998) were obtained, and for ENVISAT scenes orbit data from Doppler Orbitography and
Radio-positioning Integrated by Satellite (DORIS) instrument were obtained.

The differential interferometric methodology that will be used in this study was basically the PSI based on the Interferometric Point Target Analysis (IPTA) algorithms included in GAMMA software. The IPTA is a toolbox that can support many different methodologies including different methodologies for candidate scatterers selection, spatial and temporal phase unwrapping, etc. Subsidence within the delta plain was estimated through the IPTA.

In order to investigate the influence of sediment compaction on the differential subsidence within the delta plain, boring log sediment descriptions of 17 boreholes were considered. Borehole data were obtained from a geophysical study conducted by the Ministry of Agriculture during the late 1970s at the deltaic plain. These boreholes were drilled as part of a proper water resources exploration program in the deltaic plain, initiated because of the disturbance of the hydrogeological conditions of the broader delta area caused by the construction of a dam at the upper reaches of the river. For each borehole the percentages of coarse- and fine-grained sediments in the drilling log was estimated. A buffer zone of 200 m around the location of each borehole was created, and mean annual subsidence rates were calculated for the time period under study. Then a plot of the percentage of fine sediments in the boring logs vs. mean annual subsidence rate was created.

In an attempt to determine the main causes of variability of deformation rates in different parts of the delta plain, data and observations regarding the geomorphology of the subaerial delta plain, the subaqueous prodelta, as well as the delta shoreline retreat, were also collected.

GEOLOGY AND GEOMORPHOLOGY OF THE STUDY AREA

The Mornos River delta is a Gilbert-type fan-shaped alluvial body located on the northern side of the western Gulf of Corinth. It occupies an area of 28 km² and has a mean delta plain gradient of 0.004% (0.2').

According to the delta classification proposed by Galloway (1975) it should be classified among those affected mainly by fluvial sediment supply and wave activity, while its development began during the Late Holocene with the relative stabilization of the sea-level rise. The configuration of the delta is the result of suitable conditions for delta formation during the Late Holocene. Intensive weathering and erosion over the catchment area of the Mornos River has resulted in the production of large quantities of sediments readily available for transportation. This process was enhanced by the lithology and climate conditions of the drainage basin as well as by the characteristics of the receiving basin (Gulf of Corinth). A large part of the drainage basin (54.4% of the total area) consists of clastic sedimentary rocks, which are mainly fluvial formations of great erodibility. Additionally mean annual precipitation is high enough, fluctuating between 600 mm near the delta to more than 1200 mm in the N and NE highlands with most of the rain falling between November and February. Mean annual discharge is approximately 40 m³/s and follows the precipitation trend with the greatest flow recorded during the winter months. The flow of the river has been regulated since 1980 by a dam constructed in the upper reaches of the basin in order to supply Athens with potable water. The suspended sediment load of the river prior to the dam construction was estimated between 0.5–0.8 tons/y/km² (Piper et al., 1990).

Subaerial Morphology

The Mornos River has a braided gravel channel aligned and enclosed by artificial levees along its entire delta length to its present mouth in the western part of the delta. The 1945 aerial photographs show that there were two active distributaries with the main channel located in the central SE part of the delta plain while the present river channel was a lesser distributary. The eastern course had a more meandering pattern and was flowing through the center of the deltaic plain discharging 3.7 km east of the present active river mouth. This channel was partially abandoned after the artificial alignment of the now active channel that took place in 1961. Following construction of the dam in the upper reaches of the drainage basin in 1980, the sediment supply decreased significantly downstream, and this channel has been totally abandoned. Karymbalis, Gaki-Papanastassiou, and Maroukian (2007) mapped older abandoned channels and grouped them in four systems that begin from the apex of the delta leading to the present shoreline. Old reliable maps of 1852 and 1885 depict that there was one active distributary channel located in the western part of the delta during that period. This now abandoned river path lies about 0.6 km west of the present channel. In the 1885 map, flooded abandoned channels are also visible in the central part of the deltaic plain. Another abandoned channel system begins from the apex of the delta ending SE of Managouli village about 1.9 km NE of the Bouka Karahassani mouth and seems to be older than that because it has undergone intense retreat that is attributable to marine erosion. The easternmost channel system has a W-NW–E-SE direction north of Logos village leading to the 0.5 km north of Chiladou at the eastern end of the deltaic plain (Figure 2). This channel maintains a meandering pattern for the last 1.4 km before reaching the shoreline. These traces seem to be the oldest visible distributary channels of the Mornos River delta. The arcuate shape of the fan delta, the abandoned channels, and the dominance of gravel suggests that delta growth took place by gradual shifting of braided distributaries westwards.

Shoreline Shift

Today coastal erosion is the dominant geomorphic process along the delta coastline because of construction of the dam that has drastically reduced the sediment flux leading to subsidence of the deltaic environment and enhancing the wave activity effectiveness. The eastern coast, NE of the most recently abandoned river mouth, has retreated approximately 86 m between 1945 and 1986, corresponding to a rate of 2.14 m/y (Karymbalis, Gaki-Papanastassiou, and Maroukian, 2007). Retreat rate accelerated to 3.25 m/y for the period between 1986 and 1998. Today, the only region where the fan delta progrades is the area between the present mouth and Bouka.
Karahassani. A progradation rate of 3.4 m/y is estimated between 1945 and 1998 following the redistribution of the sediment derived from the erosion of the abandoned mouth and the eastern shores by longshore drift from the east.

Although the main distributary prograded at a rate of approximately 4 m/y between 1945 and 1986, a retreat of 11.4 m/y is observed between 1986 and 1998 because of the construction of the dam.

**Subsurface Stratigraphy**

The subsurface stratigraphy of the deltaic sediments is based on the description of 17 borehole logs distributed over the delta plain (Figures 3 and 4). The basement of the Mornos River delta is composed of a compaction-free Mesozoic substratum overlain by a Late Holocene sediment sequence. This basement is constructed by the geological formations of flysch and limestone that belong to the geotectonic zones of Pindos. Test drilling and geophysical investigation detected the existence of three main foldings of the rocks that form the deltaic sediments basement. The axes of these forms have an almost N-S trend and divide the subsurface waters in three different parts. The borehole logs indicate that the deltaic alluvial body of the Mornos River consists of a series of fluvial deltaic sediments with a thickness ranging from 60 to 150 m.

The stratigraphy of the recent deltaic sediments is not uniform and is laterally variable. The subsurface sedimentary sequences are characterized by alternations of coarse sediments (gravels and pebbles), fine-grained layers (silt and sand), and mixed deposits (gravels, pebbles, and silt). Detailed stratigraphic information is unavailable for much of the delta plain, and stratigraphic heterogeneity leads to uncertainties where borings are unavailable. Although the stratigraphy of this recent complex delta is obviously not uniform but laterally variable and deviating from an idealized scheme, the sedimentation pattern seems to be typical of a fan delta. The logs of the boreholes that are located near the apex and the margins of the delta are represented by the abundance of coarse material. On the other hand the southernmost borehole logs consist of fine-grained layers interrupted by coarse materials. Fine sediments, which probably represent overbank sediments, deposit during flood events in the evolutionary phases of the delta. Pebbles and gravels correspond to channel sediments deposited by older, now buried distributary braided channels. Under the delta three distinct aquifers can be distinguished: the quaternary, the flysch, and the karstic limestone aquifers (Louis et al., 2004).
Subaqueous Morphology

The western Gulf of Corinth, where the study area is located, is a complex asymmetrical graben and is presently the most tectonically active part with geodetic extension rates reaching up to 14–16 mm/y (Bernard et al., 1997) and intense seismicity (Lyon-Caen et al., 2004). The morphology of the broader area of the subaqueous part of the Mornos delta is shown in Figure 5. Seismic profiling surveys and recent swath bathymetry provide accuracy on the submarine topography (Piper et al., 1990; Tinti et al., 2007). The northern edge of the central graben is marked by a sea-floor fault scarp running down the center of the Gulf. This fault scarp is obscured both by progradation of the Mornos delta and by more distal mud deposits.

The southern prodelta slope of the Mornos has flat reflective bottoms (sandy channels, lobes, and slumps) on 3.5-kHz profiles and is floored by silty sand. Seaward of the SW active distributary mouth of the Mornos, the sea floor on the prodelta slope is irregular. Seaward of the abandoned SE distributary mouth there is a deeply incised valley. The prodelta slope to the SW of this valley is locally modified because of slumping. To the NE of the valley the muddy prodelta is cut by a series of gullies, while on the lower prodelta slope where there is a broad elongated depression, it is interpreted as a slump scar. Slumps have been mapped off the Mornos delta, and slumped material or debris flows seem to be important locally.

Recent swath bathymetry performed by the Hellenic Centre for Marine Research revealed that the most prominent potentially unstable bodies of the western Gulf of Corinth are found along the east-facing steep prodelta slopes off the abandoned distributary channel of Bouka Karahassani (Tinti et al., 2007). Much of the suspended load of the river is probably deposited on the prodelta slope. This suspended sediment accumulation, which is estimated as 0.5–0.8 tons per year,
corresponds to a 2 cm/y sedimentation rate if all of this sediment is distributed uniformly over the entire prodelta slope. The morphology of the flank, which is dominated by steep slopes (gradients immediately off the river mouth are 18°) and the presence of large amounts of sediments discharged by the Mornos River, create favorable conditions for sediment failure under seismic or gravitational load (Lykousis, Sakellariou, and Roussakis, 2003). For instance between 1889 and 1939, the Patras–Corinth no. 2 telegraph cable broke several times off the Mornos delta (Heezen, Ewing, and Johnson, 1966). Two breaks were associated with seismic activity; the remaining occurred between the months of October and early May and was probably related to sediment slumping or turbidity currents following heavy river discharge (Piper et al., 1990). These gravitational mass movements seem to affect the subsidence along the deltaic coastal zone and especially the east-facing coastline.

INTERFEROMETRIC PROCESSING

Preprocessing

Two separate processing procedures were carried out for ERS and ENVISAT datasets, respectively. The first common step was the coregistration of the SLC scenes so that each scene obtains the same geometry. For each dataset the geometry of the first scene (November 12, 1992, for ERS and October 20, 2002, for ENVISAT) was used as reference geometry. The achieved coregistration accuracy was satisfactory with standard deviations of individual range and azimuth offsets from the offset regression fit, less than 0.3 pixels.

Moreover, the geocoding equations were applied on the DEM in order to convert its geometry into the SLC scene geometry.

Main Processing

Based on the coregistered SLC scenes, two candidate lists of PSs were initially estimated using two different selection approaches. The first list was generated based on phase properties. More specifically this approach identifies point targets with low spectral phase diversity. The spectral phase characteristics are averaged over the stack of SLC scenes, and afterwards the average spectral behavior is used to designate the candidate PS. The second approach is based on low intensity variability as the intensity and phase depend on the point-target cross section and position. Then, the two candidate point lists were combined into a single one, which finally was used for the analysis. A total number of approximately 18,000 and 20,000 candidate points for ERS-1, 2 and ENVISAT dataset, respectively, were determined. The spatial distribution of the candidate points is not homogeneous with high densities of PS located in built-up areas and low densities over fields.

The IPTA methodology requires one single scene as reference in order to form multiple pairs and produce interferograms. The criteria by which the reference scene was selected were the following: (i) forming interferometric pairs with the minimum baseline (Bp), (ii) acquisition date near the central date of the time period for which there are available SAR acquisitions, and (iii) reference scene to present low atmospheric distortions. The scenes that fulfilled the previous criteria were June 3, 1995, for
the ERS dataset with an average Bp of 379 m, and May 22, 2005, for the ENVISAT with an average Bp of 78 m. Afterwards the initial differential interferograms were produced using the coregistered SLCs, the DEM heights, and the preceding point lists. This is performed by simulation of the unwrapped interferometric phase based on the initial baselines and the DEM. Then, the differential interferograms were analyzed in the temporal and spatial domain in order to obtain information on the atmospheric phase term, deformation phase term, and baseline errors. Thus, processing proceeds by applying a least-squares regression on the differential phases in order to estimate terrain height and deformation rate relative to a reference point target.

Because the aforementioned terms depend on the distance between points in the image, differential interferograms were thus divided in patches, and for each patch the PS with the highest quality was selected as a reference PS point. Then for each PS, phase differences between the reference PS point and its phase values were introduced in the regression analysis in order to estimate (i) the baseline error and correct the PS-height value, and (ii) the deformation and atmospheric rate relative to the reference point.

Based on the regression analysis, the quality of the PS candidates was further evaluated through the estimated standard deviation of the phase difference. PSs with a phase standard deviation larger than the indicated threshold (in this case, 20 m) were discarded.
case 1.0 radian in both datasets) was rejected, significantly reducing the number of points. The majority of the rejected points were located over mountainous areas. A total number of 3353 and 3857 scatterers for the time period 1992–2000 and 2002–09, respectively, were detected.

Moreover, because residual phases contain the atmospheric term, nonlinear deformation, and error terms, they were further processed in order to compensate atmospheric and noise effects. Thus, residual phases were spatially filtered by applying a low-pass spatial filter. Atmospheric and error terms were reduced by the spatial filtering around the reference points, assuming that stability occurred in the region of the area. Further iteration was done in order to apply additional corrections in the final regression model.

The generated results consist of height corrections, linear deformation rates, atmospheric phase, refined baselines, temporal coherence, and nonlinear deformation histories for each scatterer. Finally the deformation phases were transformed into displacements and geocoded to the selected cartographic reference system (UTM, wgs’84).

RESULTS AND DISCUSSION

Following the transformation of the interferometric phases from range–Doppler coordinates into map geometry (geographic coordinates), PSs were imported into a GIS environment and plotted on a high-resolution Quickbird image (Figures 6 and 7). In both time periods it is obvious that the majority of the scatterers, which show subsidence, are located within the delta.

The diagram of percentage of fine sediments of the boring log vs. subsidence rate indicates that differential natural compaction attributable to subjacent grain-size variability is a significant factor (Figure 8). For instance studies in the Rhine-Meuse delta in The Netherlands provide an example of >6 m of differential compaction that could be related to a subsurface sand body. The plot shows a positive correlation between subsidence rate and the thickness of the fine-grained sediment participation in the subsurface sedimentary sequence. Thus natural compaction of delta sediments seems to be the main reason for the observed ground subsidence of the delta plain surface. Natural compaction happens as new sediment (weight) is added to the deltaic sedimentary sequence, and the underlying sediment is reduced of its water content because of reduction of the void spaces between grains (Meckel, Ten Brink, and Williams, 2007). According to Meckel, Ten Brink, and Williams (2007), compaction rates vary over three orders of magnitude, but 80% of the rates are between 0.7 and 2.2 mm/y with heterogeneity in sediment layers increasing the rate of compaction. As shown in Figures 6 and 7, relatively lower subsidence rates within the delta plain are observed in its central portion between the villages of Ag. Polykarpos and Malamata along the abandoned distributary channel. Both the surface and the underlain deposits of this area are dominated by coarse-grained channel sediments characterized by significantly lower rates of natural compaction.

Scatterers located over mountainous areas and also over the major part of Nafpaktos show stability or slight uplift. It is observed that for both periods, point targets show the same deformation pattern. Specifically, moving from the city of Nafpaktos toward the delta, the linear deformation rates of point targets from positive values become negative. This change occurs along a line separating the alluvial fan of Skala
Figure 7. Linear component of ground deformation over Mornos delta broader area for the period 2002–09. Point targets are plotted on a high resolution satellite image. Star symbol represents the reference point.

Figure 8. Diagram of percentage of fine sediments of the boring log vs. subsidence rates.
torrent from the western Mornos delta deposits. The observed vertical motions on the two sides of this linear path, as well as the existence of an offshore fault scarp at its SW continuation, presented on maps produced by a seismic profile survey (Papanikolaou et al., 1987) indicate the presence of a NE-SW trending normal fault buried under the alluvial deposits. Differential vertical movements are the result of aseismic slip along the fault during the observation period.

Concerning the period 1992–2000, the maximum observed subsidence is approximately −7.2 mm/y, while the maximum uplift is about +2.2 mm/y. For the period 2002–09, the linear deformation rate varies between −6.8 mm/y and +4.1 mm/y. The average estimated rate uncertainty is approximately ±0.2 mm/y.

Using statistical analysis tools, frequency histograms of deformation rates were generated (Figures 9 and 10). For the time span 1992–2000 the highest density of the point targets is between −2.2 mm/y and −0.6 mm/y, while for the 2002–09 period the highest density occurs between −1.5 mm/y and +0.5 mm/y. Moreover, the amount of points that are characterized by extreme rates of maximum and minimum is quite small.

An additional attempt of a detailed study was made within the Mornos delta. Specifically, the average deformation rate was estimated for every rural community located in the delta (Managouli, Chiliaou, Logos, Malamata, Ag. Polýkarpos) and towns and villages located at the edge of the delta (Nafpaktos, Efpalio, Kastraki, Xiropigado). As shown in Figure 11, the settlements show almost the same deformation pattern in both periods. Most of the villages show higher subsidence during the 2002–09 period than the 1992–2000 period.

The villages Kastraki, Xiropigado, and Efpalio are exceptions as they show decreased subsidence for the period 2002–09 compared to that of 1992–2000. Furthermore, the maximum deformation rate of subsidence is observed at Managouli with rates between −2.9 mm/y and −3.5 mm/y, at Chiliaou with rates between −2.6 mm/y and −3.4 mm/y, and at Malamata with rates between −2.6 mm/y and −3.2 mm/y, for 1992–2000 and 2002–09, respectively. Settlements located at the edge of the delta show much lower subsidence rates than villages located within the delta plain. This has to do with the sediment distribution and the morphology of the valley basement relief. It is evident that in deltaic areas where the recent deposits are underlying by gradually varying size unconsolidated deposits, the coarse-grained materials are expected to be close to the initiation of delta.

Additionally it is interesting to note that for both time periods the highest subsidence is observed at Bouka Karahasaní (the old mouth of delta). This area is dominated by permanent marshes and fine sediments attributable to the long distance from the apex of the delta, which also explains the highest rate of subsidence. Moreover, the instability because of the gravitational load of the SE prodelta slope unconsolidated deposits affects the ground subsidence of the eastern delta front. Complete cessation of sediment load supply after the...
Figure 10. Frequency histogram of deformation rates for the period 2002–09.

Figure 11. Average deformation rate for each village located in the Mornos delta covering the time span between 1992 and 2009.
abandonment of this distributary channel attributable to the modification of the natural flow of the river is also responsible for the accelerated subsidence of the old river mouth (Bouka Karahassani). River-flow anthropogenic modifications include the construction of the upstream dam and the artificial confinement of the western distributary channel. Extremely high retreat rates of the eastern shoreline (2.14 mm/y between 1945 and 1986 and 3.25 mm/y for the period between 1986 and 1998) postdate the construction of the dam and seem to be the result of intense subsidence (Karymbalis, Gaki-Papanastassiou, and Maroukian, 2007).

CONCLUSIONS

Persistent Scatterers Interferometry (PSI) served as a methodology of ground deformation detection and estimation for the broader area of the Mornos River delta for the time period between 1992 and 2009. In most cases the technique has been applied to monitor deformation over urban and suburban areas. Natural terrains, as in this case the deltaic, attributable to surface coverage with strong presence of vegetation are not considered optimal environments for the application of the technique. Nevertheless, the technique performance was satisfactory because of the presence of dispersed settlements in the region of interest. Although a relatively limited number of reflectors were identified, sufficient spatial distribution has allowed indirect conclusions to be reached regarding the causes of observed ground deformation.

Subsidence seems to be a dominant process for the Mornos River deltaic plain, while relative stability or slight uplift was observed for the mountainous areas surrounding the alluvial deposits. For the time period 1992–2000 the maximum subsidence rate was estimated to be −7.2 mm/y, while the rate was approximately −6.8 mm/y between the years 2002 and 2009, however, the uplift rates range between +2 mm/y and +4 mm/y. The uncertainty of the deformation rate estimation is almost ±0.2 mm/y.

The main causes of land subsidence are natural sediment compaction, aseismic slip along a buried active fault zone, submarine mass movements on the SE prodelta steep slopes, and reduction of sediment supply because of human activities.

In the study area the main cause of ground subsidence seems to be natural compaction of the loose deltaic sediments. The relatively high subsidence rates are the result of high compaction rates attributable to the heterogeneity in sediment layers. Difference in mean subsidence depends partially on the architecture of the underlying Holocene strata that dictate differential natural sediment compaction rates primarily controlled by the relative thickness of fine- and coarse-grained sediments. The settlements of Kastraki, Xiropigado, Nafpakto, and Epalfio, which are located at the edge of the delta, show much lower mean annual subsidence rates (ranging from −1.7 mm/y to −0.3 mm/y) than the villages of Managouli, Ag. Polykarpos, Logos, Chiliaoud, and Malamata (mean subsidence rates between −3.5 and −1.0 mm/y), which are located within the delta plain. This can be attributed to the delta deposits’ distribution and the valley basement relief. The recent coarse-grained sediments are located close to the apex and the periphery of the delta where the free-compaction rocky basement exists.

The highest subsidence rate (∼7.2 mm/y) is observed at Bouka Karahassani where the old, most recently abandoned mouth of the river is located. Compaction of fine-grained deltaic sediments can only account for a part of the observed subsidence in this part of the delta. The premier force seems to be submarine slumping and mass movements on the steep prodelta of the eastern delta coastline. These gravitational slides seem to contribute significantly to relative sea-level rise and intense erosion along the eastern delta shoreline.

The fact that surface subsidence and the related marine invasion postdate both the construction of the dam at the upper reaches of the basin and the abandonment of the eastern distributary channel shows that the cessation of sediment supply because of manmade modifications is another factor responsible for the delta surface subsidence and shoreline erosion. Moreover, the results of the applied methodology assume the existence of a possible NE-SW trending normal fault buried under the alluvial deposits of the Skala torrent at the NW flank of the delta. Aseismic slip along this fault line has affected the ground deformation at its vicinity.

Future efforts should focus on the quantification of the contribution of each individual deformation factor through simulation and modeling in order to allow response and mitigation actions.

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LITERATURE CITED


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