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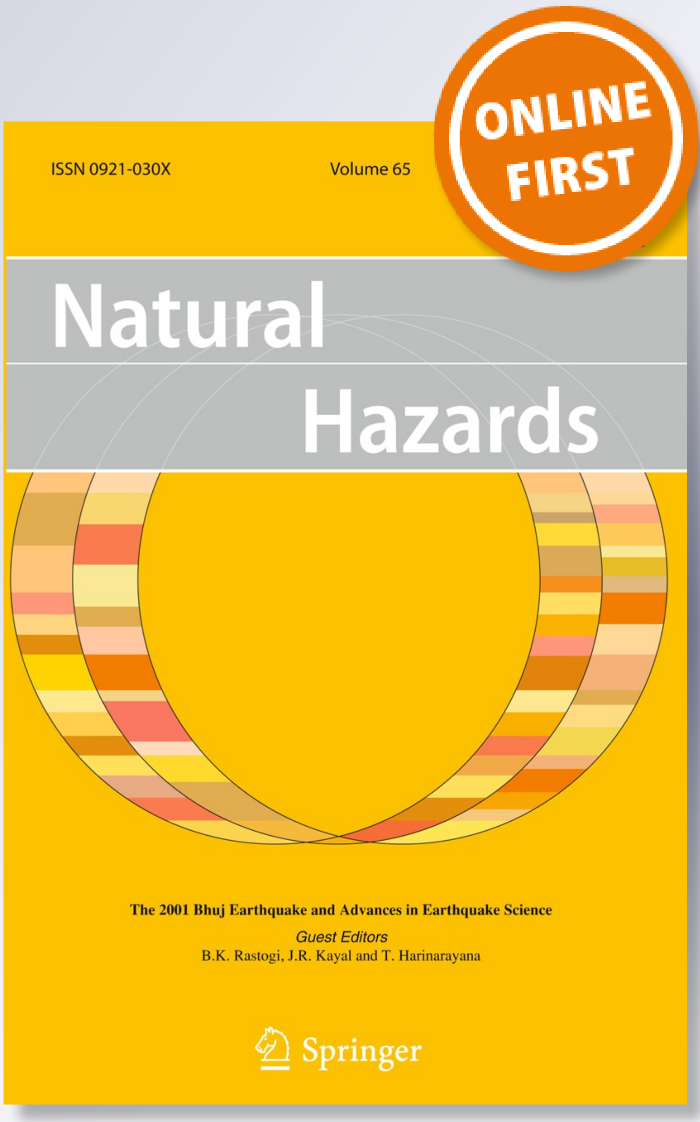

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ORIGINAL PAPER

Analysis of the Marmara flood in Turkey, 7–10 September 2009: an assessment from hydrometeorological perspective

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Abstract Turkey often suffers from flood-related damages and causalities as a result of intense and prolonged storms that are usually convective or cyclonic in origin. The impact is more distinctive in Aegean and Mediterranean coasts of the country where quantity and distribution of rainfall is influenced by Mediterranean cyclones, especially in late autumn and early winter. The floods sometimes became very hazardous when combined with urbanization effects, especially in the densely populated coastal communities and major cities. Severe weather was marked in the early parts of September 2009 that produced record-setting rainfall amounts across the Marmara region of Turkey and led a series of flash floods which affected İstanbul and Tekirdağ provinces especially. The overall flooding was the result of successive and persistent intense rainfall episodes over a 3-day period which produced more than 250-mm rainfall over portions of the region. The floods resulted in death of 32 people and caused extensive environmental and infrastructural damage in the region. This study provides in-depth analysis of hydrometeorological conditions that led to the occurrence of flash floods in Marmara region during 7–10 September 2009 period and also discusses non-meteorological factors that exacerbated the flooding conditions. Main meteorological settings that led to intense storms were presence of cold air in the upper atmosphere, a slow-moving quasi-stationary trough, and continuous resupply of moisture to the surface low from the warm Aegean Sea. Radar images showed the development of clusters of convective cells that remained quasi-stationary over portions of the region. The 24-h rainfall amounts varied between 100 and 253 mm in most parts of the region during the flooding period with diverse spatial patterns. The southern locations received the highest amount of the rainfall as compared to stations located in northern slopes of the region. Typical effects of orography that enhance rainfall in the coastal areas, however, were not observed during the Marmara flood. Some features of the synoptic pattern observed prior and during the flooding period, supported the back door cold front concept. This is characterized with easterly to northeasterly surface flows forced by an anticyclone, advection of cold continental air over the warm Black Sea which

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provided anomalous moisture to trigger cyclogenesis over the Marmara region, and falling of core of the intense rainfall over the Marmara Sea. The study concluded that although the meteorological settings were favorable for the convective rainfalls, urbanization factors, such as land use changes and occupation of flood plains, played major role in aggravating the worst flood observed in the region in recent decades.

Keywords Marmara region · Turkey · Floods · Mediterranean cyclones · Convective systems · Back door cold front · Instability indices · Urbanization

1 Introduction

Floods are the most frequent cause of loss from natural hazard events. In the last few decades, occurrence of weather-related hazards, such as floods, is on the rise as compared with geophysically-induced disasters (Adikari and Yoshitani 2009). About 196 million people in more than 90 countries were found to be exposed on average every year to catastrophic flooding (UNDP 2004). Europe alone suffered over 100 major damaging floods between 1998 and 2002, including the catastrophic floods along the Danube and Elbe rivers in 2002 (Barredo 2007, 2009). Since 1998, floods have caused some 700 fatalities, the displacement of about half a million people and at least €25 billion in insured economic losses across Europe. In the Mediterranean region, frequency and intensity of severe winter storms and floods have increased, and as a result, the number of fatalities and economic losses has been rising in the eastern and the southern regions (Brauch 2003). Deaths caused by floods in the Mediterranean region alone from 1990–2006 exceeded 4,500 people (Llasat et al. 2010). During the same period, reported damage exceeded € 29 billion, Italy being the country with the greatest losses followed by France, Romania, Turkey, and Spain. A study by the European Environment Agency (2001) stated that the Mediterranean region is prone to frequent floods due to occupation of the potential flood areas through uncontrolled building and inadequate land use planning. Even more devastating weather-related hazards are expected to occur in the Mediterranean region as a result of the anticipated global climate change that is projected to be accompanied by increases in both the frequency and the intensity of extreme weather events (Dankers and Feyen 2009).

Flooding in meteorological terms is usually defined as a localized hazard that is generally the result of excessive and localized precipitation in a short time period over a given location. The World Meteorological Organization (2011) identifies around 10 different types of floods based on seasonality, location, meteorological conditions, and resulting impacts. Among them, flash floods and single-event floods are the most common. Flash floods are distinctly characterized by very rapid rise and recession, usually associated with debris flows and landslides. These floods are frequently associated with convective storms of a short duration falling over a small area. The severity of a flooding, however, is controlled by a number of other local factors, including terrain, antecedent soil moisture, and land use conditions. Another common type of flood is the single-event floods. They are typically induced by heavy rains that are associated with cyclonic disturbances, mid-latitude depressions, and storms and can last several hours to a few days.

Intense autumn storm events delivering very high amounts of rainfall within a short period of time are specific features of the Mediterranean floods (Gaume et al. 2009). Jansa et al. (1991) indicated that the heaviest rainfall in the Mediterranean region is usually observed in winter period when cyclogenetic activity produces maximum rainfall. Turkey frequently suffers from floods associated with torrential rains during the period of early autumn to winter. Most of the flood incidents that occur especially in coastal parts of Turkey are triggered by cyclones originating from the Mediterranean Sea, with exception of some local influences (Çelik et al. 2007). The Mediterranean Sea acts as a primary source region for moist air masses that produce intense rainfalls over the windward slopes of the coastal mountain ranges (Türkes 1996). Orographic lifting then pushes the conditionally unstable and extreme moist air upslope into higher terrain of the Taurus Mountains and causes heavy rainfall along the Mediterranean coasts. Intense rainfalls induced by orography are also common along the Black Sea coasts of the country in north. On the other hand, interior parts of the country are mostly affected by convective precipitation which develops during the transition seasons of spring and autumn. The most damaging type of floods occurs in the coastal regions when orographic and frontal lifting of the saturated air masses causes surface convergence, leading to very intense rainfall.

The Marmara region, which is located in northwestern part of Turkey, suffered from a series of floods during 7–10 September 2009, with 32 human losses and more than $100 million in economic damage. It was found that although meteorological conditions seemed to be favorable for the flash floods, additional factors such as land use changes, urbanization, poor drainage, and construction and settling in the flood-prone areas worsened consequences of the floods, especially in major urban areas of the region. Therefore, a better characterization of flash floods occurrences in urban areas is sought in this work as an important aspect of hydrometeorology in general and to provide inputs for better flood risk management in particular in İstanbul which is highly prone to such flash floods. The aim of this research is threefold: (a) to analyze hydrometeorological aspects of the flash flood events that occurred in the Marmara region during the period from September 7 to 10, in light of meteorological, climatological and remote sensing data, (b) to characterize synoptic patterns of the severe weather that led to the floods in order to guide for analysis of similar events in the future, and (c) to provide some insight gained with this analysis for better flood management in the city of Istanbul.

2 Historical aspects of floods in Turkey

Floods are the second most destructive type of natural disaster in Turkey, after earthquakes. Nearly 30 % of all the natural disasters in the country consist of flood events. According to EM-DAT database, 34 flood events occurred in Turkey between 1950 and 2007 and 1,016 people died, and about 1.5 million people were affected (EM-DAT 2010). According to a survey conducted by UNDP (2004), nearly 2 million of people on average are exposed to floods every year, which makes up more than % 10 of population of the country (Table 1). Temporal trends of Turkish flood occurrences do not portray steady increases or decreases rather they fluctuate, but they are on rise since the mid-1990s (Komuscu and Ceylan 2007). Figure 1 illustrates temporal trends in flood events in Turkey. Based on the 60 years of flood occurrences, 4 distinct periods of flood occurrences were identified. The flood events initially tend to increase until the mid-1960s and then portray fluctuating trends. Early and mid-1980s and the last decade have been characterized by increasing trends in the flood events while sharp decreases were observed during the early and mid-1990s which were mostly associated with dry periods observed with climate of the country.

Flash floods associated with intense and prolonged rainstorms are common phenomenon, especially in coastal parts of Turkey. The Marmaris flood on December 1992 and İzmir and Antalya floods on November 1995 are typical examples of such devastating

Table 1 Disaster risk for floods in Turkey between 1980 and 2000 (UNDP 2004)

Average number of events per year Event (year)	Number of people killed per year Killed (Year)	Average number of people killed per million inhabitants Killed (million)	Average physical exposure per year People (year)	Relative vulnerability Killed (million exposed)	Physical exposure in percentage of population %	Density of population (living in the watershed exposed to flood) Inhab. (km^2)	Gross domestic product (capita, ppp)
0.67	20.90	0.36	1,883,782	3.26	11.10	97.01	4,681

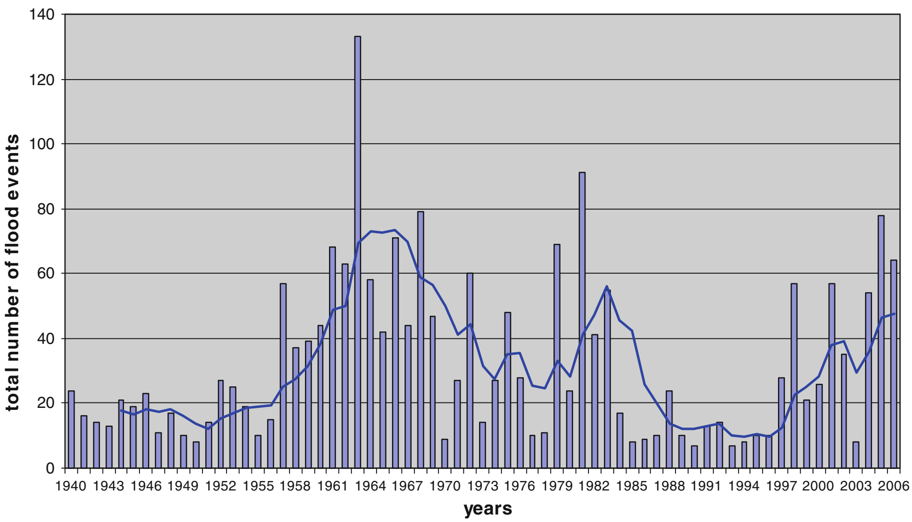

Fig. 1 Historical trends of flood occurrences in Turkey

floods that occurred on the coastal areas as a result of cyclones developed over the Mediterranean Sea. In the last few years, damaging floods also have been affecting other parts of the country, including northeastern Black Sea coasts where terrain conditions play a major role along with the synoptic conditions. Black Sea region floods, which took place in May 1998, were one of the most devastating floods in Turkey in recent years, and it claimed 20 lives and caused more than 150 million dollars economic damage in nearly 500 localities. Flood impacts in Turkey are felt more severely in major cities of the country which suffer from frequent floods as a result of combined effects of intense rainfalls, occupation of flood plains by residential and commercial buildings, high coverage of impervious surfaces, and inadequate drainage. A group of rainstorms swept through the Aegean and Mediterranean coasts of Turkey during early parts of November 1995 and led to devastating flash floods (Komuscu et al. 1998). As much as 212 mm of rain fell in 24 h in some parts of the Mediterranean coast during the 4 days of the flooding which claimed the lives of 61 people and caused more than 50 million dollars in damage in city of İzmir, which hosts more than 2 million people. The previous urban floods in Turkey suggest that despite the fact that meteorological conditions were favorable for occurrence of torrential rains that triggered the floods, inadequate infrastructure, illegal construction in flood plains and watersheds, and poor drainage systems also contributed to worsen consequences of the devastating floods. Flash flood prevention program implemented by State Hydraulic Authority (DSI) since 1970 achieved a great success in reducing the number of annual flash floods significantly. However, a lot of structural and mitigation efforts are still needed especially in urban areas of the country to prevent the occurrences of flash floods and minimize their impacts.

3 Marmara floods, 7–10 September 2009

A series of flash floods occurred between 7 and 10 September 2009 in Marmara Region of Turkey as a result of intense rain storms that swept the region, amounting to its heaviest rainfall in decades. İstanbul and Tekirdağ provinces of the region suffered from the floods most severely (Fig. 2). The 24-h rainfall amounts varied between 100 and 253 mm during the flooding period. The intense rain falls very quite effective in the first 2 days covering 7 and 8 September and their intensity decreased gradually in the later days. The Marmara flood was a good example of single-event flood type, as classified by WMO (2011), which appeared as a series of flash floods across the region. The Marmara floods were noted as the third deadliest water-related disaster in recent decades in Turkey after the Western Black Sea and İzmir floods. Central and southern portions of the Marmara region were severely affected from floods which resulted in 32 human losses, extensive property damage, and partial impairment of the transportation and communication networks in portions of the European side of the region. İstanbul, the largest city of Turkey with 14 million inhabitants, was the worst-hit by the flash floods. The floods submerged some suburban districts of the city and the city's highways turned into rivers and transportation and communication infrastructures were damaged. A total of 35,000 people were affected by the floods in the Marmara region. The İstanbul Chamber of Commerce assessed that the damages caused by the flash floods exceeded $80 million. The worst flooding occurred in areas in the west of the city, on the European side, where flood control structure are inadequate and flood plains are occupied by settlements and industry. Emergency authorities confirmed that some 1,700 homes and offices were flooded in İstanbul's suburbs of Silivri alone. The western provinces of Çanakkale and Tekirdağ were also flood-stricken provinces in the region where small creeks overflowed due to torrential rains, inundating houses, and agricultural fields.

İstanbul historically has been vulnerable to natural disasters. Since 1967, the city suffered 13 major floods. The city has grown rapidly over the last 40 years due to internal migration. In order to absorb the increasing population, new settlements have been built, mostly illegally on the outskirts of the city. The rapid urbanization led people to occupy flood plains to open up new spaces for development. Natural hydrologic pattern of the city changed considerably due to expansion in the transportation network and more impervious surface were added to the city's land use. Flood control structures and channel improvements in creeks were not able to accommodate the increasing urban pressure resulted expansion of the settlements and industrial sites due to internal migration. Capacity of the storm sewers and flood detention structures in the city remained inadequate to control a large flood as in case of the September 2009 flood and consequences were devastating (Fig. 3).

In this study, hydrometeorological conditions of the flash floods that occurred between 7 and 10 September in Marmara region, and more specifically in İstanbul, were investigated based on rainfall climatology and meteorological conditions that triggered torrential rains. The general precipitation patterns were also described using tools, such as radar and

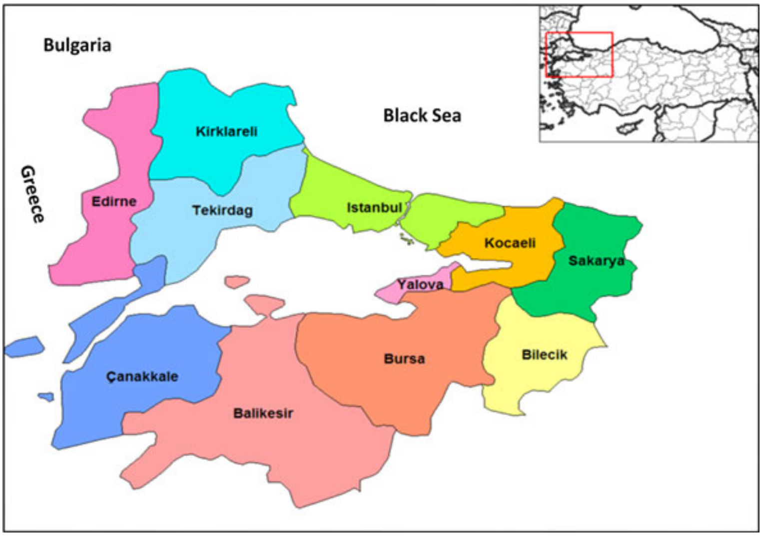

Fig. 2 Location of Marmara region and its provinces

Fig. 3 A scene from the flood devastated area near Ayamama River in İstanbul (courtesy of Anatolian news agency)

satellite images and instability indices. Finally, apart from the hydrometeorological conditions, land use and urbanization impacts were also discussed to describe the devastating consequences of the flood.

4 Study area

The study area covers Marmara region, which is located in northwestern part of Turkey (Fig. 2). The region represents approximately 8.6% of the Turkish national territory with a surface area of 67.000 km^2 and is surrounded by the Black Sea and Aegean Sea. Although the Marmara region is the smallest region in geographic size, following the Southeastern Anatolian region, it has the highest density of population and also is economically the most developed part of the country. The Marmara region hosts about 30% of the country's population and continues to trend upward due to internal migration from the other parts of the country. While the industrial activities are concentrated in the central and eastern parts of the region, agriculture remains to be the main source of income in the western and southern parts of the region where wheat, sugar beet, tobacco, olive, and sunflower productions are the leading agricultural activities.

From climate perspective, the Marmara region is located in a transition zone between the Mediterranean climate (humid and subtropical) on the Aegean Sea region and the oceanic climate on the Black Sea region. Humid continental climate prevails in the interior parts of the region more abundantly. Summers are characterized warm and humid, whereas winters are cold and wet with occasional snow storms. January is the coldest month of the year with 4.9 °C mean monthly temperature. In July, monthly mean temperatures in the region can reach as high as 23.7 °C. The region receives an average of 595-mm rainfall annually with high spatial variability. The annual rainfall reaches exceeds 800 mm in the eastern part of the region while the central and western parts reach values of less than 600 mm. Although the region is characterized with wet winters, summer rainfalls are not negligible, comprising nearly 12 % of the annual rainfall. The Marmara region has diverse vegetation cover, consisting of forests grassland and some aquatic flora. The coastal belt of the region is covered by broadleaf deciduous forests (Atalay and Efe 2010). Coniferous forests grow in the high elevations of the region where cold and humid climatic conditions prevail. While the central and western parts of the region are covered by steppe grasslands and forests, aquatic and marshy vegetation dominate lake areas of the region in the south.

The Marmara region is also one of the most tectonically active regions within the Mediterranean sector of the Alpine Himalayan orogenic system. Two destructive earthquakes (Kocaeli and Düzce) occurred in the eastern part of the region in 1999 on Northern Anatolian Fault, resulting in over 17,000 dead and an estimated $10 billion economic cost. Model studies indicated that probability of occurrence of $\geq$7.0 M (M = moment magnitude) earthquakes in the Marmara region that could cause direct impact in the İstanbul metropolitan area is 44 $\pm$ 18% in the next 30 years (Parsons 2004).

5 Hydrometeorological analysis

5.1 Rainfall conditions

The floods followed a three-day period of intense and continuous rainfalls which began on 7 September. During the evening of 8 September, the rain became increasingly strong leading to flash floods across portions of the region, but mostly in low-lying areas to the west of the city of İstanbul. Analysis of the rainfall distribution over the Marmara region indicated intense rainfall occurrences at a number of localities. Silivri and Çatalca towns located west to İstanbul and area between Tekirdağ and Bandırma received record rainfalls between 7 and 9 September that eventually led to the occurrence of flash floods (Fig. 4). The temporal distribution of the rainfall indicated that the severe storms first affected western parts of the Marmara region on 7 September and then moved eastward covering İstanbul, Silivri and Çatalca where the impact was felt most severely in the next 2 days (Fig. 5). Total rainfall amounts mostly varied between 100 and 270 mm in the flooded parts of the region during period covering the 4 days between 7 and 10 September 2009.

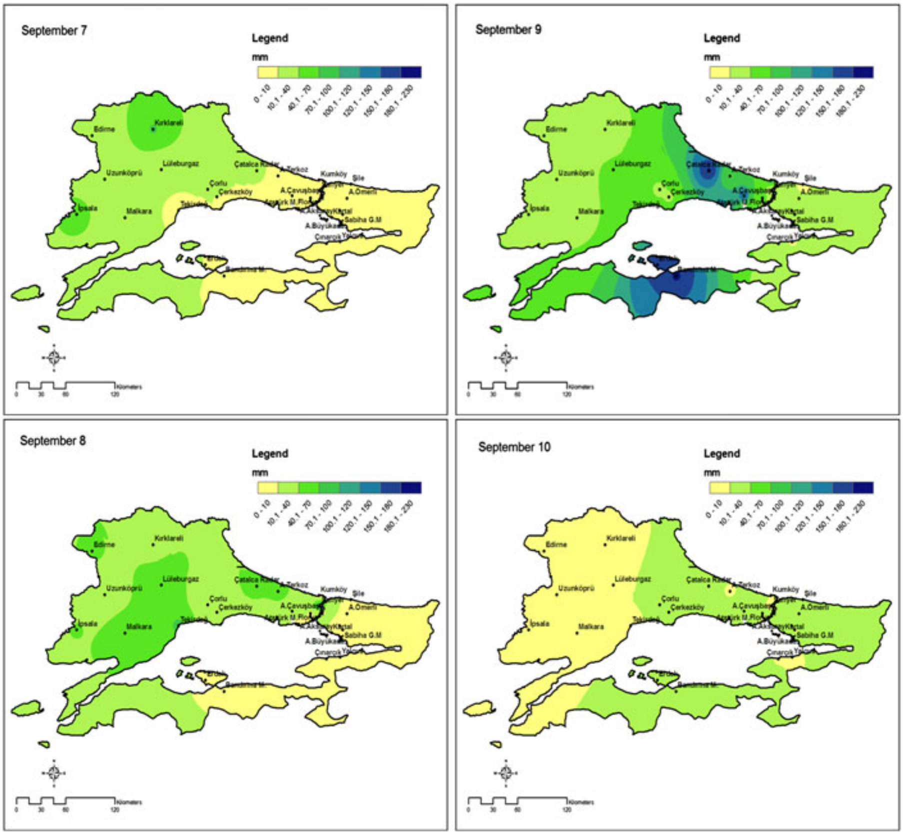

Fig. 4 Daily rainfall totals over the Marmara region between 7 and 10 September 2009

The highest 24-h rainfall amounts were recorded at Bandırma, Çatalca, Erdek, and Silivri stations with 253, 205, 170, and 128 mm, respectively. Figure 6 illustrates spatial distribution of cumulative rainfalls recorded across northwestern region of Turkey and SE Europe between 2 and 9 September 2009. The figure shows clearly that mass of the rainfall is concentrated areas west to İstanbul, especially between Bandırma and Tekirdağ. It is interesting to note that core of the highest rainfall is located slightly off the northeastern coast of the region over the sea.

Over 74.1 mm of rainfall was recorded for the Marmara region in average during the 4 days, between 7 and 10 September 2009. This amount is well over the long-term averages for the month of September, which is 36.3 mm. As indicated in Table 2, the 24-h rainfalls recorded in some stations significantly exceed the long-term total rainfall for the month of September. Bandırma and Çatalca stations experienced the highest amount of 24-h cumulative rainfall and their recurrence intervals were well above the 100 years. The 24-h cumulative rainfall in Çatalca station on 8 September was recorded as 205 mm, which is approximately one-third of its annual average (Fig. 7). Moreover, both the Bandırma and Çatalca stations recorded highest amount of 4-day cumulative rainfall as compared to the other locations, 270 mm and 254 mm, respectively.

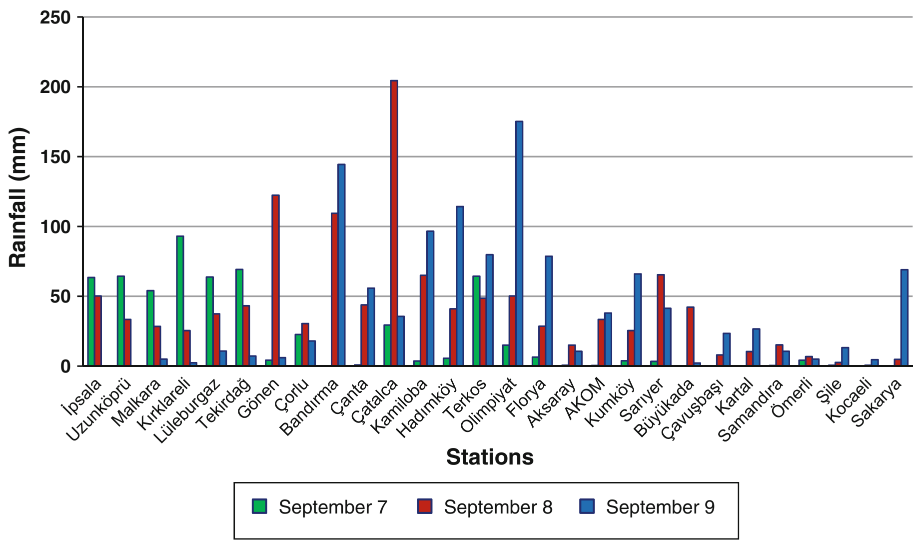

Fig. 5 Daily rainfall recorded at different locations in W–E direction across the Marmara Region

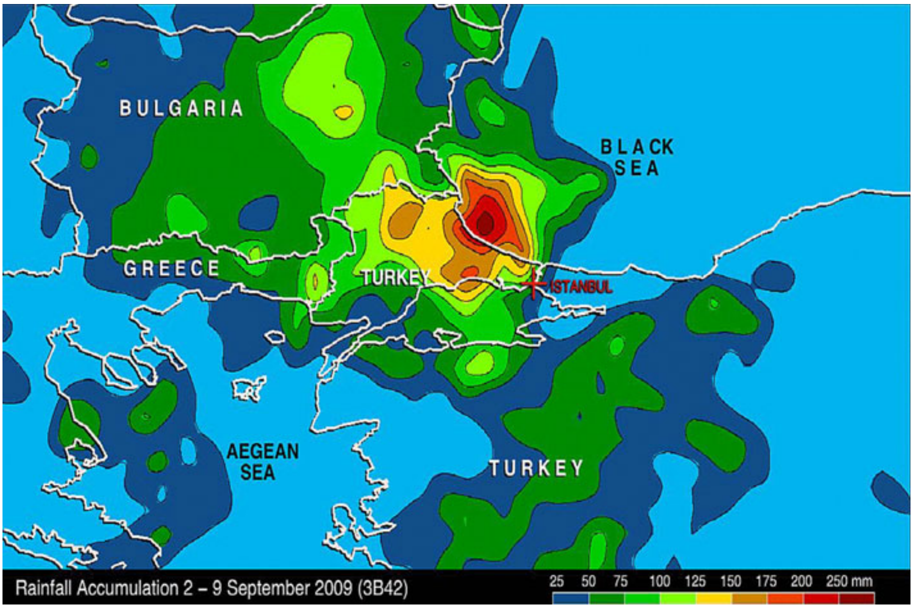

Fig. 6 Spatial distribution of cumulative rainfalls over the NW region of Turkey between 2 and 9 September 2009. *Source*: SSAI/NASA GSFC

Hydrologic consequences of the intense rainfalls were assessed by Einfalt and Keskin (2010) who performed hydrologic simulations to predict discharge at Ayamama River during the flooding period. In their study, they tried to simulate the discharge of the Ayamama River both using radar and rain-gauge data. They found that the concentration time decreased with resulting higher peaks during the flood that affected vicinity of the

Table 2 Maximum rainfall intensities observed during the flood period and comparison with the historical maximums in some stations

Station	Date	Starting time	Ending time	Duration (in h)	Amount (in mm)	Recurrence Interval	Note
Bandirma	08.09.2009	14:20	16:20	2	82.2	100-years	Max rainfall recorded in 2-h period was 73.9 mm in 1991
Bandirma	09.09.2009	04:20	08:20	4	125.0	100-years	Max rainfall recorded in 4-h period was 124.4 mm in 1991
Çatalca	08.09.2009	12:30	15:30	3	134.4	100-years	Max rainfall recorded in 3-h period was 62.4 in 1971
Çatalca	08.09.2009	07:30	15:30	8	166.8	100-years	Max rainfall recorded in 8-h period was 104.4 mm in 1991
Gönen	08.09.2009	08:10	11:10	3	83.8	100-years	Max rainfall recorded in 3-h period was 62.1 mm in 1979

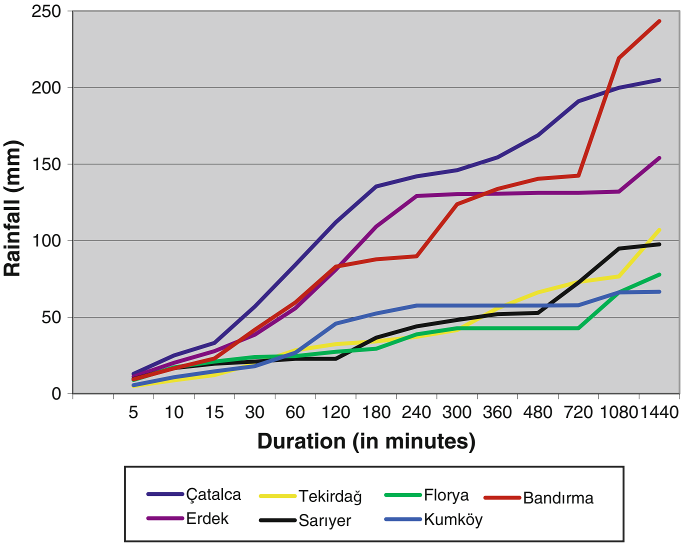

Fig. 7 24-h cumulative rainfalls for the stations located in main flood areas of the Marmara region on 8 September 2009

Ayamama river and found that the radar data discharge has two peaks with 250 and 220 m^3/s while the station data discharge had a peak value of 210 m^3/s. Considering the average value of 20–30 m^3/s for the Ayamama river during non-rainy period, the observed values are quite significant to indicate the severity of the flooding.

5.2 Meteorological conditions of the heavy rain events

5.2.1 Background

Analysis of meteorological conditions prior to the floods is always essential to assess the weather patterns that eventually develop into unstable atmospheric conditions. What exactly cause heavy rains and resulting flash floods is the subject of many studies and research both in meteorology and hydrology. It is apparent that each region has its own unique meteorological forcing mechanisms which are mainly determined by its geographic position, land water distribution, global, regional and local atmospheric circulations patterns, and orography. Chappell (1986) claims that most damaging flash floods are produced by quasi-stationary convective systems. The same argument is also supported by Doswell et al. (1996) who pointed out that rainfall rates associated with convective activities tend to be higher than other rain-producing weather systems. He further added that certain ingredients must exist for developing of heavy rain and flash flood events. These ingredients include high moisture content, convectively unstable or buoyant air mass, mechanism to lift the air mass to its level of free convection, and the absence of processes which reduce precipitation efficiency, such as entrainment. A well-known study done by Maddox et al. (1979) identifies a number of features that are common to many of intense rainfall events, including (a) most flash floods were associated with convective storms, (b) high surface dew points, (c) presence of relatively high moisture contents through a deep tropospheric layer, (d) presence of weak to moderate vertical wind shear through the cloud depth, (e) repeated movement of convective storms and/or cells over the same area, and (f) a weak, mid-tropospheric meso-a scale trough that helped to trigger the storms. Such meteorological conditions may develop easily over different regions of the United States, particularly during the summer months. The Mediterranean region, on the other hand, is characterized by its own meteorological features that are especially distinctive in the late summer and autumn period. Frontal Mediterranean cyclones associated with the southwesterly air flows create favorable conditions for heavy rainfall, especially in the southern and western coastal parts of the region in late autumn and early winter (Jansa 1992). The Mediterranean Sea provides a considerable moisture supply and low static stability in the overlying air following summer's insolation (Romero 2000). Moreover, coastal mountain ranges in the southern Mediterranean lift moist and alter the low-level flow, which favor specific mesoscale processes prone to the development of convection and intense rainfall producing systems in the region (Martin et al. 2007). Romero et al. 2006 argues that heavy rainfall episodes in the Mediterranean area are linked to a rapid and small-scale baroclinic cyclogenesis in response to the upper level forcing and adds that the stationary systems provide necessary environmental ingredients for heavy precipitations to occur as slow moving cyclones exhibit high precipitation potential. Winter cyclogenesis occurs over the Aegean and Black Seas, when an upper-trough moves over the relatively warm water basins (Trigo et al. 2002). In another study, it was found that precipitation in the southern part of the eastern Mediterranean (EM) region is also mainly associated with cyclonic systems of Mediterranean origin during the cold season (Maheras and Anagnostopoulou 2003). Pastor et al. (2001) simulated rainfall along the Mediterranean coasts of Spain in separate cases and showed that SST had a major influence on torrential rains and further proved that accurate input of real-time SST data can greatly improve numerical model predictions, in particular, the peak precipitation levels. In another study done by Millán et al. (2005), changes in precipitation patterns were studied for the coastal and interior parts of Spain. The study attributed the decrease in precipitation from coastal areas toward the interior parts to "backdoor cold fronts", which produce opposite effect of frontal systems. They associated the heavy rain events along the east coast of Spain with easterly advection of continental air over a warmer Mediterranean Sea which usually occurs in autumn and winter. According to the "back door cold front" concept, the cold front is generated by the northerly, northeasterly, or easterly flow of colder continental air over the warmer Mediterranean Sea. Pastor et al. (2001) explained the torrential rains over eastern Spain based on this concept which included two-step process, namely formation of a potentially unstable air mass through the advection of the colder air over the warmer sea easterly and the movement of the potentially unstable air mass toward the coastal regions where orographic lift can trigger the precipitation development. The term "backdoor cold fronts" is most commonly used in the northeast U.S. to define advection of the cool Atlantic maritime air from the east or northeast to replace the warmer continental air (Eichler and Shulman 1987). The approach, however, has gained a lot of attention in recent years to analyze precipitations associated with Mediterranean cyclogenesis especially over the Iberian Peninsula (Millán et al. 2005).

In this study, we tried to associate the meteorological settings of the Marmara flood with the approach set by Maddox et al. (1979) and the "backdoor cold fronts" approach and identify features that resemble the either approach.

5.2.2 *Synoptic conditions*

In this part of the study, synoptic conditions that led to the development of the severe rainfall conditions over the Marmara region are investigated using surface and upper air charts, instability indices, and satellite and radar images.

A synoptic pattern prior to the flooding indicated the presence of two main meteorological forcings. First is the Iceland low-pressure system which moved from Northern Europe and affected western parts of Turkey. The system originated from Northern Europe and moved southerly toward south of Italy. Another weather pattern originated from northern Africa and caused the development of a warm ridge over central Mediterranean Sea. Areas to the west of Turkey compared to the Central Europe were warmer, and therefore, the temperature gradient between Turkey and Europe greatly enhanced strong instability in northwestern parts of Turkey.

Starting from 7 September, a low-pressure system and associated front system began to affect Eastern Europe, Balkans, and northwestern parts of Turkey (Fig. 8). The surface chart for 7 September shows the presence of a 1,004 hPa low pressure in central parts of Turkey while the Marmara region and Central Europe were characterized with relatively higher pressure values, 1,013 and 1,026 hPa, respectively. The most noticeable synoptic feature in the days prior to the convective system development is the temperature gradient observed between eastern and western parts of the Marmara region. The surface temperatures in areas west to the region remained around 15–17 °C with effect of northerly and northwesterly flows, while the east of the region experienced temperatures varying around 20–22 °C with effect of southeasterly and easterly flows. As observed on the 500 hPa map, the trough and cold air located over the Aegean Sea were approaching the Marmara region. The temperature gradient between east and west of the region led to the strengthening of the northeasterly flows which advected moist air to the region, producing necessary ingredient for the development of convection. An analysis of synoptic situation on 7 September indicates unstable behaviors of the convective system, which began to affect northwestern parts of Turkey. Figure 9 shows vertical velocity fields derived from the NCEP/NCAR (Kalnay et al.1996) reanalysis data at 700 hPa level averaged from 7 to 8

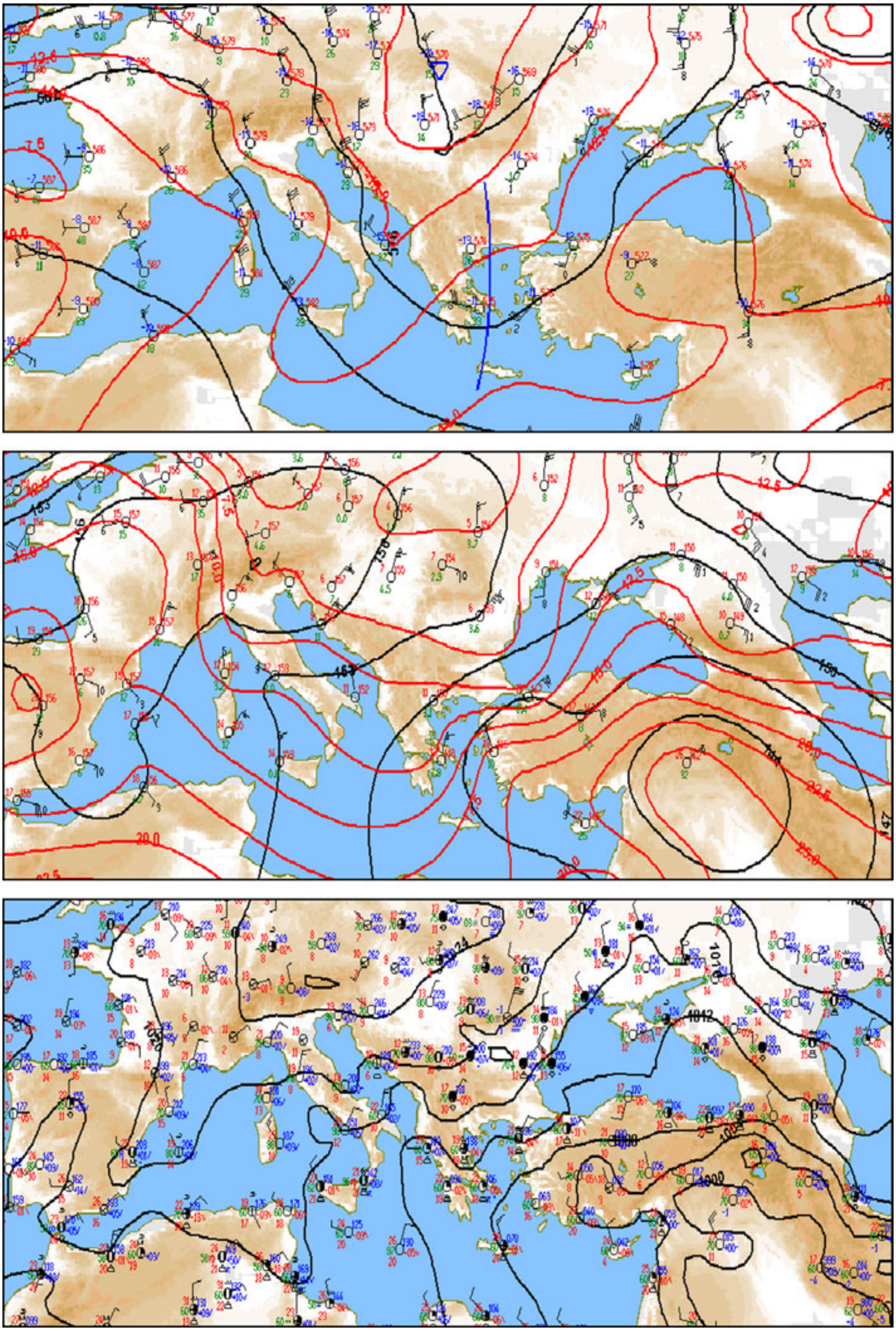

Fig. 8 00 UTC Surface (*upper*), 500 hPa (*middle*), and 850 hPa (*lower*) charts, 7 September 2009

September 2009. The negative omega values over the Marmara region are associated with ascending motion of the air where the convective activity is intense. In fact, the convection had already caused heavy rain over Balkan countries on the same day before moving toward Turkey. The presence of low-level warm sector induced a frontal instability over Turkey and triggered a sudden updraft of the warm air over the surface. With influence of cold air in upper atmosphere, even more atmospheric instability ensued.

On 8 September, it was also observed that the frontal system gained further instability which helped to develop intense rainfalls in western parts of the Marmara region and southeast parts of Bulgaria. The 500 hPa map of the same day indicates presence of well-developed trough over the western part of the region aligned in SE–NW direction and a ridge in the eastern part of the region oriented in the same direction (Fig. 10). Besides the northwesterly flows, moist air advection from the Black Sea also provided additional moisture supply to the cyclonic activities over the region. In other words, easterly to northeasterly surface flows forced by an anticyclone advected cold continental air over a warm Black Sea and thus provided the additional moisture required to trigger cyclogenesis over the Marmara region.

The 500 hPa analysis further illustrates the approach of a trough toward the Marmara region and presence of cold air damming with temperatures recorded as low as −15 °C. Axis of the trough of the cold air extends in SE–NW direction and forms a cutoff low center over the region with 570 dam. In other words, the frontal system that affected the northwestern Turkey was disconnected from the main frontal system, located over Balkans, and turned into a deep cutoff over the northwestern part of Turkey.

When the 850 hPa map is analyzed, it is observed that a cutoff low with a cyclonic move at 144 dam is noticeable over the Aegean Sea. At this level, while southerly and easterly winds dominate over the Marmara region, to the west over Greece northerly winds are more prevalent. A similar atmospheric pattern also is observed at southern Ukraine and northern Black Sea zone. The northerly and southerly strong winds converge over west of the Marmara region where intense rainfalls develop. In short, the presence of cold air in upper atmosphere and the sudden uplift of the warm air at surface enhanced the moisture capacity of the atmosphere over the region and caused torrent rainfalls. Continuous moisture supply from the Aegean Sea enhanced the convection. Static behavior of the developed convective cells facilitated long-lasting rainfall production over the same area for a few days, which resulted in floods in most part of the Marmara region. The convective cells moved gradually from western parts of the Marmara region toward the central and northern parts, increasing in coverage throughout the region. The prolonged rainfalls continued almost 20 h. At 10:00 UTC on 8 September, highest amount of rainfall was recorded at Çatalca station as 70.6 mm.

The 500 hPa map for 9 September indicates that the cool air damming settled over the Western Turkey with a cutoff low center over southern Marmara region (Fig. 11). At this level, air temperature was −13 °C and wind speed was mild. At 850 hPa, the ridge of warm sector was present over southern Ukraine while the cutoff was located over southern Marmara region. The northeasterly winds blowing over the Southern Ukraine converge with cooler northerly flows coming from Balkans over western parts of the Marmara region to enhance intensity of the storms. In other words, the moisture influx from the Black Sea enhanced the convective storm development in the region.

Overall, the synoptic patterns over the Marmara region on 9 September indicated that system originally developed at synoptic scale, disconnected from the main low-pressure system, and was developed into a closed small-scale system. The upper air chart indicates that the cutoff was centered over the Western Anatolia but the warm air sector was located

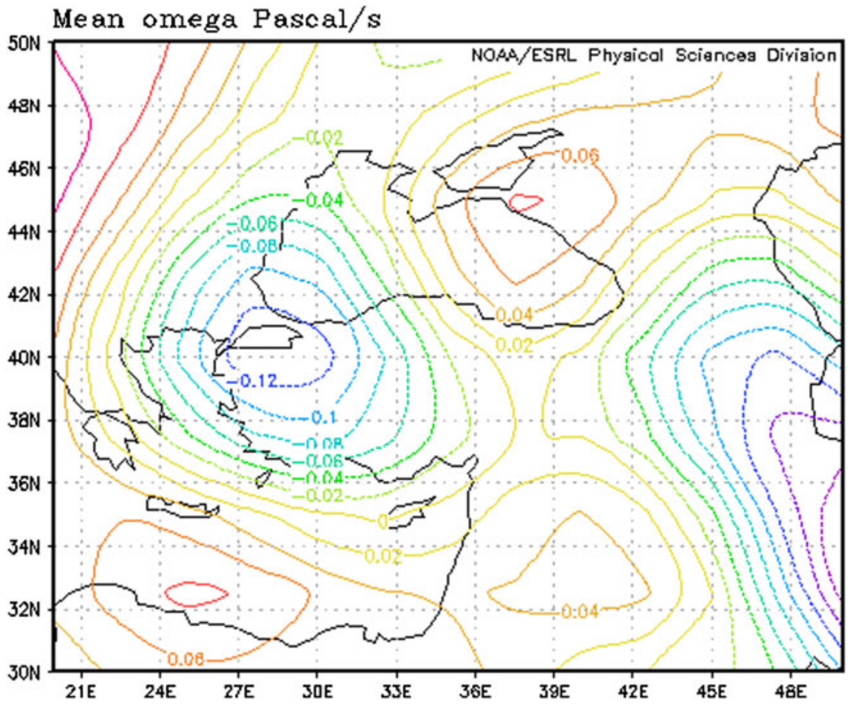

Fig. 9 24-h vertical velocity at 700 hPa averaged from 7 to 8 September 2009. *Source*: NOAA/ESRL

over southern parts of Russia. Eventually, the northeasterly flows that originated from southern Russia and Black Sea coasts joined with the colder flows coming from Bulgaria and Romania which further enhanced the development of convective cells.

At general synoptic description, a strong pressure gradient existed between Turkey and western parts of Russia at surface level. A low-pressure center at 1,008 hPa was settled over Turkey while the high pressure center over western Russia measured almost 1,032 hPa. On the other hand, the pressure gradient observed over the Marmara region shifted to the southern Ukraine. Temperatures in western parts of the Marmara region were between 15 and 17 °C while they reached 20 °C in the eastern parts of the region where the northerly flows were dominant.

Meteorological conditions that induce flash floods, as described earlier, develop under extremely unstable atmospheric environments and can lead to the development of convective systems which can be enhanced by local effects at times. Most studies, however, prove that a moist and unstable atmosphere is the key ingredient, rather than, orography to trigger severe storm development (Schroeder et al. 1987). There are many examples of such severe weather cases in North America where severe weather developed in areas between the cold air sector-associated trough extension and the warm air sector-associated ridge extension (Pontrelli et al.1999). In fact, a similar flow pattern is observed in 500 hPa map over the Marmara region on 8 September 2009. A trough was located over western part of the region in SE–NW direction while a ridge was present over eastern part of the region in the same direction. Moreover, moisture flux from the Black Sea enhanced the convective storm development in the region.

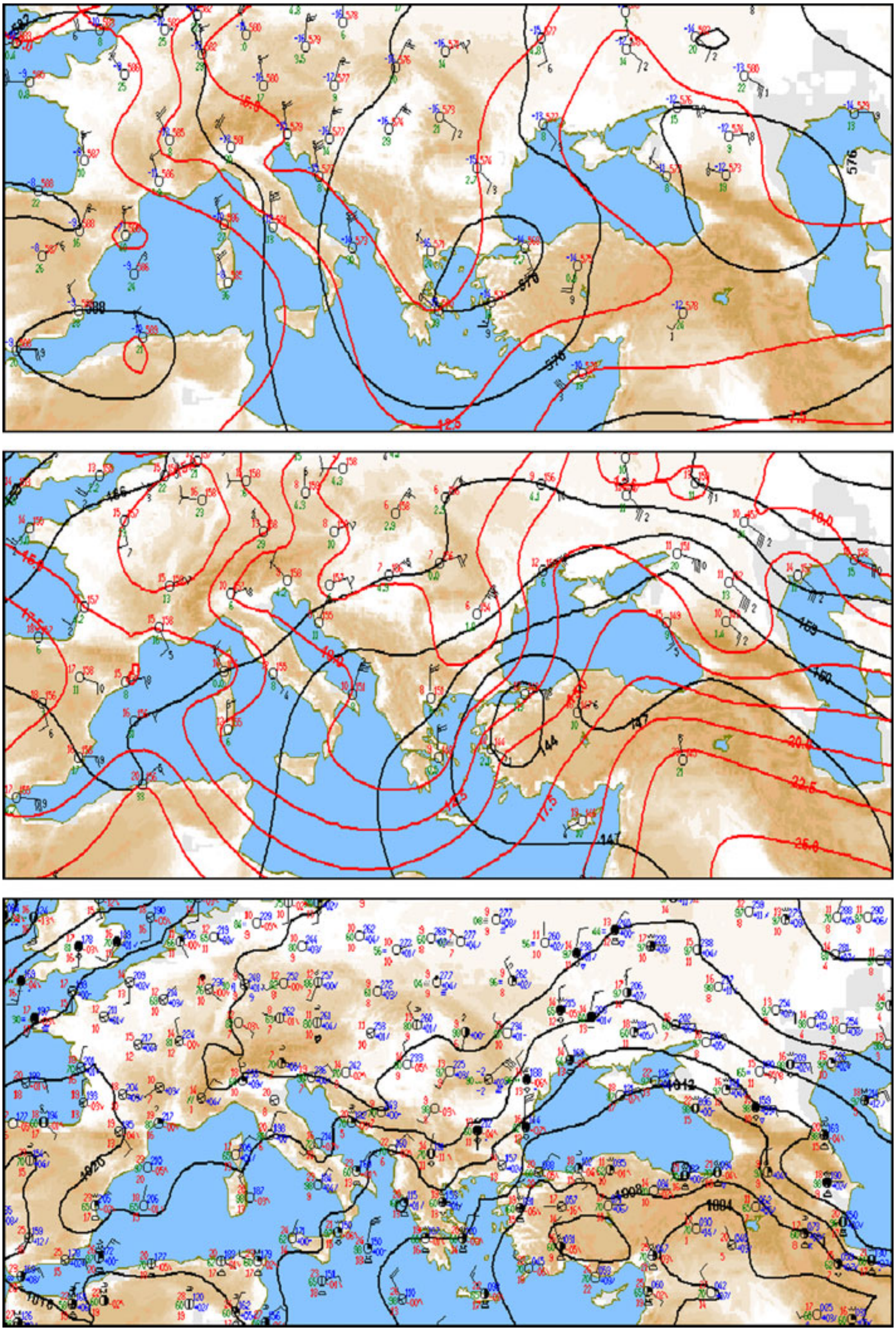

Fig. 10 00 UTC Surface (*upper*), 500 hPa (*middle*), and 850 hPa (*lower*) charts, 8 September 2009

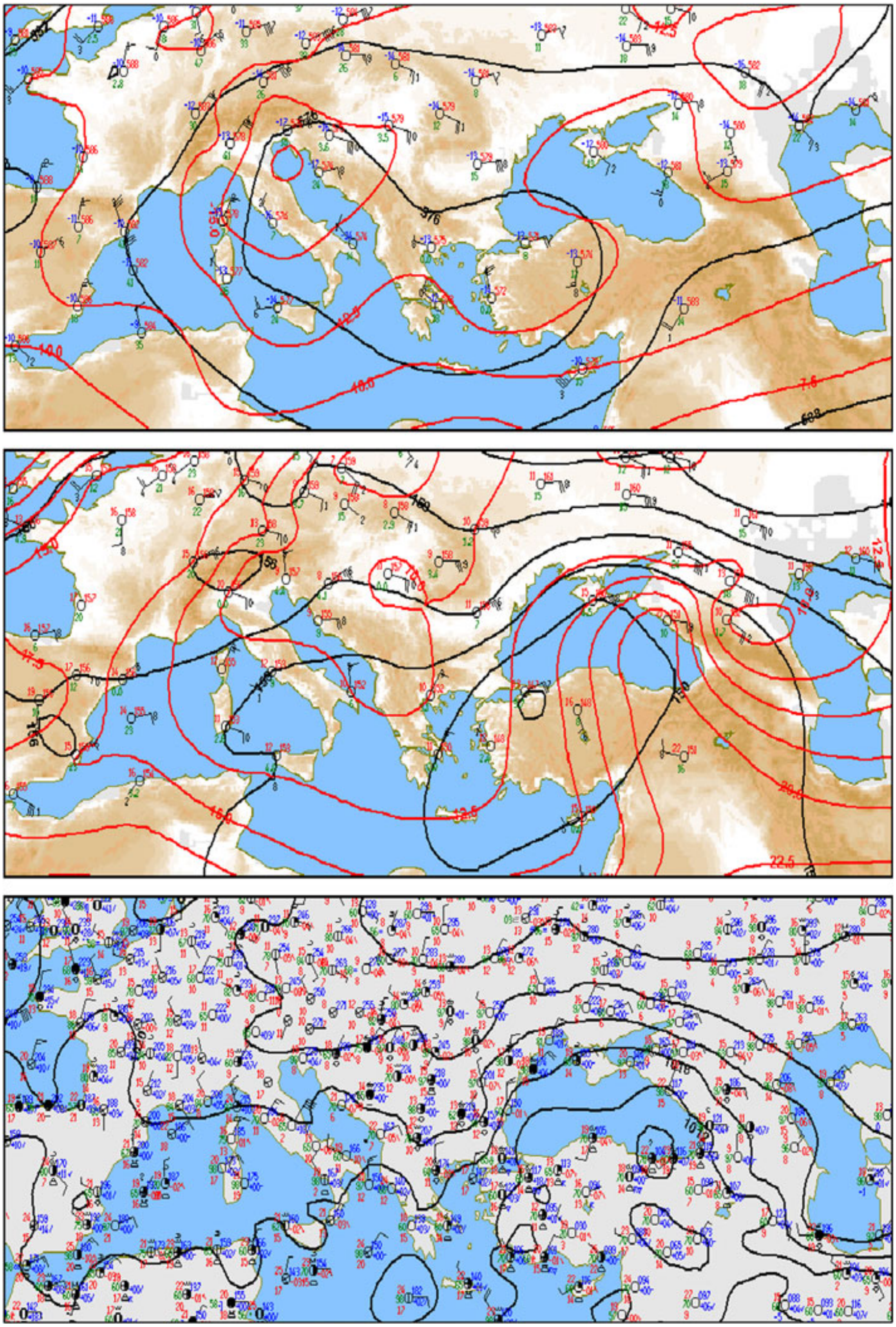

Fig. 11 00 UTC Surface (*upper*), 500 hPa (*middle*), and 850 hPa (*lower*) charts, 9 September 2009

If we try to associate the meteorological settings of the Marmara flood with the approach set by Maddox et al. (1979) and "backdoor cold fronts" approach, we can argue that the conditions do not fit one approach perfectly, rather they indicate common features of the both approaches. It is our view that the storms that triggered the Marmara flood were initiated by one or more forcing mechanisms. One of them was a stationary or slow-moving "backdoor" surface cold front which entered the region from the easterly-north-easterly direction, supported by moisture flux from the Black Sea which enhanced convective storm development in the region. Those observed meteorological settings resemble features of the "backdoor cold fronts" approach. However, the presence of a weak middle-tropospheric short-wave trough advanced from the south/west is reminiscent of the features noted by Maddox et al. (1979). On the other hand, the lack of stationary fronts and strong winds contradicts with the ingredients set by the Maddox et al. (1979) approach. What makes the situation different from both approaches are the orientation of the front axis and presence of large water bodies in both sides of the region, which advected warm and moist air from both directions. The spatial distribution of the rainfall distribution indicates that that core of the intense rainfall is located over the sea not on the northern or southern slopes of the region. As discussed earlier, Erdek and Bandırma stations, located in southern part of the region, received the highest amount of the rain as compared to Çatalca and Silivri stations located in northern and southern slopes of the region, respectively. Those arguments also support close resemblance of the rainfall conditions to the "backdoor cold fronts" approach.

In conclusion, the meteorological environment that led to intense storms were presence of cold air in the upper atmosphere, a slow-moving quasi-stationary trough, continuous resupply of moisture to the surface low from warm Mediterranean Sea, and the northerly flows from Black Sea. It should be added that typical effects of the orography observed in Mediterranean cyclones to enhance rainfall in the coastal areas are not observed in the Marmara flood. It is apparent that the convergence within the low pressure was enough to provide the initial ascent in feeding the flow.

5.3 Analysis of the other parameters

5.3.1 Instability indices

Various instability indices obtained from the upper air sounding for İstanbul are presented in Table 3 to indicate severe weather potential and storm development during the 6–11 September 2009 period. It is noted that almost all the instability indices values indicated unstable atmospheric conditions prior to the flooding period. Figure 12 illustrates skew-T

Table 3 00 UTC instability indices for the 6–11 September 2009 period

	06 Sept. 09	07 Sept. 09	08 Sept. 09	09 Sept. 09	10 Sept. 09	11 Sept. 09
Lifted	7.44	−0.48	−3.12	−1.48	−1.03	−0.13
Sweat	51.40	185.20	185.60	162.80	156.30	164.20
Cape	0.00	62.59	720.80	526.10	325.10	147.50
Total	41.20	45.40	49.30	46.50	47.40	44.70
K	14.30	15.50	32.40	32.30	34.90	30.10
PW (mm)	19.27	30.95	38.97	37.57	41.92	37.40

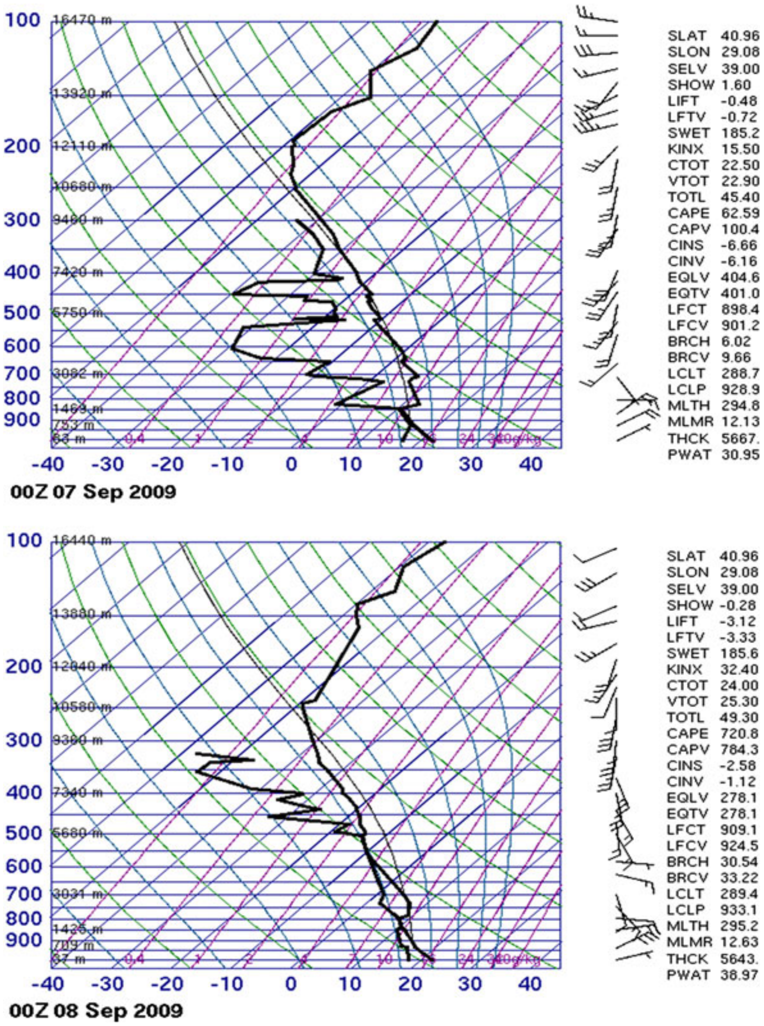

Fig. 12 Skew-T diagrams for İstanbul on 7 and 8 September 2009 at 00 UTC

diagrams for 7 and 8 September at 00:00 UTC. The diagrams indicated the unstable column of air on the surface and within the mid-level of atmosphere prior to the flooding. In the first diagram for 7 September, the unstable and humid air column was limited to first 1,500 m, but the next day, unstable atmospheric conditions extended further up, to 6,000 m, indicating a deepening convective layer.

When the rainfall was most abundant on 7–8 September, the instability indices at 00 UTC, especially Sweat, K, and TT indices, had borderline values. In fact, almost all the indices values were above the marginal boundary, especially the K index values, are significantly above the threshold set by Maddox et al. (1979) to indicate severe weather situation. The high Sweat Index values are indications of high variation in wind directions both at ground and in upper atmospheric levels. The PW values of above 30 exceeded the threshold level set by Doswell (1982) to indicate potential for severe rainfall. Figure 13

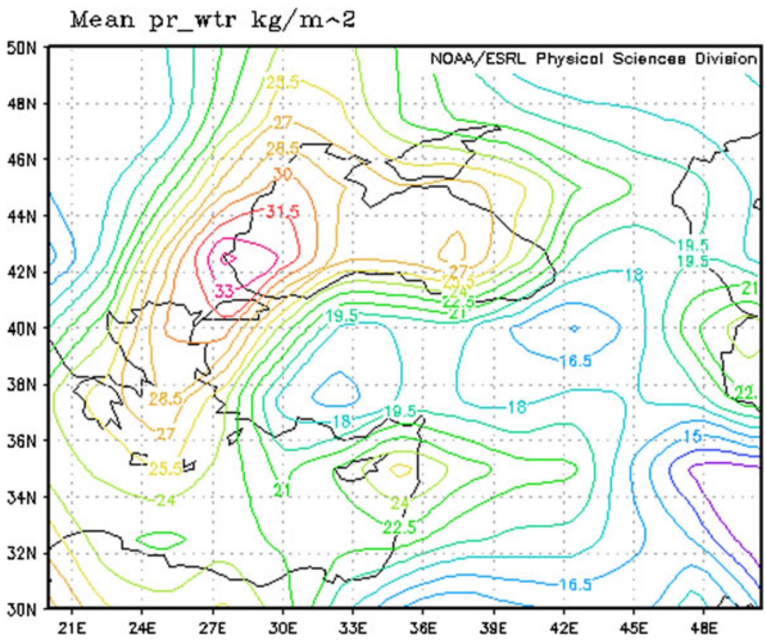

Fig. 13 24-h precipitable water (PW) values valid from 7 to 8 September 2009

presents areas where the PW values reached maximums and it is clear that the areas flooded during 7–10 September were characterized with the highest PW values. Instability of the air both over the land and sea is also supported by high humidity fields, which were derived from the NCEP/NCAR (Kalnay et al.1996) reanalysis data (Fig. 14). The relative humidity values exceeded 90 % over the Marmara region, Black Sea, and the Aegean Sea. As stated earlier, moisture advection from the Black Sea provided additional source to enhance convective storm development in the region.

5.3.2 Analysis of radar and satellite images

Radar and satellite images analyzed for the flooding period in the Marmara region provide additional tools to visualize areal distribution of the intense rainfalls. The radar images are obtained from Doppler weather radar in Çatalca (İstanbul), operated by State Meteorological Service of Turkey. The images for the consecutive days clearly indicate how the storms developed, spread, and decayed in spatial terms over the region (Fig. 15). The storms were particularly potent on 8 September in İstanbul, but weakened the next day and left the region completely on 10 September. As seen on the image for 7 September, the storms were approaching the region from the northwest, creating a NE-SW oriented zone of intense rainfalls. As explained earlier, this was a result of the low-level warm sector which induced frontal instability, triggered by sudden updraft of warm air from the surface. On the same image, scattered clusters of storms are noted over the central parts of the region near the Black Sea coast. These storms were the result of the advection and uplift of the moist air from the northerly flow of the Black Sea. The radar images for the next day clearly show that the intense storms covered nearly the entire northern and central portions of the region. As noted earlier, this was a result of the

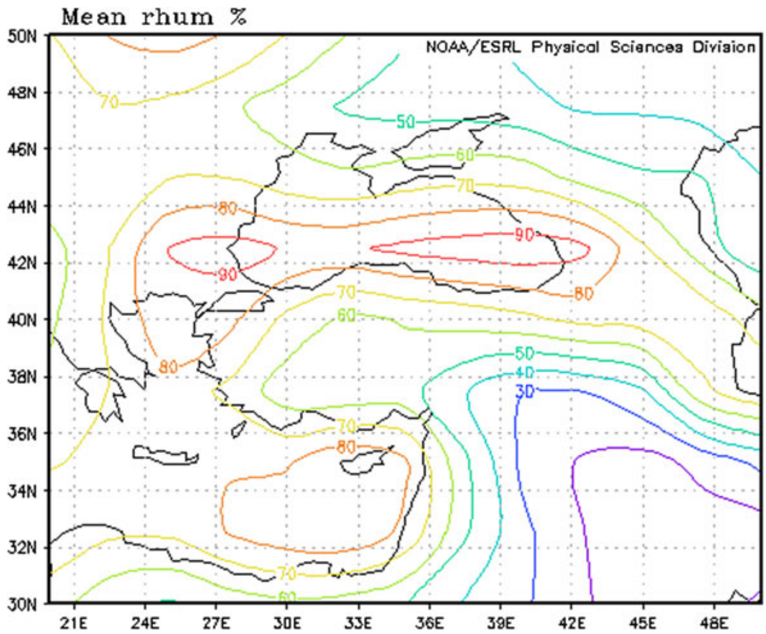

Fig. 14 Relative humidity from 7 to 8 September 2009 at 1,000 hPa over Turkey. *Source*: NOAA/ESRL

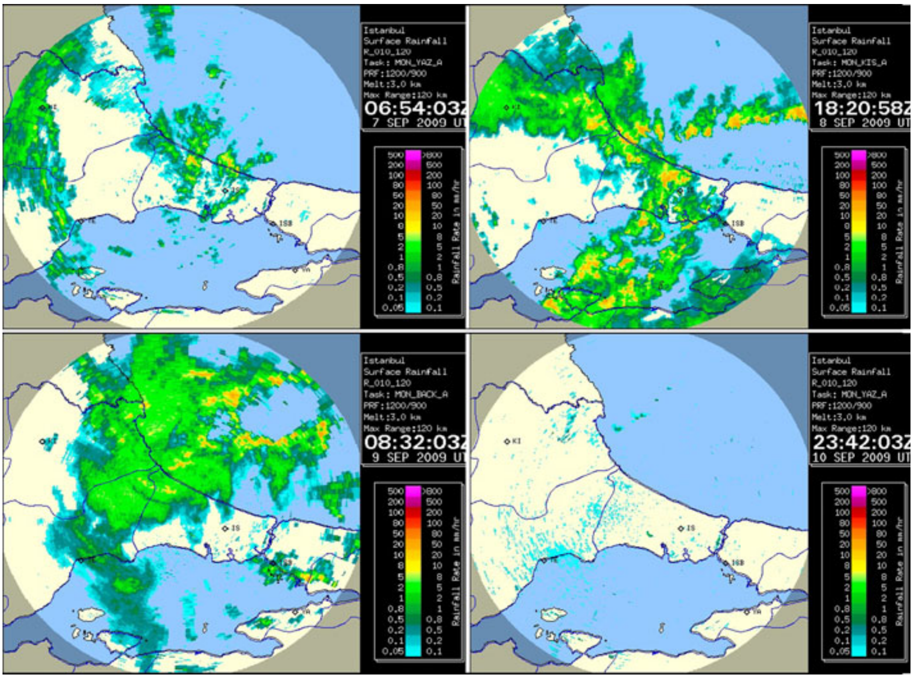

Fig. 15 Rainfall intensities observed by İstanbul radar during 7–10 September 2009 at selected times (mm/h)

Table 4 Rainfall intensities recorded by the İstanbul Radar during the 7–10 September 2009 period

Days	Rainfall intensity in minutes (mm)													
	5	10	15	30	60	120	180	240	300	360	480	720	1,080	1,440
Sep-7	2.2	3.2	4.8	7.8	12	13.6	16.8	19.2	25	33.8	44.6	173	195	205
Sep-8	13	25	33.2	57	84.2	112	135	142	146	154	169	191	200	205
Sep-9	5.8	8.8	9.6	13.4	15.8	16.6	16.6	16.6	18	18.6	19	28.6	35.6	35.6
Sep-10	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6	1

upper air trough over the western part of Turkey and continuous moisture supply from the Aegean Sea. This enhanced single- and multiple-cell convective activities, and static behavior of the systems, and moisture influx from the Black Sea which further enhanced convective storm development over the region. On 9 September, the spatial coverage of the storm enhanced both over the land and sea areas because of the northeasterly flows originating from southern Russia and Black Sea coasts and its joining with colder air advected from Bulgaria and Romania, all of which culminated to enhance the development of convective cells. More importantly, the low-pressure system located over the Balkans which disconnected from the main frontal system, turned into a deep cutoff over the northwestern part of Turkey on this day.

Table 4 presents rainfall intensities obtained from the İstanbul radar for the 4-day period starting from 7 September. Twenty-four-h rainfall exceeds 200 mm in first 2 day of the flooding period, but the intensities dropped suddenly in the third day of the flooding period and became negligible in the fourth day when the storms decayed. It should be noted that the radar rainfall data agreed well with the data recorded at the same station.

Spatial development of the storms was even better identified with the MSG infrared satellite images for the 7–10 September period (Fig. 16). The images indicate that a NE-SW oriented storms system moved over the Marmara region from Southeast Europe on 7 September and covered almost the entire Marmara region in the next 2 days, leaving the region gradually on 10 September. Clustering structure of the clouds over the region indicates the presence of widespread cumuliform clouds during the flooding period. Overall, both radar and satellite images support separate cases of convective storm development over the western Turkey and their move to the Marmara region.

6 Impacts of land use and socio-economic factors on the development of floods in İstanbul

Continued urbanization of floodplains cause significant loss of life and damage to property worldwide during floods and the trend is increasing alarmingly. The urban areas have particular hydrologic characteristics which affect surface runoff characteristics, and modification of the natural drainage systems cause changes in timing and magnitude of peak flows in urban areas. A major effect of urbanization is increase in the frequency of high-flow discharges and reduction in the time to reach peak discharges due to adding more impervious surface and increased runoff. In general terms, human activities can influence flooding in two ways. They either affect the run off patterns through deforestation, urbanization, and river canalization or increase the possible impact of flooding on people through the occupation of flood plains (Brauch 2003).

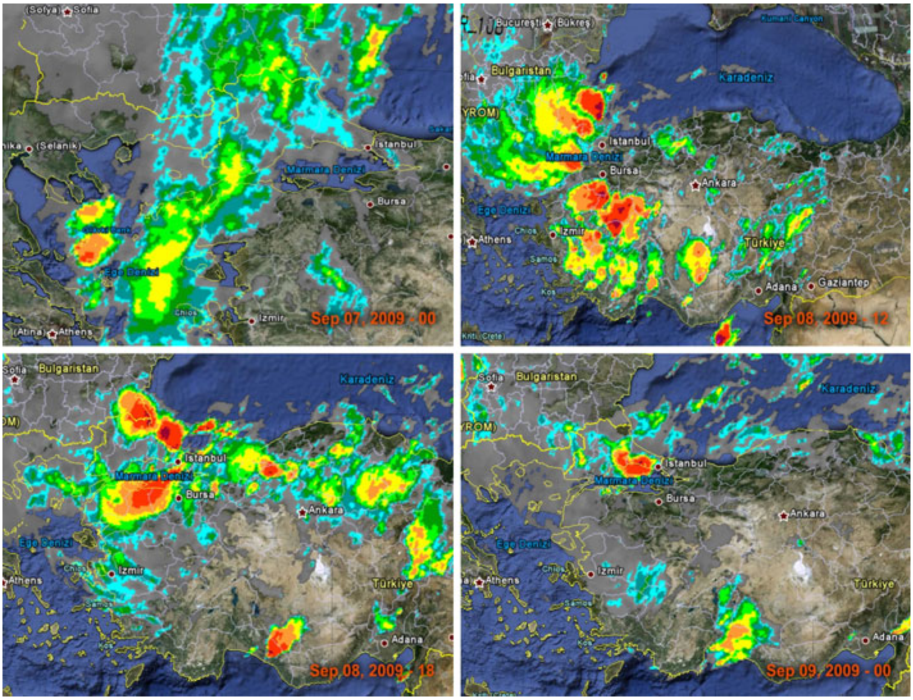

Fig. 16 Daily MSG Infrared satellite images for 7, 8, 9, and 10 September 2009

Previous part of the study concluded that the meteorological conditions were favorable for the development of intense storms that led to floods in the northern Marmara region in early parts of the September 2009, but they alone fail to explain consequences of the flood which resulted in considerable human loss and economic damage in urbanized parts of the region. Considering the fact that almost all the human casualties were observed in İstanbul and its vicinity, we had to consider effect of the urbanization factors and change in land use to explain devastating consequences of the flooding.

Rapid urbanization and improper use of watersheds result in serious flooding problems in Turkey (Usul and Turan 2006). This study shows that urban areas such as İstanbul are more vulnerable to floods due to exposure of densely populated areas with inadequate infrastructure and settling in flood-prone areas. Two main parts of the city where the floods heavily impacted in İstanbul during the September 2009 floods were the Ayamama River and İkitelli industrial site. The Ayamama River and its watershed, which is heavily urbanized, suffered from the rising flood water severely. The Ayamama River runs through most industrialized part of the European side of İstanbul and especially middle and lower parts of its basin are heavily urbanized and experienced rapid land use changes in recent decades (Fig. 17). The river was not able carry the vast amount of water that built up because its flood plain was blocked with buildings, factories and truck parking. The Ayamama river basin and its surrounding areas were designated as recreational areas originally according to the city development plan, but an amendment was made in 1997 to develop it into a residential area (Ozcan and Musaoglu 2010). The İkitelli Industrial site is located in the watershed of the Ayamama River and therefore suffered extensively a result of rising water levels and flood waters which occupied factories and small operations.

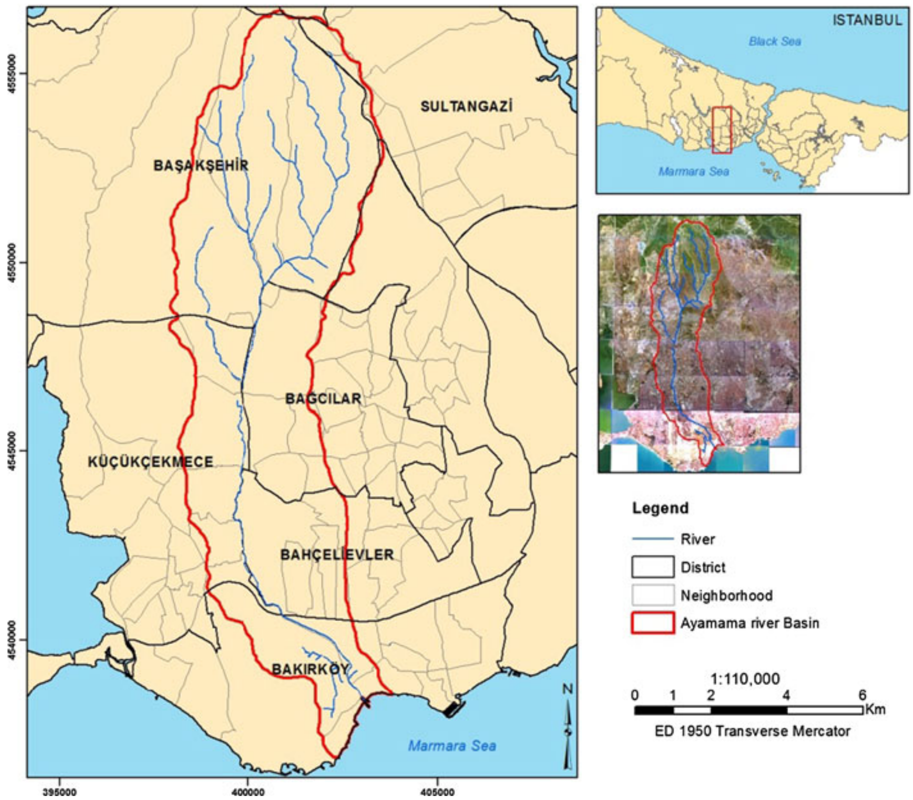

Fig. 17 Ayamama River Basin (Adapted from Reyes-Acevedo et al. 2011)

Ozcan and Musaoglu (2010) assessed the flood risk zones in the Ayamama River watershed based on satellite data blended with a digital terrain model and found that nearly 420 buildings which 287 of them industrial buildings, in the watershed, were found to be in high vulnerability zones. The areas adjacent to the Ayamama river basin attracted large number of population in the last 2–3 decades due to its potential for multiple economic activities and high property values. According to the İstanbul branch of the Environmental Engineers Chamber, the issuing of permits for buildings close to riverbanks without providing sufficient infrastructure was a major factor in worsening of the flood damages. Another main criticism was about the inadequate flood mitigation measures which usually received less attention by the local authorities in İstanbul. They have, in their disaster planning, focused more on seismic activity risks in the city which is settled in a close proximity to a major fault line at Marmara Sea.

Apart from the socio-economic factors mentioned above, several other factors had considerable impact on the flooding conditions in İstanbul. The first was the change in the land use as a result of the growing population and urbanization of the metropolitan area of İstanbul. As the most populated city of Turkey, many new settlements have been built in and around the city in order to absorb the increasing population. According to the 2007 census data, population of İstanbul exceeded 12 million and current estimate indicate a population of 15 million for the metropolitan area of İstanbul. Infrastructure in the newly established residential and commercial areas of the city did not grow in parallel to the

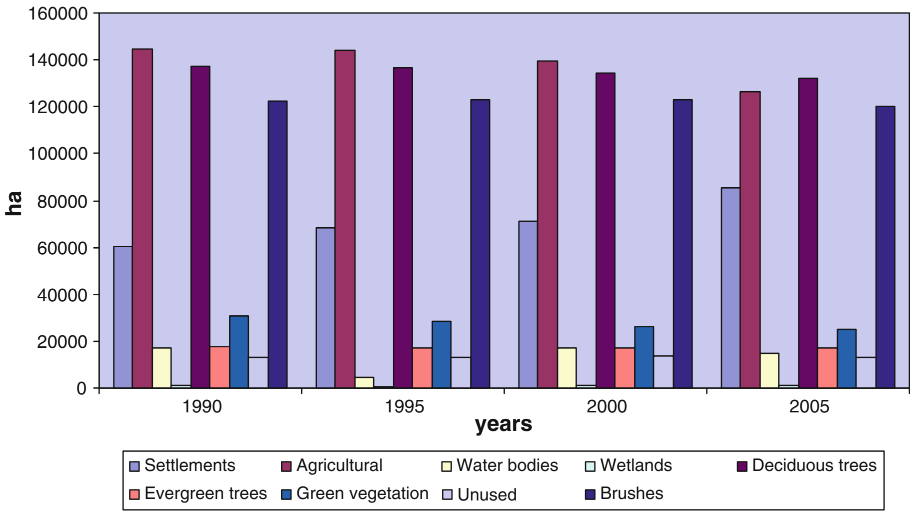

Fig. 18 Land use changes in İstanbul in the last 2 decades

population, and therefore, the current infrastructure of the city is not adequate even to accommodate runoff from a moderate rainfall. Moreover, in parallel to the urbanization, land use in İstanbul also changed considerably to open new areas for development to accommodate the growing settlements and industrial activities. Establishment of new transportation networks, concentration of industrial and commercial activities at flood-prone areas of the city has further accelerated the land cover changes, especially in the last two–three decades. In other words, urban expansion in the flood-prone areas created pressure to open up space for new settlements and commercial use, often without inhabitants being aware of the risks they are taking. Geymen and Baz (2007) assessed land cover changes in İstanbul between 1990 and 2005 based on analysis of Landsat TM and Landsat GeoCover LC satellite images. They found that urban growth of the city was considerably high and settlement areas in the city expanded at the expense of the agricultural and vegetative areas (Fig. 18). Uncontrolled urbanization accompanied by insufficient infrastructure has caused degradation of forest and barren lands in vicinity of the city. Another important point that played key role in occurrence of floods in İstanbul, in general, was lack of consideration of natural hydrological conditions of the region in planning of infrastructural and construction projects. In a study done by Turoglu (2011), it was found that the city's highway transportation network which lies in a east–west direction is inconsistent with the natural drainage pattern where flow accumulation and flow direction extend roughly in a north–south direction. Therefore, transportation network in the city acts as vertical barriers against the surface runoff. This was a considerable handicap in discharge of the flood waters quickly during the flood.

7 Summary and conclusion

This study aimed to provide in-depth analysis of hydrometeorological conditions that led to the occurrence of flash floods in the Marmara region, particularly in İstanbul, between 7 and 10 September 2009 and discussed consequences of the flood in relation to urbanization factors. The meteorological analysis indicated that Silivri and Çatalca towns located west to İstanbul and area between Tekirdağ and Bandırma received the highest amount of rainfalls that eventually led to the development of flash floods which resulted in 32 deaths and considerable economic losses across the region, mainly in İstanbul.

To summarize outcomes of this study in brief;

- Main meteorological settings that led to intense storms were presence of cold air in the upper atmosphere, a slow-moving quasi-stationary trough, continuous resupply of moisture to the surface low from both the Aegean Sea and the Black Sea
- A very unstable meteorological environment prior to the floods supported by high surface temperature contrast, high relative humidity, and high PW
- Re-development of convective cells over the same region enhanced the rainfall intensity
- No typical effects of orography to enhance rainfall in the coastal areas were observed
- High concentration of rainfall intensities over the west of the city of İstanbul and off the northeastern coast, and the core of the intense rainfall is located over the sea not on the northern or southern slopes of the region
- Some resemblance between the meteorological settings of the Marmara flood and the Maddox et al (1979) and "backdoor cold fronts" approaches were identified. The settings, however, did not fit either approach perfectly, rather they indicated common features of the both approaches, and
- Although the hydrometeorological conditions were greatly favorable for the occurrence of widespread floods across the portions of the Marmara region, additional factors such as land use changes, modification of the natural drainage network, inadequate drainage, and illegal occupation of the flood-prone areas by buildings and factories set the stage for the devastating consequences of the floods

In conclusion, it is our view that the knowledge of meteorological conditions at both surface and upper levels, favoring the occurrence of floods can serve as a reliable early flood warning system that can further help in mitigation and risk management planning of such hazardous events. It may be also possible in the future to use "key synoptic features" of these types of events in order to forecast better the occurrence and location of flash floods.

From another perspective, the Marmara flood also emphasizes the fact that human activity can be a major contributing factor to amplify adverse impacts of flood events significantly. In fact, the economic losses and adverse impacts associated with the floods observed in recent years in urban areas of Turkey have drawn attention to proper flood management and mitigation measures to minimize the cost and impacts on infrastructures and properties. Managing flood risks in densely populated areas such as İstanbul, however, has been always challenging. Because of its large impervious areas, İstanbul is potentially exposed to floods even during a moderate rainfall since its current drainage network and flood control structures cannot accommodate large surface runoffs. Also given its high population density, even small-scale flash floods may cause considerable damage in the city. As long as people continue to occupy flood-prone areas of the city and economic assets located in the flood risk zones continues to grow, it would be difficult to reverse the current trends related to adverse consequences of floods in İstanbul. It is our view that such disastrous events would be inevitable in İstanbul in the future unless necessary measures are taken by the local governments and authorities. An initial step should be developing a comprehensive flood mitigation plan within a framework of integrated flood plain management. Flood inundations maps should prepared, based on different recurrence intervals and zones under risk of flooding, before taking any structural measures. Once the risk areas prone to floods are identified, further development in those known flood risk areas should be prevented by enforcing specific building codes. In particular, no construction activities should be allowed in the flood zones of rivers which are exposed to high risk of flooding. Present industrial facilities and residential buildings in flood zones of Ayamama and Kağıthane Rivers should be relocated to other parts of the city where the risk of flooding is lower or non-existent. Some structural measures also should be taken to control the flows in main rivers of the city, especially the Ayamama and Kağıthane Rivers which frequently overflows following intense rainfalls. A more important step would be setting up flash flood early warning system to monitor water levels in the main creeks in and around İstanbul, monitor and assess spatial and temporal distribution of rainfall, and issue warning when necessary to act promptly to evacuate the areas where there is risk of being flooded. It should be emphasized that the technical measures will certainly contribute to better disaster preparedness for urbanized areas like İstanbul. The proposed measures, however, will not be successful unless they are supported by legislative measures including specific building codes for flood-prone areas, political efforts, and public awareness to enhance their effectiveness.

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