11 Floods in Greece

D. Koutsoyiannis, N. Mamassis, A. Efstratiadis, N. Zarkadoulas, I. Markonis[*]

11.1 Introduction

The regional characteristics of rainfall and the terrain morphology differentiate Greek floods from those of Northern Europe, both in spatial and temporal scales. The hydroclimatic status of Greece is controlled by two key factors, i.e. the orography and the passage of depressions from the west. The Pindos mountain range, which extends from the northwestern coast of the mainland to the island of Crete, divides the country into two major hydroclimatic areas, the water-rich western one and the semi-arid eastern one (Fig. 1). Thus, the mean annual rainfall exceeds 2000 mm in mountainous areas of western Greece, whereas in eastern regions of mainland Greece, due to the rain-shadow effect, it is as low as 400 mm. A third climatic area comprises Western Crete and the eastern Aegean islands, which receive higher amounts of rainfall (700 mm, on average), because the westerlies-dominated circulation over the sea favours the enrichment of the atmospheric systems with water vapour and thus the generation of storms.

The striking relief patterns, the long and intricate coastline, and the abundance of islands in Greece, lead to the formation of numerous small-sized steep hydrological basins. The large majority of the streams have ephemeral flow; they are characterized by non-permanent surface runoff, often increased percolation (due to the dominance of limestone (carbonate) formations, covering 40% of the Greek territory) and flash floods. However, a limited number of medium-scale watersheds (of the range of a few hundreds to a few thousand km^2) have permanent-flow rivers. Most of these lie in the western and northern part of the country. The major rivers in Macedonia and Thrace in the north (Evros, Strymon, Nestos, Axios) are transboundary, while most of the other large rivers (Acheloos, Aliakmon, Peneios, Arachthos, Aheron, Louros) originate from the Pindos mountain range and their basins extend over Greek territory only, except for one (Aoos, which flows toward Albania). A list of the 20 largest (according to basin area) rivers in Greece is given in Table 1. The variety of the rainfall regime and the physiographic and morphological characteristics of the terrain give rise to impressive differences in the runoff and flood generation mechanisms. Thus, in some basins the mean annual equivalent runoff (i.e. runoff volume per unit area) exceeds 1000 mm (a very high value, usually found only in tropical areas), while in some other cases this amount is one order of magnitude smaller, or even less.

Generally, flood phenomena are caused by intense rainstorms that are produced by the passage of depressions, possibly accompanied by cold fronts, typically approaching from the west. Convectional weather types (characterised by a cold upper air mass that produces dynamic instability) are also responsible for many intense storms and flash floods, especially in the summer period (Mamassis & Koutsoyiannis, 1996). Snowmelt driven floods are rare, while coastal floods, although they occur in some Aegean islands, are relatively unimportant.

Although the western areas are particularly rainy, extreme floods are also common in eastern Greece and the Aegean Islands. This reflects the fact that, as we move from the west to the drier hydroclimatic areas of the east, the rainfall intensity of storms remains high. This tendency is reflected in Fig. 2, where the mean annual precipitation is plotted against the ratio of the maximum recorded daily to mean annual precipitation for 91 meteorological stations supervised by the National Meteorological Service of Greece (all stations have at least 20 years of observations). The highest ratios correspond to the driest locations. For example, in areas where the mean annual rainfall is less than 500 mm, the ratio is typically 25% or even more, which means that one quarter (or even one half) of total annual precipitation may fall in a single day. As a result, in drier areas, where rainfall is rarer, the flood risk may be greater than in the wetter areas, where people are more accustomed to the more frequent rainfall.

[*] All authors are at: *Department of Water Resources and Environmental Engineering, National Technical University of Athens, Greece*

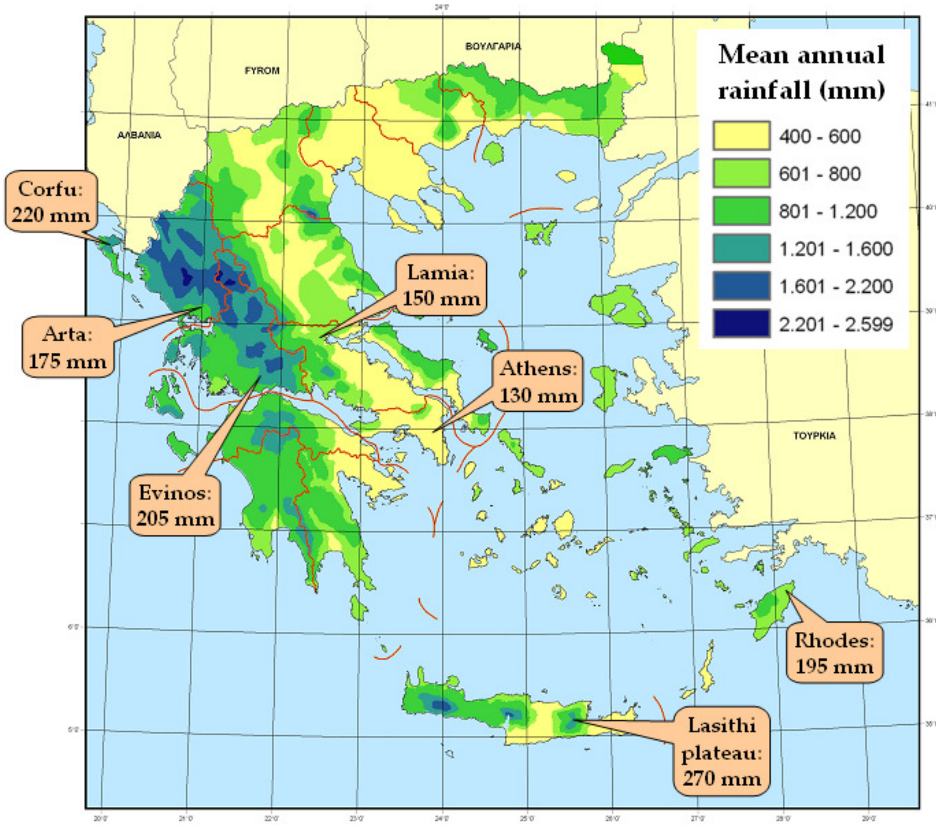

Fig. 1 *Geographical distribution of mean annual rainfall in Greece and estimates of 24-hour rainfall depth for 50-year return period at characteristic locations (source: Koutsoyiannis et al., 2008, with additional information by authors).*

Table 1 *List of 20 largest rivers in Greece (source: Koutsoyiannis et al., 2008).*

	River	Basin area (km^2)		Length (km)		Mean annual runoff	
		In Greece	Total	In Greece	Total	Volume (hm^3)	Depth (mm)
1	Peneios (Thessaly)	9500		205		2558	269
2	Aliaknon	8813		314		2724	309
3	Strymon	5990	16787	118	430	4063	242
4	Acheloos	4812		240		4383	911
5	Alpheios	3570		110		2100	588
6	Evros	3344	52788	204	639	12065	229
7	Nestos	2429	6130	130	192	3140	512
8	Aoos	2154		70	260	2200	1021
9	Arachthos	2000		128		2280	1140
10	Boeoticos Kephisos	1930		98		286	146
11	Kalamas	1900		115		1900	1000
12	Spercheios	1830		80		693	379
13	Eurotas	1738		80		760	437
14	Axios	1636	22250	76	350	3024	136
15	Filiouris	1486		58		154	104
16	Loudias	1251		60		95	76
17	Evinos	1163		92		917	788
18	Gallikos	1055		70		54	51
19	Peneios (Heleia)	1026		72		427	416
20	Mornos	974		58		404	415

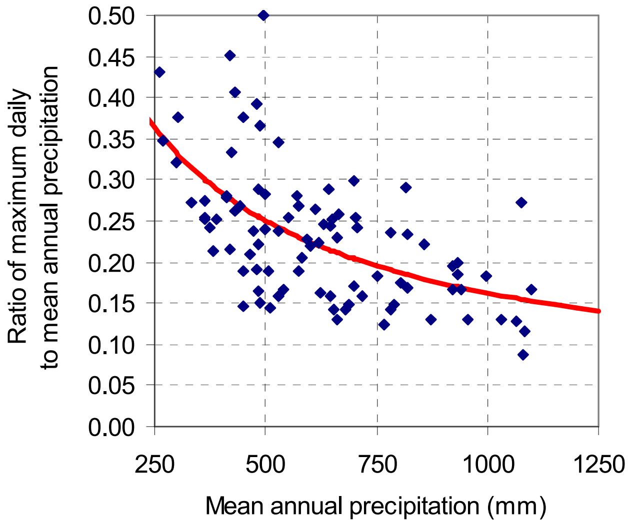

***Fig. 2** Ratio of maximum recorded daily to mean annual precipitation versus mean annual precipitation over 91 meteorological stations in Greece (data source: National Meteorological Service).*

In Fig. 1, the maximum 24-hour rainfall depth for a 50-year return period is shown at various locations, as estimated in related flood studies, on the basis of the same mathematical approach (i.e. analysis of historical rainfall maxima using the GEV-II distribution). This magnitude can be assumed to be an indicator of the flood risk, although the 24-hour duration is long when compared with the usual times of concentration of the majority of Greek basins. It is remarkable that this value is as high as 200 mm in western Greece, reduces to about 120–150 mm eastward of the Pindos mountain range, and increases again to 200 mm and more for the east Aegean islands. The highest values are found in the mountainous areas of Crete, where the daily rainfall, for the specific return period, approaches 300 mm.

Large-scale floods, mainly due to deglaciation processes (referred to as palaeofloods), together with earthquakes and volcanoes, are the major mechanisms that formed the current diverse Greek terrain. Section 11.2 provides a brief review of palaeofloods in Greece. The influence of these impressive phenomena is also reflected in some ancient Greek myths, a few of which also refer to earlier efforts of flood control and management, as explained in Section 11.3. The struggle of humans against the destructive power of floods is further testified by several structures revealed by archaeological research, as described in Section 11.4. In modern times, the dramatic change of the demographic and socio-economic conditions made imperative the construction of large-scale water projects, which in turn resulted in large-scale environmental changes. The consequences of these practices, both positive and negative, with regard to the problem of floods in Greece, are discussed in Section 11.5.

11.2 Reflections from the past: Analysis of palaeofloods

Palaeoflood hydrology is the reconstruction of the magnitude and frequency of recent, past, or ancient floods using geological evidence (Baker *et al.*, 2002). The term "*palaeo*" originates from the Greek word "*παλαιό*", which means old. Such techniques are used for estimating floods over various time scales, not only geological ones. Most palaeoflood studies cover the last five thousand years, and focus on even shorter time periods. Palaeoflood evidence is supported by the indirect physical effects on natural indicators, such as sedimentary flood deposits or scour lines. These palaeoflood indicators can be correlated to define the palaeoflood water surface profiles along the river channel (Benito & Thorndycraft, 2005).

Palaeoflood techniques cannot estimate the hydrological regime accurately, because palaeofloods are strongly affected by changes in catchment vegetation and, for periods after the onset of human civilization, land use. This factor increases in importance for large time scales, because in geological times the vegetation characteristics of broader areas may vary to a great extent, and in the Mediterranean this seems to be the rule (Macklin *et al.*, 2002; Hayes *et al.*, 2005; Dormoy *et al.*, 2009). However, they can be used in conjunction with other proxy climatic data, such as pollen records or sediment isotopes, and offer a more global perspective to the links between climate variability and flood frequency and magnitude.

Another critical factor concerning the study of prehistoric floods is the overall climate regime. It is well known that global climate is dominated by long ice-ages, accompanied by shorter interglacial periods.

Although the main body of the glaciers that covered northern and central Europe did not reach Greece, the glaciers of the Greek mountains did grow large in size (Hughes *et al.*, 2006). During each deglaciation phase there are two important mechanisms that affect the flood genesis: the direct melting of the ice that is stored in the glaciers and indirect changes in the global and regional climate because of the changes in temperature, precipitation and humidity. Furthermore, major cataclysmic events may have occurred when the ice-dams that constrained mountainous lakes collapsed, releasing enormous amounts of water (Reuther *et al.*, 2006).

In addition, serious flow increase may also have occurred during glaciation development. An explanation for this is the effect of cooling on the vegetation, which causes the transformation of forest-covered areas to more steppe-like ones. Thus, a relatively small change in climate within these areas would have a large effect on hillslope vegetation, and thus on slope stability and runoff response (Macklin *et al.*, 2002). For example, the alluviation event that occurred 109 to 111 thousand years BP (Before Present) and is recorded in a wide range of Mediterranean catchments is close to the global-cooling event in Marine Isotopic Stage (MIS) 5d. This correspondence becomes more evident during three, relatively recent, alluviation phases that coincide with abrupt decreases in sea surface temperature in the northeast Atlantic between 23 to 26, 15.5 to 18 and 11.5 to 13 thousand years BP (Schulte *et al.*, 2000).

Over the past 200 000 years there have been two glaciation eras in the global climate history, while at least 13 major alluviation episodes of different amplitude, frequency and duration have been identified in the Mediterranean basin. The synchroneity of these events, although they correspond to catchments with very different characteristics, shows that there is a strong flood–climate relationship. Moreover, the timing of these events shows an evident sensitivity to abrupt climate changes in the North Atlantic due to its effect on the vegetation of the Mediterranean region and the corresponding modulation of catchment erosion and river alluviation, which is more intensive than the relatively subdued response of northern European river systems (Macklin *et al.*, 2002).

In Greece, the earliest glacier formation is identified in the interval between 128 to 132 thousand years BP, according to the Ioannina pollen record (Tzedakis *et al.*, 2004), while the last glaciers formed in Greece between 20 to 17 thousand years BP (Woodward *et al.*, 2009). During these periods, the relative abundance of temperate tree populations, like species *Juniperus* and *Pinus*, varied in accordance to temperature and precipitation (Fig. 3). It is obvious that, during the period between 50 to 15 thousand years BP, dry and cold conditions prevailed, which led to low, steppe-like vegetation. Therefore, the transition towards a moister climate that occurred after the Younger Dryas (12 000 BP), also supported by the Lake Xynias level record (Digerfeldt *et al.*, 2000), should have been accompanied by frequent extreme flood events, due to the combination of ice melting, low vegetation and precipitation increase. This would have been intensified by the contrast between moist upland and dry lowland climates that is observed in mainland Greece (Hughes *et al.*, 2006). Unfortunately, this period has not been reconstructed yet by any of the existing palaeoflood records.

The study of Voidomatis River system (a tributary of the Aoos River, in northwest Greece) showed that glaciers were much smaller during the last cold stage (MIS 5d to MIS 2), with respect to the two previous ones taking place during the Middle Pleistocene (MIS 12 and MIS 6). This record shows that, during the last glacial to interglacial transition, glaciated Mediterranean catchments saw major changes in their flood generation mechanisms, sediment fluxes and sediment sources. This geomorphological response may be representative of earlier periods of change in the Middle and Late Pleistocene, but the last (MIS 5d) transition may have been more abrupt than earlier terminations because of the small size of the glaciers (Woodward *et al.*, 2009).

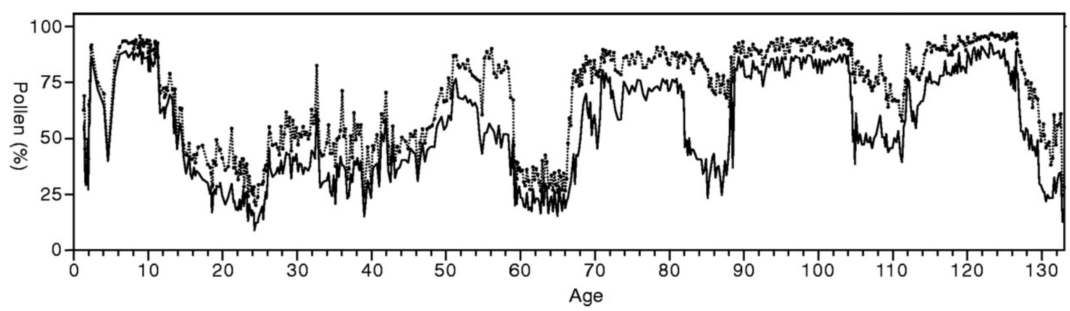

***Fig. 3** Summary pollen percentage curves from the I-284 sequence (Ioannina pollen record); they represent changes in vegetation structure (relative degree of forest versus open vegetation communities). Dashed line, Total Arboreal Pollen; solid line, Arboreal Pollen – (Juniperus + Pinus), representing the relative abundance of temperate tree populations (Tzedakis et al., 2004).*

After the Younger Dryas more temperate conditions were established, while the seasonal precipitation regime of the period up to the present day was characterized by hot dry summers and cool wet winters. During the last ten thousand years this regime was influenced by the North Atlantic Oscillation (NAO), the intensity of the Siberian High and lower latitude monsoons (Kotthoff *et al.*, 2008), with short-term climate changes being more strongly expressed and dryer in the Aegean region (Dormoy *et al.*, 2009). These short-term changes, and more specifically moisture availability, were the dominant factor controlling Holocene deforestation, probably leading to an increase of flood events. The strongest event (from 8.4 to 8.0 thousand years BP) represents the regional expression of the 8200 BP cold event widely known from the Northern Hemisphere, while similar, but weaker events occurred from 7.5 to 7.2 and 8.8 to 8.6 thousand years BP (Kotthoff *et al.*, 2008), or even during the Older Dryas from 14.1 to 13.9, 13.5 to 13.4 and 13.0 to 12.6 thousand years BP (Dormoy *et al.*, 2009).

The palaeoflood research on the river systems sheds light on some additional evidence for these short periods of increased flood activity which span a few hundreds of years. A recent study of Anapodaris Gorge, in south-central Crete, showed that there were two distinct periods (4.86 to 4.20 and 3.40 to 3.00 thousand years BP) of higher frequency of erosive rainfall events and floods (Macklin *et al.*, 2010). The first of them appears also in Kranidhi alluvium in southern Argolid (Pope & van Andel, 1984). These periods are associated with cooler conditions, an expansion of the Siberian High and negative NAO index values. By contrast, extensive valley floor incision down to about present channel bed levels occurred between 3.00 and 2.07 thousand years BP under warmer and drier conditions. Similar timings of mid to late Holocene and Little Ice Age valley floor aggradation episodes elsewhere in the Mediterranean suggest that climate variability has been the primary control of Holocene river behaviour in most steepland catchments (Macklin *et al.*, 2010).

11.3 Reflections from the past: Flood mythology

The rich Greek mythology includes many stories related to floods. Ancient Greek literature contains numerous references to these stories, thus enriching the narration on different topics. Although similar stories can be found in the mythologies of almost all ancient civilizations, Greek myths have a great importance because of their age and the variety of the sources. A close inspection of those myths reveals a process-understanding dimension as well as a technological dimension concealed in the myth narrative. The former dimension is reflected in the reference to space–time evolution of geophysical processes such as rainfall, runoff, soil erosion and its link to floods, and the groundwater regime and its links with springs and rivers, whereas the technological dimension is manifest in the struggle of mankind against the devastating power of water. Several mitigation and adaptation measures are mentioned (sometimes symbolically, other times more explicitly, e.g. the abandonment of unsafe flood-prone areas and the preference for occupation of mountainous areas during flooding periods) in order to control rivers, drain swamps or confine floodplains. Accordingly, the following subsections focus on these two dimensions.

11.3.1 Cataclysmic myths

Three cataclysmic or “great deluge” myths were very popular in ancient Greece, and were attributed to the periods of reign of the mythical kings Deucalion, Dardanus and Ogyges.

The first myth, which is very similar to Biblical Noah, is referred to by Apollodorus (Library A.7.1): Zeus (Jupiter) provoked extended rainfall in order to punish the hubris of the Pelasgians (i.e. the earlier population living in the Greek territory). Many parts of Greece were overwhelmed by water and a few people fled for refuge to the high mountains. Before the deluge, Titan Prometheus had been advised his son Deucalion, king of Phthia in Central Greece, to construct a larnax (chest). The larnax, with Deucalion and his wife Pyrrha, floated for nine days and nine nights, before the passengers disembarked to Mount Parnassus.

The second myth is referred to by Dionysius of Halicarnassus (Book 1.61–62): Dardanus and his elder brother Iasus reigned in Arcadia, in the Peloponnese. After a great deluge the plains were overwhelmed by water. As the waters remained for a long time, people moved to the mountains but were not able to cultivate much land there. Because the land was insufficient to feed all the population, they decided to split into two groups. The first group remained in Arcadia under the reign of Deimas (son of Dardanus) and the second group, under the leadership of Dardanus, embarked on a large fleet and sailed along the coast of Greece. After a temporary settlement in Samothrace (an island in northern Greece), they disembarked to the Hellespont strait in Asia Minor. Idaeus, son of Dardanus, occupied a mountainous area (now called the Idaean Mountains) and Dardanus founded a city in a region called the Troad. We can assume that the preference for mountainous areas by Idaeus is related to the fear of another deluge. According to Plato

(Laws, 682b), Ilium, the epicentre of the Trojan War, was founded many years after the deluge, when Greeks moved from the highlands down to the plain area. It is very interesting to see the comment of the Athenian (a character in Plato's Laws, 682c) that Greeks "*seem to have been strangely forgetful of the catastrophe now mentioned, since they placed their city, under a number of rivers descending from the mountains, and relied for their safety upon hillocks of no great height*".

The third myth is the Ogygian flood, for which rare and conflicting references are found in ancient literature. The flood occurred in the area of Attica (Greater Athens area) and Boeotia at the time that the mythical king Ogyges reigned. Plato, in his books *Kritias* and *Timaios*, provides some interesting references about a deluge that afflicted an ancient Athenian civilization (but it is unclear whether it refers to the Ogygian or Deucalion's flood). Most impressive is the fact that Plato estimates the occurrence time of the deluge as 9000 years before his time (*Timaios* 23e; *Kritias* 111a), a time that coincides with the end of the last glacial age. As we know today, a rapid melting period after the Younger Dryas cold episode (at about 10 250 BP) caused a sea level rise of several tens of metres. Also he relates that, during the last 9000 years, many floods had occurred and that three of them happened before the Deucalion deluge (*Kritias* 111; 112a). As a result, large quantities of soil were moved from the land to the sea, and Plato compares the ground from which the fertile and soft soil was removed with the bones of an ill body. Also, he assumes that before the soil loss, rain water was stored under the mud that covered the Earth and was feeding the springs and the rivers. At that time, there were many forests in the mountains, fruit trees in the plains and plentiful grassland for flocks. As evidence of this story he refers to the presence of temples in places that once upon a time were springs (*Kritias* 111d). Plato's work contains other references to flooding, such as that of Atlantis, a huge island that sunk after earthquakes and floods (*Timaios* 25d).

A theory of alternating periods of flood and drought is attributed to Xenophanes by Hippolitus. According to contemporary knowledge, such alternation of flood and drought regimes is the rule in Nature and is manifest at several time scales, including those characterizing the glaciation and deglaciation periods. Xenophanes, an Ionian philosopher who had a great impact on ancient physical sciences, supported his theory by the discovery of fossilized sea organisms at three island locations. According to Hippolitus (*Elenchos* I, 14.5): "*Xenophanes considers that a mixture of the land with the sea comes but in time the land is separated from the fluid and he says that there are proofs for these considerations. Shells are found in mainland and in mountains and he says that there are quarries in Syracuse where impresses of fish and seals or seaweed were found. Also there is in Paros the impress of a laurel leaf in the deep of the stone and on Malta slabs containing all of the sea organisms. He says that all these were created a long time ago when they were covered by clay and the impress was created by the drying of the clay. The mankind was vanished when land was transported to sea and became mud. Later the process of birth restarts and this is the beginning or modification of all universes.*"

11.3.2 Flow and flood control myths

Several myths are related to the mitigation of flood risk and the control of streamflow. Hercules fights against Acheloos, the largest (in discharge) river lying totally in Greek territory, which was worshiped as a God by ancient Greeks. A Greek vase depicts Hercules defeating Acheloos, which has metamorphosed into a snake (Fig. 4). According to Diodorus and Strabo, the victory of Hercules symbolizes the construction of dykes in order to confine the river. Remnants of such dykes are also referred to by Strabo in Peneios on the Thessaly plain.

According to another myth, Hercules is the constructor of swallow holes at Pheneos, a fertile mountainous plateau in the Peloponnese. These transferred water to Hades (the Underworld) and made the land suitable for farming. These holes were used by goddess Demetra for entering to Hades to seek her daughter Persephone.

Three of the Hercules labours are related to flood mitigation and flow control. The slaying of the Lernaean Hydra and of the Stymphalian Birds can be associated with swamp drainage and management. The Lernaean Hydra was a water serpent that lived in Lake Lerna and had many heads and poisonous breath. Although for each head that Hercules cut off two new ones grew, Hercules finally killed the monster. The Stymphalian Birds were man-eaters that lived at Lake Stymphalia and had bronze bills, sharp metallic feathers and poisonous dung. Hercules, with the help of goddess Athena, finally killed the Birds. It is obvious that both myths symbolize the suffering of the local population due to the stagnant water of two Peloponnesian lakes and the related mitigation measures. In another myth, Hercules cleans Augean stables from a huge amount of dung that had accumulated over 30 years. Hercules achieved his task in one day by diverting the waters of the Peneios and Alpheios rivers through the stables. Water quality concerns related to this lumped input of pollutant load were not addressed in this myth.

Clearly, the above myths symbolize the efforts of mankind to adapt to climatic evolution and to control water flow. However, only a few ambiguous remnants of evidence of this prehistoric era have been preserved.

Fig. 4 *The battle of Hercules against Acheloos has inspired artists: (upper) depiction based on an Attic red figure vase, 6th century BC, kept in the British Museum (redrawn, courtesy of Manos Christofakis); (lower) a contemporary version (wall painting in Athens City Hall) by the 20th century writer, painter and hagiographer Fotis Kontoglou.*

11.4 Reflections from the past: Flood control in Greek Antiquity

The mental achievements of the ancient Greek culture, such as poetry, philosophy, science and politics, as well as the artistic feats in architecture, pottery and sculpture, have monopolized the interest of researchers of the Greek civilization. As a consequence, most of the ancient Greek technological exploits are still relatively unknown. However, the technological achievements in various fields, including water resources, were remarkably advanced (Angelakis & Koutsoyiannis, 2003). To gather information and investigate such technological achievement, development of a web-based information system for the inspection of the hydraulic works in ancient Greece (http://www.itia.ntua.gr/ahw/works/) is currently ongoing as part of an unfunded research programme. Currently, the system contains data for almost a hundred important hydraulic works from the Minoan era up to the Roman period. However, most of them concern water supply and sewerage, and only a few (10%) flood-related infrastructures and land drainage have been recorded as yet (Table 2).

Table 2 *Major works related to floods in Ancient Greece.*

	Flood prevention	Land drainage
Mycenaean	Tiryns dam	Kopais, Olympia drainage, Arcadian Orchomenos
Classical	Heridanos stream control, Alyzia dam, Olympia stream control	Oidiades drainage, Phechae drainage, Stratos drainage

The sub-sections below discuss several of the items that are registered in the web-based information system and are organized according to the phases of Greek civilization, from prehistoric to classical. However, it should be kept in mind that ancient Greek culture was more pro-active than reactive. That is, no major city was located on flood-prone areas in Greek antiquity, which indicates a good understanding of natural river behaviours and related risks. It is a more modern “achievement” of subsequent civilizations, up to present, to live on such areas and to build structures that have adverse effects on the flood regime.

11.4.1 Early developments: small scale urban sewage and drainage systems

It appears that there was a good understanding of flow mechanisms and processes at very early stages of Greek civilization: sewerage and stormwater drainage systems first appeared in Crete at the Knossos, Zakros and Phaistos palaces during the Minoan period (2nd millennium BC), giving us a clear indication of the level of development in the Minoan civilization. Urban sewer systems have also been found on the island of Thera (Santorini) and at other prehistoric sites of the Aegean civilization (*ca*. 3400– 1200 BC; Angelakis *et al*., 2005). This early period is characterized by the absence of major civil flood protection infrastructures: all of the above structures are urban and limited to the scale of the palace or the city.

11.4.2 Mycenaean era

Large-scale flood control and drainage infrastructures first appeared in mainland Greece during the Mycenaean period. It can be speculated that the need for those infrastructures was for several developments, including the following:

– The first clear signs of human modifications of vegetation can be dated to between 1900 and 1300 BC, i.e. in the Mycenaean period (Fouache & Pavlopoulos, 2011).
– At about the same period, it was perhaps understood that irrigation of crops is necessary to sustain or enhance agricultural production and, at the same time, that water storage projects are necessary to remedy the scarcity of water resources during the irrigation period (Koutsoyiannis & Angelakis, 2007). It is noted that, in modern Greece, irrigation is responsible for more than 85% of water consumption and to provide this quantity several large hydraulic works have been built.
– The increasing population must have dictated an expansion of the agricultural activities far beyond the urban areas. As Greece is mostly mountainous, a small percentage of the territory is appropriate for intensive agricultural production: closed water basins and the floodplains of the rivers, both of which, however, suffer from flooding.

An excellent example of this technology is the Mycenaean infrastructure of Kopais Lake, a unique case of prehistoric large-scale multi-purpose hydraulic works (Koukis & Koutsoyiannis, 1997; Wilson, 2006, pp. 183–184). The lake is located in the downstream part of the Boeoticos Kephisos River basin, which is the largest (about 1850 km^2) closed (endorheic) basin in Greece and mostly located on karstic geological formations. As explained in Section 11.5, the drainage of Kopais was the first major hydraulic project in the Modern Greek state; however, effective drainage works were initiated as early as 2000 BC. Strabo, the geographer, and Pausanias, reported that the Minyans, the Mycenaean inhabitants of Boeotia, had successfully drained the lake and cultivated the plain. Excavations made at the end of 19th century revealed an impressive drainage system, including dykes (Fig. 5, left) and three main canals, as well as an apparent system of fortified enclosures or settlements encircling the lake. Until the end of 19th century, some of these dykes were still used as roads (Champlin, 1895). The canals conveyed the flows of the Boeoticos Kephisos River and its tributaries away from the central bed and towards a number of natural sinkholes to the northeast, through which they were drained into the sea. The canals traversing the former lake area were 40–50 km in length, 40–80 m wide, and had parallel walls up to 2–3 m thick. Low and long walls, along with diversion canals and huge earthen dykes furnished with cyclopean walls were built. The drainage system also included the construction of polders and artificial reservoirs for flood water retention and storage, and the improvement of the drainage capacity of the natural sinkholes (Koutsoyiannis & Angelakis, 2007).

The Minyans managed not only to protect the land from floods, but also to re-arrange the water storage using shallow dams. It is difficult to explain the exact operational scheme of their infrastructures, because they are interrelated in complex ways. Generally, it can be assumed that the basic concept was to reduce inundation area and duration and to store water for irrigation. The Minyans must have realized that it is feasible to regulate water flow in the Kopais basin and that regulated waters can be stored for use when needed.

Water infrastructures are exposed to damage and sedimentation, and thus could hardly be preserved for millennia. In this case, their preservation is primarily a result of their cyclopean masonry technique, which dominated the Mycenaean structural technology: their scale and the increased effort needed in order to dismantle and transfer masonry to another site for re-use helped cyclopean works survive through the centuries.

It is clear that this was an advanced technology, not only in terms of the scale or conception of the mechanisms behind the water flow phenomena (including a comprehensive understanding of the exceptionally complex surface water and groundwater interactions that characterize this area), but also because such infrastructures require advanced management practices. The richness and the prosperity of the Minyans depended on the success of the project. Their ability to manage the water cycle of the Kopais basin is, technologically, of greater importance than the cyclopean infrastructures needed for water storage and flood control. These projects played an important role in the establishment of Mycenaean agricultural technology and generally must have been a key element in the prosperity of the Mycenaean civilization.

Fig. 5 *(left) Cyclopean masonry of the Mycenaean dykes in Kopais, as preserved today; (right) The Alyzia Dam with its cyclopean masonry; the spillway is to the right of the dam wall.*

According to mythology, the Kopais project was destroyed when Hercules flooded the area by digging out the river during his fight with the Minyans. Later efforts in Hellenistic and Roman times did not succeed. Strabo (IX 406) mentions unfinished attempts to drain the lake by Crates of Chalcis, a mining and hydraulic engineer of Alexander the Great, in 336–323 BC. Nevertheless, a complete draining of the lake was achieved only by the end of the 19th century.

There are strong indications of the existence of additional Mycenaean flood control and land reclamation infrastructures in various places. According to Knauss (1991), between the Boeotian and the

Arkadian Orchomenos, along the straight way across the Corinthian Gulf, spectacular hydraulic structures existed in some poljes; these structures can also be attributed to the Mycenaean period. Within the closed valley of Thesve, south of Kopais, two well-preserved barrages creating artificial reservoirs and a special water diversion scheme were identified by topographical surveys (Knauss, 1991). North of the double basin of Orchomenos and Kaphyai, in each of the closed valleys of Pheneos and Stymphalos, an artificial reservoir for flood water storage was detected and, at Pheneos, a long and deep drainage canal also existed.

11.4.3 Classical era

Rather few and clearly inferior—in scale and complexity—flood prevention projects of classical Greek antiquity have been found. The most notable among them is the dam of ancient Alyzia in western Greece, the only non-Mycenaean dam that survives in mainland Greece. It is situated close to the coastline of Akarnania, in the fringes of the Akarnanika Mountains. The exact period of its construction is still unknown, but researchers usually place it to the Golden Age (5th century BC).

It is a stone dam with a lateral flood control channel. The body of the dam has two slopes. The bottom part is characterized by blocks of rectangular shape, irregularly placed and with smaller blocks filling the gaps between larger ones. In the top part, where the slope is gentler, the stones are uniformly shaped, very regularly placed, and with such small gaps that filling is not required. These superior upper courses suggest more evolved construction methods. Although the reservoir above the dam has been filled by sediments, the dam is intact thanks to the successful operation of its flood control channel (spillway; Fig. 5, right).

The reasons that led to the construction of Alyzia Dam are not clear. Some research has concluded that it was built for irrigation or drinking purposes and diagnosed that it was rapidly silted up with materials from winter runoff. A recent study (Zarkadoulas, 2005) proposes a different scenario: Floods in the valley of ancient Alyzia were exceptionally intense, leading to serious problems in the urban and suburban areas of the city. To mitigate the floods and hold back the coarse sediments that inundated the valley, the inhabitants of Alyzia constructed the dam in the most suitable site of the watercourse.

11.5 Modern Greece: positive and negative experiences

The areas that suffer today from floods in Greece can be classified into three categories. First are the plain areas traversed by large rivers, the discharge capacity of which was insufficient to route the natural floods, as well as closed hydrological basins in karst areas, which normally are drained by natural sinkholes with limited drainage capacity. Second are the urban areas where the urbanisation of natural floodplains has created a threat to both wealth and human life. Third are floodplains downstream of dams, where the natural system has been heavily modified and new activities developed, according to the mistaken perception that the flood risk has been eliminated completely. Next, the positive and negative aspects of each category are discussed, exemplified by characteristic case studies.

11.5.1 Drainage works in rural floodplains and closed basins

The evolution of flood mitigation and management practices in modern Greece followed the corresponding demographic and socio-economic development. By the end of the 19th to the early 20th century, the key priority was agricultural development and food self-sufficiency for the country. In this context, emphasis was given to the construction of large-scale hydraulic works in the floodplains and the wetlands, which had suffered due to the insufficient capacity of the stream network. This allowed the "release" of extensive areas of high fertility and, simultaneously, radically improving the health conditions and the quality of life of inhabitants. Combined drainage systems, stream-lining works and land reclamation projects have been constructed that diminished most of the negative impacts of floods. Such works are found at the Thessalia plain (Peneios River), Agrinio plain (lower Acheloos River), the plain of Pamissos River in Peloponnese, Arta plain (Arachthos and Louros rivers) in Epirus, Thessaloniki and Giannitsa plain (Aliakmon, Axios, Loudias and Gallikos rivers), Artzan-Amatovo marsh (Axios river), and Serres and Drama plain (Strymon river) in Macedonia. In most of these cases, the discharge capacity of the river network was insufficient to route flood events of even moderate frequency, thus flood damage occurred quite often (Koutsoyiannis & Mimikou, 1996).

Flood control was also imperative in a number of closed (endorheic) basins and plateaus, most of which are surrounded by mountains of karstic limestone and drained by natural sinkholes. These areas were very sensitive to floods, because of the limited draining capacity of the sinkholes, which usually resulted in the formation of shallow lakes and peats, permanent or intermittent, in the lowest areas.

The first important hydraulic project in modern Greece involved the drainage of Kopais Lake, in the lower part of Boeoticos Kephisos basin. The river network of the basin originates from altitudes as high as 2400 m and reaches downstream to a plain with an area of about 250 km^2 and a mean ground elevation of 95 m (Rozos *et al.*, 2004). Prior to 1860, the plain was permanently flooded by the basin's runoff, thus giving rise to the formation of a shallow lake with an area of about 150 km^2. However, during periods of high flows, the lake expanded to 250 km^2 as the capacity of the karstic sinkholes was insufficient. As already mentioned, although effective drainage works were initiated in early antiquity, the problem was effectively remedied only at the end of the 19th century, after the construction of an extended drainage network of canals, drains and levees. The drainage system reaches a tunnel that diverts the entire surface water resources of the basin to the neighbouring Lake Hylike. Consequently, the storage capacity of Hylike increased by almost an order of magnitude, and the lake was, from 1950 to 1980, the primary source of the water supply system of Athens.

However, the flooding problem of the region is not fully resolved yet. Owing to a design philosophy that gave protection priority to the plain of the former Lake Kopais, various hydraulic works were constructed in the middle and upper course of Boeoticos Kephisos so as to temporarily store floods, thus attenuating the discharge downstream. These works have resulted in a transfer of the flooding problem from downstream to upstream areas. As a result, each year, a few km^2 of agricultural land in these areas are flooded (Koutsoyiannis & Mimikou, 1996).

Other examples of closed basins that were effectively drained during the last century are Lake Karla in Thessaly plain, Lake Xynias (central Greece), the Ioannina plateau in Epirus (northwest Greece) and the Lassithi plateau (Crete). Interestingly, part of Lake Karla was restored recently, following a more integrated and environment-friendly policy, in which ecological benefits and landscape quality have a key role in water resources planning and management.

11.5.2 Urban drainage systems: the disappearance of natural streams in urban areas

For many decades during the 20th century, urbanization in Greece was seldom combined with flood protection works, such as natural channel improvement and storm drainage networks. In contrast, most of the ephemeral natural streams and tributaries lying in urban areas were converted into the road network. Moreover, there are cases where buildings were illegally constructed over or very close to stream beds. Even some of the larger streams with permanent flows were covered, and their natural bed was replaced by artificial channels, the discharge capacity of which was inadequate to convey extreme floods (the typical return period for the hydrological design of such projects ranges from 10 to 50 years). For these reasons, urban flooding in Greece is probably the most frequent type of flood hazard. During the last century, fatalities due to urban floods exceeded 200. Although this number is relatively low if compared to other regions worldwide, it is very large considering the small scale of the river basins and the magnitudes of the flood events.

Some of the most catastrophic events have occurred in the Athens metropolitan area. The city of Athens spreads over the river basin of Atticos Kephisos (381 km^2). The basin is surrounded by three mountains (Parnes, Pentele, Hymettus), which favour generation of orographic storms. The urbanization of the greater region is strongly related to major historical events, starting from the Asia Minor Catastrophe (ethnic cleansing) in 1922. Instantly, almost 250 000 refugees moved to the Attica region, which corresponded to half of the then population. In order to handle the problem of providing homes for the refugees, the state favoured building without planning for infrastructures. This first severe urbanization wave was only directed to "virgin" areas, such as the western part of Attica, and the foothills of Parnes and Hymettus. After World War II, rapid and uncontrollable urbanization continued, as a result of new waves of settlers arriving in Athens after the end of the civil war (1945–1949). At present, the built-up area of the Kephisos River basin amounts to 70% of its total extent and hosts more than three million people. Moreover, large parts of the non-urbanized areas of the basin are degraded due to deforestation.

The two most hazardous flood events in modern Athens are those of 6 November 1961 and 2 November 1977, with 40 and 36 casualties, respectively, and enormous economic consequences (Fig. 6). The common characteristics of the two events are the following: (a) the disasters were concentrated in the southwestern areas of the basin, where the hydraulic infrastructures were, at that time, very poor; (b) most rainfall fell in a relatively short period (5 and 4 hours, respectively), which is close to the time of concentration of the local sub-basins; (c) the estimated return periods of rainfall intensities were much higher than typical design values for urban sewage systems; (d) most of the victims were children and elderly people; and (e) many people were carried away by the Kephisos River and found in the sea.

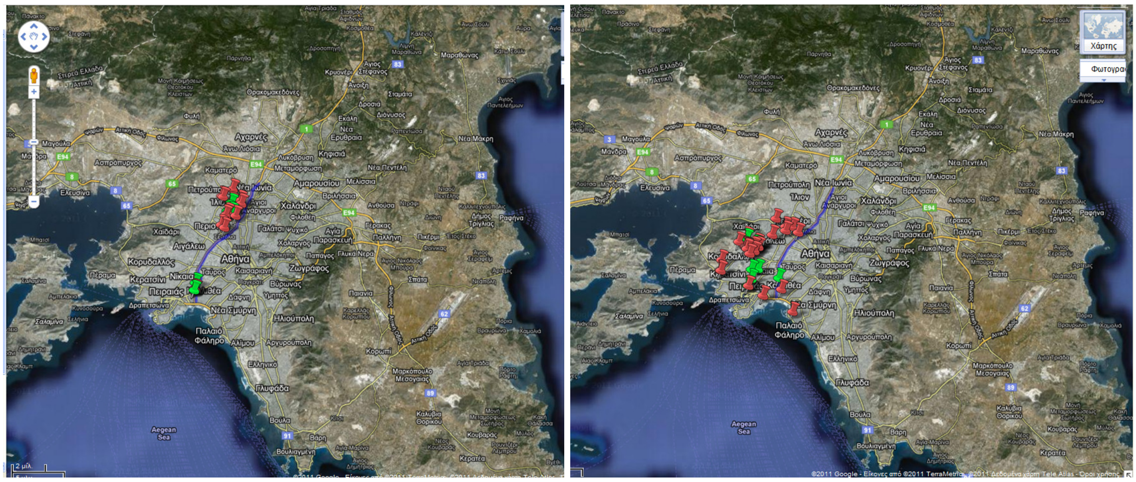

Fig. 6 *Distribution of casualties (red pins) and severe damage (green pins) during the flood events of (left) 6 November 1961 and (right) 2 November 1977 (source: Vahaviolos, 2011).*

11.5.3 Dams and reservoirs: when people forget flood risk

After World War II, a number of large dams were constructed to support the economic growth of the country. Most were designed primarily as hydropower projects, but over time, they also served other uses, typically irrigation and water supply, also attracting, in a few cases, tourist activities. These large-scale interventions changed the flow regime of the biggest rivers of Greece and, in particular, the temporal distribution and spatial extent of floods. In addition to the aforementioned water uses, dams and their reservoirs also operate as major flood control structures, as they can store huge quantities of water and route them downstream with safety, through the turbines (in the case of hydroelectric dams) and occasionally, the spillway. In fact, their hydrological design ensures protection against extremely rare flood phenomena.

Although the regulation of flows and the significant decrease of flood risk are big advantages of reservoirs, in the Greek case they have had negative consequences for the status of the downstream system. Given that the discharge downstream of dams is much more stable if compared to the previous pristine conditions, a false impression was established regarding the natural regime of most rivers, since the "memory" of high flow events was lost. Consequently, inhabitants of the surrounding area and even local authorities, erroneously assuming that the flood risk has been eliminated, exploit floodplains for various purposes.

A typical case of such exploitation is the course of the lower Acheloos River, which ends up at a sensitive estuary. As already mentioned, the Acheloos is one of the most important rivers of Greece, having a mean annual discharge of about 140 m^3/s. Three major dams and power stations are installed in the middle and lower course of the river, and produce more than one third of the hydroelectric energy of the country. After the completion of the three dams (1988), the floodplains in the downstream part were occupied by agricultural activities and temporary settlements. This was possible because the spillways operate very rarely and thus the maximum flow downstream of the dams does not exceed the discharge capacity of the penstocks. In the most downstream power plant of Acheloos (Stratos) this capacity is 500 m^3/s. According to the record of mean daily inflows to the most upstream reservoir (Kremasta), the threshold of the 500 m^3/s was exceeded in all years of the sample period (1966–2008). As shown in Fig. 7, the maximum daily inflow to Kremasta was 3500 m^3/s, which means that the peak discharge downstream of Stratos should be rather greater. Evidently, at some time in the future during extreme floods the spillway will unavoidably operate, adding up to 4000 m^3/s to the penstock discharge of 500 m^3/s and thus causing severe damage downstream. It is relevant to this problem that currently the dam owner and operator, the Public Power Corporation, employs a hydrosystem control that is far from optimal. It aims to have the spillways out of operation all the time, by keeping empty storage in the reservoir. A more rational strategy would be to enforce deliberate operation of spillways and inundation of the downstream areas on a regular annual basis. This would discourage illegal occupation of floodplains and also would have positive effects in the river ecosystems (Koutsoyiannis, 2011).

Furthermore, in a few cases even permanent residential uses have appeared downstream of dams. A characteristic example is the area downstream of the Marathon Dam, which is the oldest in Greece, constructed in 1931 for the water supply of Athens. After 80 years of operation, and 60 years after the last spill event, the natural environment has been considerably modified and the river has practically disappeared (Fig. 8). The Water Supply Company of Athens (EYDAP), in order to diminish the probability of spill, which would have catastrophic impacts to the downstream areas, is obliged to maintain the water level in the reservoir much lower than the optimal, which in turn reduces the regulating capacity of the reservoir.

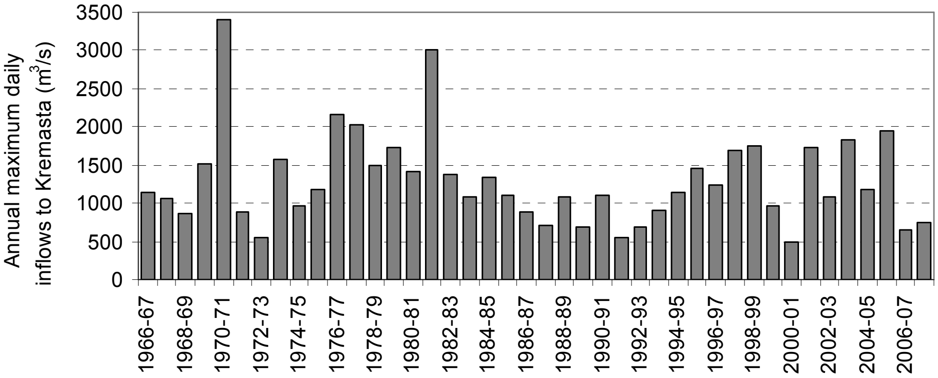

Fig. 7 *Annual maximum inflows to Kremasta dam, estimated on mean daily basis.*

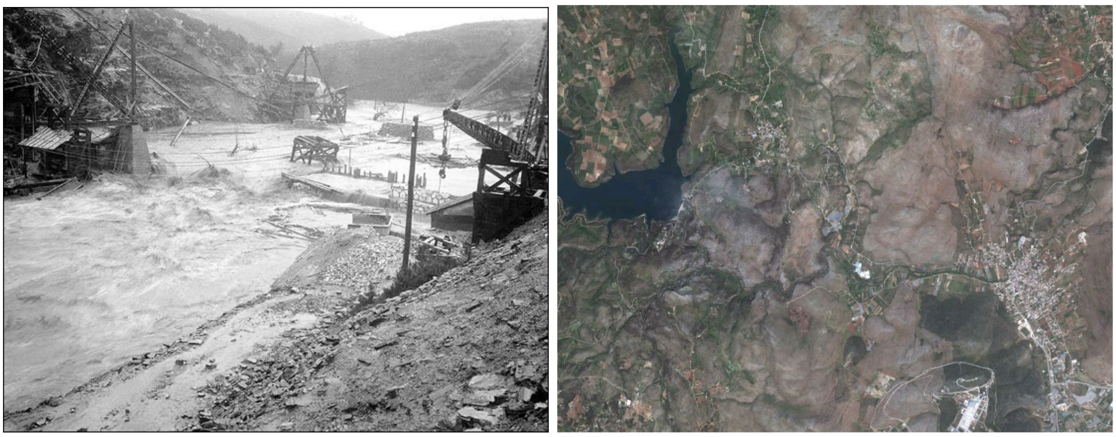

Fig. 8 *(Left) Damage due to a severe flood during the construction of Marathon Dam (about 1928; source: EYDAP archive); (right) overview of the area downstream of the reservoir, mostly occupied by residential uses (source: Google Earth).*

11.6 Concluding remarks

Palaeoflood data, mythological narrations, written documents and archaeological evidence suggest that floods have created severe problems to humans at all stages of civilization, and also that river flood regimes have changed continually. Such changes reflect the perpetual change of climate but are also influenced, in a positive or negative manner, by human interventions for land use and the human struggle to control river flows. Evidently, such interventions have been magnified in recent decades. However, despite technological progress, the example of Greece, where civilization has flourished for millennia, suggests that the problems with respect to floods are more severe today than they were in ancient times. Above all, urbanization has amplified the problems and has resulted in degradation of urban streams. Restoration, maintenance and water quality control of urban streams along with source control and flood retention constitute big challenges for modern societies. In modified rivers, a balance of flood control measures and environmental conservation practices, with particular emphasis on aquatic ecosystems is strongly needed.

References

Angelakis, A. N. & Koutsoyiannis, D. (2003) Urban water engineering and management in ancient Greece. *The Encyclopedia of Water Science* (ed. by B. A. Stewart & T. Howell, 999–1007. Dekker, New York.

Angelakis, A. N., Koutsoyiannis, D. & Tchobanoglous, G. (2005) Urban wastewater and stormwater technologies in ancient Greece. *Water Research* 39(1), 210–220.

Baker, V. R., Webb, R. H. & House, P. K. (2002) The scientific and societal value of palaeoflood hydrology. In: *Ancient Floods, Modern Hazards: Principles and Applications of Paleoflood Hydrology* (ed. by P. K. House, R. H. Webb, V. R. Baker & D. R. Levish), 1–19. Water Science and Application, vol. 5. American Geophysical Union, Washington DC.

Benito, G. & Thorndycraft, V. R. (2005) Palaeoflood hydrology and its role in applied hydrological sciences. *J. Hydrol.* 313, 3–15.

Champlin, J. D. (1895) Prehestoric engineering at Lake Copais. *The Popular Science Monthly* 48(10), 209–219.

Digerfeldt, G., Olsson, S. & Sandgren, P. (2000) Reconstruction of lake-level changes in Lake Xinias, central Greece, during the last 40 000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 158, 65–82.

Dormoy, I., O. Peyron, Combourieu Nebout, N., Goring, S., Kotthoff, U., Magny, M. & Pross, J. (2009) Terrestrial climate variability and seasonality changes in the Mediterranean region between 15 000 and 4000 years BP deduced from marine pollen records. *Climate of the Past* 5, 615–632.

Hayes, A., Kucera, M., Kallel, N., Sbaffi, L. & Rohling, E. J. (2005) Glacial Mediterranean sea surface temperatures based on planktonic foraminiferal assemblages. *Quatern. Sci. Rev.* 24, 999–1016.

Hughes, P. D., Woodward, J. C. & Gibbard, P. L. (2006) Late Pleistocene glaciers and climate in the Mediterranean. *Global and Planetary Change* 50, 83–98.

Fouache, E. & Pavlopoulos, K. (2011) The interplay between environment and people from Neolithic to Classical times in Greece and Albania. In: *Landscape and Societies* (ed. by I. P. Martini & W. Chesworth), 155–166, Springer.

Knauss, J. (1991) Arkadian and Boiotian Orchomenos, centres of Mycenaean hydraulic engineering. *Irrigation and Drainage Systems* 5, 363–381.

Kotthoff, U., Pross, J., Muller, U. C., Peyron, O., Schmiedl, G., Schulz, H. & Bordon, A. (2008) Climate dynamics in the borderlands of the Aegean Sea during formation of sapropel S1 deduced from a marine pollen record. *Quatern. Sci. Rev.* 27, 832–845.

Koukis, G. C. & Koutsoyiannis, D. (1997) Greece. *Geomorphological Hazards in Europe* (ed. by C.&C. Embleton), 215–241, Elsevier.

Koutsoyiannis, D. (2011) Scale of water resources development and sustainability: Small is beautiful, large is great. *Hydrol. Sci. J.* 56(4), 553–575.

Koutsoyiannis, D., Andreadakis, A., Mavrodimou, R., Christofides, A., Mamassis, N., Efstratiadis, A., Koukouvinos, A., Karavokiros, G., Kozanis, S., Mamais, D. & Noutsopoulos, K. (2008) *National Programme for Water Resources Management and Preservation*, *Support on the compilation of the national programme for water resources management and preservation*, 748 pages, Department of Water Resources and Environmental Engineering, National Technical University of Athens, Athens (in Greek).

Koutsoyiannis, D. & Angelakis, A. N. (2007) Agricultural hydraulic works in ancient Greece. *Encyclopedia of Water Science, Second Edition* (ed. by S. W. Trimble), 24–27, CRC Press.

Koutsoyiannis, D. & Mimikou, M. (1996) Country Paper for Greece, Management and Prevention of Crisis Situations: Floods, Droughts and Institutional Aspects. *3rd EURAQUA Technical Review*, Rome, 63–77, EURAQUA.

Koutsoyiannis, D., Mamassis, N. & Tegos, A. (2006) Logical and illogical exegeses of hydrometeorological phenomena in ancient Greece. *IWA 1st International Symposium on Water and Wastewater Technologies in Ancient Civilizations*, Iraklio, Greece.

Macklin, M. G., Fuller, I. C., Lewin, J., Maas, G. S., Passmore, D. G., Rose, J., Woodward, J. C., Black, S., Hamline, R. H. B. & Rowan, J. S. (2002) Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change. *Quatern. Sci. Rev.* 21, 1633–1641.

Macklin, M. G., Tooth, S., Brewer, P. A., Noble, P. L. & Duller, G. A. T. (2010) Holocene flooding and river development in a Mediterranean steepland catchment: The Anapodaris Gorge, south central Crete, Greece. *Global and Planetary Change* 70, 35–52.

Mamassis, N. & Koutsoyiannis, D. (1996) Influence of atmospheric circulation types in space-time distribution of intense rainfall. *J. Geophys. Res.–Atmos.* 101 (D21), 26267–26276.

Pope, K. & van Andel, T. (1984) Late Quaternary alluviation and soil formation in the Southern Argolid: its history, causes and archaeological implications. *J. Archaeol. Sci.* 11, 281–306.

Reuther, A. U., Herget, J., Ivy-Ochs, S., Borodavko, P., Kubik, P. W. & Heine, K. (2006) Constraining the timing of the most recent cataclysmic flood event from ice-dammed lakes in the Russian Altai Mountains, Siberia, using cosmogenic *in situ* ^{10}Be. *Geology* 34, 913–916.

Rozos, E., Efstratiadis, A., Nalbantis, I. & Koutsoyiannis, D. (2004) Calibration of a semi-distributed model for conjunctive simulation of surface and groundwater flows. *Hydrol. Sci. J.* 49(5), 819–842.

Schulte, L., Gomez Ortiz, A. & Passmore, D. G. (2000) Sobre los supuestos restos periglaciares Pleistocenos en los llanos de la Peninsula Iberica. In: *Procesos y formas periglaciares en la Montana mediterranea* (ed. by J. L. Pena, M. Sanchez-Fabre & M. V. Lozano), 281–297. Instituto de Estudios Turolenses, Teruel, Spain.

Tzedakis, P. C., Frogley, M. R., Lawson, I. T., Preece, R. C. Cacho, I. & de Abreu, L. (2004) Ecological thresholds and patterns of millennial-scale climate variability: The response of vegetation in Greece during the last glacial period. *Geology* 32, 109–112.

Vahaviolos, T. (2011) Determination of flood-vulnerable areas according to 2007/60 Directive. Diploma Thesis, Department of Water Resources and Environmental Engineering, National Technical University of Athens, Athens, Greece (in Greek).

Wilson, N. G. (2006) *Encyclopedia of Ancient Greece*. Routledge, 800 pp.

Woodward, J. C., Hamlin, R. H. B., Macklin, M. G., Hughes, P. D. & Lewin, J. (2009) Glacial activity and catchment dynamics in northwest Greece: Long-term river behaviour and the slackwater sediment record for the last glacial to interglacial transition. *Geomorphology* 101, 44–67.

Zarkadoulas, N. (2005) The dam of ancient Alyzia (*Το φράγμα της Αρχαίας Αλυζίας*). Postgraduate Thesis, Department of Water Resources, Hydraulic and Maritime Engineering, National Technical University of Athens, Athens, Greece (in Greek).