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Hydrological Modeling for Flood Adaptation under Climate Change: The Case of the Ancient Messene Archaeological Site in Greece

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Abstract: There is a growing global awareness about the impacts of climate change on cultural and natural heritage sites. In Greece—a homeland of important historical and cultural resources—archaeological sites are vulnerable to climate change-related flood events. In order to investigate the flood risk of the archaeological site of Ancient Messene under different climate change projections, a physically-based hydrological model was implemented and six climate change scenarios were examined. Additionally, the effectiveness of a soft structural nature-based solution adaptation plan was evaluated. Based on the results, the archaeological site of Ancient Messene is shielded against small or larger flood events and only in case of extreme precipitation events is the area likely to be at risk. This flood risk can be further eliminated after implementing the soft structural nature-based solution adaptation plan proposed. Nature-based solutions provide a cost-effective alternative approach for flood risk reduction and climate change adaptation, with minimum possible disturbance, while hydrological modeling, even in case of data scarcity, constitute a valuable tool for flood risk estimation and adaptation plan management. Nature-based solutions seems to be most effective against small or medium precipitation events, and to limit the damages of extreme events. Their benefits for flood adaptation should not be underestimated.

Keywords: cultural heritage; flood risk management; mitigation; physically-based hydrological model; flood model; MIKE SHE; nature-based solutions



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1. Introduction

Cultural heritage sites and monuments have been identified as having historical, scientific, or other forms of significance and, therefore, they need to be protected and preserved for future generations [1]. Globally, cultural heritage sites are subjected to possible disasters and suffer from the adverse effects of natural and/or human-induced hazards [2], which increase their vulnerability [3]. Floods have been identified as being one of the major hazards and potentially devastating natural events, which may result in different degrees of damage or, less commonly, total destruction of cultural heritage sites [4].

Flood risk and impacts are expected to intensify due to human activities and climate change [2,5]. Disaster risk management and climate change adaptation, with regard to cultural heritage preservation, has been highlighted at the United Nations (UN) Sendai Framework for Disaster Risk Reduction 2015–2030 [6] and the 2030 Agenda for Sustainable Development (Sustainable Development Goal 11.4 Strengthen efforts to protect and safeguard the world's cultural and natural heritage) [7]. Subsequently, at the European level, the Flood Directive 2007/60/EC supports the assessment and management of flood risks, aiming at reducing the adverse consequences for, among others, cultural heritage [8], while the European Union (EU) Action Plan on the Sendai Framework underlines the need to

develop good practices, regarding the essential integration of cultural heritage in national disaster risk reduction strategies in EU Member States [9].

In Greece, the impact of climate change on cultural and historical sites is already evident. Longer and more intense summer droughts were responsible for the summer fires in 2021, which threatened Ancient Olympia in Peloponnese, and increased erosion risk [10]. The Temple of Apollo Epikourios at Bassae in Peloponnese is extremely vulnerable to extreme weather conditions, especially storms and increased daily temperature variance [11]. Landslides threaten the Acropolis of Ancient Siphai in Boeotia, while floods cause damage in archaeological sites, such as the Sanctuary of the Great Gods at Samothrace Inland [12]. Finally, Delos archaeological site is subjected to multiple climate change-related hazards, such as the submersion of antiquities, caused by the combination of a higher sea level and rainwater, and marble damage, due to sea and wind erosion [13].

For this reason, the awareness of climate change impact on cultural and natural heritage sites has recently risen in Greece. In the National Strategy for Adaptation to Climate Change of Greece, adaptation actions (regarding cultural heritage) were proposed [14]. In 2019, an international scientific conference for the protection of cultural heritage from the impacts of climate change was organized in Greece (“Impacts of climate change on cultural heritage: Facing the challenge”, 21–22 June 2019, Athens) [15]. The conclusions and outcomes were subsequently circulated as an official document of the UN General Assembly [16] and the proposal “Addressing climate change impacts on cultural and natural heritage” was launched [17]. Furthermore, a coordinator unit housed at the Academy of Athens for the implementation and support of the international initiative of Greece, in the context of the UN Summit [17] for the protection of cultural heritage and monuments of nature from the impacts of climate change, was established in 2021 [15,18].

Nature-based solutions (NBSs) for flood risk reduction and climate change adaptation have emerged as alternatives to traditional approaches and can help mitigate flood risk, decrease vulnerability to climate change, and benefit the environment and local communities [19]. NBSs can be used to meet the main flood risk management objectives, e.g., reduction of flood flows, enhance resistance in waterways, and eventually adapt to floods [20]. Most NBSs for water involve the conservation, restoration, and management of existing natural and seminatural landscapes, through non-structural or structural interventions, or a combination of both [21].

Under this scope, recently, several research projects in Greece have focused on the study of climate change impacts, and especially flood events, on cultural heritage sites and archaeological monuments, such as Ancient Olympia [22], the archaeological site of Dion [23], and the archaeological site of Ancient Messene [24]. In the present paper, in order to investigate the flood risk of the archaeological site of Ancient Messene under different climate change projections, a physically-based hydrological model (MIKE SHE 2020) was implemented and six (6) climate change scenarios from the Intergovernmental Panel on Climatic Change (IPCC) were examined. Additionally, the effectiveness of a soft structural nature-based solution (NBS) adaptation plan that would increase infiltration locally and restore the old flow path of surface runoff was evaluated. The main objective of the present study is (a) to have a better understanding of the vulnerabilities of archaeological sites regarding flood risk to possible future climate change; and (b) to investigate the effectiveness of an adaptation plan and a mild intervention at the archaeological site in order to increase flood resilience.

2. Materials and Methods

2.1. Study Area and Flood Vulnerability

Ancient Messene is located at the southwestern part of Peloponnese in Greece, south of the village Mavrommati or Ancient Messene (Figure 1a). The archaeological site of Ancient Messene was declared as a protected archeological site under national legislation [25,26], and it is included on Greece’s tentative list of sites and monuments for potential nomination for UNESCO World Heritage status [27]. Although the area has been inhabited since the

late Neolithic or early Bronze Age and during the 9th and 8th centuries BC, the city of Ancient Messene is mainly known for its architectural monuments, built following its foundation in 369 BC by the Theban general Epaminondas [28,29].

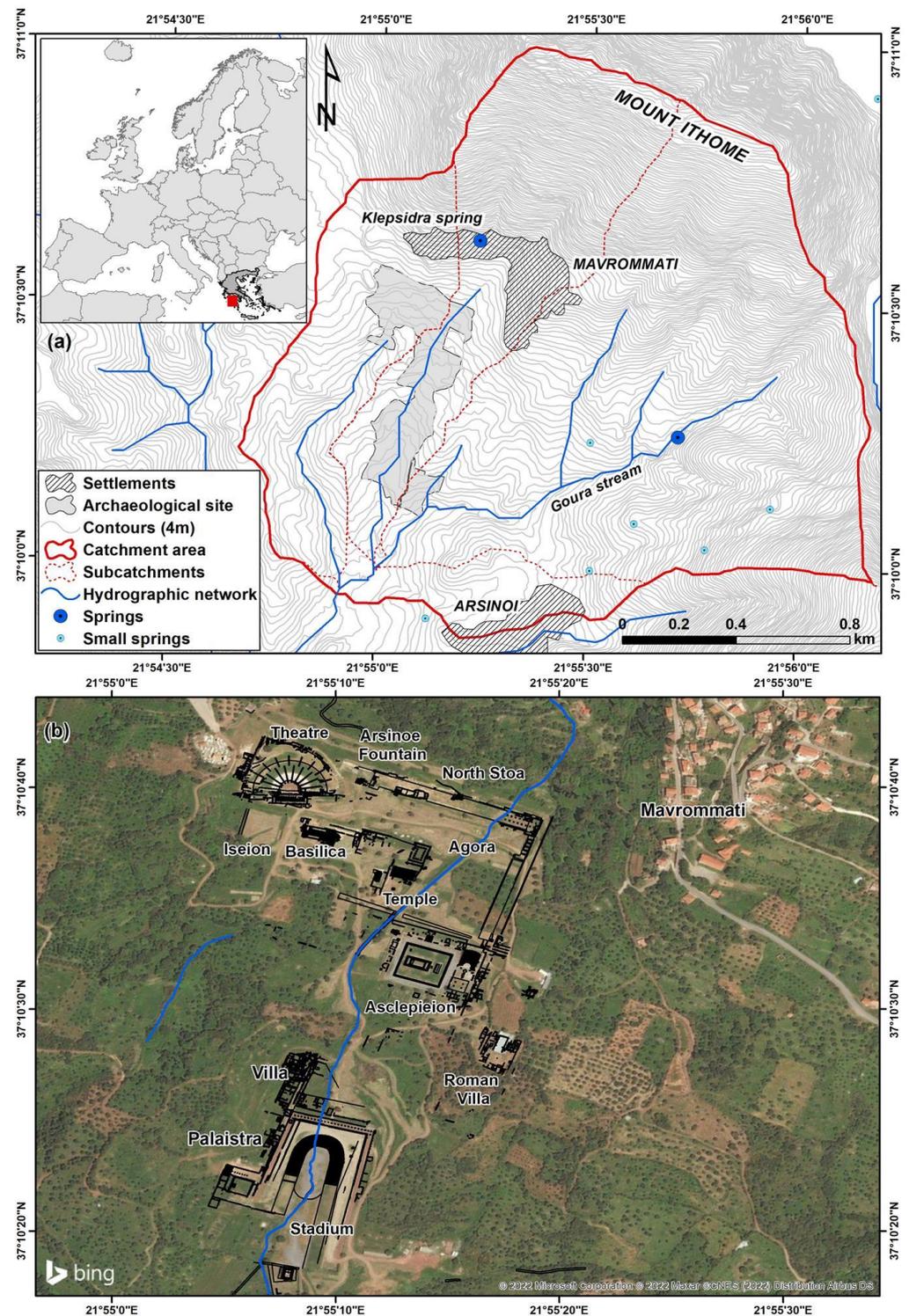


Figure 1. Catchment area (a) and detailed plan (b) of the Ancient Messene archeological site.

The catchment area of Ancient Messene is 3.2 km². The average altitude of the catchment is 420 m, and the average slope is 35%. The main anthropogenic activities are agricultural (50% of the area), while 5% is covered by artificial surfaces (discontinuous urban fabric and road network), and 40% is covered by forest. The archaeological site of

Ancient Messene covers 5% of the catchment area (Greek Payment Authority of Common Agricultural Policy Aid Schemes—OPEKEPE [30]). The northern part of the catchment is structured by limestones, while the central and southern parts are structured by porous formations of small thickness, overlaying impervious formations (calcareous sandstone and radiolarite) [31]; therefore, the unconfined aquifer of the wider area is of low capacity and the groundwater recharge through infiltration is limited [32].

Two anonymous streams of northeast–southwest directions cross the archeological site (Figure 1a). The smaller stream of northeast–southwest direction crosses the northeastern part of the archeological site, south of the Theater, and meets the eastern stream at the southwestern part of the catchment (Figure 1a). The most important stream in the east traverses the archeological site from the northeast to the southwest, the Agora and the Stadium in particular (Figure 1b). Based on geomorphological and photogeological evidence, during the antiquity, the streambed of this anonymous stream was likely located at the eastern part of the Ancient Messene, but since then, the stream changed its course [32]. Indeed, based on maps and archives of travelogues since the nineteenth-century travelers in Greek inland, the remains of a small streambed on the eastern part of the archeological site of Ancient Messene, with a northeast–southwest direction, is evident [33–35]. This old streambed was likely aggraded and is, nowadays, not visible [32]. The stream is mainly recharged by surface runoff and the Klepsidra or Kalliroi karstic spring (National Register of Water Abstraction Points code: EMSY 0100005761059) located on the north, near Mavrommati village. The discharge of the Klepsidra spring ranges between 5 and 70 m³/h during dry and wet periods, respectively [32]; nowadays, the water is partially harvested for domestic use [36].

The archaeological site of Ancient Messene had been occasionally subjected to flood events, leading to the partial aggregation of the area with debris, and to the need for an extensive excavation program that started in 1895 by the Archaeological Society of Athens (and is being conducting to this today) [37]. One such two-day flood event took place in November 1909, during which the ancient Arsinoi Fountain and parts of the archaeological site that were (then) recently excavated were buried again under debris [38]. In order to protect the Asklepieion monument between the Agora and the Stadium, the eastern stream was partially diverted. A drainage ditch was constructed in 1969 after the suggestion (and supervision) of the archeologist, Orlandos [39] (Figure 2a). The diversion was constructed in hard bedrock about 30 m west of the monument, and has a northeast–southwest direction, 230 m length, 2 m width, and 0.6 m depth [32].

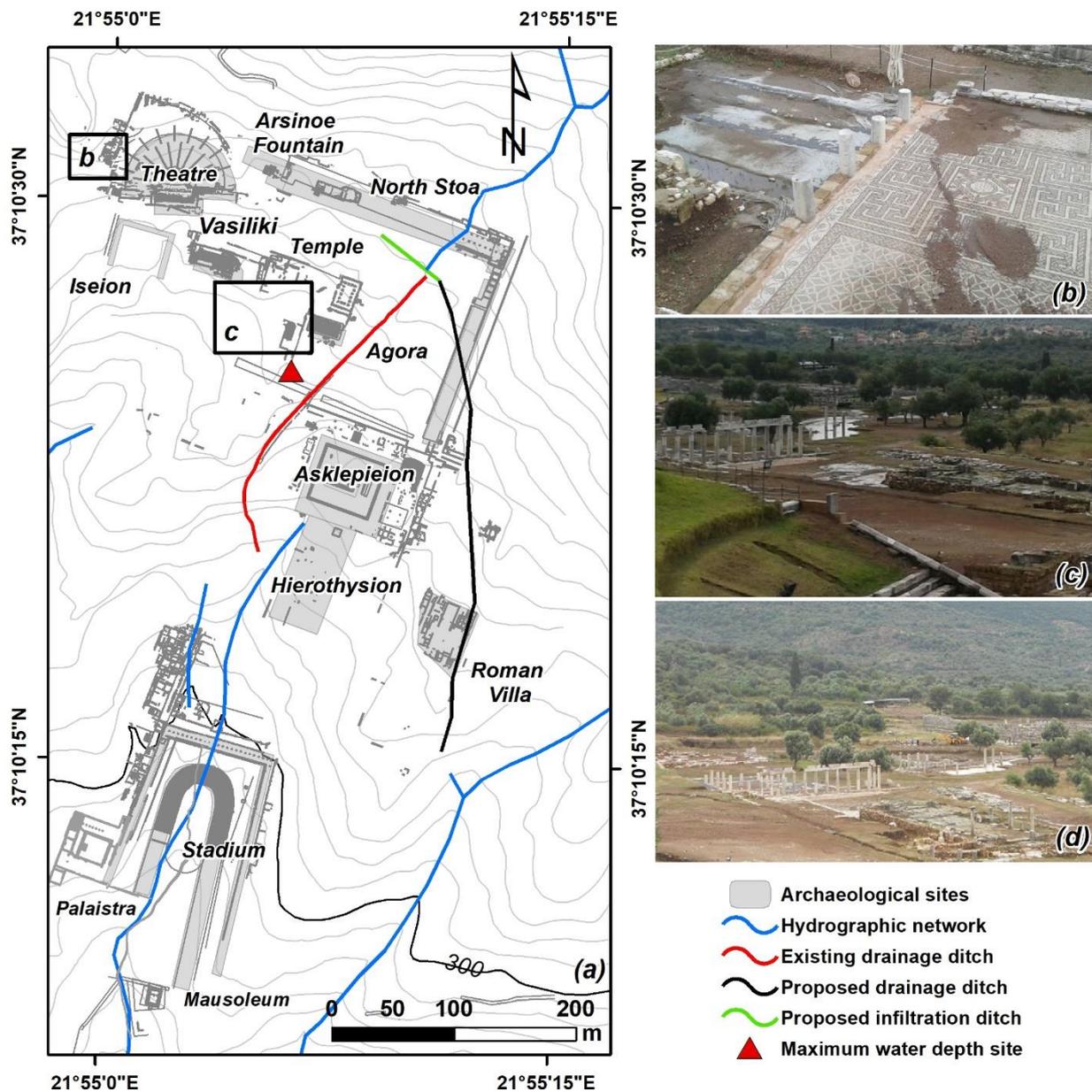


Figure 2. (a) Detailed plan of the Ancient Messene archeological site; (b) debris deposition related to the 6–8 September 2016, flood event [40]; (c) aspect of the flooded Temple at Agora on 8 September 2016 [40]; and (d) aspect of the flooded archaeological site from upstream on 8 September 2016 [40].

The drainage ditch is only partially effective since it was constructed focusing on the protection of the Asklepieion monument alone, while after heavy rainfalls, the other archeological sites are still flood prone [32]. Indeed, between 6 and 9 September 2016, another flood event took place, attributed to a cut-off upper level low located southwest of the country that caused severe thunderstorms with heavy rainfalls, floods, landslides and, locally, tornadoes [41]. The flood event affected the wider area of the Messenia regional unit the night of 6 September, it peaked on 7 September, and continued until the morning of 8 September (Table 1). The closest to the Ancient Messene operational meteorological station (National Observatory of Athens-NOA, Arfara station, LGU6), recorded 279 mm of cumulative precipitation during the period 6–8 September 2016 [42].

Table 1. Development of the flood event that took place between 6 and 8 September 2016, in Messenia regional unit (Hellenic National Meteorological Service-HNMS, Kalamata station, WMO-ID: 16726).

Date	Time	Precipitation (mm)
5 September 2016	06:00	0
	12:00	0
	18:00	0
6 September 2016	00:00	0
	06:00	0
	12:00	14.0/6 h
7 September 2016	18:00	55.0/12 h
	00:00	6.0/6 h
	06:00	132.6/24 h, 78.0/12 h
8 September 2016	12:00	9.0/6 h
	18:00	9.0/12 h
	00:00	0.0/6 h
9 September 2016	06:00	91.0/24 h, 0.4/12 h
	12:00	Trace/6 h
	18:00	Trace/12 h
10 September 2016	00:00	0.0/6 h
	06:00	0.0/12 h, Trace/24 h
	12:00	0.0/6 h
11 September 2016	18:00	0.0/12 h
	00:00	0.0/6 h

2.2. Flood Modeling

Hydrological models are useful tools used to assess climate change impacts and flood risks for the development of adaptation strategies [43]; they have been successfully used for the better understanding of nature, and to provide analytical tools to water managers and design engineers for risk assessment, and project planning and implementation [44]. In particular, in concerning NBSs, hydrological models are often used to quantify the hydrologic impacts of potential NBSs within watersheds [21,45]. The modeling tool used in the present study for the simulation of floods in Ancient Messene was MIKE SHE 2020, developed by the Danish Hydraulic Institute Water and Environment–DHI Water and Environment, a built-on coupled physics-based model for overland flow, unsaturated flow, ground water flow, and a fully dynamic channel flow, including all of the complex feedbacks and interactions [46,47]. MIKE SHE was successfully used in many studies to simulate the potential of NBSs for mitigating flood risks and climate change impacts (e.g., [45,48,49]).

The model was first set-up for the period 2013–2016. The model domain was chosen to be the entire hydrological catchment of the archaeological site of Ancient Messene. The grid cell size was 2 m, so as to combine the best possible accuracy and model speed. The topography of the study area was retrieved from the most detailed elevation data available (digital elevation model (DEM) with a grid size 2×2 m from National Cadastre S.A., derived from the large scale orthophoto maps 25-LSO25 project [50]). The necessary information concerning land cover was retrieved from the corresponding 1:5000 scale dataset of the Greek Payment Authority of Common Agricultural Policy Aid Schemes (OPEKEPE); these data were developed after aerial imagery of the year 2016 photointerpretation and are considered the most detailed [30].

Due to lack of climatological data (precipitation, temperature) of high temporal resolutions, a daily time step was used for flood modeling, and the data from Arfara meteorological station (NOA, LGU6), the closest to the study area, and most reliable, were used as forcing for the model. The lack of relative humidity, solar radiation, and wind speed precluded the use of the Penman–Monteith equation for the estimation of daily reference evapotranspiration (ET). Therefore, ET was estimated using the Hargreaves empirical approach [51], which provides satisfactory results with an error rate of 10–15% or 1 mm/d, whichever is greater [52,53].

The model was calibrated for the flood event of 6–8 September 2016. Since conventional flood-related data (water depth measurements or high-water marks of the most affected areas) were not available, the model calibration procedure was based on qualitative data regarding the spatial distribution of the water inundation after the flood event (photographs and reports or press publications) and eye-witness observations regarding the flood peak. Based on these reports, the western part of Agora, Vasiliki, the central part of Asklepieion, and the northern part of the Stadium were inundated on 8 September 2016 (Figure 2b–d).

Subsequently, six (6) climate change scenarios adopted from IPCC future projections concerning climatic variables were examined. Based on the fifth assessment report (AR5), four different twenty-first century pathways of greenhouse gas (GHG) emissions, atmospheric concentrations, air pollutant emissions, and land-use changes can be projected. These pathways can be described by four representative concentration pathways (RCPs)—a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high GHG emissions (RCP8.5) [54]. Therefore, for the present study, three RCP scenarios (one stringent, one intermediate, and one extreme) for two time projections (2031–2060, near future period; 2071–2100, distant future period) were examined (Table 2). The necessary time series concerning daily precipitation (P) and minimum, mean, and maximum temperature (T_{\min} , T_{mean} , T_{\max} , respectively) were retrieved from the regional climate model RCA4 of the Swedish Meteorological and Hydrological Institute-SMHI [55] driven by the low-resolution (LR) version of Max Planck Institute Earth System Model (MPI-ESM-LR) of the Max Planck Institute for Meteorology (MPI) [56,57]. Potential evapotranspiration was estimated using again the Hargreaves approach [51]. The flood events occurring at the six (6) climate change scenarios examined were distinguished by examining the water depth at the site where the maximum water depth was observed during the 6–8 September 2016 flood event.

Finally, the effectiveness of a nature-based solution (NBS) flood adaptation plan proposed by Kampouroglou and Chatzitheodorou [32], for the protection of the archaeological site of Ancient Messene, was examined (Figure 2). Based on this flood protection study, a soft structural NBS plan that would locally increase the infiltration rate, restore the initial watercourse, and drain the storm water on the eastern part of the archaeological site was proposed. The proposed construction consisted of a 50 m long, 3.75 m deep, and 1.0 m wide infiltration ditch filled with cobble or boulder and gravels, and covered with clayey layer of 20–25 cm thickness, which would lead the subsurface flow to a 410 m long, 1.20 m deep, and 1.10 m wide drainage ditch [32]. In order to incorporate these interventions to the model, the topography in the intervention area was adjusted based on the geometry of the proposed projects, and the ponded drainage module that allowed the storm water drainage to local depressions was enabled in MIKE SHE [47].

Table 2. Climate change scenarios investigated.

Scenario	Period	RCPs	Mean Annual Precipitation (mm)	Mean Annual Potential Evapotranspiration (mm)	Mean Annual Temperature (°C)		
					Minimum	Mean	Maximum
Reference	1971–2000	-	1037.4	1128.3	9.8	14.8	19.9
Sc1	2031–2060	RCP 2.6	874.0	1183.5	11.1	16.1	21.3
Sc2	2071–2100	RCP 2.6	1107.0	1175.1	10.8	15.9	21.1
Sc3	2031–2060	RCP 4.5	946.9	1185.5	11.4	16.4	21.5
Sc4	2071–2100	RCP 4.5	821.4	1199.7	11.7	16.7	21.8
Sc5	2031–2060	RCP 8.5	845.6	1196.6	11.6	16.6	21.8
Sc6	2071–2100	RCP 8.5	606.9	1292.7	14.1	19.1	24.4

3. Results

3.1. Flood Modeling

Based on the results of the flood modeling, the phenomenon started on 7 September 2016, and gradually retreated until 15 September 2016. The maximum water depth was noted at the Agora southwestern part and reached 0.6 m on 8 September 2016

(Figures 3, 4a and 5a; Table 3). As mentioned above, the cumulative precipitation during the period from the 6 to 8 September 2016, was 279 mm. Additionally, based on the results, the central and southwestern part of Agora site, Vasiliki, the central part of Asklepieion and the northern part of the Stadium were inundated during the 6–8 September 2016, flood event (Figure 4a). This agrees with the photographs and the press reports regarding the specific flood event (Figure 3). The total inundated area at the archaeological site of Ancient Messene was calculated to be $5.1 \times 10^3 \text{ m}^2$ on 8 September 2016.

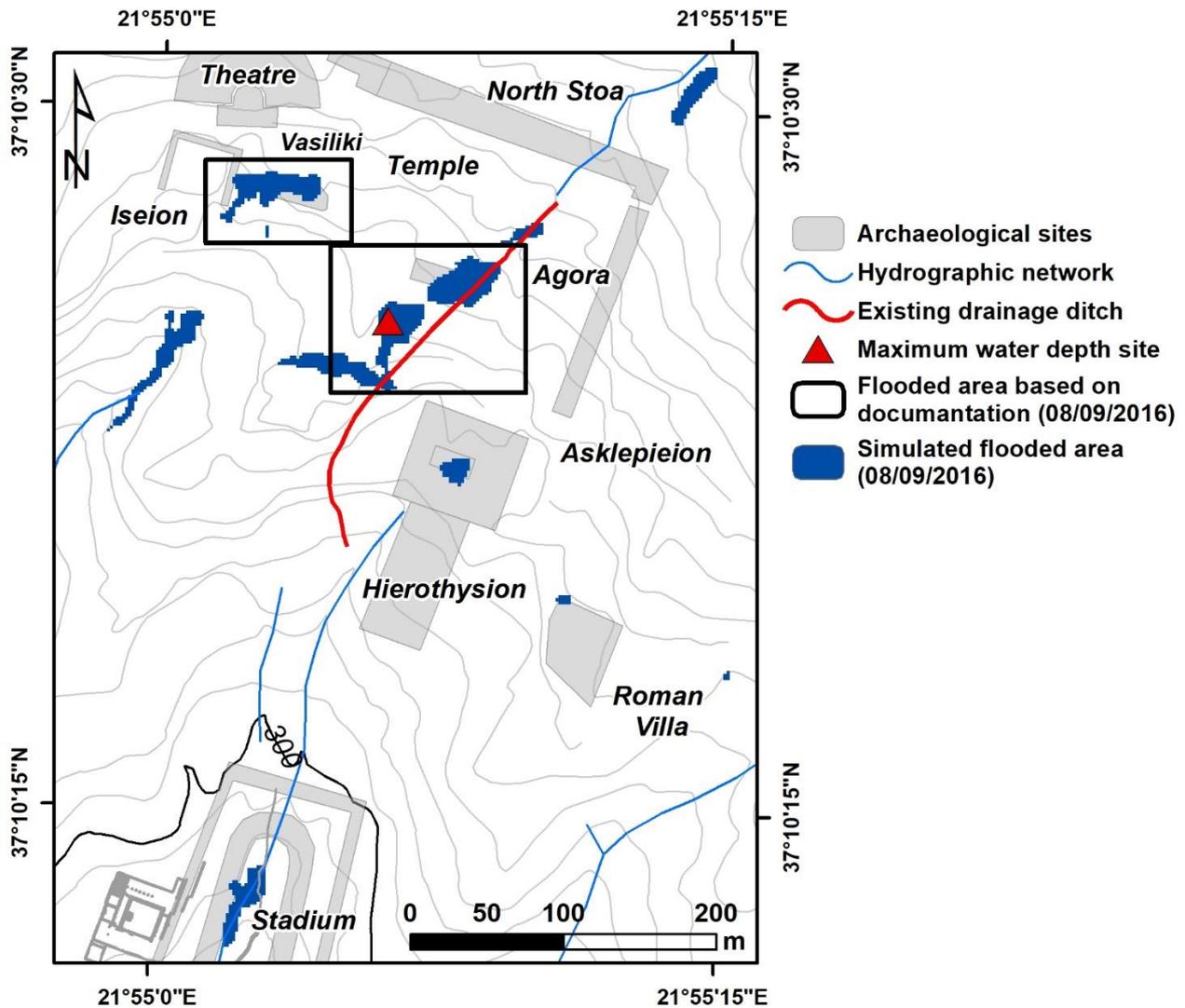


Figure 3. Documented and simulated inundated area of the Ancient Messene archaeological site on 8 September 2016.

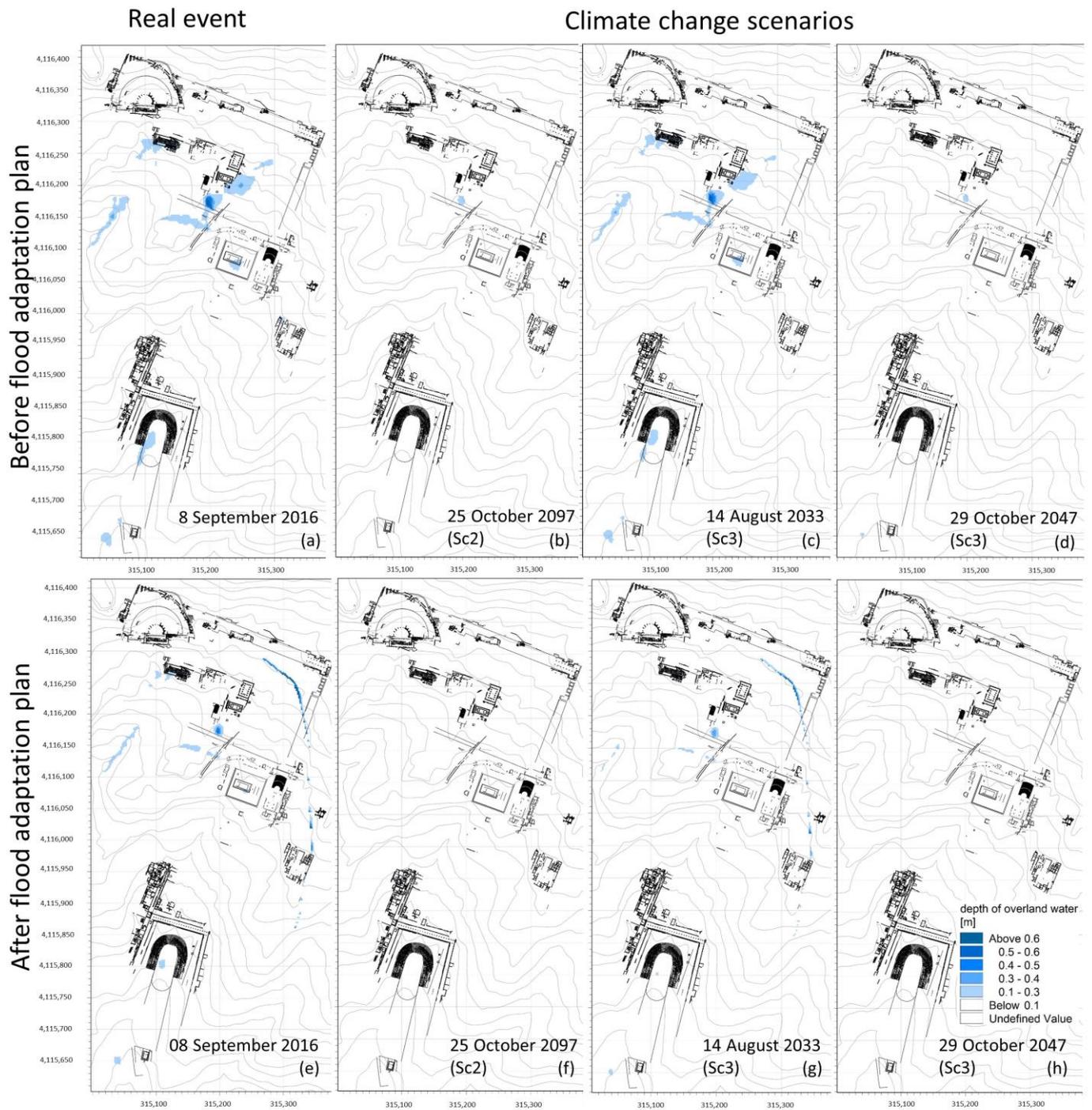


Figure 4. Results of the flood modeling—maximum water depth spatial distribution for the flood events examined before the flood adaptation plan (a) on 8 September 2016; (b) on 25 October 2007 (Sc2); (c) on 14 August 2033 (Sc3); (d) on 29 October 2047 (Sc3); and after the flood adaptation plan (e) on 8 September 2016; (f) on 23 October 2007 (Sc2); (g) on 14 August 2033 (Sc3); and (h) 29 October 2047 (Sc3).

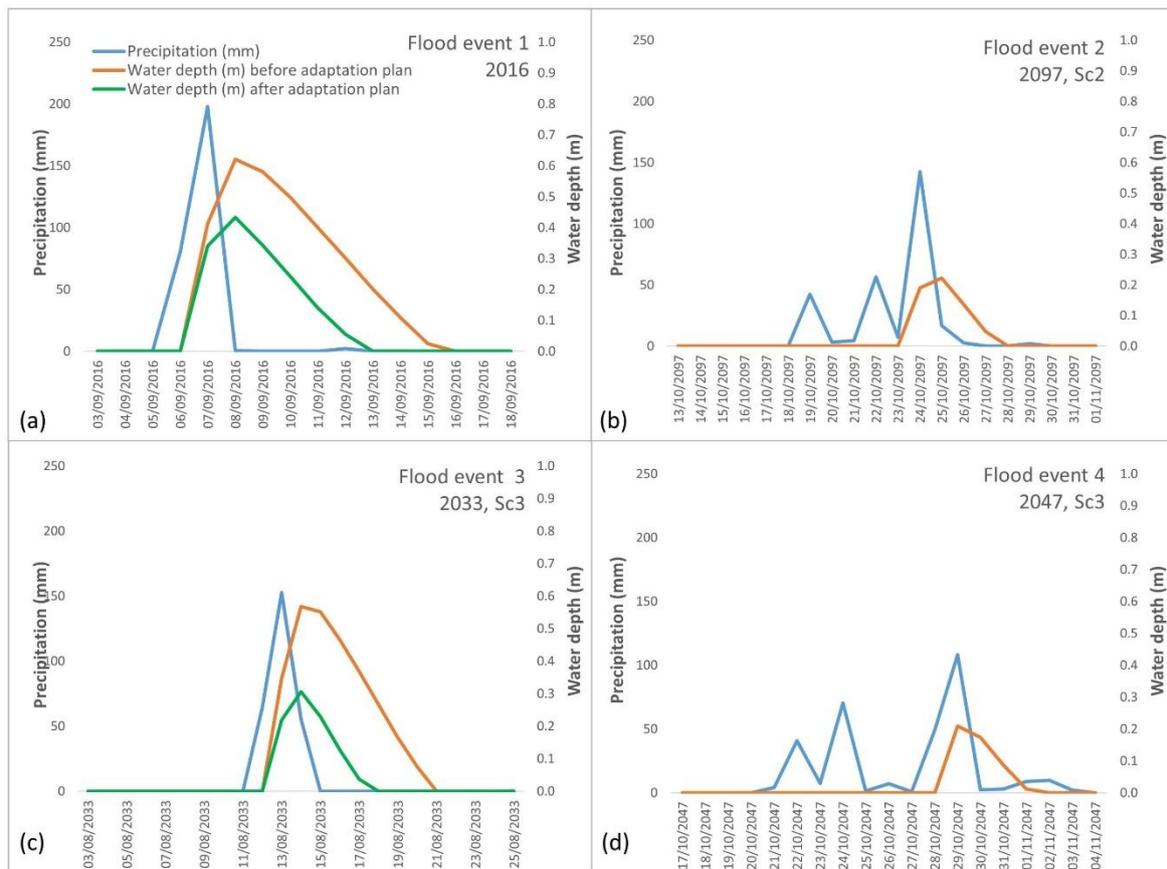


Figure 5. Results of the flood modeling. Precipitation vs. maximum water depth, before and after the flood adaptation plan, at the Agora site (maximum water depth site; see Figure 2); (a) of the 6–8 September 2016 flood event; (b) of the Sc2 19–24 October 2097 flood event; (c) of the Sc3 12–14 August 2033 flood event; and (d) of the Sc3 29 October–1 November 2047, flood event.

Table 3. Investigated flood events at the archaeological site of Ancient Messene.

Flood Event	1	2	3	4
Scenario	Real Event	Sc2	Sc3	Sc3
Precipitation dates	6–8 September 2016	19–26 October 2097	12–14 August 2033	21 October–3 November 2047
Cumulative precipitation (mm)	279.0	274.9	272.2	314.9
Precipitation duration (d)	3	8	3	14
Precipitation intensity (mm/d)	93.0	34.4	90.7	22.5
Before adaptation plan				
Flood dates	7–15 September 2016	24–27 October 2097	13–19 August 2033	29 October–1 November 2047
Flood duration (d)	9	4	8	4
Date of flood peak	8 September 2016	23 October 2097	14 August 2033	29 October 2047
Maximum water depth (m)	0.6	0.2	0.6	0.2
Maximum inundated area ($\times 10^3$ m ²)	5.1	0.2	4.1	0.2
After adaptation plan				
Flood dates	7–12 September 2016	-	13–17 August 2033	-
Flood duration (d)	6	0	5	0
Date of flood peak	8 September 2016	25 October 2097	14 August 2033	29 October 2047
Maximum water depth (m)	0.4	0	0.3	0
Maximum inundated area ($\times 10^3$ m ²)	1.3	0	0.5	0

It should be noted that there is a one-day time lag between precipitation and water depth that can be attributed to the coarse temporal resolution of the precipitation dataset.

3.2. Climate Change Scenarios

In Figure 6, the water depths at the Agora site (maximum water depth site at Agora; see Figure 2) for the climate change projections examined are presented. Based on the simulation results, flood events occurred only at climate change scenarios Sc2 (one flood event) and Sc3 (two flood events). More specifically, and after a more detailed examination of the flood events highlighted, the following can be reported:

Based on the results, during the reference period (1971–2000 reference period, P 1037.4 mm, ET 1128.3 mm) no flood event occurred in the archaeological site of Ancient Messene.

Likewise, during climate change scenario Sc1 (2031–2060 near future period, RCP2.6–stringent scenario, P 874.0 mm, ET 1183.5 mm) no flood event occurred in the archaeological site of Ancient Messene.

During climate change scenario Sc2 (2071–2100 distant future period, RCP2.6–stringent scenario, P 1107.0 mm, ET 1175.1 mm), one flood event occurred between 24 and 27 October 2097, with cumulative precipitation amount of 161.7 mm. It should be noted that the period prior to this flood event (19–24 October 2097), the cumulative precipitation was 113.2 mm, leading to soil saturation that favored flooding. The flood occurred at Agora and the maximum depth was 0.2 m and the total inundated area at the archaeological site of Ancient Messene was $0.2 \times 10^3 \text{ m}^2$ on 23 October 2097 (Figures 4b and 5b, Table 3).

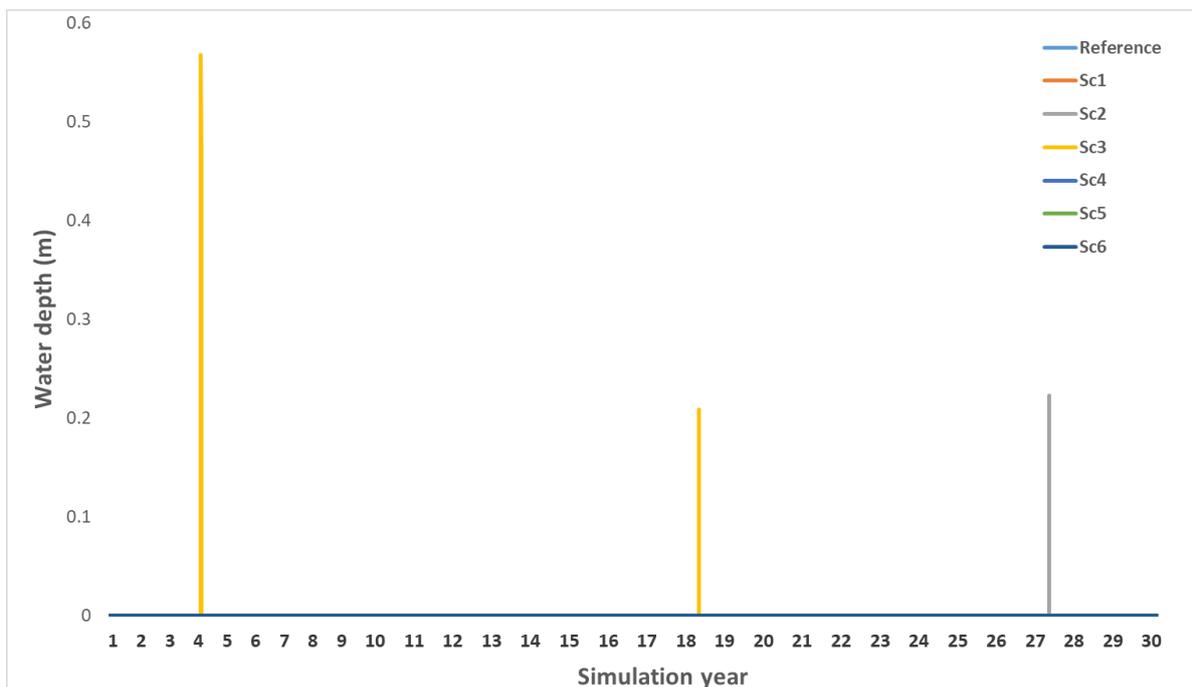


Figure 6. Results of the climate change scenario flood modeling. Water depth at the Agora site (maximum water depth site; see Figure 2).

During climate change scenario Sc3 (2031–2060 near future period, RCP4.5–intermediate scenario, P 946.9 mm, ET 1185.5 mm), two flood events occurred. The first was triggered by a 272.2 mm cumulative precipitation during the period 12–14 August 2033, and it lasted seven days (13–20 August 2033). The maximum depth at the Agora area was 0.6 m and the total inundated area was $4.1 \times 10^3 \text{ m}^2$ on 14 August 2033 (Figures 4c and 5c, Table 3). The second flood event occurred between 29 October and 1 November 2047, and it can be attributed to 314.9 mm of cumulative precipitation during the period between 21 October

and 3 November 2047. The maximum depth at Agora was 0.2 m and the total inundated area was $0.2 \times 10^3 \text{ m}^2$ on 29 October 2047 (Figures 4d and 5d, Table 3).

During climate change scenario Sc4 (2071–2100 distant future period, RCP4.5–intermediate scenario, P 821.4 mm, ET 1199.7 mm), no flood event occurred in the archaeological site of Ancient Messene.

Likewise, during climate change scenario Sc5 (2031–2060 near future period, RCP8.5–extreme scenario, P 845.6 mm, ET 1196.6 mm), no flood event occurred.

Finally, during climate change scenario Sc6 (2071–2100 distant future period, RCP8.5–extreme scenario, P 606.9 mm, ET 1292.7 mm), no flood event occurred in the archaeological site of Ancient Messene.

3.3. Flood Adaptation Plan

Based on the results of the flood modeling after applying the adaptation plan proposed for flood protection of the archaeological site of Ancient Messene, for the flood event of 2016, the maximum water depth in the area of Agora decreased from 0.6 to 0.4 m and the inundated area in the archaeological site from 5.1×10^3 to $1.3 \times 10^3 \text{ m}^2$. Additionally, the Stadium and the Vasiliki were the high-risk areas (Table 3, Figure 4e). Nevertheless, the central part of Agora and the Asklepieion monument were not flooded.

Likewise, for the flood event in 2033 (Sc3), the maximum water depth in the area of Agora decreased from 0.6 to 0.3 m and the inundated area in the archaeological site from 4.1×10^3 to $0.5 \times 10^3 \text{ m}^2$ (Table 3, Figure 4g). In the specific scenario, the stadium, the Vasiliki, the Asklepieion, and the central part of Agora were not flooded.

The heavy precipitation events in 2097 (Sc2) and 2047 (Sc3) did not result in flooding events after the adaptation plan and the total inundated area in these scenarios were eliminated (Table 3; Figure 4f,h).

4. Discussion

There is a growing global awareness about the impacts of climate change on cultural and natural heritage sites. Greece, a homeland of important historical and cultural resources, which provide educational, aesthetic, scientific, spiritual, and recreation services [58], and consist tourist attractions that significantly contribute to the economic growth of the country [59], is vulnerable to future, extreme, climate change and global warming-related, flood events [60].

Based on the results, the flood prone sites of the archaeological site of Ancient Messene are the central and southwestern parts of Agora site, Vasiliki, the central part of Asklepieion, and the northern part of the Stadium. The primary mechanism triggering the floods can be associated with the surface runoff of the anonymous stream crossing the archaeological site.

The maximum water depth during the 2016 flood event occurred at the southwestern part of Agora, and reached 0.6 m on 8 September 2016. Likewise, based on the results of the Sc3 climate scenario simulation, a 3-day precipitation event of 272.2 mm of cumulative rainfall between 12 and 14 August 2033, resulted in a flood event with a maximum water depth of 0.6 m at Agora. Nevertheless, two four-days flood events (24–27 October 2097, Sc2 and 29 October–1 November 2047, Sc3) resulted from 274.9 and 314.9 mm of cumulative precipitation, respectively, and led to 0.22 and 0.21 m of maximum water depth at Agora, respectively. Precipitation intensity was a critical factor that affected flood generation mechanism. The precipitation events in 2016 (flood event 1) and Sc3 in 2033 (flood event 3) with high rainfall intensities (93.0 and 90.7 mm/d respectively) resulted in flood events, while the precipitation events Sc2 in 2097 (flood event 2) and Sc3 in 2047 (flood event 4) with low rainfall intensities (34.4 and 22.5 mm/d respectively) did not, although the cumulative precipitation was similar, and in the case of flood event 4—higher than the first two (Table 3).

It should be noted that, regarding the methodological approach adopted in the present study, uncertainties rise due to the lack of climatological data with high temporal resolution and the lack of conventional flood-related data (water depth measurements or high-water

marks of the most affected areas) for the model calibration. In particular, the latter can lead to misevaluations regarding the detailed flood inundation mapping, which cannot be easily quantified in the present study. Nevertheless, simple binary (eye-witness) observations regarding the presence or absence of flooding in establishing a reliable model structure to predict the flood extent, when other data are not available, can be valuable [61], despite the uncertainties. Especially at vulnerable and valuable sites, such as sites of cultural heritage, which are usually not efficiently monitored, such approaches have proven to be valuable tools for the development of flood risk reduction and climate change adaptation strategies, since they provide enough data for decision making.

5. Conclusions

Cultural heritage sites, archaeological sites in particular, are vulnerable to climate change-related hazards, such as floods. In this study, flood risks at the archaeological site of Ancient Messene, under different climate change scenarios, were examined. Under this scope, a physically-based hydrological model (MIKE SHE 2020) was implemented for the flood event of September 2016 and six (6) climate change scenarios adopted from the Intergovernmental Panel on Climatic Change (IPCC) were examined. Finally, the effectiveness of a soft structural adaptation plan was examined.

Based on the present study, the archaeological site of Ancient Messene is shielded against small or larger storms; only in cases of extreme or high intensity precipitation events is the area likely to be at risk. This flood risk can be further eliminated after implementing a nature-based solution soft structural adaptation plan proposed for flood protection of the archaeological site. Based on the results, this intervention was able to completely extinguish the consequences of smaller precipitation events and limit the damages of extreme events.

Interventions to cultural and natural heritage sites with respect and understanding to the landscape and to their unique characters, can be challenging. NBSs provide cost-effective alternative approaches for flood risk reduction and climate change adaptation, with minimal possible disturbances. NBSs seem to be the most effective against small or medium precipitation events, which nevertheless are the largest contributors to overall flood impacts due to their frequent occurrences. Therefore, NBSs benefits for flood adaptation should not be underestimated.

Hydrological modeling, towards this scope, even in case of data scarcity, proved to constitute a valuable tool for the design and evaluation of such solutions, for flood risk estimation and adaptation plan management.

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