Representing the operation of ancient reclamation works at Lake Copais in Greece.

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Abstract Water has been playing a vital role in Greeks' life during their long history. Ancient Greek societies were very active towards water management, having presented an impressive variety of hydraulic works. The main purpose of this paper is to represent the operation of one of the most ancients and extended hydraulic works. The drainage project of Lake Copais (is located in Central Greece) was developed and operated by Minyans, a powerful Mycenaean race. Minyans, partially diverted two large rivers which fed the lake. The water was conveyed towards labyrinthine natural sinkholes, which were formed in limestone terrain. Through sinkholes the water slowly discharged to the sea. This impressive ancient water management system of Copais has gained the attention of many scientists and has been extensively studied by archaeologists and engineers. Still important questions exist about the way that the hydrosystem worked. Trying to provide some reliable answers, we have attempted to study the Minyans' interventions to hydrosystem, from a hydraulics engineers' perspective. All the available archeological, hydrological and geological information of the area was used, to evaluate the operation of the hydrosystem. The main elements of the hydrosystem, are presented here and their purpose is examined. For this, (i) a water balance model was developed and (ii) the hydrosystem was simulated using synthetic time series of the hydrological processes. Several operational cases were examined in order to define critical parameters of the system, such as the Copais' water level variation and the water accumulation at the sinkholes' area. The analysis reveals some significant factors, which were combined with the archaeological findings, to lead us to some interesting conclusions for hydrosystem's performance.

Keywords. Ancient hydraulic works, hydrologic simulation, Minyans, land reclamation, Lake Copais, sinkhole, drainage system, hydrosystem operation

1. Introduction

1.1 General

It is widely accepted that ancient Greek civilizations have significantly contributed to human societies' development in various ways. One of the technological fields that they emphasized to (like most of the great societies of the past) was the control and exploitation of water resources. In ancient times, the civilizations that prospered in the Greek peninsula made a remarkable progress in understanding water - related processes. Also in many cases, they developed integrated systems, which were consisted of large or smaller hydraulic works. These works served the fundamental water needs, such as water supply (for urban use or irrigation), land and urban drainage, flood prevention, sanitary facilities and urban sewage.

In the island of Crete, during the Minoan period (3500-1200 BC), a technological step happened regarding water capture, conveyance and utilization. The archaeological investigation in the palaces of Knossos, Phaistos and Malia, which were the center of life for the Minoans, revealed very important hydraulic infrastructures. Systems for water transportation, wastewater and stormwater management and bathrooms with flashing toilets, have been found. Sewage systems as well as bathrooms and bathtubs were also found in the island of Thera the major center of the Cycladic civilization.

In the island of Samos, in about 540 BC (later Archaic period), engineer Eupalinos constructed an underground tunnel with a length that exceeded 1000 m. This tunnel supplied the city with water that was coming from the nearby mountain. Given the limited available technical resources of that period, the "Eupalinean digging" is one of the greatest hydraulic works of the antiquity (Angelakis et al., 2014).

Later, during the Classical Period (500-336 BC), several water technologies were developed in ancient Athens. Aqueducts which conveyed drinking water to the city, sewage systems (such as the Athenian Agora canals), public baths and latrines, were constructed. These hydraulic works, along with many others, prove the vivid interest of ancient Greeks concerning water exploitation. All these achievements are a valuable cultural and technological heritage to the humanity (Zarkadoulas et al., 2008).

As ancient societies were developed, the agricultural production became more important. The hydraulic works, which secured crop irrigation, were related to water capture, storage and conveyance. Agricultural lands had to be protected from flooding and in specific cases, new areas were reclaimed by drainage (Koutsoyiannis and Angelakis, 2007; Mariolakos 2009). Considering that Greece had always been an extremely fertile area, therefor suitable for a wide variety of agricultural activity, the importance of such hydraulic works is obvious.

Furthermore, the archaeological findings related to flood prevention and reclamation land projects are significant since:

- Ancient Greeks generally avoided, if possible, living in areas with problems that would require the construction of major engineering projects. Therefor flood control projects were not common, as habitation in areas with no frequent flooding problems, was preferred.
- This kind of projects requires more attention related to design parameters than other categories of hydraulic works, because the cost of life and the economic damage from a possible failure are particularly high. Deep understanding of natural processes, expertise, meticulous study and careful implementation are required for reliable design and operation.

1.2 Study area

This paper focuses on the first historically documented successful attempt to drain a shallow lake. Lake Copais, is located in Central Greece, and was partially drained during 13th century BC. A portion of the water volume of the main rivers that fed the lake diverted towards natural karstic sinkholes and finally to the sea. According to Strabo (IX 406-407, 414-415), drainage works were made by Minyans, inhabitants of Copais area during the Mycenaean Period (1550-1150 BC). Historical investigation makes clear that Minyans were very willing to develop commercial relationships with other Greek races, and acquired great wealth and power. However, they focused primarily to control the unique natural resources of their territory and then to develop trade relationships (Kountouri et al, 2013).

The works date in the late Mycenaean period, probably around 1400-1300 BC, a period that Minyan civilization reached its peak. The drainage of Copais Lake has always been a very important issue for the inhabitants of the surrounding area. If this problem was solved a fertile land of about 25 km^2 could become available for cultivation. After 3000 year, in 1882 Greek state started a drainage project and achieved to complete it 50 years later. The extended hydraulic works which were constructed during that period proves the significance of the Minyan reclamation system.

Important elements of ancient Copais drainage system came during the construction period of the modern system from the English company ‘Lake Copais Company Limited’. Since then, the Minyan hydraulic works attached the attention of the scientific community.

Several studies on ancient Copais drainage system have been carried out by several researchers (Rachet, 1993; Schnitter, 1994; Knauss, 1995; Knauss, 2000). Knauss, 2000, characterized the Minyan works as “extraordinary and ingenious”. He also claimed that the "first hydraulic civilization of Europe" was born in the Mycenaean Copais and suggested that this area was the ‘‘fat province’’ of Boeotia, mentioned by Homer in Iliad, Book 7 (219–224).

According to Knauss, 1995, Minyans attempted to gain land from Copais Lake in two main phases. Initially, low but extended earth dams were constructed. These dams enclosed land (polders) used for agricultural and other purposes. After dams' failure, perhaps due to intense hydrological phenomena, a second system was developed. The most important structure of this second attempt was a 25 km long canal which carried water from Copais basin to the natural sinkholes located in the northeast part of the area. The canal served three main purposes:

- It reduced and stabilized the water level of Copais Lake in order to gain land for agricultural use and settlements. In addition, the old protective polders were used again even under extremely wet periods.
- It facilitated the water supply of settlements and crops.
- It created an inland navigation scheme along the northern part of the basin, facilitating the transport of merchandise from the harbors close to the northeastern edge of Copais, to the major city of Orchomenos.

According to Strabo, the area flooded again, few years later (at about 1100 BC), probably because of earthquakes. Some ancient myths relate Hercules with the destruction of Copais drainage works and the flooding of the area, indicating that war actions (related to the inter-Mycenaean rivalry during Greek Dark Ages) destroyed that project.

2. The Hydrosystem

2.1The natural system

Former lake Copais was located in Boeotia (Central Greece) and, before its drainage, used to be the largest lake in Greece. Its surface ranges between 15 km^2 in the dry years to 25 km^2 in the wet ones. Copais is the largest endorheic basin in Greece, stretching along an area of about 750 km^2. The hydrological elements of the hydrosystem are presented in Figure 1. The main river is Boeotian Kephisos which supplies the basin with approximately 179 hm^3 of water each year but with a great temporal variation in monthly and annual basis. The water basin of this river at the entrance to the lake covers an area of about 1100 km^2. Boeotian Kephisos enters Copais basin from the east, and before the construction of the modern drainage works, it continued its course until it branched about 2.5 km south of Orchomenos city. The main part kept flowing eastward following the northern edges of the basin and reached the (clogged) sinkholes which are located at the south - eastern edge of it, while the smallest part poured into the basin.

Another important component of the hydrosystem is Melas River with an annual water discharge of about 130 hm^3. Melas is not characterized by significant annual and monthly variations because its water comes from springs. Its course begins from the north - west edge of the basin and before the 19th century interventions, it joined Kephisos River. The hydrosystem also includes the rivers Erkyna, Pontzas, Lofis and several smaller streams and torrents, which flow mainly from the south. Their total average annual water discharge is estimated to about 44 hm^3.

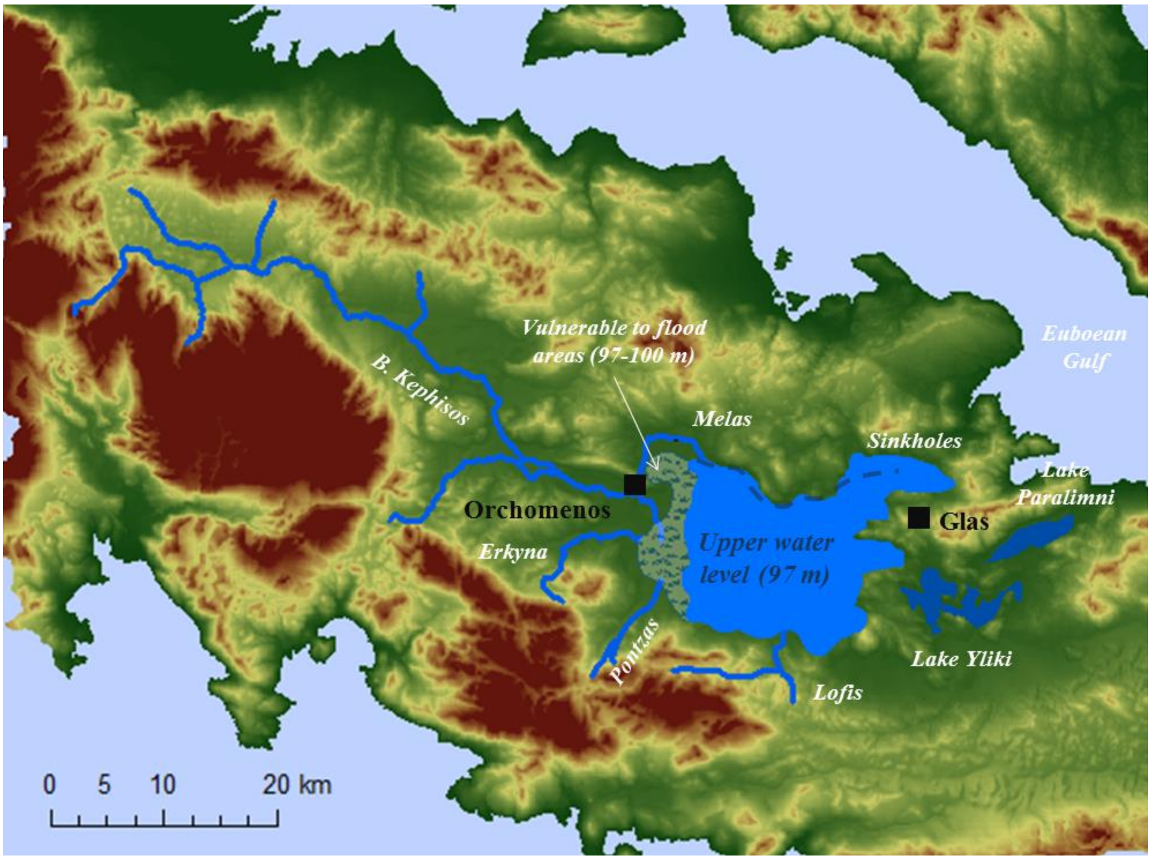

Fig. 1 Copais basin natural hydrosystem.

Copais was a shallow lake whose bottom level was, in its greater part +92 m a.s.l. while water level varied between +92 and +97 m a.s.l. Above the level of +97 m, water discharged to the Euboean Gulf through sinkholes, which were located on the east fringes of the basin (Constantinidis, 1984). Depending on the actual capacity of the sinkholes and the flood water accumulation, the western areas of the lake (between +97 and +100 m) were vulnerable to floods.

The creation of sinkholes (underground crevices and tunnels in limestone) is a very common geological process in Copais. Limestone rocks which cover approximately 40% of the subsoil (Efstratiadis et al., 2004) appear largely cracked due to the intense seismic activity. Thus, water easily infiltrates into the discontinuities of the limestone and gradually erodes it.

Nowadays, many of these sinkholes are, to a greater or lesser degree, clogged, as a result of earthquakes, landslides and water flow materials backfilling.

2.2 Modern drainage works

Today, Copais is a plain spreading across an area over 25 km^2 which was formed by the drainage of the homonymous lake at the beginning of the 20th century. The drainage works ensured the exploitation of remarkably fertile soils. Over the years, Copais transformed into one of the most important agricultural centers in Greece and various plants (cotton, tobacco, cereals, grapes, corn, clover and various vegetables) were cultivated.

The modern drainage system is presented in Figure 2. After entering Copais, Boeotian Kephisos is diverted to the south through an artificial channel called "Grand Canal". This channel follows the southern edges of the basin and collects the water of rivers Erkyna, Pontzas, Lofis and other smaller streams and torrents. Melas' route, on the other hand, coincides to the drainage canals at the northern part of the basin. At this point, Melas river is partially diverted to the southeast joining Kephisos' artificial bed. The total water supply is finally poured into Yliki Lake through "Emissary Canal" and "Karditsa" tunnel. The project includes a dense network of internal drainage canals.

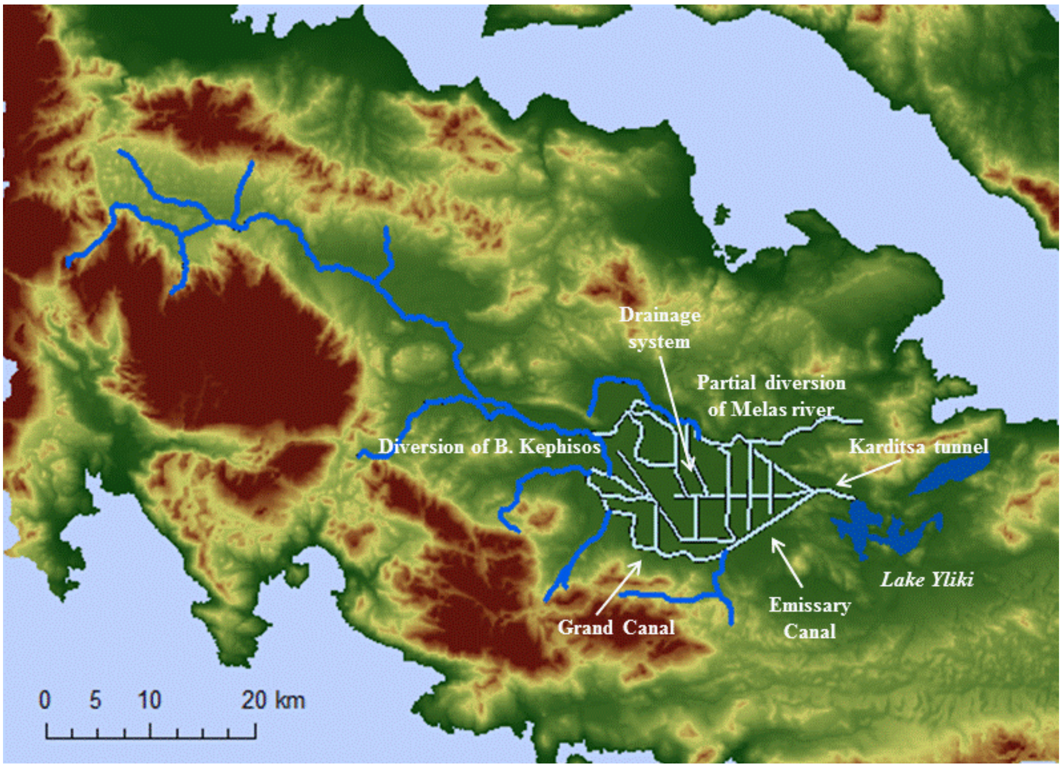

Fig. 2 Copais basin hydrosystem today.

3. The Minyan interventions

3.1 Society and water needs

Minyans' land was the greater area of Copais basin in Boeotia. Although their capital was Orchomenos (at the east of Copais basin), in the early 13th century BC Minyans built a citadel at Gla hill, which was surrounded by cyclopean walls. Gla was a palatial place and it was located at the northeastern part of Copais basin, close to the sinkholes (Figure 1). Remnants of granaries and officials' residences have been found there. It is assumed that these facilities were used by Minyans to storage the harvest and to supervise Copais' water management system.

We can have useful information from Homer's Iliad (Rhapsody B, verses 494-759) about Copais' area population. It is mentioned that Minyans participated to the Trojan War by sending a fleet of 30 ships while Crete contributed with 80 ships. In about 1700 BC (a few centuries before the Trojan War), the largest site of Minoan civilization, Knossos, numbered about 80.000 inhabitants (Angelakis et al., 2006). Assuming that the total population of Crete at that time was approximately double (i.e. 160.000 people), we suppose (comparing the number of ships with the populations) that the Minyan civilization numbered about 60.000 people. We assume that the domestic water consumption per person was about 3.5 m^3 per year. Solon (Athenian legislator, 639-559 BC) who lived about 800 years after Minyan civilization, considered that this quantity was sufficient. Therefore, the total annual quantity of domestic water in Minyans' settlements is estimated to about 0.2 hm^3. As mentioned above, Melas River, whose springs were very close to Orchomenos (the greatest Minyan settlement), has a mean water discharge of about 131 hm^3 per year. This discharge has a small variation on monthly and yearly basis, therefore Minyans never had problems to cover their basic water needs.

Considering the: (a) irrigation water needs, (b) dietary habits of ancient Greeks and (c) microclimate of the study area, we developed a theory about the cultivation pattern in Copais during the Minyan era. We assumed that about 40% of the plain was cultivated with cereals, 30% with vegetables and another 30% with vineyards. We used the Doorenbos - Pruitt method to calculate the potential evapotranspiration in the area. According to our assessment from the data, Minyans cultivated approximately 100-120 km^2. So the total irrigation needs were estimated to about 74 hm^3 per year. The values per month are presented in Table 1 of Chapter 4.

3.2 Minyans' works

In ancient time, Boeotian Kephisos, the largest river in the study area, entered Copais plain from the west and as it could not find a way out, outpoured to the southeast part of plain. There, it created an extensive shallow lake, the size of which intensively varied in time, depending mainly by river's discharge. Meanwhile, Melas River, flowing along the northern part of the basin, discharged through the sinkholes of the north - eastern edge. The water sunk into those sinkholes and reappeared at the North Euboean Gulf. Minyans assumed that if both Kephisos and Melas rivers discharged to the sinkholes, the lake's size would greatly be reduced and become stable. The hydraulic works aimed at:

- Reclaiming land from the eastern part of the lake for cultivation
- Protecting these areas from floods
- Increasing the draining capacity of the sinkholes
- Supporting the irrigation works

The main interventions by the Minyans are presented in Figure 3 and included:

- A diversion channel in order to convey a portion of Kephisos water discharge to the karstic sinkholes at the northeastern edge of the basin
- A levee in the northern part of the basin in order to protect the irrigation areas from of Kephisos and Melas River's floods
- A tunnel which was constructed (not completed) very close to the natural sinkholes. Th tunnel drained the water volume, which was accumulated in the sinkhole area, towards the sea
- Cleaning and maintenance works for the sinkholes so that their draining capacity was ensured
- Water cisterns in order to ensure that their irrigation needs will be fulfilled even during dry seasons

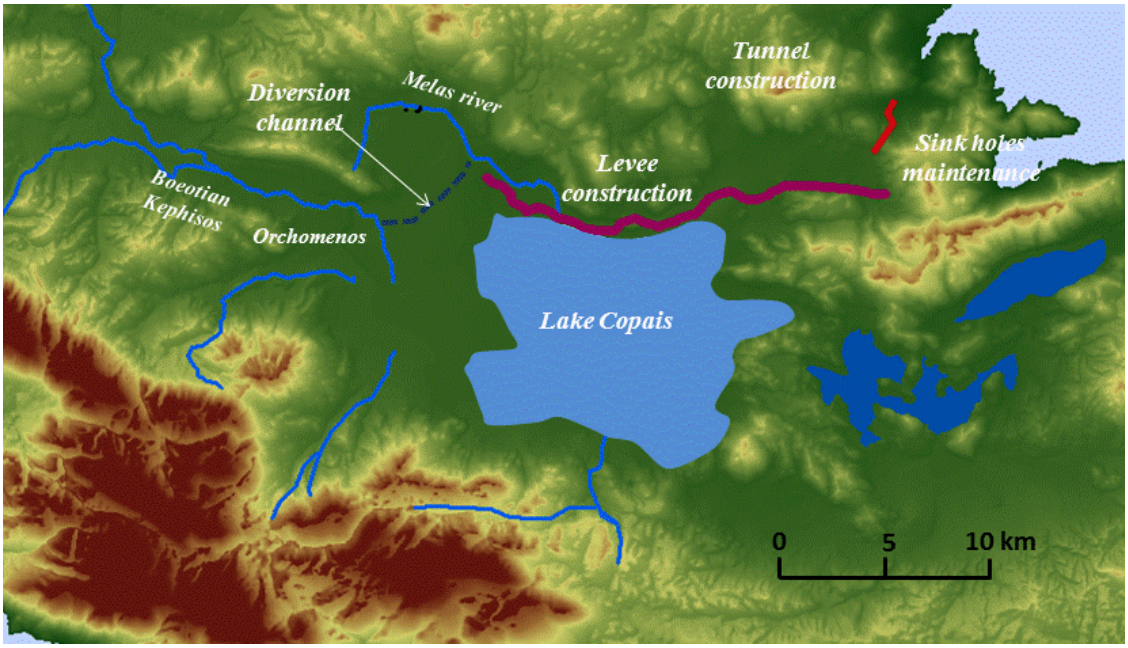

Fig. 3 The Minyan interventions.

3.2.1 The levee

Minyans first constructed a barrier in order to divert Kephisos (its largest part) from its natural course to an artificial channel towards Melas River’s riverbed. This possibly was located about 2.5 km south of the city of Orchomenos, although remnants of the diversion levee have not been found until today. So, Kephisos joined Melas (probably about 3 km north of Orchomenos) and the two rivers continued together their course towards the sinkholes.

In order to reduce the possibility of a flood due to water overflow, Minyans constructed a strong levee (Figure 3) south of Melas riverbed and almost parallel to it. This levee’s direction was from the west to the east, and it was the boundary between the flooded part of Copais (north part) and the cultivated one (south part). The construction technique of this “barrier” is one of the most impressive elements of ancient Copais reclamation system (Kountouri et al., 2013). Some technical characteristics are given below:

- The exterior sides of the levee were reinforced by cyclopean retaining walls. The main purpose of these walls was to prevent, as much as possible, the levee’s erosion. Additionally, they increased its resistance to water pressure.
- For the construction of the retaining walls, large boulders were placed externally into layers more or less having the same height, while smaller stone were used inside. The interior of the walls was filled with yellowish clay (Figure 4). This clay was found in large quantities in the former lake bottom, as it was carried by water flow. It is characterized by its high plasticity and waterproofing properties. The above construction technique is similar to the modern way of building earth dams and it demonstrates solid knowledge. Minyans known the materials’ properties and the characteristics of erosion process.

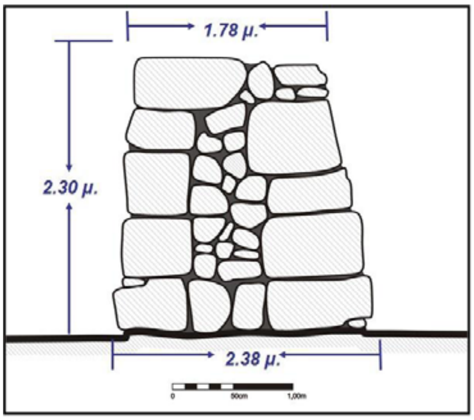

Fig. 4 Cross section of the Minyan levee’s retaining wall at the site of Anteras. Source: Kountouri et al., 2013.

- The phases of building a retaining wall was the following: First, the Minyans dug a trench foundation, a little wider than the wall. The trench was filled with a thick layer of clay in which small stones were placed. This structure was waterproof due to the clay. The stones of the first layers were placed above it (with the clay between them as a flange) and the upper layers were constructed on top.

- The exterior side of the wall inclined and the boulders of the lower layers were extended more than the higher ones. In contrast, the inner side of the walls was almost vertical.
- The proper construction of the retaining walls, allowed them to reach up a height of 2.3 m in some cases, while the stones which were found around them, indicate that their original height was about 3.0 m. Their width varied because of the geomorphology of the surrounding area and the proximity of the walls to the slopes of the basin.
- About 6 km east of Orchomenos, the total width of the levee and its two retaining walls was approximately 30 m.

Excavations which have been carried out have revealed several positions of the ancient levee. Although it was constructed before 3.000 years, is generally in good condition and still has keep a height over 2 m and a width over 10 m. Nowadays, Copais is a fairly smooth plain without especially acute morphological changes, so the contrast between the flat terrain and the bulky levee is intense. Using aerial photographs and satellite images of Copais, we can find out the traces of the levee to the ground. After a detailed study of the available data, we approximately determined the course of the Minyan levee and we estimated its total length to about 22 km.

3.2.2 The tunnel

The deposition of sediments into the sinkholes gradually decreased their capacity to convey water from the basin towards the sea. Also, earthquakes possibly clogged them even totally. So, Minyans had to clean the sinkholes occasionally in order to keep or to increase their capacity to drain the basin.

The drainage system could not entirely be depended on the sinkholes, as the supervision of their condition, especially in their deepest parts, was a difficult task. So Minyans attempted to dig a tunnel in the site of Kephalari, which was very close to the sinkholes. This tunnel was designed to divert water of B. Kephisos and Melas rivers to a small torrent and finally to Euboean Gulf. Its function was similar to the sinkholes and it enhanced the drainage of the basin. Its length was scheduled to be over 2.2 km with a continuous slope of about 1.15% (Kambanis, 1893). It had a cross section of 1.45 m width and 1.55 m height, while its discharge was 7 m^3/s approximately. To supervise the construction and operation of the tunnel, 16 vertical shafts were dug with a total depth of about 650 m (Figure 5). Recent exploration revealed that finally, only about one - fifth of the tunnel was completed. In addition, most of 16 shafts never completed and some of them gradually backfilled. The tunnel starts from a sinkhole, continues for about 400 m and suddenly stops (under the shaft 3) to a solid rock. Another proof of the tunnel’s unsuccessful construction found at the bottom of shaft 14, where the tunnel has been dug to both directions for 7 m and stops to solid rock. The ceiling of the tunnel was constructed as a relieving triangle over lintels that distribute the weight into the supporting walls. That was a classical Mycenaean technique. It has to be mentioned that some researchers believe that the Kephalari tunnel was constructed by the Macedonians of Alexander the Great.

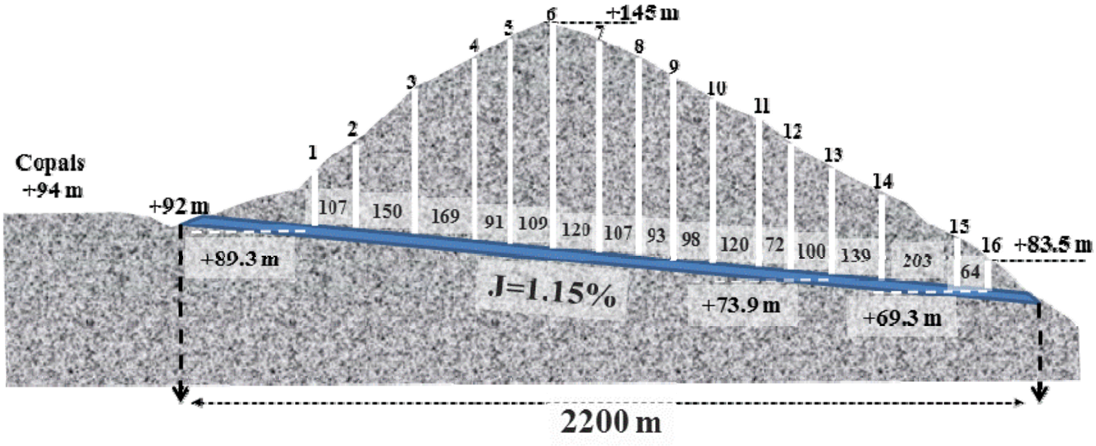

Fig. 5 Kephalari tunnel. Section constructed by data in Kambanis (1893).

3.2.3 Small cisterns

Comparing Minyan's water needs with the combined water volumes of Boeotian Kephisos and Melas rivers we realize that, except from the summer months, the rivers discharges were sufficient for their needs. During summer there was a shortage in water resources and at that period, Minyans could retrieve the water which was stored in the lake in order to irrigate their fields. Kephisos and Melas rivers flowed in higher levels compared with the cultivated land and the lake water resources were in lower levels. So, it is reasonable to assume that Minyans preferred to use the river flow as it would allow them to irrigate very easily using gravity. Thus, artificial cisterns, which stored small water quantities during winter, could be part of the Minyan water management system. Cisterns provided irrigation water using gravity, during dry summer periods.

A possible location of an artificial cistern was found about 6 km east of the city of Orchomenos. At that site, the route of levees unexpectedly curves without any obvious reason (like e.g. terrain morphology). Perhaps this design served the creation of an area where water could be stored in order to be exploited during dry periods. If the slope of the ground was suitable, water could be stored in an area of about 1.5 km^2 (Figure 6). As the height of the levee was about 3.0 m, approximately 4.5 hm^3 of water could be stored in the above location. Moreover, it is possible that this curve also served as the system's spillway.

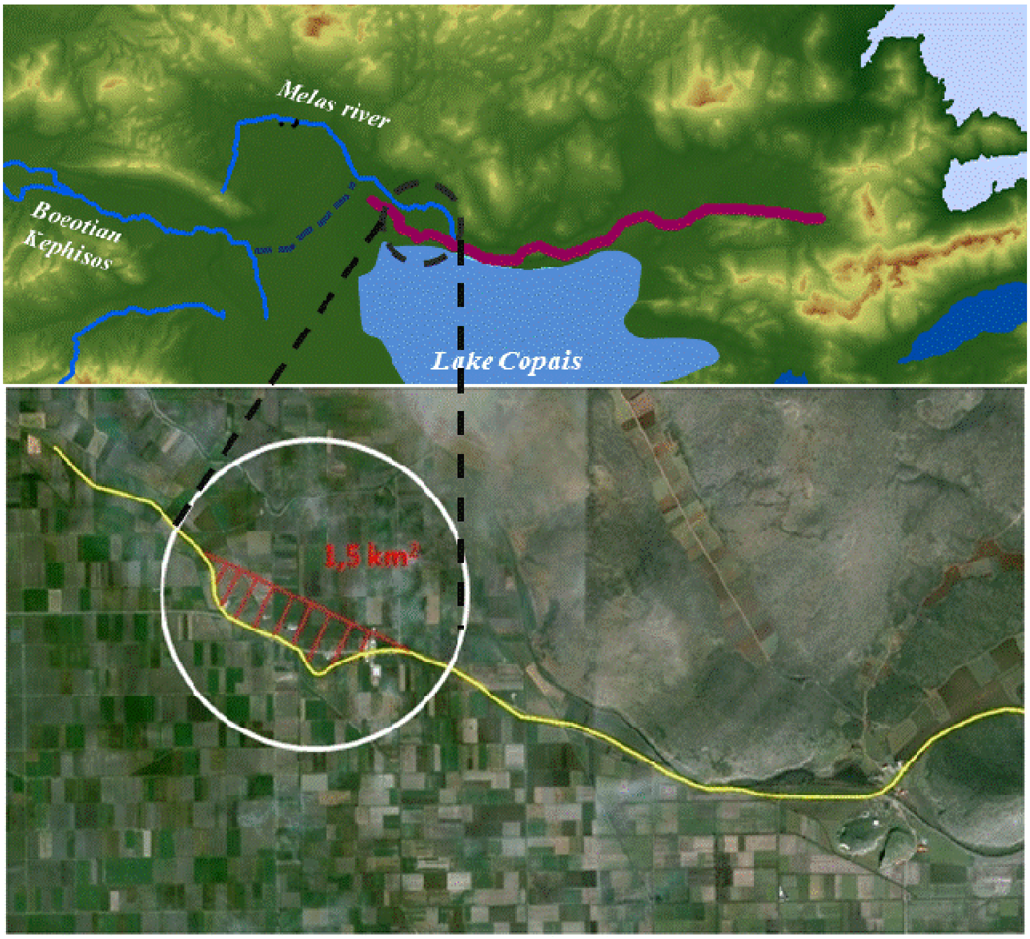

Fig. 6 Possible location of an artificial water cistern

4. Hydrosystem modeling and simulation

4.1 Model formulation

After the completion of the Minyan drainage system (and during the time it was kept in operation), Copais basin was divided (as mentioned in chapter 3.2.1), into two parts: one at the north of the levee and another at the south of it. The northern part was flooded by the combined water supply of Boeotian Kephisos and Melas rivers, while most of the southern part was partially reclaimed. Still, less important rivers and torrents (such as Erkyna, Pontzas and Lofis) outpoured into the southern part.

In order to evaluate several aspects of the hydrosystem (the size of the area that Minyans managed to drain, lake extent etc), historical time series of the most important hydrological processes have been examined. In Table 1 the mean monthly values of the main components of hydrosystem are presented (monthly river discharges, irrigation needs, precipitation, evaporation).

Table 1 Mean monthly values of main hydrosystem components (Eystatiadis et. al 2004)

	$Qkif_n$ (hm^3)	**$Qmel_n$ (hm^3)**	**$Qepl_n$ (hm^3)**	**$Virr_n$ (hm^3)**	**$Qsink_n$ (hm^3)**	**P_n (mm)**	**E_n (mm)**
Oct	9.8	10.9	3.9	1.1	18.7	71.8	74.9
Nov	14.1	11.0	4.4		18.1	87.4	38.6
Dec	21.2	10.7	5.4		18.7	107.8	31.3
Jan	27.4	11.0	5.3		18.7	96.0	33.5
Feb	28.7	11.6	4.9		16.9	81.3	44.7
Mar	30.7	12.4	4.6		18.7	70.5	71.0
Apr	21.4	11.5	3.6	7.8	18.1	40.8	115.5
May	11.1	11.3	3.1	12.5	18.7	34.7	164.6
Jun	5.5	11.2	2.4	19.2	18.1	21.6	206.7
Jul	1.9	9.5	2.0	15.3	18.7	6.6	221.6
Aug	1.6	8.9	2.0	12.4	18.7	13.4	195.6
Sep	5.9	10.1	2.4	5.6	18.1	30.0	132.2
Year	179.3	130.1	44.0	73.9	220.8	661.9	1,330.2

In order to study the operation of the hydrosystem by the Minyans a hydrological model is developed and is presented in Appendix.

Using this model, several elements of the hydrosystem are considered or calculated in monthly basis, such as: (1) the discharges of the five rivers (Boiotikos Kephisos, Melas, Erkynas, Pontzas, and Lofis), (2) the irrigation needs, (3) the precipitation and lake evaporation rates, (4) the withdrawal from Copais lake in case that irrigation needs are not satisfied, (5) the discharge capacity of sinkholes, (6) the storage and area of Copais lake at the end of each month and (7) the storage of sinks lake at the end of each month

The operational rules of the hydrosystem are the following:

(1) A portion of the monthly discharges of Boiotikos Kephisos and Melas flow to Lake Copais and the remaining water is diverted to the sinkhole area.

(2) The storage of the lake which is formed in front of the sinks at the end of the month is calculated considering the discharge capacity of sinkholes

(3) The irrigation needs are fulfilled by the remaining monthly discharges of Boiotikos Kephisos and Melas rivers and from the total monthly discharges of Erkynas, Pontzas and Lofis streams.

(4) In case that the river’s discharges are less than the irrigation needs, a withdrawal from lake Copais was performed

(5) The storage of lake Copais is calculated considering the hydrological balance of the area

The levels and the areas of the lakes were calculated through level-area-volume curves. These curves have been extracted using the Digital Terrain Model (DTM) of the area.

There are several uncertain points about the discharge data and the Minyans water needs, so estimations of statistical characteristic of the main components were used for the hydrosystem's simulation. The statistical behavior of historical data was examined and synthetic monthly time series for a 100 year period were generated. With this method we inspected several operational rules and their effect to lake's water level and fulfillment of the water demand.

The main task of the levee's construction was to divert large quantities of water to the sinks in order to lower the Copais lake level. Minyans had two main purposes: (a) to secure agriculture land which was located above 97 m and (b) to reclaim new land in the areas between 94 - 97 m. It is obvious that during many periods with permanent drought the lake lowered down to 92 m.

Even in case they achieved to exploit the sink capacity to the maximum point, the remaining discharges of the surrounding rivers were about 130 hm^3 (Table 1). This water was used for irrigation needs (about 75 hm^3) and the remaining directed to Copais' lake. Considering that the evaporation is double from the precipitation, the average net evaporation losses could close the balance of the lake.

There was not a stability of the lake, as during wet years the lake's level increased significantly and the neighboring areas which were cultivated, flooded. On the other hand, the accumulated water volume which could be stored near the sinks was limited, due to the topography. That water was stagnant and therefor bothersome for the inhabitants of the neighboring city of Gla. Also, the area between 95-96 m was vulnerable to floods, so maybe it was not cultivated.

4.2 Hydroystem's simulation

The main purpose was to examine different operational and constructional procedures that Minyans might have used to drain Lake Copais and gain more agricultural area.

Several operational cases were examined considering: (a) various sets of monthly portions of diverted water (the diverted water volume from the rivers is divided by the total river discharge), (b) sinkhole capacities and (c) initial conditions of the system (Appendix, Table 1).

The most important operational decision that Minyans had to take was the monthly water quantity which had to be diverted from Kephisos and Melas to the sinkholes. This monthly water volume was expressed as a portion of the total monthly discharge of the rivers. Five main cases were examined. Two with constant portions for all months and three with different portions for wet (October-March) and dry (April- September) periods. Cases 1 and 2 consider that the percentage of monthly discharges which is diverted to the sinkholes is 50% and 60% respectively. According to case 3 during the wet and dry period the 50% and 75% of the discharge is diverted to the sinkholes respectively. Finally these quantities are also considered as 60% and 40% (case 4) and 65% and 30% (case 5). Also for each case two sub cases (a and b) for different sink capacities (7 and 8 m^3/s) were examined.

Several components of the hydrological balance were calculated during each simulation, such as the volumes of the two lakes, the sink outflow and the withdrawal from the Lake Copais in order to cover irrigation needs. In Figure 7, the monthly time-series of three components (inflows, Lake Copais level, sinks' outflow) of the hydrosystem for a 100 year simulation period, are presented.

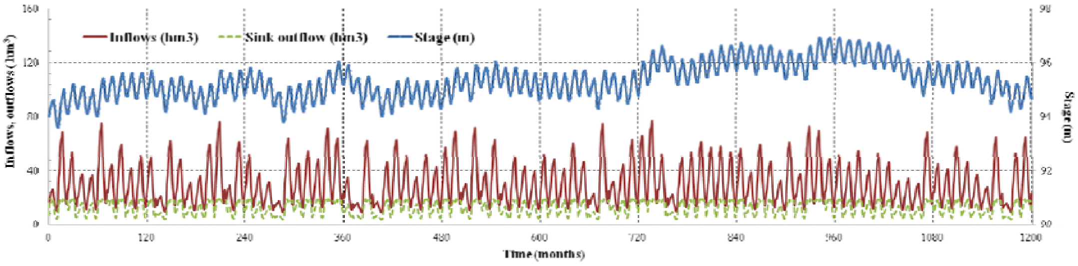

Fig. 7 Monthly timeseries of inflows (hm^3), level of Lake Copais (m) and sink outflow (hm^3)

In order to quantify the hydrosystem's operation, considering the previous cases, specific values were calculated from the 100 year simulated time series. Specifically were examined:

(a) The variation (maximum and minimum values) of Lake Copais level

(b) The percentage of the water that outflowed from the sinks, compared with the total sink capacity

(c) The maximum accumulation of water to sink area

(d) The maximum withdrawal from Lake Copais and

(e) The percentage of months that was necessary to use lake's water, to fulfill irrigation needs

The results of the simulation for these different cases are presented in Appendix (Table 2).

From these results we can conclude the following:

In case 1, the water volume of Boeotian Kifissos and Melas, fed the lake and the sinkhole area equally, during whole year. The Lake Copais level varied between 93.7 and 96.9 m, regardless the sinkhole capacity.

In case 2, the volume that diverted to the sinkholes increases (from 50 to 60 % of the rivers discharges) and the level of Lake Copais is strongly lowered and never exceeded the limit of 95 m. Although the sinks were exploited more, the water accumulation in the sinkhole area strongly increases. Taking into account that the sinkholes' lake can hold about 100 hm^3 according to case 2a sink area was be flooded. According to case 2b sinkholes capacity increased and the flooding of the area was be avoided.

In case 3, the volume that diverted to the sinkholes during irrigation period (April-September) increases from 50 to 75% of the rivers discharges and remains 50% (as in Case 1) during winter months. That operational rules lead to a slight increase of Copais level (maximum 95.2 m) related to case 2 and to a decrease of water accumulation at sink area (104 and 60 hm^3 for cases 3a and 3b). At the same time the water volume, which was extracted from Lake Copais (to fulfill irrigation needs), was increased, as the larger portion of summer river discharges was diverted to sinkhole area. According to this case more than one third of the months (36%) there was a need for water withdrawal. The greater necessary monthly volume was approximately 15.5 hm^3

In case 4, according to operational rules more water is transferred to Lake Copais during irrigation period (60% of the monthly river discharges) and less during winter period (40% of the monthly river discharges). These operational rules lead to: (a) a serious increase of Copais' level (exceeds the limit of 96 m) and (b) a serious decrease of water accumulation in the sinkhole area. At the same time water withdrawal from Lake Copais to fulfill irrigation needs, is decreased in a similar way to case 3. In this case for the 26.5% of the months there is a need for water withdrawal. The greater necessary monthly volume was approximately 12 hm^3.

Finally**, in Case 5,** the rules are similar to those of Case 4 but a little more water is given to Lake Copais during irrigation period (70% of the monthly river discharges) and less during winter period (35% of the monthly river discharges). In this case there is (a) no change in Lake Copais level, (b) a slight increase in water accumulation to sinkhole area and (c) a small decrease of water withdrawal from the Lake Copais.

4.3 Summary

- In order to keep the lake Copais under the level of 95 m a large amount of water has to be diverted into the sinkhole area.
- The operation of the sinkholes includes the control of the accumulated water in order to achieve the maximum exploitation of sinkhole capacity (especially in summer months) but the accumulation volume had to be limited down to100 hm^3.
- The withdrawal from the lake during irrigation period is inevitable according to all cases. That leads to the idea that some small quantities of winter discharges could be stored in small cisterns at the edges of irrigation areas in order to succeed irrigation under gravity.

- The need to construct works in order to remove more water from the sinkholes area is obvious. So, clean sinkholes must have been an important task and construction of the tunnel would be necessary.

4.4 Evaluation of sediments

It is obvious that nowadays the geomorphologic characteristics of the Copais lake area are not the same as 3000 years ago. The large amounts of sediments that were transferred during this period must have changed the bottom of the lake. In order to have a gross estimation of this parameter, a calculation of sediment transport was performed. We estimated the sediment transport using a formula developed for Greek basins (Koutsoyiannis and Tarla, 1987), which takes into account the precipitation regime and the geological formation of the area. A value of 500 t/km^2 was calculated for the area and we considered that about 1000 km^2 of the higher part of the basin were eroded. So a total volume of about 1500 *10^6 t of sediments must have been transported to the lower areas of the basin during the 3000 years period. The average sediment density was considered 1.2 t/m^3, so the total volume of the sediments is estimated to be 1250 hm^3. This volume covered the lower parts of the basin, including Lake Copais an area that is estimated to be 900 km^2. If the sediments distributed equally over the lowlands area an average increase of 1.4 m to the altitude after 3000 years is reasonable. The lake is located at a distance from the rivers and the sediments mainly deposited to the upper Kephisos basin, so we suppose that the lake area 3000 years ago was about 1 m lower than today.

5. Representation of system’s operation

Taking into account the sediments’ transport and the hydrological simulation of chapter 4, we attempted to represent hydrosystem’s operation (Figure 8). The key challenge for the Minyans was to secure the cultivation of flood plains above 97 m and to reclaim the areas between 94-97 m. The area between 97 and 100 m is about 40 km^2 and the reclaimed area between 94-97 m is about 63 km^2. Therefore, the total area available for cultivation is estimated to be more than 100 km^2. To reclaim land from Copais Lake, Minyans constructed the levee in order to divert huge amounts of river discharges into the sinkholes’ area.

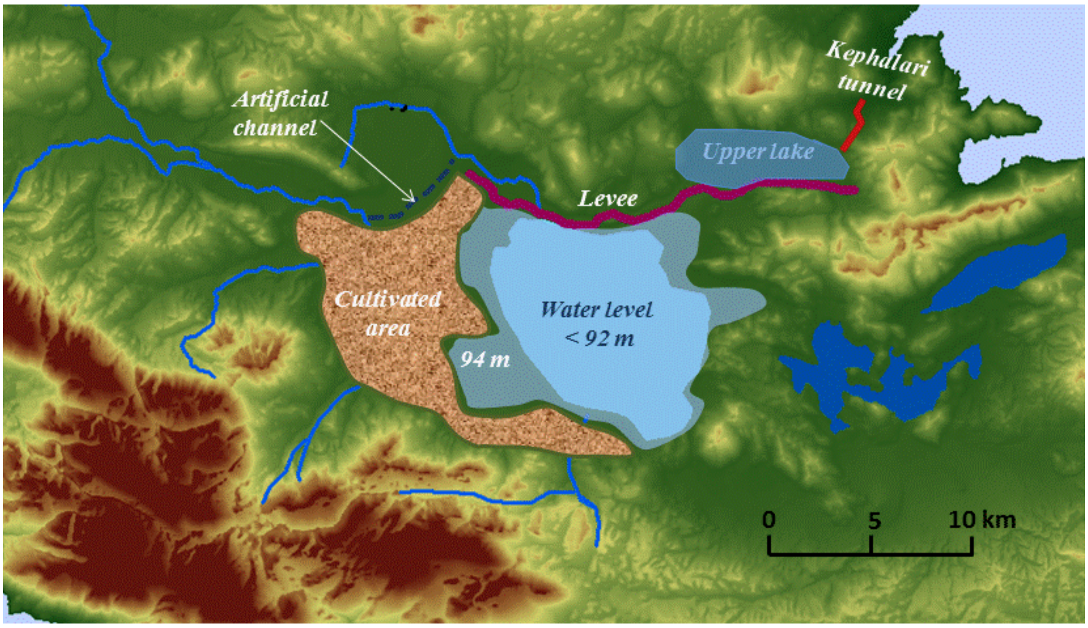

Fig. 8 The hydrosystem as it was configured by the Minyans.

The results of the hydrological simulation prove the difficulty of the complete drainage of the lake. Although during long periods of hydrological drought the lake recessed significantly, it rarely drained totally. On the other hand, it is possible that during long wet periods some areas around 94-95 m were temporarily flooded. This result is compatible with the works of Rachet (1993) and Schnitter (1994). Both studies come to the conclusion that Lake Copais had never been completely drained by the Minyans.

Minyans continuously struggled to keep water level of both lakes as low as possible. The main operational decision was the amount of water, which had to be diverted towards the sinkholes. According to previous operational cases which were examined in chapter 4, operational rules that could achieve this task might have been applied. Additionally, Minyans could change the operational rules in specific time periods in order to improve the performance of the system as it is described in chapter 4.

An important factor of the system performance was the capacity of the sinkholes which is strongly relevant to the accumulation of water towards the sinkholes' area. Also, the permanently reclaimed areas, were analogous to the sinkhole capacity. It was the reason why the Minyans (or their descendants) made efforts not only to clean regularly the sinkholes but also to increase the amount of water that could be extracted from the hydrosystem. To complete that task they constructed the tunnel at Kefalari.

Another issue that came up from the hydrosystem simulation is the possibility of existence of small cisterns, which were used during irrigation period. In all cases of chapter 4, there is a deficit between the summer water quantities that which were used for the cultivation areas and the irrigation needs. Even if the rivers' summer discharge was totally available for irrigation, water deficit is possible. In the cases that were examined, this deficit was quantified using two indices: (a) the maximum withdrawal from the lake and (b) the percentage of the months during which a withdrawal from the lake was necessary, considering that cisterns did not existed and the deficit had to be covered using water from Copais Lake. In all cases that we examined, the maximum withdrawal from the lake was between 11-15.5 hm^3 and the time percentage with such a need was between 25-36 %. Although the recent excavations have not revealed specific clues about the existence of cisterns, that hypothesis has to be further investigated. An area besides the levee was identified, using a detailed digital elevation model, and it is worth a further research.

Finally, this study indicates that water level variations (reflecting wet and dry periods) were essential for prosperity of the Minyans. As a result, they constructed these extensive hydraulic works, to control their aquatic environment. Minyans' reclamation project is admirable as it is the most ancient in the world and equals to modern ones.

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APPENDIX

1. Hydrological Model Equations

For each monthly time step *n* the following components of the hydrosystem are defined:

- $Qkif_n$, the monthly discharge of Boiotikos Kephisos river in hm^3
- $Qmel_n$, the monthly discharge of Melas river in hm^3
- $Qepl_n$, the total monthly discharge of Erkynas, Pontzas and Lofis rivers in hm^3
- $Qsink_n$, the monthly discharge capacity of sinkholes in hm^3
- $Virr_n$, the monthly irrigation needs in hm^3

- $Wcop_n$, the monthly withdrawal from Copais lake in case that irrigation needs are not satisfied in hm^3
- $Skop_n$, the storage of Copais lake at the end of the month n in hm^3
- $Ssink_n$, the storage of sinks lake at the end of the month n in hm^3
- $Acop_n$, the mean monthly area of Copais lake in km^2
- P_n, the monthly areal precipitation in mm
- E_n, the monthly areal lake evaporation in mm

The operational rules of the hydrosystem are the following:

A portion a_i of the monthly discharges of Boiotikos Kephisos and Melas discharges flow to Lake Copais and the remaining water is diverted to the sinkhole area. The storage of the lake formulated in front of the sinks at the end of the month is given by the equation

$$Ssink_n = Ssink_{n-1} + (1 - a_i) * (Qkif_n + Qmel_n) + P_n * Asink_n - E_n * Asink_n - Qsink_n \quad (1)$$

The irrigation needs are satisfied by the remaining monthly discharges of Boiotikos Kephisos and Melas rivers and from the total monthly discharges of Erkynas, Pontzas and Lofis streams. In case that the river discharges are less than irrigation needs a withdrawal from lake Copais is performed.

The withdrawal from Lake Copais is given by the equation

$$\text{if } a_i * (Qkif_n + Qmel_n) + Qepl_n \geq Virr_n \qquad Wcop_n = 0$$

Else: $Wcop_n = Virr_n - a_i * (Qkif_n + Qmel_n) - Qepl_n$(2)

$$Wcop_n = \begin{cases} 0, & a_i * (Qkif_n + Qmel_n) + Qepl_n \geq Virr_n \\ Virr_n - a_i * (Qkif_n + Qmel_n) - Qepl_n, & a_i * (Qkif_n + Qmel_n) + Qepl_n < Virr_n \end{cases} \quad (2)$$

The storage of lake Copais at the end of the month is given by the equation

$$Scop_n = Scop_{n-1} + a_i * (Qkif_n + Qmel_n) + Qepl_n + P_n * Acop_n - E_n * Acop_n - Virr_n \quad (3)$$

2. Simulation procedure

The hydrosystem was simulated for fixed initial conditions and for two different sink capacities that are presented in Table 1

Table 1 Hydrosystem fixed initial conditions and two different sink capacities

Initial volume of sinks lake	50 hm^3
Initial volume of Copais lake	288.6 hm^3 (level +94 m)
Sink capacity	Case a: 7 m^3/s Case b: 8 m^3/s

Table 2 Operation of the hydrosystem for different cases

Case	Maximum level of Copais lake (m)	Minimum level of Copais lake (m)	Sink capacity used (%)	Maximum sink accumulation (hm^3)	Maximum withdrawal from lake (hm^3)	Months with withdrawal from lake (%)
1 a	96.9	93.6	69.8	58.3	13.0	27.6
1 b	96.9	93.6	61.3	50.0	13.0	27.7
2 a	94.9	92.2	82.5	129.9	14.0	30.4
2 b	94,9	92.2	73.1	76.1	14.0	30.4
3 a	95.2	92.3	81.3	104.3	15.5	36.4
3 b	95.2	92.3	71.8	59.9	15.5	36.4
4a	96.1	93.3	73.6	81.3	12.0	26.5
4 b	96.1	93.3	64.7	66.9	12.0	26.5
5 a	96.1	93.4	73.1	95.1	11.0	25.5
5 b	96.1	93.4	64.3	81.2	11.0	25.5