



Can Reservoirs Combine Flood Protection and Irrigation? A Case Study for Larissa City, Greece

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Abstract

Urbanization and climate change have put large segments of the population at risk of heavy rainfall, river, and coastal flooding. In order to keep up with sustainable development, cities need to protect flood-prone areas, which require significant investment in green infrastructure solutions. Determining which flood protection to fund typically involves an analysis of key costs and benefits. The importance of implementing green infrastructure for flood protection is widely accepted. This research combines a series of structures in order to decrease or eliminate flood effects on the surrounding area of Larissa city, Greece. At the same time, that combination of installation can partly solve the irrigation water shortage during summer months at a certain region of prefecture of Larissa. Thus, a powerful pumping station is proposed to be installed at the riverside of Pinios outside of Amygdalea village, capable of pump almost 5 million m³ per day. The pumped water is going to fill a large reservoir next to the pumping station, which is going to be connected to a long network of irrigation canals. As a result, floods could be avoided and the excess water could irrigate thousands of acres throughout the year.

Keywords Flood control · Levees · Dam · Self-closing barriers · Pumping stations · Water reservoirs · Flood management

1 Introduction

Natural disasters and flood events are part of nature. They have always existed and will always exist. With the exception of some floods caused by dam failures and landslides, floods are climatic phenomena that are influenced by geology, topography, relief, soil, and vegetation conditions. Meteorological and hydrological processes can

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occur rapidly or slowly, resulting in flash floods or more predictable slow-moving floods (fluvial floods). Societies are becoming more vulnerable to natural disasters, although floods are a natural phenomenon, conditions across the basin have changed significantly due to human activities and human intervention in natural processes. At the same time, risks and vulnerabilities in flood-prone areas are steadily increasing.

Floodings seem to be the worst socio-economic and environmental threat. During extreme flood situations, it can cause damage to properties and human losses. The great infrastructure development combined with urbanization and overpopulation may emerge crucial situations during floods, if there are no provisions and precautions. According to Rosenthal and Hart (1998), researchers which are concerned with natural disasters should be precise and reliable with their warnings and information about countermeasures that should be taken [1].

Many studies have focused on the design/operation of rainwater pumping stations and capacity/location of storage tanks. However, no previous research has been conducted on the coordinated operation of pumping stations and storage tanks. Collaborative operations are beneficial because pumping stations and tanks are part of the catchment system and their operations can significantly affect water levels and flooding in the drainage network. This study involves the surrounding area of Larissa, Greece, which is prone to large-scale floods and the combined construction of a pumping station and a reservoir. The main point of this research is to provide obvious benefits of such facility, while taking under consideration the climate of the area according to structural data of the reservoir tank and the operational potential of the pumping station.

2 Historical Background

During the last decades, the recurrence of extreme flood events has increased around the world, particularly in Europe. There are three different kinds of floods: coastal floods, fluvial (river) floods, and flash (surface) floods [2, 3].

Some of the largest flood events that have happened around the world after the 1990s include the 1993 US Great Flood at IOWA which occurred after 20 days of precipitation [4], the 1997 Red River flood in Minnesota that caused 3.5 billion dollars damages [5], the 2006 Surat flood event where 150 people were killed [6], the 2010 Pakistan floods that caused 1985 casualties and 43 billion dollars damages [7], and the 2021 Turkey floods where 81 people lost their lives, to name but a few [8] (Figs. 1 and 2).



Fig. 1 Floods of IOWA 1993 (left), Red River Minnesota 1997 (middle), and Surat 2006 (right) [9–11]



Fig. 2 Floods of Pakistan 2010 (left) and Turkey (right) 2021 [12, 13]

Similarly, flood events that happened in Greece and more specifically in the surrounding area of the city of Larissa during the last 30 years include the 1994 events in Karditsa and Larissa where thousands of acres were covered in water and a lot of villages were evacuated; the 2010 large floods on the surroundings of Gyrtioni, Larissa; the 2018 and 2020 flood that took place after a period of heavy precipitation and destroyed thousands of acres with crops; and lastly, the 2022 flood incident which severely affected the North and Northwest agricultural areas and districts of Larissa [14] (Figs. 3 and 4).

On 5–7 September 2023, Thessaly was hammered by a once-in-a-1000-year weather event (Storm Daniel) where extreme rainfall caused extensive floods in some cases irrevocably affecting population, agriculture, livestock, and small industries. The water volumes were 700 mm in 48 h or 3.7 billion m³ of rainwater. The estimated cost of damage is over 2 billion euros [20] (Fig. 5).

Primary flood effects include the following: streams and rivers reach high water levels and velocities during flood events, and as a result, large particles such as rocks, houses, and automobiles are being transported and creating vast amounts of sediments that exist for a long period. Great and violent moving quantities of water may cause extended erosions under bridges and levees making them to collapse. Buildings and structures are subjected to great damages either with minor or severe flood incidents. Agriculture and livestock sectors undergo great havoc since croplands and cattle may be annihilated. The great concentration of debris, garbage, and toxic pollutants is very high after flood events, igniting health hazard situations [22].

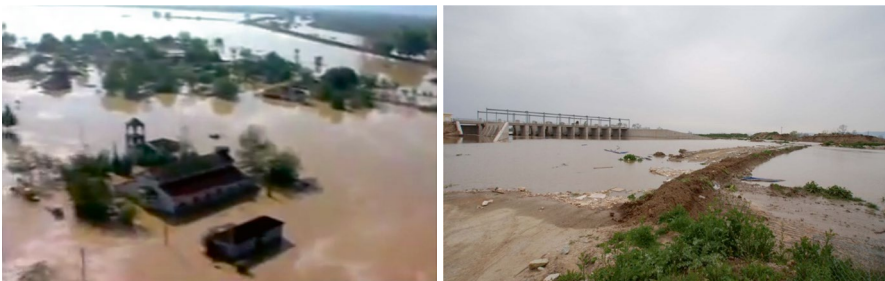


Fig. 3 Flooded area of Metamorfofi Karditsa (left) and Gyrtioni dam (right) [15, 16]



Fig. 4 High level of Pinios river (left), flooded area of Gyrtioni (middle), and flooded tributary of Pinios through Larissa city [17–19]

3 Methodology

3.1 Flood Prevention Techniques

Fifteen percent of the global population is expected to live in flood-prone areas, and about 90 million people were affected by coastal river floods during the last three decades. Flood countermeasures are the ultimate way in order to armor areas and cities against extreme flood events. Self-closing flood barriers (SCFB), diversion canals, dams, and river defenses are methods for flood prevention.

3.1.1 Self-closing Flood Barriers

It is a unique and effective flood defense system to protect people and properties from floods which are caused by heavy rainfall, gales, or rapid snow melting. That system has been developed in the Netherlands in order to protect areas from extremely high water level. It is a simple and intelligent idea which uses the pressure from the approaching flood water to automatically raise the barrier. The mechanism of those barriers does not need energy source to function, not even manpower. It combines low maintenance with a long life of up to 80 years. The barriers stay hidden below the surface and rise only when reach a critical level. Then, the wall rises before the flood water enters the city and remains in place until the water level subsides [23] (Fig. 6).



Fig. 5 Flooded areas of Thessaly (Palamas area, left) (Trikala area, right) [21]



Fig. 6 Self closing flood barriers [24]

3.1.2 Diversion Canals

The purpose of diversion canals is to maintain the river's mainstream in low level. A diversion canal's segment, which imposes the maximum flow that may be diverted, has a hydraulic function limit. It is reasonable to think about diverting flow that corresponds to common floods, but it is not advisable to think about diverting unusual or extraordinary floods, unless the diversion canal ends up at sea [25] (Fig. 7).

3.1.3 Dams

The purpose of a dam is to store water for several reasons: flood control, water supply for people or livestock, and irrigation, to name but a few. A dam can hold sediments instead of feeding downstreams or shores. They provide a perfect habitat for aquatic species, and furthermore, they decrease or extinct flood effects [27] (Fig. 8).

3.1.4 River Defense

Levees and other flood protection structures, including urban flood walls and flood protection dams, have been playing a key role in reducing the risk of such situation. The majority of levees and protection systems are found along rivers, but a significant fraction of levees has been built along the coasts and estuaries.

Levees are predominant earth structures (also called dikes or digues) whose primary objective is to provide protection against fluvial and coastal flood events along coasts, rivers, and artificial water waves. Levees form part of flood defense systems that may also include flood walls, pumping stations, gates, natural features, and



Fig. 7 Red Bluff Diversion Dam and canal [26]

other associated structures. In many cases, levees have been built up and extended over decades or sometimes for centuries [29] (Fig. 9).

3.2 Proposed Methodology

Our proposed methodology includes a flood control pumping station (FCPS) (Fig. 10) and a flood restrain reservoir (FRR). It is suggested the construction of a



Fig. 8 The Douglas dam [28]



Fig. 9 Levee Portsea Island [30]

powerful pumping station on the upper area of Pinios River and outside of Amygdalea village. Its pumping potential could reach the charge of $180,000 \text{ m}^3/\text{h}$ with a maximum manometric height of 9 m [31].

Fig. 10 Pumping station at Megas River Karditsa [32]



The construction of a reservoir (Fig. 11) is proposed for the second part of the project in order to receive the excess flood water volume. The reservoir capacity is being calculated between 4.5 and 5.0 million m^3 , and it is supposed to be installed next to the pumping station. The quantity of the stored water may be used for irrigation during the dry periods of the year.

The area of research implicates the flood restrain facilities and the area that is prone to floods. Flood protection installations are supposed to be located outside of Amygdalea village where only croplands exist, and it has a mean altitude of 76 m. On the other hand, the recently flooded area is located between Larissa and Koulouri villages, and it consists of cropland and a few small livestock farming businesses [34] (Figs. 12 and 13).

The main element of the prefecture of Larissa is the Pinios river which enters the plains from the Kalamaki region flowing through Thessaly and up to the Aegean Sea. Neochorititis, Lithaios, Portaikos, Pamisos, Kaletzis, Sofaditis, Farsaliotitis, and Enipeas river merge with Pinios a few kilometers outside of Amygdalea and that fact creates overflow conditions during extreme rain periods. The mentioned river section is the continuity of the Paleolacus-Trive environment with large meanders. Except for the water volume that Pinios river receives from the confluence with Enipeas, a lot of karstic springs send water to the mainstream. It mainly consists of Alpine formations under the quaternary formations (mostly marbles, gneisses, and schists).

The hydraulic characteristics of Pinios river at this location include a mean water flow of $54 \text{ m}^3/\text{s}$, a maximum flow of $1420 \text{ m}^3/\text{s}$ during a 25-year flood event, and a river depth up to 4 m just before a flood incident takes place [35].



Fig. 11 Water reservoir at Kalamaki, Thessaly, Greece [33]



Fig. 12 Amygdalea area outside Larissa [32]

The characterization of an area’s climate is crucial for the dimensioning and construction of flood protection infrastructures. For that reason, temperature and precipitation data of the 2022 year were evaluated and combined with Emberger-Sauvage index (Eq. 1) [36].



Fig. 13 Flood zone between Larissa and Giannouli [32]

$$Q = \frac{1000 \times P}{\left(\frac{M+m}{2}\right) \times (M - m)} \quad (1)$$

where: P : total annual precipitation, m : mean lowest temperatures of coldest month in kelvin, M : mean highest temperatures of warmer month in kelvin

According to meteorological services, the total annual precipitation of 2022 was 403.3 mm, the mean temperature of the lowest values of the coldest month was 274.75 K, while the mean temperature of the highest values of the warmer month was 307.55 K. Applying Eq. 1, the value of Q is 42.23, and according to the diagram, the area's climate is characterized as semidry.

In terms of comparison, the climate of previous decades is being characterized according to the same methodology. For that reason, the mean values are being used from 1981 to 2010, and consequently, the mean annual precipitation has been calculated as 412 mm; the mean temperature of the lowest values of the coldest month was 273.9 K, while the mean temperature of the highest values of the warmer month was 306.6 K. Applying Eq. 1 once more, the value of Q is 26.68, and according to the diagram, the area's climate is characterized as arid.

Taking under consideration both climate categorizations, it is generally accepted that semidry and arid climates are characterized by low rainfall, high wind velocity, intense solar radiation, and high evapotranspiration. Flood events are more common in such environments due to dry soils not being able to absorb heavy and scarce rainfalls. The agriculture in those regions faces versatile threats in terms of deterioration in natural resources and decrease in productivity. Alternatives in cropping way, irrigation, and mixed farming should be adopted in arid and semidry areas [36].

3.2.1 Dimensioning of Pumping Station

The criterion that affected mostly the dimensioning of the pumping station was the flooded area during the last flood event in 2022 on the outskirts of Larissa. During that event, the water covered an area of 3.5 km² with an average depth of 1.5 m which corresponds to almost 5.5 million m³ of river water. The history of such phenomena showed that their duration was up to 3 days, and the peak of the situation was during the first 24 h. Thus, the pumping station should be able to pump 80% of the above-mentioned flood volume that is 4.5 million m³, during the first day. In order to make the optimal selection for pumps, the DP pumps (Fig. 14) are being used (Fig. 15).

Taking under consideration the maximum head (H), it is concluded that for that specification, the maximum flow rate (Q) of the pump is 16,200 m³/h (Fig. 16). It is selected to install ten pumps of that size with a maximum flow rate of 3.9 million m³/day. In addition, reserve pumps should be installed with regard to reach the flow of 4.5 million m³/day. Thus, four reserve pumps with flow rate 7200 m³/h each are selected to be installed. The overall pumping potential of the station is 3.9–4.6 million m³/day [37].

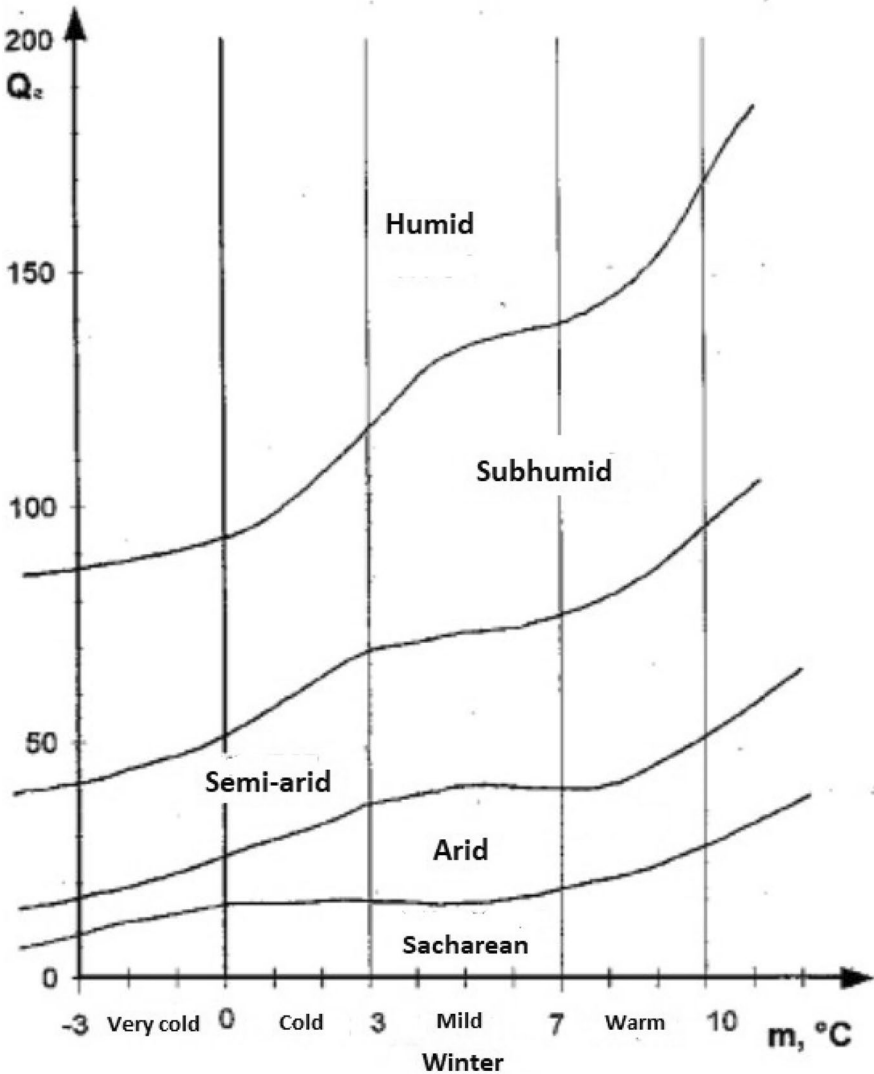


Fig.14 Emberger-Sauvage diagram [36]

In combination to the pumping station, a water reservoir is suggested to be installed next to the station in order to receive the water discharge. The proposed capacity of the reservoir is ± 5.0 million m^3 , but the final capacity will be calculated after the following dimensioning [34].

Firstly, the crown of small embankments fluctuates from 4 to 5 m, so a 4-m crown is selected for our case (Fig. 17). Considering the height (H) of the embankment to be 6 m, the base is calculated through the following equation (Eq. 2) [34]:

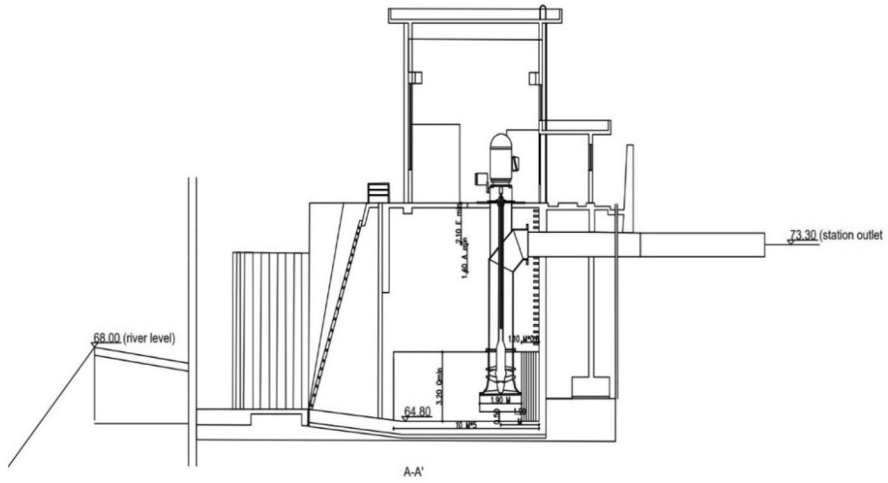


Fig. 15 Indicative schematic section of the proposed pumping station

$$L = 10 + \frac{3}{5} \times H \text{ (m)} \tag{2}$$

Similarly, the width of the clay core at the base of the embankment follows Eq. 3 [34]:

$$B = 6 + 0.2 \times H \text{ (m)} \tag{3}$$

Summarizing, the geometrical characteristics of the embankment are as follows [34]:



Fig. 16 DP Pump performance diagram (head/capacity) [37]

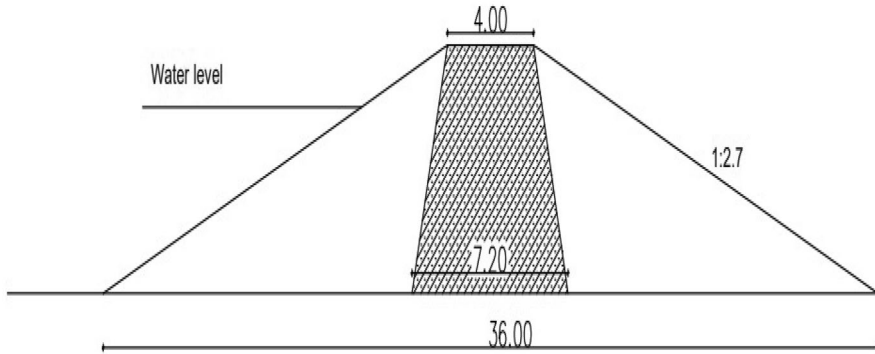


Fig. 17 Indicative schematic section of the embankment of the proposed reservoir

- Crown, 4 m
- Base, 36 m
- Clay core width, 7.2 m
- Slope inclination, 1:2.7

In order to finalize the dimensioning of the embankment, the safety factor should be greater than 1, and it is calculated as below:

The shear strength (C_u) of the material of the embankment is 50 kpa; the specific weight (γ') of the material is 20 kN/m³, but due to the upward force of the water, the final weight (γ') would be 10 kN/m³. It is specified that the area (A) of a slice for the embankment with the surface is 120 m², the radius (R) of the sliding surface is 14.87 m, the length (L) of the sliding arc is 31.66 m, and the distance (x) between the center of the sliding circle and the gravitational center G is 9.60 m [6].

Safety coefficient of the embankment is calculated by Eq. 4 (Fig. 18):

$$F = \frac{M_r}{M_o} \tag{4}$$

where:

$$M_r = C_u \times L \times R$$

$$M_o = W \times x = \gamma' \times A \times x$$

The safety factor is:

$$F = \frac{23539.21}{11520} = 2.04 > 1$$

Precipitation and evapotranspiration are significant parameters or the function of the reservoir since the water level should be within limits, meaning that neither it should stay without water nor the surface of water should overcome the crown of the embankment [38].

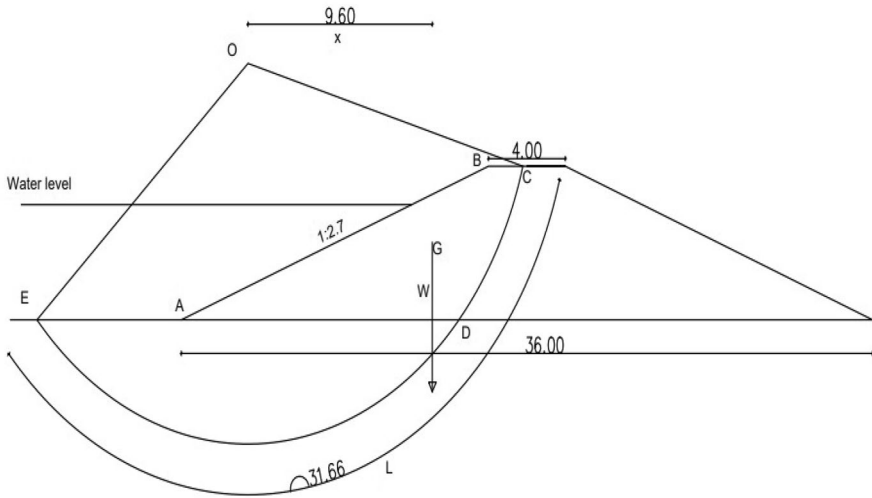


Fig. 18 Safety coefficient schematic section

The Harbeck equation (Eq. 5) is a simple way to examine the evapotranspiration of water from the surface reservoir [39]:

$$E = 1.46 \times 10^{-4} \times A^{-0.05} \times u_2 \times (e_s \times e_2) \text{ (cm/day)} \tag{5}$$

where:

- A, surface of reservoir (km²) (1.153km²).
- u₂: wind velocity (cm/s) (J, 123.33; F, 159.44; M, 180; A, 169.72; M, 169.72; J, 210.83; J, 210.83; A, 195.55; S, 175; O, 138.89; N, 97.78; D, 97.78 cm/s)
- e₂: actual vapor pressure (mb) (J, 7.115; F, 7.388; M, 8.625; A, 10.862; M, 14.074; J, 8.477; J, 16.965; A, 17.277; S, 15.603; O, 13.122; N, 10.360; D, 7.964 mb)
- e_s: standard vapor pressure (mb)

Equation 6 of relative humidity can be rewritten in terms of calculating actual vapor pressure e₂ [39]:

$$e_2 = \frac{h_r \times e_s}{100} \text{ (mb)} \tag{6}$$

where:

- h_r: relative humidity % (J, 79.9; F, 74.8; M, 72.2; A, 68; M, 60.6; J, 48.8; J, 46.2; A, 49.9; S, 59.4; O, 70.4; N, 79.5; D, 82.3%)
- e_s: standard vapor pressure mb (J, 8.905; F, 9.877; M, 11.947; A, 15.974; M, 23.225; J, 17.372; J, 36.721; A, 34.623; S, 26.267; O, 18.639; N, 13.031; D, 9.676 mb)

The Magnus-Tetens equation (Eq. 7) provides the standard vapor pressure e_s [40]:

$$e_s = e_{s0} \times e \times \left(\frac{a \times \theta}{\beta + \theta} \right) \text{ (mb)} \tag{7}$$

where:

α , 17.38 (over a surface of water)

β , 239 C (over a surface of water)

θ : mean temperatures °C (*J*, 5.3; *F*, 6.8; *M*, 9.6; *A*, 14; *M*, 19.9; *J*, 15.3; *J*, 27.5; *A*, 26.5; *S*, 21.9; *O*, 16.4; *N*, 10.9; *D*, 6.5 °C)

The precipitation volume could easily be calculated by multiplying the annual precipitation by the top surface of the reservoir [34]:

$$V_{\text{rain}} = P_{\text{annual}} \times A_{\text{reservoir}} \tag{8}$$

where:

P, 0.425 m

A, 1.153 km²

Finally, the water balance of the water is [32]:

$$V_{\text{water}} = V_{\text{F}} - V_{\text{evaporation}} + V_{\text{rain}} \tag{9}$$

where:

V_{rain} , 496963 m³

V_{evap} , 825234 m³

$$V_{\text{F}} = \frac{h}{6} \times [A \times b + a \times B + 2 \times (a \times b + A \times B)] = 5145522 \text{ m}^3 \tag{10}$$

A, 1230 m (length at the top of reservoir)

B, 950 m (width at the top of reservoir)

a, 1214.29 m (length at the bottom of reservoir)

b, 934.29 m (width at the bottom of reservoir)

h, 4.50 m.

The function parameters of reservoir include a quantity of water between 4.3 and 5.6 million m³ and water level between 3.8 and 4.9 m that is less than 5 m which is the upper safety limit inside the reservoir.

A series of common floods on the surrounding area of Larissa city showed that the highlighted area is the most affected by floods. The indicated area is about 5.5 km², and the average water level reaches 1 m during flood events (Fig. 19).

A secondary use of the stored water inside the reservoir is for the irrigation of the croplands which are located around Platanoulia, Dendra, and Giannouli through a network of irrigation canals. There is a double profit for that area since not only it may cover a percentage of the irrigation needs but also the irrigation canal can increase the potential capacity of a flood flow. Assuming that the constructed length of those irrigation canals could be 20 km, with a trapezoid geometry, as it is suggested, the base is 4 m, small base is 2 m, and depth is 2.50 m. The total potential of that network could be up to 150,000 m³.

Paschalis E. (2016) studied the needs for irrigation water for 10,000 acres of crop fields which are divided as 60% cotton, 20% corn, lucerne 20%, and 10% industrial tomato. Cotton, corn, and industrial tomato were going to be irrigated with a drop-by-drop system, while lucerne was going to be irrigated with watering nozzles (artificial rain). After evapotranspiration of crop fields, precipitation, and water loss,

according to irrigation system, were taken under control, he concluded that irrigation water needs would be up to 5.5 million m^3 , for a reference period of 20 years. Comparing the suggested reservoir at Amygdalea with the reservoir of Paschalis E. research, one could clearly perceive that the quantity of water inside the reservoir could cover the needs in irrigation water for almost 10,000 acres, which is 1/3 of the area among Agia Sofia, Dendra, Giannouli, and Larissa [34].

4 Results

According to this study, it is proved that a powerful pumping station has the potential to decrease or eliminate flood incidents around a city. In our case, a pumping station is capable of pumping up to 4.6 million m^3 of water per day. It consists of ten main pumps with peak flow of 16,200 m^3 /pump and four secondary pumps with peak flow 7200 m^3 /pump. Both kinds of pumps would have a manometric height of 9 m.

The pumped water would channel to a large reservoir that is capable of withdrawing up to 5.6 million m^3 of river water. The above quantity is equal to the flood water volume during the last flood incident in Larissa in 2022. The geometric characteristics of the embankments of the reservoir include a 36-m base, a 4-m crown, and a 6-m height, which covers an area of 1.26 km^2 .

The stored river water is going to be used for irrigation during the dry periods of the year, which, according to Paschalis E. research, it is able to cover the needs in irrigation water for almost 10,000 acres of crops. The prementioned crop fields are supposed to consist of 60% cotton, 20% corn, 20% lucerne, and 10% industrial tomato.



Fig. 19 NE area of Larissa which is prone to common floods

5 Conclusions

Summarizing this research, two different methods were combined in order to achieve flood protection and storage of water for the purpose of irrigation during dry periods or not. A powerful pumping station has been theoretically installed on the upper area of Pinios river outside of Amygdalea village which is capable of pumping up to 4.6 million m³ of water per day, with a maximum manometric height of 9 m. The suggested pumping station includes ten plus four vertical pumps with a maximum flow of 180,800 m³/h.

The above-mentioned pumping station is going to supply with water a large reservoir which is supposed to be installed next to it. The capacity of the reservoir is suggested to be 5.6 million m³, with a maximum water level of 4.9 m. A total cost of those installations is estimated about 40 million euros.

In addition, a network of irrigation canals would be connected to that reservoir, being capable of distributing water in order to cover the irrigation needs of 10,000 acres with different crops. Furthermore, large stored bodies of water offer a natural habitat for birds and aquatic life which may help endangered species of the adjacent area to recover.

Finally, storing the excess water during a flood and using it for irrigation purposes could protect the underground wells of fresh water.

Author contributions Anna Zahidou and Ilias Boufikos provided all the needed data for this research. Nikolaos Alamanis provided help in terms of evaluating the stability of the embankment. Nikolaos Xafoulis provided help with the hydraulic parameters of the research. Evangelos Paschalis conceived the idea this research and along with Dimitri Tselio and Grigorio Papageorgiou processed all the data, applied the proper equations, reached out the results and finally wrote the article.

Declarations

Conflict of Interest The authors declare no competing interests.

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