DRAFT MASTER PLAN

WATER MANAGEMENT IN THESSALY

IN THE WAKE OF STORM DANIEL

How to Address Thessaly's Water-Related Agricultural Challenges

VOLUME I: FLOOD DEFENSE INFRASTRUCTURES

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Introduction

General outline

The Master Plan for flood management in Thessaly builds on the findings and conclusions of the fact-finding missions. A summary of the water-related issues is presented in this introduction, and based on the Fact Finding Report. The largest chunk of investments in flood management will be needed for defense infrastructures, which are presented in this volume ("VOLUME I: FLOOD DEFENSE INFRASTRUCTURES").

The Master Plan is founded on key assumptions with respect to priorities in the socio-economic development of Thessaly, aligning with both national and regional policies. These assumptions are presented in the Chapter 'Development benchmarks for Thessaly'. They serve as benchmark for the Master Plan and the proposed measures for flood management.

The Chapter titled 'Starting points flood defense infrastructure' presents main concepts and issues regarding the development of flood defense infrastructure. This includes an evaluation of costs and benefits, safety standards, prioritization, planning and design considerations, and the organizational aspects involved in their implementation.

The overall approach for the implementation of flood defense infrastructures in Thessaly is presented in the Chapter: 'Development strategy for flood defense infrastructure '. This chapter provides a comprehensive explanation of the decision-making rationale in light of the pressing need for immediate action. It outlines the overarching strategy for infrastructure development in Thessaly, emphasizing the strategic choices made to address the urgent situation at hand.

The subsequent chapters elaborate on measures for the various regions in Thessaly. The Chapter "Flood Management in Mountainous areas" presents flood defense measures for these areas, the Chapter "Flood defense infrastructure in the Trikala and Karditsa prefectures" deals with measures in the Trikala and Karditsa prefectures, the Chapter "Flood defense infrastructure in the Larissa area" with the city and surroundings of Larissa, and the Chapter "Flood defense infrastructure in the Lake Karla area" with the area of Lake Karla.

Integration of Master Plan in plans and policies

The Master Plan is not merely a standalone or rigid blueprint for flood management. The components herein need to be integrated into the existing and future Water Management Plans, Flood Management Plans, EU directives such as the EU Floods Directive (2007/60/EC). Additionally, alignment with development plans for the agricultural and livestock sectors is imperative for a wholistic and effective approach.

The strategies and measures proposed in this Master Plan are specifically intended to be integrated with the ongoing revision of the Government of Greece's existing Flood Management Plan. The updated plan is envisioned to evolve into a robust operational tool for comprehensive flood management. This includes the advancement and assessment of infrastructures, the establishment of early warning systems, and effective procedures for flood recovery.

Summary of the Fact Finding Report

Flood risk management and mitigation, henceforth referred to as "Flood management," constitute an integral component of overarching water management objectives. The overarching goal is to ensure the timely and location-specific availability of the appropriate quantity and quality of water, contributing to water security. Additionally, Flood management places emphasis on water safety, encompassing measures for protection against floods.

Integrated approach

A wholistic approach is key for effective water management and flood management. Integration, in this context, involves the seamless coordination of water usage across various social and economic sectors and sub-sectors during the planning and execution of interventions that may impact water resources. Integrated flood management is grounded in the utilization of three safety layers, which, when employed collectively, offer comprehensive protection against floods and work in tandem to minimize the impacts of flooding:

- Safety-layer 1: Prevention: Protective measures and infrastructure that prevent floods.
- Safety-layer 2: Governance: Integration of water management and spatial planning.
- Safety-layer 3: Crisis management / emergency measures: to minimize and mitigate the impacts of floods.

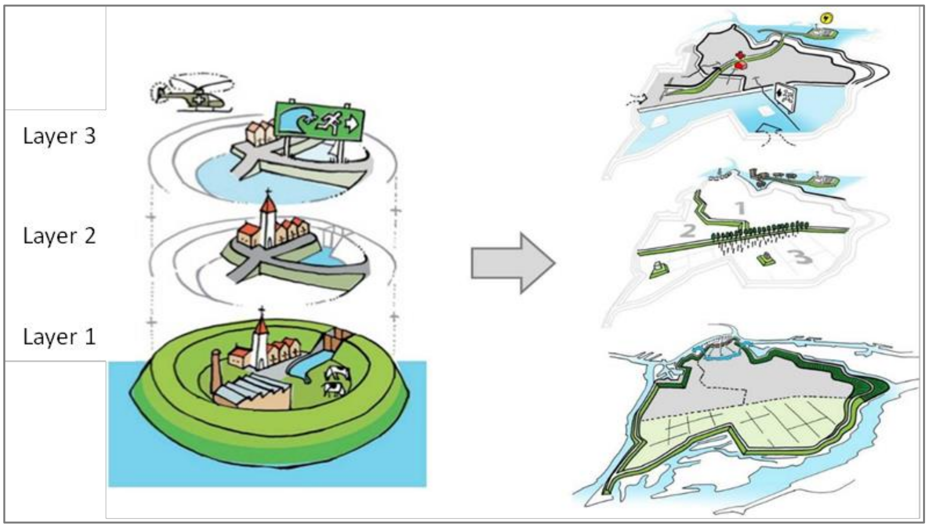


Figure 2: Concept of 3-layer safety model

The fact-finding missions unveiled shortcomings across all three safety layers, prompting the comprehensive approach of this Master Plan. Consequently, this plan tackles not only the technical and infrastructural shortcomings but also addresses issues within water governance to ensure an effective resolution.

Flood Management Plan

The existing Flood Management Plan (FMP) demonstrated a lack of functionality, as it did not contribute to the prevention or mitigation of the flood disaster in September 2023. Additionally, it was not utilized for flood prediction, warnings, or post-disaster recovery efforts. The new FMP for Thessaly must be designed as a genuine operational tool in flood management, strategically addressing all three safety layers to ensure comprehensive preparedness, response, and recovery.

The new Flood Management Plan (FMP) must incorporate guidelines for the development of flood defense infrastructure, as outlined in this Master Plan. Flood defenses should adhere to current safety standards and be customized based on the specific social, economic, and environmental functions of each area. Determining safety standards is predominantly a political decision, considering factors such as monetary returns (costs of measures versus reduction of damages). Non-monetary returns, including social security, environmental protection, biodiversity, and the safeguarding of historic sites, must also be taken into account. While it may not be feasible to protect all areas to the desired safety standards, setting priorities in spatial planning and socio-economic development is essential. In some instances, relocation of certain communities and businesses may be necessary.

Safety-level 1: Prevention

Given the recurrent nature of floods in Thessaly, it is a must to adapt preventive measures to include extreme, sudden-onset events such as medicanes, which are expected to increase both in frequency and severity due to global warming and climate change.

The fact-finding missions determined that river discharges from Storm Daniel resulted in "*flash floods*" characterized by minimal attenuation of surface runoff. The existing drainage networks, rivers, and streams are ill-equipped to handle the water volumes anticipated from future medicanes. The extent of flood damage was further worsened by inadequate maintenance and obstructions in floodplains, including debris, vegetation, and structures. Illegally constructed small dams, undersized bridges, culverts, offramps, among other factors, contributed to the challenges.

Essential to flood prevention is the need to reduce large water volumes by maximizing retention capacity. This involves addressing infrastructure shortcomings, enhancing maintenance practices, and mitigating obstructions in floodplains, ensuring a more resilient system capable of managing the impact of both regular floods and extreme events such as medicanes.

This Master Plan outlines a comprehensive set of intervention measures to achieve effective flood prevention, including:

- Moving dykes to greater distances from the rivers and streams (“*Give the rivers room*”);
- Constructing an intermediary floodplain by building secondary (higher) dykes and installing gates in primary (lower) dykes, enabling controlled inundation and subsequent drainage of the area between the two dykes;
- Deepening the riverbeds via dredging;
- Controlled inundation of designated areas;
- Nature based solutions aimed at restoring natural systems, such as temporary and permanent wetlands as well as riparian buffer strips and smaller water and sediment retention dams in upstream areas;
- Reservoirs and dams.

These intervention measures are designed to effectively reduce peak discharges and peak water levels by extending the duration of discharges. The augmentation of capacity in Thessaly's rivers, streams, and drains will primarily focus on critical points, especially those vulnerable points that were breached during Storm Daniel. In order to ensure optimal functionality, bridges and culverts that are no longer appropriately sized will need to undergo removal or remodeling, enhancing the overall resilience of the water management infrastructure.

Safety-level 2: Governance

In accordance with the European Framework Directives, water management in Thessaly must align with hydrological boundaries, specifically river basins. This necessitates the establishment of a River Basin Authority (RBA) for Thessaly endowed with executive powers. The RBA is tasked with implementing national water policies in the region and developing plans in line with national directives. Responsibilities also encompass all necessary water management activities, with the authority to administer water laws and by-laws. This approach transforms local organizations involved in land improvements, dam operations, municipalities, and prefectures into key stakeholders in water management. In order to ensure seamless coordination and integration, formal structures must be instituted to harmonize spatial planning, town planning, and water management efforts. This framework promotes a unified and efficient approach to water resource management within the context of river basins and aligns with European directives.

Safety-level 3: Crisis management

In order to enhance flood preparedness and response, the establishment of a 24/7 operational Early Warning Centre (EWC) is crucial. This center will continuously collect, analyze, and process relevant flood information from various weather monitoring services in real-time. Properly formatted data exchange is a fundamental element of this process, ensuring seamless communication.

This Master Plan outlines the necessary expertise and tools required for the EWC to provide accurate forecasts and assessments. A key role of the EWC is to effectively communicate with stakeholders in potentially affected areas. Additionally, a Central Management Unit (CMU) with authority and expertise is essential for imposing appropriate measures in the event of a flood disaster. A tiered emergency management organization is proposed, with coordinating units at different governance levels activated by the CMU based on the severity of the flooding event.

The EWC's protocols specify actions to be taken, including the coordination of emergency services such as fire brigades, police units, national guard (E.T.A.K.), hospitals, and contractors. Repositories for rescue operations and equipment capable of emergency repairs and debris removal should also be established to ensure efficient response and recovery efforts.

Development benchmarks for Thessaly

Socio-economic development

Over the past few decades, the Thessaly region has emerged as one of Greece's largest and most important agricultural hubs, contributing substantially to the national economy. It presently represents around 25% of Greece's overall agricultural output and contributes 5% to the country's Gross Domestic Product (GDP). Often referred to as the "*breadbasket*" of Greece, Thessaly plays a pivotal role in the nation's food production, generating 25% of its wheat and barley.

Moreover, Thessalian farmers play a crucial role in supplying the country's agricultural commodities, producing 30% of Greece's cotton, a third of chickpeas, lentils, and pistachios, 20% of the hay utilized in livestock farming, and a noteworthy 50% of all industrial tomato production. Before the occurrence of Storm Daniel, Thessaly held a dominant position in the country's livestock sector, accounting for approximately 16% of pork production, one-third of lamb and mutton, 50% of all cheese production, and nearly one-fifth of total milk production.

Thessaly has a cultivated land area of approximately 430,000 hectares, with approximately 250,000 hectares being sustained by irrigation practices. This marks a significant rise from the 1960s when only about 50,000 hectares were irrigated. The ongoing expansion of agricultural lands, coupled with substantial investments in irrigation and drainage infrastructure, has played a key role in the increasing agricultural productivity.

However, the developments in agricultural practices, particularly in the area of irrigated agriculture, have not been without challenges. The intensification of farming practices has put substantial pressure on water resources, leading to the structural overexploitation of groundwater resources. This underscores the need for a nuanced approach to sustainable water management as the region navigates the delicate balance between agricultural expansion and the preservation of vital water sources.

A notable drawback of agricultural development in Thessaly is the region’s reduced natural resilience to droughts and floods. Areas that could potentially contribute to the area's ecological balance are currently being exploited intensively. Historically, valleys and floodplains of rivers and streams served as crucial spaces for water storage after rain showers and groundwater replenishment. Regrettably, the once-prominent sponge function of landscapes has diminished significantly.

Numerous rivers and streams are now wedged between dykes to maximize cultivated areas, disrupting the natural flow dynamics. These alterations have rendered Thessaly more susceptible to both floods and droughts. Coupled with the escalating impact of global climate change, Thessaly faces heightened vulnerability to extreme weather events, amplifying the urgency of addressing and mitigating these challenges.

While the future socio-economic trajectory of Thessaly hinges on political decisions, this Master Plan operates under the assumption that Thessaly will maintain a predominantly agricultural area. Agribusiness is envisaged to continue being the primary economic driver, even though there may be substantial reductions in the size of cultivated areas, especially in the irrigated sectors. The envisaged transformation involves converting these areas into more extensive agricultural spaces or alternative land uses. Such changes are deemed essential for effective flood management and are imperative to curtail water consumption, fostering the restoration of ecosystems. These measures are seen as inevitable, particularly if other interventions to address water scarcity prove insufficient.

The safeguarding and strengthening of Thessaly's agricultural and livestock sectors are key priorities. Therefore, HVA has developed flood protection measures and strategies that aim to minimize their impact on currently cultivated land and mitigate any withdrawal of land from productive use.

Nevertheless, the need to reform Thessaly's agricultural sector is indisputable. This reform is essential not only to confront challenges posed by climate change but also to address issues of water scarcity, along with broader concerns such as profitability, competitiveness, and resource efficiency. Volume IV (Agriculture and Livestock) outlines the necessary actions and reforms crucial for strengthening the agricultural and livestock sectors. These efforts are pivotal for securing the livelihoods of Thessaly's population and preventing the younger generation from abandoning the region.

Water resources

The emphasis on agriculture as the primary economic activity in Thessaly extends beyond implications for flood management strategies; it significantly influences the overall development and management of water resources. Parallel to the necessary revisions in the Flood Management Plan, the Water Management Plans of both the Greek central and regional governments require substantial re-evaluation. Urgent and decisive political action is imperative to address the challenges posed by the agricultural focus in Thessaly and to ensure sustainable water resource management aligned with the region's economic priorities.

Regrettably, water resources management in Thessaly over the past several decades has led to an unsustainable status quo, marked by significant overexploitation of groundwater resources. The Thessalian agricultural sector, utilizing over 90% of the total water in the region amounting to approximately 1.5 billion m^3 annually, with 70% derived from groundwater sources, underscores the urgent necessity for substantial reforms. The critical point has been reached, compelling the imperative for serious and immediate actions to address the unsustainable use of water resources in Thessaly. The high number of boreholes in Thessaly has surged, escalating from a mere 7,000 in 1975 to the current count of 33,000.

Figure 3 hereunder illustrates the positions of around 22,000 documented wells. Alarmingly, over 10,000 boreholes remain unregistered, lacking both accurate abstraction data and effective control mechanisms. This situation is untenable.

Compounding the issue, the decentralized Water Departments, responsible for overseeing borehole licensing, have been severely understaffed. Their practices do not align with requirements for sustainable groundwater use, lacking considerations for renewability and safe yields of groundwater resources. Rectifying this situation is urgent to ensure responsible and sustainable management of Thessaly's groundwater resources.

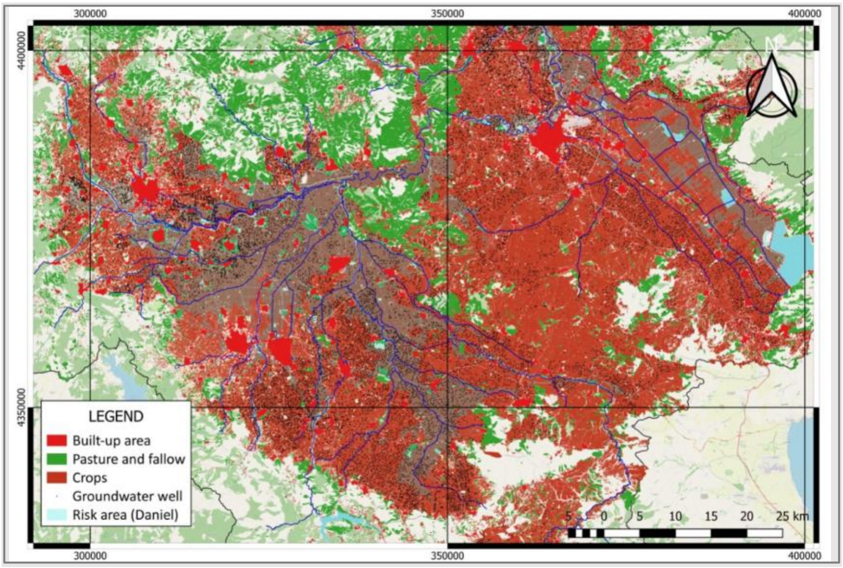


Figure 3: Locations of registered boreholes

Some hydrologists have approximated the annual overexploitation of groundwater at 477 to 511 million m^3 over recent years. However, HVA's hydrologists consider this to be a conservative estimate, pointing out that the groundwater recharge may be less than accounted for in these calculations. Therefore, there is a pressing need for the verification of groundwater recharge concerning the overall groundwater balance.

It is critical to emphasize that the water deficit extends beyond the annual overexploitation of groundwater. An estimated additional volume in the order of 3 billion m^3 is required to replenish depleted aquifers. This highlights the critical necessity for a substantial reduction in groundwater consumption to facilitate the recovery of depleted and degraded aquifers. Addressing this issue is pivotal to ensuring the long-term sustainability of Thessaly's water resources.

Achieving sustainable groundwater management necessitates a comprehensive assessment and monitoring of both the volumes and patterns of groundwater abstractions. Additionally, thorough studies on the mechanisms and quantities of groundwater recharge are imperative to enhance the precision of determining sustainable abstraction rates. In order to promote long-term viability, it is crucial to identify and dismantle unsustainable groundwater abstractions.

Combatting water scarcity

Addressing Thessaly's water scarcity crisis requires the implementation of three main strategies:

1. Supply management: In order to enhance water conservation and management in the region, various options are available. These include the construction of dams, inter-catchment transfers sourced from the Achelous River Basin, the implementation of both in-situ and ex-situ water harvesting techniques, artificial recharge methods, and the reuse of drainage and wastewater.
2. Demand management: In order to improve the efficiency of water utilization among farmers. These include the adoption of technical solutions such as water-saving techniques and infrastructural enhancements, revising crop selection to favour those with lower water consumption, and introducing financial incentives such as water pricing mechanisms. Furthermore, existing subsidies for energy used to pump groundwater need to be reviewed.
3. Adaptive management: In order to optimize the allocation and reallocation of water resources, the goal is to prioritize the most socially, economically, and environmentally productive uses.

These strategies are typically formulated in response to escalating water scarcity, a situation that coincides with rising political complexity and the imperative for decisive decision-making.

In light of the changing circumstances brought about by climate change, the significance of the third strategy is expected to grow. Despite potential conflicts with the assumptions outlined earlier in this chapter, especially in the short term, the reduction of irrigated areas appears to be an unavoidable necessity. VOLUME IV: AGRICULTURE & LIVESTOCK focusses on the need for alternative crop selection and land uses as a means to address this evolving scenario.

While current efforts by authorities focus on advocating water-saving irrigation techniques, it is evident that these measures alone may not be adequate. Implementing water demand management measures, including the pricing of water, despite being potentially unpopular, has demonstrated effectiveness in other countries.

Supply management

It is essential to recognize that relying solely on water-saving options will not sufficiently address the critical water deficit issue in Thessaly. In the event that a significant reduction of irrigated land within a relatively short time frame is deemed unrealistic, inter-catchment transfers from the Achelous River Basin is necessary to augment water resources. While the construction of the Enipeas Dam east of Skopia has the potential to alleviate some of the strain on groundwater resources, there is an expectation that this water will primarily be utilized to expand the irrigated area rather than serving as a direct replacement for groundwater in irrigation practices.

Hydrological system analysis

In order to formulate and maintain effective strategies for mitigating the current water scarcity, it is crucial to consider the following hydrological system factors. These factors should encompass the following key elements:

- The actual groundwater resources, focusing on groundwater recharge and determining safe yields. The groundwater should be followed by a monitoring network of groundwater observation wells, this is essential for accurate data collection.
- The surface water discharges and their responsiveness to rainfall patterns across different hydrological years, providing valuable insights into the dynamics of surface water systems.
- Water needs and requirements of crops in the area. This will contribute to a better understanding of agricultural water consumption patterns.
- Groundwater abstractions specifically for irrigation purposes: utilize crop water requirements as a basis, supplemented by on-site inspections and the installation of water meters to accurately quantify abstracted groundwater.
- Uses of groundwater beyond irrigation, utilizing records from drinking water companies. This will shed light on the diverse ways groundwater resources are utilized.
- Information from Technical Evaluation and Oversight Bodies (TEOBs) about surface water usage for irrigation. This data provides a comprehensive overview of irrigation practices and their impact on surface water resources.

The insights gained from the hydrological system analysis are to be leveraged to continuously evaluate the feasibility and impacts of different scenarios. This includes reviewing the implications of altering cropping patterns and implementing more efficient irrigation systems to achieve water savings.

Starting points flood defense infrastructure

Costs and benefits

Generally, the construction of flood defense infrastructures requires substantial investments. Nevertheless, international studies consistently confirm the positive cost-benefit of most flood defense measures. This confirms that the monetary benefits resulting from reduced flood damage typically outweigh the otherwise incurred costs. Furthermore, flood defense infrastructure frequently contributes to various non-monetary benefits, including social, health, and environmental advantages.

Establishing retention areas and modifying buildings to prevent or mitigate flood damage emerge as the most economically viable measures for Thessaly. Research supports the positive benefit-cost ratio of improving dyke systems (Dottori F, 2020). Additionally, retention areas offer environmental advantages, promoting the restoration of natural floodplain functions and enhancing various ecosystems.

Despite their potential benefits, the relocation of people and industries is often deemed less cost-effective, particularly considering the elevated costs involved (Dottori F, 2020). This option should be considered only as a last resort if all other alternatives prove insufficient.

Recognizing that different interventions in flood defense infrastructure may yield varied returns on investment, it is crucial to adopt a tailored approach for Thessaly. Flood management cannot rely on a one-size-fits-all strategy; instead, a combination of measures should be implemented, customized to suit the specific characteristics of each area. Not all interventions may be universally applicable, and a diverse set of measures is essential to achieve the required levels of protection.

Safety standards

Flood defense infrastructures must adhere to established safety standards, which should be carefully developed, taking into account the specific social, economic, and environmental significance of the respective areas. These standards need to be differentiated based on the importance of the area to which they are applied.

Safety standards encompass both financial considerations and non-monetary dimensions. Financially, they involve assessing the risk and potential damage to assets, equipment, and the economy in comparison to investments in protective infrastructure. Moreover, safety standards extend beyond monetary aspects to include social, cultural, ecological, and emotional dimensions. This encompasses considerations such as the preservation of lives and well-being, safeguarding of livestock, protection of archaeological and ecological values, and addressing the psychological impacts on flood victims. The fact-finding missions carried in September and October 2023 revealed a failure of safety standards for Thessaly.

Establishing safety standards is a complex technical and financial process and requires alignment with political decisions. For instance, the Netherlands bases its safety standards on the criterion that the risk of casualties in the event of a flood should be less than 1 in 100,000; a benchmark that requires years to translate into concrete, tangible measures.

This Master Plan observes that Thessaly is not able to afford the luxury of spending numerous years on exhaustive studies and discussions to formulate a comprehensive set of safety standards and cost-efficient solutions for flood defense infrastructure. The current state of urgency demands a swift process and immediate actions. Consequently, a pragmatic approach has been embraced, wherein safety standards are linked primarily with the functions and uses of land rather than individual safety levels.

In this Master Plan, HVA has prioritized the rapid implementation of "*no-regret*" measures, recognizing their urgency and effectiveness. Simultaneously, more comprehensive safety standards can be developed by the Government of Greece, and designs for future infrastructures can be adjusted accordingly as the initial works progress. This approach aims to strike a balance between urgency and long-term planning.

This Master Plan differentiates between six distinct safety standards, each aligned with the specific uses and functions of the respective land areas:

Area function	Safety standard[1]
Large residential and -industrial areas, vital services (energy, telecommunication)	6 (highest)
Small residential and -industrial areas, archaeological sites[2]	5
Livestock[3]	4
Irrigated agriculture[4]	3
Non-irrigated agriculture	2
Pastoral land, nature areas, forestry	1 (lowest)

Table 1: Safety standards per land-use.

Prioritization for flood defense infrastructure

1 The numbers do not relate to return periods, but merely show the ranking.

2 Although that the individual impact of a flood is the same for a resident of a village and a city, the total flood damage to villages is mostly less than for cities. Evacuations from cities are also, mostly, more complex.

3 In principle livestock can be evacuated, which would argue for a lower safety standard. However, many livestock farmers have installations that represent a high capital value. See also VOLUME IV: AGRICULTURE & LIVESTOCK

4 Irrigated agriculture can be further subdivided according to the risk of damage to installations (e.g. to underground and open tertiary systems) and crops. This requires the collection of more detailed data.

The prioritization of flood defense infrastructure implementation is based on the severity of potential flood disasters, as determined by safety standards, and the likelihood of a flood disaster occurring. These factors, along with the integration of safety standards and probability, have been incorporated into a comprehensive risk matrix.

The Master Plan adopts the following risk matrix:

		Likelihood of flooding	
		High	Low
Required safety standard	6	Unacceptable (highest)	Medium
	5	Very high	Medium
	4	High	Low
	3	High	Low
	2	Medium	Very low
	1	Low	Negligible

Table 2: Likelihood of flooding risk - matrix

The proposed assessment of risk levels is open to be approved by Greek authorities and may be adopted or further refined prior to the implementation of infrastructure works. The risk matrix in the Master Plan currently categorizes the likelihood of floods into two qualitative levels, namely "*High*" and "*Low*."

This simplification comes from the acknowledgment that the existing statistical benchmarks for calculating the likelihood of floods, based on return periods of 50, 100, and 1000 years, are no longer deemed accurate. Instead, this Master Plan operates on the assumption that events like the Storm Daniel, which caused significant flooding, are now "*likely to occur*"[5] with increased frequency and intensity. Recognizing the evolving nature of extreme weather events, particularly in the context of climate change, Thessaly requires protection appropriate for these changing realities.

Therefore, the Master Plan designates the areas that experienced inundation following Storm Daniel as those with a high likelihood of flooding[6]. Additional differentiations regarding the levels of likelihood of flooding can only be determined through detailed modelling. This modelling will assess the impacts of various ensembles of rainfall events across diverse climate scenarios. The extent of the area

[5] Note that this is not in agreement with the existing flood management plan 2014-2020 and the existing analyses on the return period of such storms. The Master Plan, however, assumes that the huge uncertainties about the impacts of climate change justify very high standards: the storm Daniel is considered the norm. The Greek government also communicated that the Master Plan should use Daniel as benchmark.

[6] The area flooded by Storm Daniel was fairly comparable to the areas that were predicted in the Flood Management Plan (FMP) would be inundated in a 1:1000 years event.

categorized as having a "*high likelihood of floods*" is illustrated in Figure 4: Areas with high likelihood of floods.

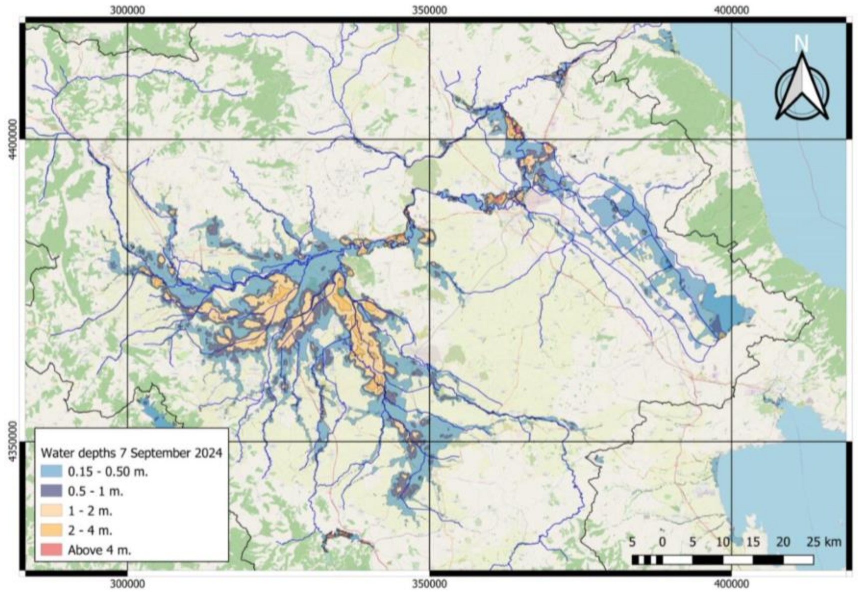


Figure 4: Areas with high likelihood of floods

Building on the risk matrix, the Master Plan establishes six levels of prioritization for the development of flood defense infrastructure[7]:

Priority	Areas
Maximum	Large residential and industrial areas in flood-prone areas
Very high	Small residential and industrial areas, archaeological sites in flood-prone areas
High	Livestock and irrigated agriculture in flood-prone areas
Medium	Residential and industrial areas, archaeological sites in non-flood-prone areas, non-irrigated agriculture in flood-prone areas.
Low	Pastoral land, nature areas and forestry in flood-prone areas, livestock and irrigated agriculture in non-flood-prone areas.
Very low/zero	Non-irrigated agricultural areas, pastoral land, nature areas, and forestry in non-flood-prone areas.

Table 3: The six levels of prioritization for flood defense infrastructure

Integrated approach

[7] Priorities need further discussion with the Government of Greece. The table is aimed at showing the concept.

In order to achieve the necessary protection against floods, it is essential to design and construct a range of complementary flood defense infrastructures. These infrastructures must be planned, harmonized, and ultimately designed for the entire basin, rather than in isolation. This wholistic approach is crucial because interventions in any land or water system anywhere in Thessaly can have repercussions on other water uses and downstream areas. For instance, enhancing the discharge capacity of upstream river basins, as evidenced by the Storm Daniel case (impacting Larissa and Lake Karla), can potentially lead to floods downstream. Therefore, an integrated approach is imperative to address the interconnected nature of water systems and ensure the overall effectiveness of flood defense measures.

Hydrological modelling

Given the complex nature of hydrological processes and the interplay between land and water systems, the formulation of effective and cost-efficient flood defense infrastructures requires the use of a very detailed and elaborate hydrological model. An all-inclusive field surveying campaign is essential to collect accurate and critical input data for this model, which will also serve as the foundation for Early Warning and Emergency Measures/Preparedness (see also Volume III).

The hydrological model must possess the capability to precisely quantify the impacts of the proposed flood defense measures outlined in this Master Plan and optimize their designs. It should calculate design hydrographs for both streams and rivers, extending to downstream river sections. These design hydrographs will then be compared with the existing capacity of the surface water system, enabling the optimization and alignment of various measures. This ensures that peak water discharges and levels do not surpass the enforced safety standards.

Hydrological models for Thessaly have been previously developed and are presently employed in the formulation of the new Flood Management Plan. However, the fact-finding missions have identified certain shortcomings in the existing models, particularly in their suitability for planning and designing infrastructure, as well as for Early Warning and Crisis Management. In light of these findings, it is strongly recommended that the developers of these models receive this report. This collaboration will enable them to restructure and refine the models, potentially seeking the expertise of external flood modelling professionals.

The objectives, setup, and application of the hydrological model for planning and designing flood defense infrastructure are comprehensively outlined in Annex 1. Infrastructure and early warning systems.

The subsequent chapters present guidelines for flood defense infrastructures and various measures across different regions of Thessaly. Significant infrastructural undertakings such as dykes and dams require detailed studies and designs before becoming viable, bankable projects.

For the effective execution of the Master Plan, we recommend to establish a Task Team comprising technical, social, financial, and environmental experts, as well as policy makers from both regional and central government levels. This Task Team should take the lead in initiating and overseeing proposed interventions, facilitating coordination among ministries, provincial departments, and institutions at both central and local levels. Additionally, it should manage the final designs and actual implementation carried out by consultants and contractors. The Task Team should be tasked with the day-to-day implementation of the Master Plan.

Simultaneously, we recommend the forming of a Steering Committee to ensure that interventions align with national and regional policies. The committee's role includes monitoring the progress of works, addressing potential setbacks, and handling strategic issues. Comprising decision-making authorities, the Steering Committee should convene approximately 3 or 4 times per year.

The Task Team must also prioritize improving intersectoral communication and interaction, especially between policymakers and the knowledge sector. This enhancement is crucial in addressing the anticipated future challenges in water and flood management, which are expected to become more complex and acute.a

Concepts and types of flood defense infrastructure

"Grey infrastructure" refers to fixed, man-made structures designed for flood protection. Traditional grey flood defense structures, such as dykes and levees, are employed to confine flooding to dedicated areas, primarily rivers, streams, and lakes, preventing the inundation of residential, industrial, and agricultural lands. Additional grey flood defense structures include dams, reservoirs, drainage systems, and diversion channels.

The development of grey infrastructure has frequently led to the violation of vital ecological values, resulting from alterations to hydrological regimes and the disruption of connections between rivers and natural floodplains. The pursuit of grey infrastructure options has, at times, encountered technical limitations (e.g., dyke height) and involved excessive costs. Nevertheless, grey infrastructures have been utilized for centuries, and there exists substantial knowledge concerning their construction, operation, and maintenance.

It is essential to acknowledge that while grey infrastructure has proven effective in managing floods, the associated environmental impacts and potential drawbacks should be carefully considered. Striking a balance between the benefits of flood protection and the preservation of ecological integrity is crucial for sustainable water management strategies.

Nature-based solutions (“Green engineering”)

A relatively innovative approach to simultaneously address flood and drought risks while enhancing resilience to climate change is through the implementation of "nature-based solutions" (NBS). In NBS, ecosystems, landscapes, and natural processes are harnessed for functional water management purposes. The United Nations defines NBS as "actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems."

For instance, reforestation and replanting initiatives can enhance water retention, improve soil infiltration capacity, and stabilize soils, thereby reducing the risks of erosion, landslides, and flash floods. Additionally, NBS can prove effective in augmenting low water flows during dry periods.

However, the evidence supporting the effectiveness and efficiency of NBS in large-scale projects, such as mitigating flooding in river basins, is currently limited. It is noteworthy that NBS generally requires significant space, with wetlands and forests occupying larger areas compared to conventional structures such as dykes and dams.

While NBS offers promising ecological benefits and aligns with sustainable practices, ongoing research and evaluation are crucial to better understand its scalability, efficiency, and overall impact on water management. Striking a balance between traditional grey infrastructure and nature-based solutions may offer a comprehensive and sustainable approach to water resource management.

Hybrid solutions

Frequently, a synergistic approach involves the integration of "*grey infrastructure*" and "*nature-based solutions*" (NBS), creating what is commonly termed "hybrid nature-based solutions" or simply "*hybrid solutions*." These solutions represent a blend of ecosystem elements and man-made structures designed to restore natural systems. Examples include the incorporation of (temporary) wetlands and riparian buffer strips, coupled with the construction of small water and sediment retention dams in upstream areas.

The primary objective of hybrid solutions is to harmonize the benefits of both natural and engineered components. This approach seeks to leverage the advantages of NBS, such as enhancing biodiversity, promoting sustainable land use, and mitigating environmental impact, while also incorporating the reliability and structural integrity associated with grey infrastructure. By combining these elements, hybrid solutions aim to optimize the effectiveness and resilience of water management strategies.

This integrated approach recognizes the need to address complex challenges by utilizing the strengths of both nature-based and traditional infrastructure solutions. It underscores the importance of adaptive, flexible strategies that can provide comprehensive and sustainable solutions to water-related issues.

Payments for Environmental Services

The concept of "*Payments for Environmental Services*" (PES) is intricately linked to Nature-Based Solutions (NBS). However, its scope extends beyond mere green engineering. PES entails compensating those negatively affected by NBS, with the beneficiaries offering recompense to groups facing adverse impacts, ensuring a net positive benefit for the entire community. For instance, citizens may financially compensate farmers who agree to a temporary inundation of their land to safeguard residential and industrial areas. The effective implementation of PES necessitates a robust regulatory framework and a foundation of trust in governance[8].

Space for the rivers

The process of creating space for rivers involves resizing or eliminating potential obstacles within floodplains, including dykes, levees, bridges, roads, railways, and urban structures. Although not a novel concept, it marks a departure from the earlier emphasis on "*getting rid of the water*" through flood defense infrastructures. A paradigm shift occurred in the 1990s, favoring a more adaptive strategy: providing room for the river itself. This approach, successfully implemented in the Netherlands, gained recognition and was adopted by the European Commission in 1999[9].

[8] Agreements with farmers who adapt their land use, so that their land may be inundated in the case of emergencies are also a form of PES.

[9] In December 2023 the concept “Space for the rivers” proved to be effective, as major flooding of rivers in the Netherlands resulted in limited local disturbances.

Development strategy for flood defense infrastructure

The planning, design, and development of flood defense infrastructures consist of an iterative and often lengthy process, spanning decades. This involves comprehensive technical and financial assessments alongside policy dialogues. Political decisions on safety standards, spatial planning, socio-economic priorities, and environmental and biodiversity objectives must harmonize with technical and financial constraints.

Contrary to the usual timeline, this Master Plan recognizes the pressing need for immediate action in Thessaly, acknowledging that the region cannot afford to wait for decades to address its challenges. The overarching development strategy outlined herein can be swiftly implemented without compromising scientific accuracy or financial constraints.

The Master Plan not only addresses the urgency but also brings up key political discussions regarding Thessaly's socio-economic development and priorities, aligning with safety standards previously presented in this Volume. It is essential to note that the Master Plan's content may undergo significant changes if the assumptions outlined in this Volume lack political support.

This Chapter delineates the overall approach for applying the adopted safety standards and prioritizing among various options for flood defense infrastructures.

Recognizing the need for designating vast cultivated areas for temporary inundations during severe floods, this Master Plan adopts a careful approach to avoid large-scale conversion of agricultural lands into permanent flood retention areas. The aim is to prevent unnecessary hindrance to Thessaly's agriculture-based socio-economic development. Instead, the focus is on implementing interventions that increase retention capacity primarily in non-cultivated areas, such as the surrounding hills and mountains.

In order to minimize land conversion, the Master Plan prioritizes additional measures such as dyke reinforcement. In cultivated areas, expansion of river space is targeted selectively at critical points, involving measures such as bridge and culvert redesigns and the elimination of local bottlenecks. The current advice avoids advocating costly large-scale restructuring of floodplains or complete remodeling of existing dyke systems. However, it acknowledges that future studies might reveal the necessity for such measures.

The Master Plan is presenting priorities and a timeline for the development of flood defense infrastructures. This includes identifying "no-regret" investments that can be promptly implemented, as well as interventions requiring more detailed assessments.

Dealing with safety standards

The highest safety standard, denoted as Safety Standard 6, is reserved for large residential and industrial areas that play vital roles, necessitating maximum protection. These areas, including cities such as Larissa, Trikala, Karditsa, and Elassona, along with towns such as Tyrvanos, Ampelonas, Agnandero, Proastio, Megala Kalyvia, Palamas, Sofades, Domokos, Nikaia, Vasilili, Kalampaka, Farsala, and Velestino (the latter three towns situated outside the risk area), will benefit from this top-tier safeguarding.

The second-highest standard, Safety Standard 5, is applied to smaller residential and industrial areas, as well as archaeological sites. Similar to the larger areas, these locations will receive maximum protection. The Master Plan advises relocation only in exceptional cases where protection cannot be assured or if protection carries significant adverse side effects. Archaeological sites, though, will not be subject to relocation but will be diligently protected. Determining the classification of residential areas as "*large*" or "*small*" requires collaboration with the central government. Notably, Safety Standard 6 will be adopted for cities and towns mentioned earlier, with special attention given to Larissa, Trikala, and Karditsa in the Master Plan.

Figure 5 denotes the locations of the residential areas, archaeological sites and important industries that are situated in areas with a high risk of inundation while Figure 6 denotes the residential areas, archaeological sites[10] and important industries that are situated in areas with a low risk of inundation.

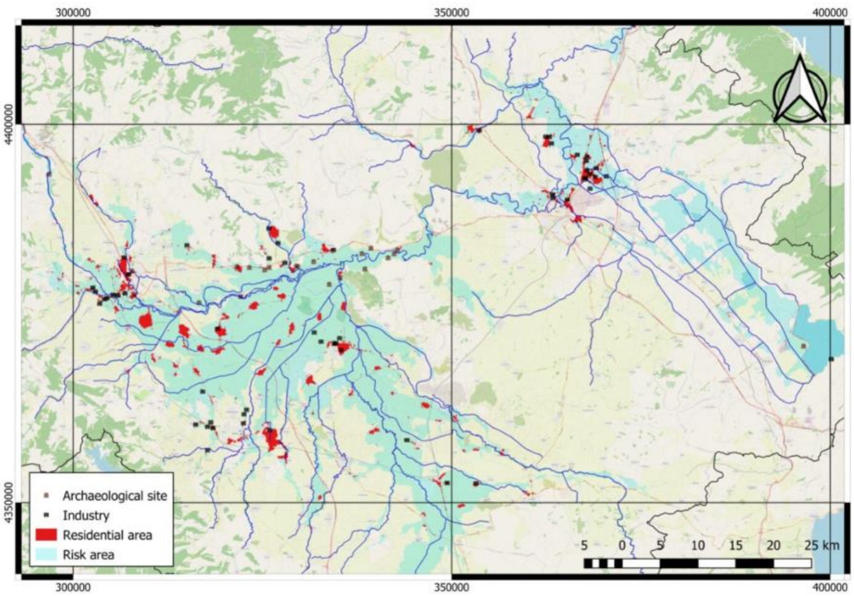


Figure 5: Residential areas, archaeological sites and industries in high-risk areas

[10] Data as provided by the Greek government

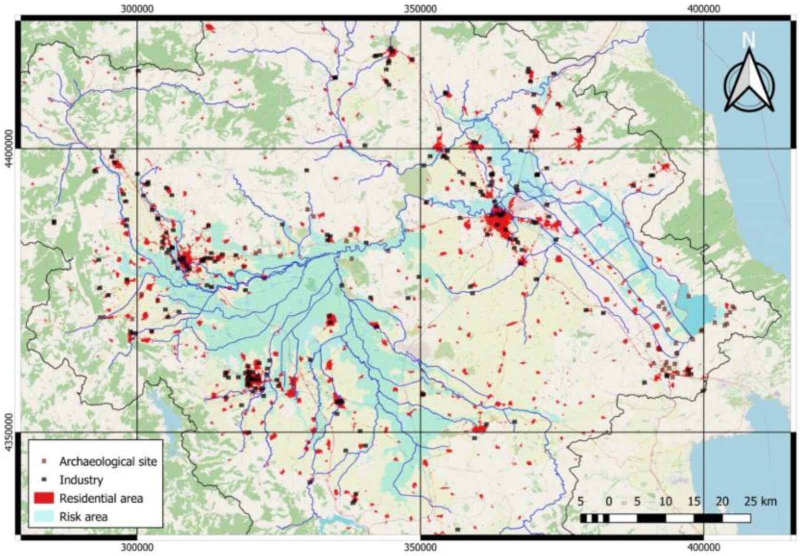


Figure 6: Residential areas, archaeological sites and industries in low-risk areas

Livestock

The designated Safety Standard for livestock is set at Level 4. Figure 7 denotes the distribution of livestock in Thessaly. A considerable number of livestock farms are situated in regions prone to high flood risks. In areas where protection is challenging or economically burdensome, it is imperative to restrict, or at the very least, discourage investments in installations and equipment that cannot be easily relocated in the event of a flood. For areas deemed unprotectable, the Master Plan recommends against rehabilitating damaged assets. Instead, the focus is on facilitating the relocation of such assets to safer locations. Detailed, area-specific information is provided in the last four chapters of this Volume.

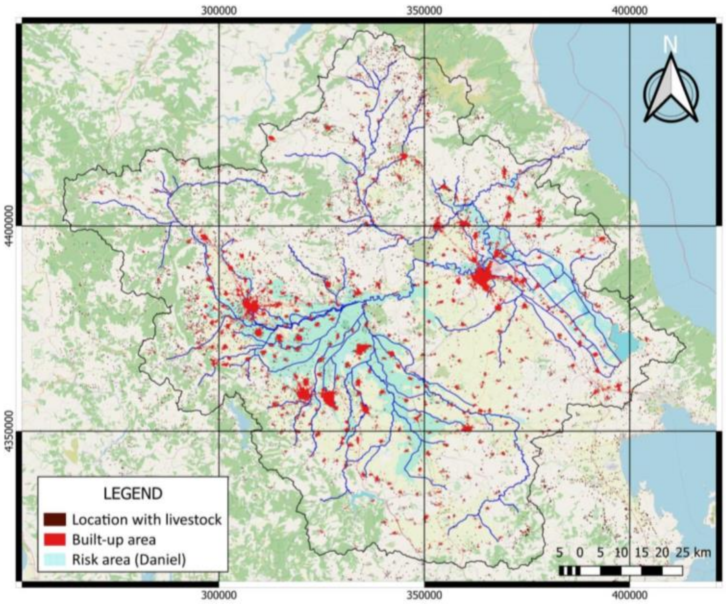


Figure 7: Locations with livestock

Irrigated and non-irrigated lands

The adopted Safety Standards for agriculture are designated as Level 3 for irrigated agriculture and Level 2 for non-irrigated agriculture. However, the available data does not provide a clear distinction between irrigated and non-irrigated agriculture. Pastoral, uncultivated, and fallow land are definitively categorized as non-irrigated.

For cropped areas, it is challenging to determine the application of irrigation with certainty, despite the likelihood of most cropped areas utilizing irrigation, given the prevalence and distribution of boreholes.

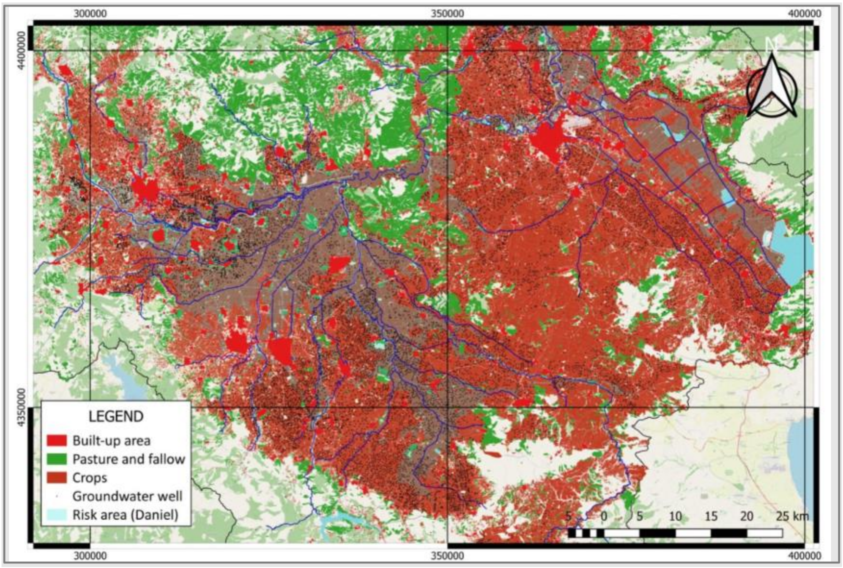


Figure 3: Locations of registered boreholesThe figure hereabove (same with Figure 3) indicates that irrigation is uniformly applied throughout the area and is not concentrated at specific locations, posing a challenge in applying equal standards. Notably, the region around Karditsa deviates from this pattern as it relies on surface water from Lake Plastiras for irrigation rather than groundwater. This distinction explains the considerably lower number of boreholes in this particular area.

The locations of the agricultural lands used for crop production, as pasture, or non-cultivated / fallow land are marked in Figure 8 and Figure 9, denoting which ones are located in areas with a high risk and low risk of inundations, respectively.

As can be seen in Figure 8 there is hardly any pastoral land in the areas that have a high risk of inundation, whereas there are many cultivated areas outside the high-risk areas. This means that the possibility of controlled inundations of pastoral land (that have a lower safety standard) during floods is limited.

Given the inevitability of extensive cultivated lands experiencing (temporary) inundation during severe flood events, it becomes essential to consider relocation strategies for premises damaged in areas affected by events like Storm Daniel, especially when adequate protection is not feasible. The subsequent chapters offer detailed insights, complemented by a series of maps.

In unprotectable areas, a shift in cultivation patterns is imperative, transitioning from crops sensitive to inundations to less vulnerable alternatives. Additionally, exploring the cultivation of more high-value crops in protected areas is a viable strategy. Alternatively, the development of comprehensive compensation schemes for farmers facing crop damage or loss due to inundations is crucial.

Among the approximately 375,000 hectares of cultivated (non-pastoral) agricultural lands, roughly 306,000 hectares are currently dedicated to the production of cotton, forage, durum wheat, corn (maize), and a few other cereals, mostly under irrigation. Cotton is categorized as a medium-value crop with sensitivity to inundation. Forage is classified as a high- to medium-value crop with moderate inundation sensitivity. Corn is considered a high-value crop with medium sensitivity to inundation. Durum wheat and other cereals are designated as high- to medium-value crops that are sensitive to inundation.

The resilience of irrigation systems must be adjusted in response to future inundation risks. In areas that pose challenges or involve high protection costs, it is necessary to avoid developing vulnerable and high-value irrigation infrastructures. Prioritizing robust and resilient irrigation systems will contribute to effective adaptation to potential inundation challenges.

Volume IV of the Master Plan addresses the agricultural development reforms needed to increase the resilience of the Thessalian agricultural sector.

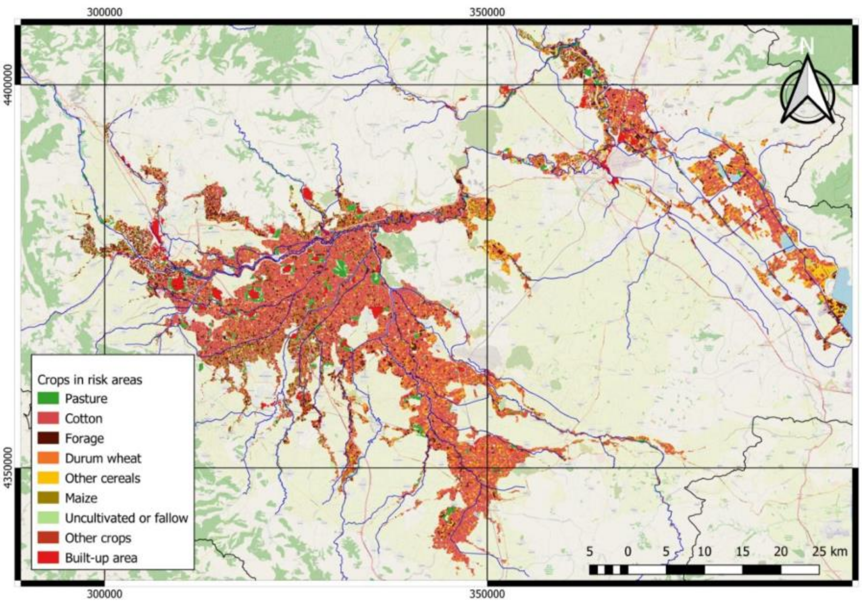


Figure 8: Locations of agricultural lands in high-risk areas

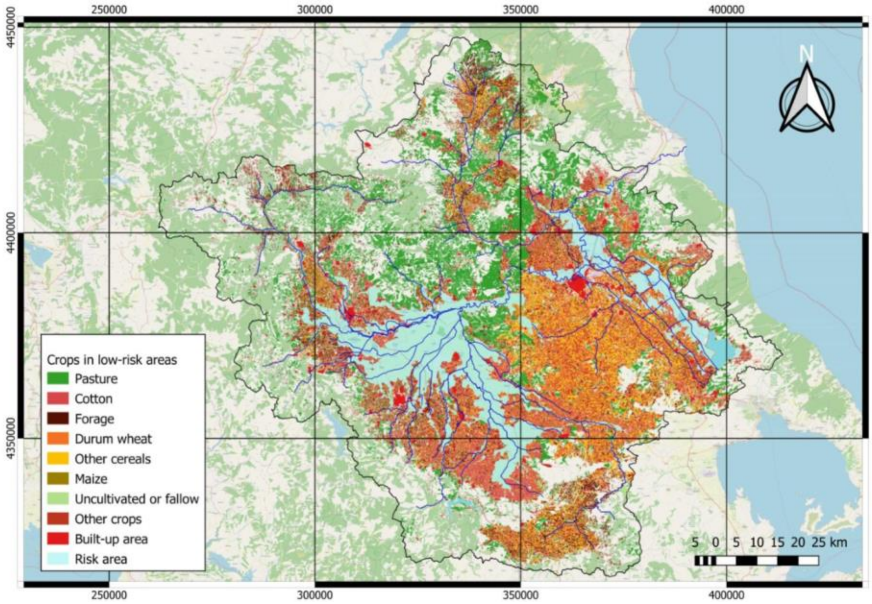


Figure 9: Locations of agricultural lands in low-risk area

Generic measures

In order to enhance Thessaly's resilience against floods, a set of generic measures must be implemented. These measures are applicable across the entire region and should be executed by the respective Greek provincial and municipal authorities. Some key considerations for these measures may include:

- Clearing debris and dismantling illegal dams to restore natural water flow.
- Demolishing abandoned or destroyed structures within the floodplain for enhanced safety and environmental preservation.
- Rehabilitating damaged dykes and culverts to reinforce flood protection infrastructure.
- Clearing floodplains of trees and shrubs to minimize potential blockages during flooding events.
- Dredging accumulated sediments in riverbeds to maintain proper water capacity and flow.
- Regular maintenance of drainage canals to ensure efficient water drainage.
- Exploring options for relocating buildings from flood-prone areas to mitigate future risks.

In addition, some generic preparatory activities are required for detailed designs. The Task Team should appoint a dedicated team or consultant to conduct these activities:

- Surveying and mapping of the surface water system, including irrigation canals and drains, to document profiles and cross-sections.
- Assessing the condition and dimensions of existing levees in Thessaly, identifying areas requiring restoration to their originally designed height levels based on fact-finding missions.

- Surveying and mapping all hydraulic structures within the floodplains, such as gates, bridges, and culverts, with a focus on determining and registering hydraulic characteristics (hydraulic perimeters) in a cadastre system.
- Documenting all assets within the floodplains, specifying their purpose and estimating their value for comprehensive asset management.
- Procuring a high-accuracy digital terrain model based on LIDAR technology, followed by meticulous processing to ensure accuracy for hydrological modelling. This includes error checks and corrections for elevated elements such as trees.

Starting the formation of a multi-disciplinary working group is necessary for the assessment and redesign of bridges, ensuring a harmonious balance between flood management requirements and the preservation of cultural and archaeological values associated with these structures. This collaborative team should ideally include professionals such as a civil engineer, an archaeologist, an architect, and a traffic expert to address diverse aspects.

An immediate ban should be implemented on all new constructions within the floodplains of rivers and streams in the valleys of Thessaly. This prohibition extends to areas outlined in subsequent chapters as zones susceptible to temporary inundations during floods. The same restriction applies to previously affected areas until comprehensive flood defense measures are fully implemented and operational. This proactive approach aims to safeguard both the environment and the communities from potential risks associated with flood-prone regions.

Area-specific measures

Thessaly, from a flood management perspective, can be categorically divided into four distinct zones: the mountainous regions, the cultivated valleys situated in the upstream sections of the Pineios river basin (Trikala and Karditsa prefectures), the cultivated areas in the downstream segments of the Pineios river basin (Larissa Area), and the Lake Karla river basin. Tailored and specific development strategies for flood defense infrastructures will be outlined for each of these four areas, ensuring a targeted and effective approach to address the unique challenges and characteristics of each zone.

- Mountainous areas;
- Trikala and Karditsa prefectures;
- Larissa Area;
- Lake Karla / Stefanovikio.

Tentative cost estimates are presented in the Chapter Recommendations of the Volume VI.

Flood management in mountainous areas

General outline

In line with common flood preparedness practices, the mountainous regions of Thessaly have historically received less emphasis in flood management plans, despite their substantial role in amplifying flood risks. The impacts of extreme hydro-meteorological events in these mountain areas have effects throughout the entire river basin, affecting both populated and cultivated zones.

Encompassing roughly half of Thessaly, these mountainous areas, primarily composed of non-cultivated and pastoral lands, represent a critical component of flood management considerations. Recognizing their significance, this Master Plan adopts a strategic approach to minimize and mitigate peak surface discharges from the mountains. This involves the establishment of numerous retention areas (approximately 100-250) in the relatively flat sections of small valleys and gullies. Where feasible, this strategy incorporates (re-)vegetation and (re-)forestation, employing Nature-Based Solutions to enhance temporary storage and encourage improved infiltration. By doing so, the Master Plan aims to create a ripple effect, mitigating flood impacts in the mountains and consequently safeguarding the cultivated and populated valleys downstream.

Furthermore, it is necessary to fine-tune the operation of both existing and future large dams in alignment with flood management requirements. The following paragraphs will delve into the potential impacts of the proposed interventions on downstream water users and on the operations of existing dam facilities.

Nature-based solutions and check dams

The Master Plan recognizes that relying solely on nature-based solutions may fall short in containing the immense water volumes unleashed during severe weather events like Storm Daniel. As a strategic enhancement, the proposal introduces a hybrid approach. This involves implementing small water retention structures complemented by nature-based interventions such as revegetation and reforestation. Together, these components synergize to fortify the region, offering not only increased protection but also enhanced capacity for floodwater retention.

Efficient mountain water retention primarily involves the construction of small structures, particularly check dams, designed to dissipate energy and curtail surface runoff and sediment flow from gullies. Supplementing these efforts, small earthworks along the contours prove effective. Notably, terracing is omitted from consideration due to the unfavorable soil properties in the mountainous Thessaly region and the associated high costs. The implementation of check dams stands out as a no-regret intervention, offering additional advantages such as diminished soil erosion.

Localization and design

The suggested structures can be promptly initiated without the need for intricate modelling. Utilizing existing GIS-based methodologies, like those pioneered by the University of Thessaloniki for the upstream Enipeas river basin (Karachaliou, 2023), can support determining the optimal locations and sizes of these structures. It is crucial to involve local residents in the final siting, design, and construction processes, particularly if local construction materials are available and can be utilized, fostering a collaborative approach to enhance community engagement and project success.

Figure 10: Selected locations for water retention in mountainous areas of Thessaly presents the pre-selection of the approximate locations for check dams in valleys and gullies in the mountainous areas. These chosen sites result from a meticulous process involving the delineation of upstream catchments and consideration of valley and gully slopes. The areas of these catchments determine runoff volume, while the slopes govern the water volume that can be retained without necessitating elevated dam construction.

In order to optimize safety and resource efficiency, the plan avoids high check dams that would demand substantial construction materials to mitigate break and washout risks. The proposed check dam lengths range from 50-100 m to over 1 km. In regions with pronounced erosion concerns, additional check dams with lower storage capacities may be necessary throughout valleys and gullies. Notably, no check dams are recommended in the areas upstream of the Smokovo Dam and the proposed Enipeas Dam, as these are intended to serve as primary retention structures for their respective catchments.

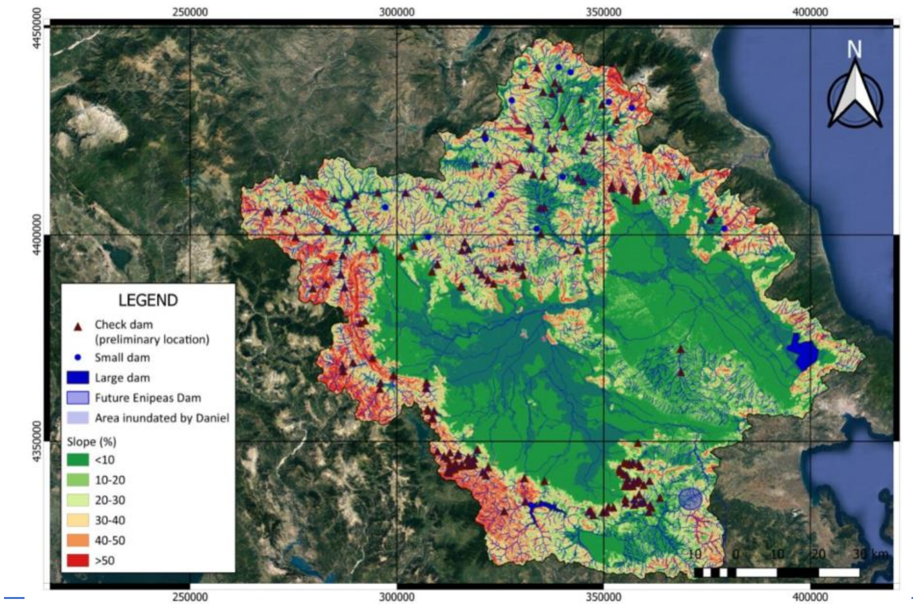


Figure 10: Selected locations for water retention in mountainous areas of Thessaly

Types of check dams

Multiple types of check dams and construction materials offer versatility in designing effective water retention structures. An adaptable variant includes the V-notch weir, offering control over the release of water. Figure 11 hereunder shows examples of water retention structures (check dams) for the mountainous areas in Thessaly.

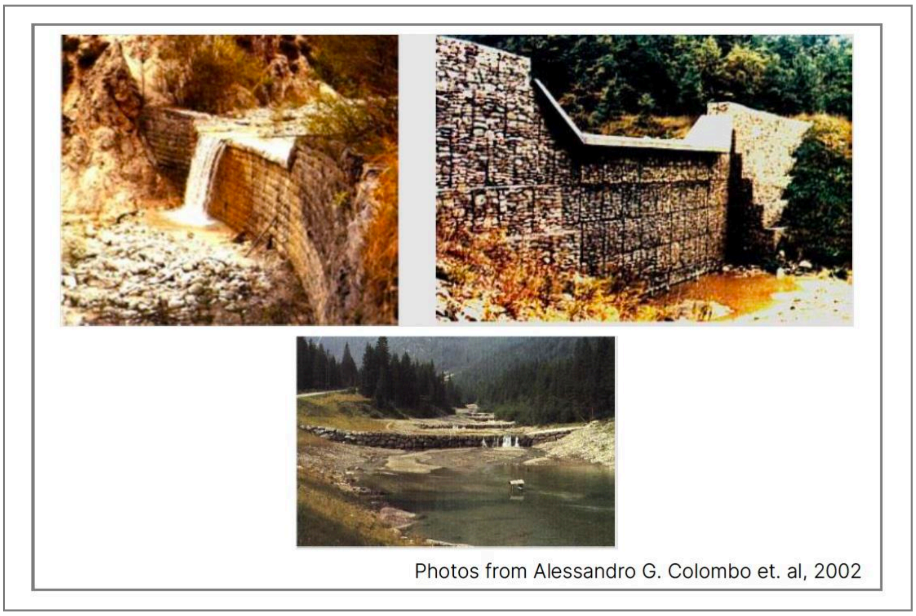


Figure 11: Water retention structures; concrete, gabion, and dry stone/wall dam

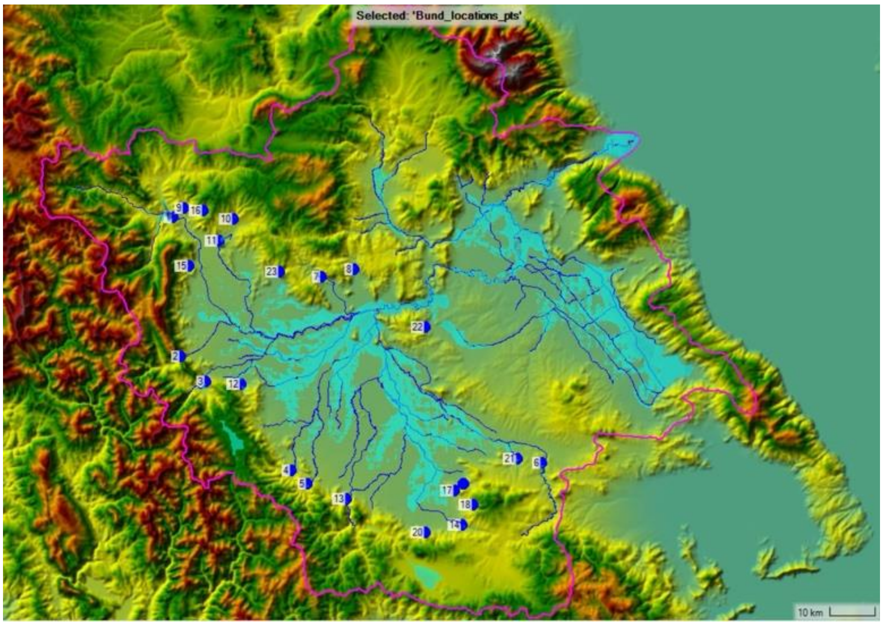
The construction of check dams is linked with the implementation of nature-based solutions, involving the planting of trees, shrubs, and grasses. This integrated approach forms a hybrid measure that serves multiple objectives. The re-vegetation and reforestation efforts are poised to mitigate the impact of future floods, diminish erosion, foster biodiversity, nurture native habitats, and contribute to groundwater recharge.

Given that certain mountainous areas are designated as Natura 2000 areas, careful consideration is imperative to assess potential environmental impacts. The meticulous design and construction of retention structures not only contribute positively to landscape conservation but also enhance biodiversity. Notably, the proposed retention structures are strategically positioned in "Special Protection Areas" designated for threatened bird species and migratory birds, aligning with conservation efforts and underscoring the importance of minimizing adverse impacts on these sensitive ecosystems.

Large dams

Whereas this Master Plan recommends to firstly explore the full potential of the construction of check dams together with nature based solutions the construction of larger dams is not ruled out. In Greece the building of dams is often promoted and chosen as the first option to solve water problems. The technical and financial feasibility of additional large dams is expected to be limited for the region of Thessaly, seeing that dams have already been constructed or planned in most viable locations. Designing cost-effective dams in the remaining, less favorable locations poses a significant challenge.

The Master Plan has, however, investigated the option to construct a limited number (23) of dams as alternative for check dams and nature-based solutions. Annex 9 present the applied methodology and tentative designs. The designs presented are conceptual and need to be refined with the use of a more detailed hydrological model. The image shows the preliminary locations of these dams.



Alternative flood retention with dams in the mountainous areas of Thessaly

Given the high costs and potential environmental impacts, new dams would necessitate rigorous technical, financial, and environmental assessments.

The already existing and planned future large dams can, however, play a pivotal role in flood management by providing substantial reservoirs for the temporary storage of floodwaters.

Flood management in the Thessalian foothills

In order to maximize water retention capacity, it is crucial to focus efforts upstream of cultivated valleys. In the far upstream riparian areas of rivers and streams, particularly at the mountain bases, the establishment of wetlands, afforestation, and other vegetation initiatives can be undertaken. These measures are considered "no-regret measures," providing benefits without significant downsides. Model calculations will play a pivotal role in determining the necessity of additional measures in the foothills. For instance, constructing an interceptor drain along the mountain base between the Kaletzis and Portaikos catchments, similar to the one in the Lake Karla area diverting water to Volos, could be considered. If implemented, this interceptor should feature gates and outlets strategically placed at key locations, such as intersections with the Megas, Pamisos, and Portaikos. These gates would be operated to control water flow, releasing it to areas with discharge capacity during flood events. Given the potential length of up to 40 km, a comprehensive study is essential due to the associated elevated costs.

Implementation:

Immediate actions (3 - 12months):

- Acquire a more detailed elevation map and determine the exact locations of the check dams. It is expected that the data from the Hellenic Cadaster have sufficient accuracy, and that no LIDAR survey will be needed in the mountains.
- Investigate the availability of construction materials from existing quarries and develop a business model for producing construction elements.
- Identify feasible (re)vegetation (nature-based solutions).
- Confirm that measures do not infringe on landscapes and biodiversity of Natura 2000 areas.
- Determine the bill of quantities.

Follow-up actions (6 - 36 months):

- Tendering and construction of check dams and nature-based solutions.

Follow-up actions (9 - 12 months):

- Use the hydrological model to assess the exact impact of the check dams and decide whether or not to investigate the need and feasibility of an interceptor drain along the foothills of the mountains.

Follow-up actions (9-48 months):

- In the case that an interceptor be needed, conduct a detailed design study, followed by the tendering and construction.

It is emphasized that existing and future large dams can play a pivotal role in flood management by providing substantial reservoirs for the temporary storage of floodwaters. The Smokovo Dam, the sole large dam so far, boasts a storage capacity of 240 million m^3. Currently utilized for electricity production and irrigating 25,000 hectares of land, it stands as an essential asset in the broader flood management strategy for the region.

Preparations are currently underway for the construction of the Enipeas Dam, situated approximately 5 km east of the community of Skopia (see also Figure 10[11]). The primary objective of the dam is to provide irrigation water to the Local Organization for Land Improvement of Farsala and the Local Organization for Land Improvement of Thessaliotida and Titanio (Prefecture of Karditsa), covering a combined area of over 10,000 hectares of irrigated land. Additionally, the dam aims to supply water

[11] No information on the exact location was available.

to the city of Farsala and thirty-one settlements in the Farsala area. The dam's anticipated capacity is 115 million m^3, with estimated costs exceeding 300 million euros.

The Smokovo Dam and the upcoming Enipeas Dam, along with other smaller existing dams and reservoirs, need comprehensive assessments. Protocols for dam operation during sudden-onset floods must be (re)developed to ensure timely water release and create additional water retention capacity. The catchment area of the Smokovo Dam, approximately 380 km^2, theoretically allows for the accommodation of around 630 mm of surface runoff. Similarly, the catchment area of the future Enipeas Dam, estimated at 450 km^2, could accommodate approximately 250 mm of surface runoff. Negotiations with dam owners should encompass financial compensations to address any potential damages resulting from adjusted management, such as reduced energy production or lower crop harvests.

The diverse functions of large dams pose potential complications for flood management, as their multipurpose roles often lead to conflicting interests. Regular dam operations, such as power generation and irrigation, may conflict with flood management objectives. Managing floods requires keeping reservoirs empty to accommodate floodwaters, while electricity companies and farmers prefer high and relatively constant water levels.

In light of the observed timing of severe storms like Storm Ianos in 2020 and Storm Daniel in 2023 occurring in the first two weeks of September due to the Mediterranean's heated seawater after a hot summer, negotiations are crucial. An agreement needs to be reached with dam owners to gradually release water from reservoirs during the dry summer months and keep them empty during the cyclone season in September when the risk of a devastating hydro-meteorological event is forecasted. Implementing a grid energy storage solution can help mitigate power shortages, providing a more balanced and adaptable approach to dam operations.[12].

Implementation:

Immediate actions (1-3 months):

- Negotiate with the dam owners on protocols for water release in the case of high risks of cyclones and floods, including compensation schemes.
- Review the design of the future Enipeas Dam, so that optimum use can be made of its capacity to prevent downstream floods.

[12] This is a well-known situation, which can be addressed by equipping large dams with radar or other early warning equipment, in order to facilitate the early release of water when intensive rainfall events are approaching. There is ample experience with this kind of technology and the developing standard operation procedures for multi-purpose dams.

Impacts on water users

The proposed flood management measures are anticipated to decrease the total annual volume of surface water discharged by streams and rivers, primarily due to enhanced water retention and evapotranspiration in the mountainous areas. Despite this reduction, the net benefits for water security are expected to be positive for several reasons:

1. Enhanced infiltration will increase the amount of groundwater recharge, which will support the recovery of the depleted aquifers and degraded ecosystems. This in turn will support farmers who use groundwater, which accounts for more than 80% of the total irrigated agriculture;
2. The base flow of streams will also likely increase, conveying water for more days during the year;
3. Rivers and streams will carry less sediments.

While the overall quantity of surface water and the net outflow of the Pineios River to the Aegean Sea may decrease, the positive impact during critical periods, such as dry months, is expected to be significant, ensuring a more reliable and sustainable water supply during crucial times of the year.

Impacts on existing dams and reservoirs

Farmers relying on surface water may face challenges due to reduced outflows from mountain sources. However, potential impacts can be mitigated:

Two primary systems dependent on surface water, namely TOEB Tavropou and the Smokovo Dam, are not adversely affected by the proposed measures. TOEB Tavropou draws water from the Plastira Reservoir in the nearby Achelous River Basin, which remains unaffected. Similarly, the city of Karditsa, utilizing a portion of this water for its municipal supply, experiences no negative consequences. Consequently, these measures enhance the safety of Karditsa without repercussions.

To address concerns related to the Smokovo Dam and the future Enipeas Dam, it is advisable to defer or reconsider implementing measures in the upstream areas until more comprehensive assessments, including model calculations, are available. Notably, the resilience demonstrated by the Smokovo Dam during Storm Daniel suggests that, for the time being, intervening upstream may not be necessary.[13].

[13] Therefore the map does not show any structures upstream of the Smokovo Dam.

The potential repercussions for users relying on surface water from smaller dams and reservoirs will be effectively mitigated. This will be achieved through meticulous selection of locations and the thoughtful design of measures in the upstream catchments.

Figure 10 denotes the locations of the smaller dams, whose characteristics are outlined in Table 4. Most of the dams are located in the far upstream portions of the catchments.

Name	Nearest city	Capacity (x 1000m³)	Reservoir area (x 1000m²)	Catchment area (km²)	Purpose
Kalivia Kokinopilou - Palaiomonastero	Karditsa	70	7		Irrigation
Kraneas "Karya 2"	Kranea Elassonas	110	25		Irrigation
Lofos (Asprochomatos)	Elassona	500	50	2.4	Irrigation
Megalo Eleftheroxori	Potamia Elassonas	300	25	1.5	Irrigation
Kranea "Livadia "	Kranea Elassonas	250	40		Irrigation
Logga	Kalabaka	390	100	3	Irrigation/Domestic
Kranea "Agelinadika"	Kranea Elassonas	140	26		Irrigation
Ornia Pournari	Sikourio	50			Irrigation
Smokovo	Karditsa	240,000		380	Irrigation/Electricity Production
Kremassi Akris	Kranea Elassonas	135	26		Irrigation
Gyrtoni	Larissa	5000	1300	7072	Irrigation/Flood Protection
Karla	Volos	13,5000	35,500	1050	Irrigation/Other/Flood Protection
Agioneri	Elassona	15,380	2000	336	Irrigation
Lithaiou (under construction)	Kalabaka	2500			Irrigation
Skepari Agia Paraskevi	Kalabaka	70	11831	1.37	Irrigation

Table 4: Characteristics of smaller dams, data from the Greek government

Flood defense infrastructure in the Trikala and Karditsa prefectures

The fact-finding missions concluded that extreme surface water runoff, characterized as "flash floods," is challenging to attenuate. The discharge capacity of existing drain networks, rivers, and streams is insufficient to manage floods of the magnitude witnessed during Storm Daniel. Recognizing this, it is imperative to implement measures to enhance retention capacity.

Given the mountainous surroundings of Trikala and Karditsa prefectures, a primary focus will be on creating retention capacity in these elevated areas. This strategic approach aims to alleviate pressure on cultivated valleys, although it acknowledges that additional measures are necessary to proactively prevent flooding. Despite these efforts, it is inevitable that certain cultivated areas will persist in experiencing inundations during extreme flood events.

The Master Plan outlines directions for flood defense infrastructure, primarily focusing on safeguarding residential areas. Additionally, it aims to provide protection for areas where valuable assets and facilities are concentrated. However, it is important to note that regions with sparse and isolated premises may still be susceptible to inundations.

Given the significant risk, the recommendation is to refrain from rehabilitating areas with limited and isolated premises. Instead, relocation is advised, particularly considering that most structures in high-risk zones are either damaged or destroyed. Comprehensive details and maps delineating the areas earmarked for protection are elaborated in the subsequent paragraphs.

The primary infrastructure recommendations revolve around the construction of river embankments, along with secondary inland dykes designed to shield vulnerable residential and developed regions in high-risk zones. These inland dykes, often referred to as "*sleeper dikes*," typically remain dry but serve as a contingency in the event of dyke breaches or excessive overland flow resulting from upstream rainfall. The approximate locations of these dykes are illustrated in the following paragraphs.

Final decisions regarding their precise locations and detailed designs will be reached through extensive dialogues with stakeholders and a comprehensive assessment of impacts (Chapter Starting points flood defense infrastructure). These new infrastructures will be customized to the local context, ensuring, for instance, that roads remain unobstructed and drainage water from protected areas can be effectively discharged. This may necessitate the establishment of temporary pumping capacity to redirect excess rainwater from protected zones into designated areas for temporary inundation.

In addition to area-specific infrastructures a number of generic measures are needed, which apply to the entire region. These measures are presented in Chapter Development strategy for flood defense infrastructure . In the following paragraphs area-specific directions for flood defense infrastructures are presented.

Trikala City and surroundings

Figure 12 shows the city of Trikala and its environs. The inundation of numerous residential areas resulted from substantial runoff originating from the northern hills, collecting in the valley of the Agiamoniotis stream, which traverses the city. Unfortunately, there is restricted space available to augment the discharge capacity of this stream.

Expanding the stream's capacity would not only be limited by space constraints but would also significantly encroach upon aesthetic values. Moreover, such a transformation is deemed undesirable from the perspective of urban development.

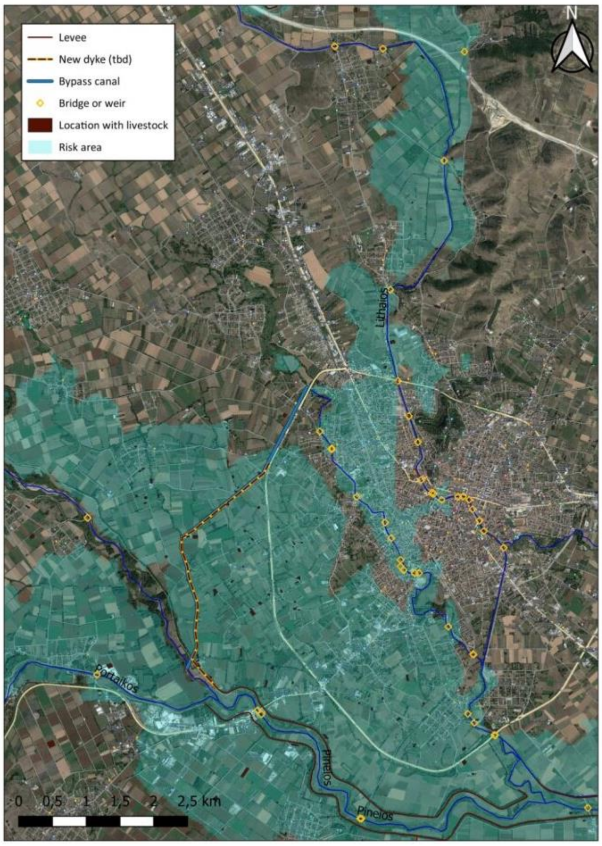


Figure 12: Flood defense Trikala City and surroundings

Hence, it is advisable to explore the feasibility of creating a bypass canal leading to the Upper Pineios, coupled with the construction of a levee spanning approximately 4 km to the west of the city. This integrated system holds the potential to safeguard the properties situated west of the ring road, facilitate the prospect of future residential expansion, and contribute to the protection of the villages Dipotamos and Rogkia, located to the west of Trikala. Precise locations and design specifications can be ascertained through an exhaustive field survey and meticulous model calculations.

Furthermore, it is crucial to uphold and clear the floodplain of the Lithaios from sediments and/or vegetation (Chapter Development strategy for flood defense infrastructure). The city of Trikala is equipped with numerous bridges, necessitating a thorough assessment of the hydraulic properties of each, especially those spanning the Lithaios. In instances where the model identifies a hydraulic perimeter below acceptable levels, excavation of the riverbed becomes imperative[14].

Figure 12 also indicates the construction of various structures within the floodplain. Although currently not posing critical obstacles, it is imperative to communicate to property owners that these premises will not benefit from the proposed protective measures. Strict regulations should be enforced to prevent the construction of any new structures in the floodplain.

The villages of Dipotamos and Rogkia, located to the west of Trikala, experienced flooding due to substantial runoff volumes accumulating in the streams running through the area. The streambeds are densely populated with vegetation and trees. Clearing these streambeds from upstream to downstream is anticipated to significantly reduce the risk of flooding. In the event of constructing the bypass canal, the stream can discharge into this bypass, situated west of Trikala.

A comparable scenario unfolds in the village of Sotira, north of Trikala. Implementing maintenance measures on the Lithaios riverbed will help alleviate the risks of inundation. Should model calculations indicate insufficient effectiveness of this intervention, consideration may be given to constructing a dyke to the east of the village (although not depicted on the map).

[14] If this turns out to have insufficient effect the bridge may need replacement.

Karditsa City and surroundings

Southern part of Karditsa City

Figure 13 shows the areas affected by the inundation during Storm Daniel in the City of Karditsa and its vicinity. The southern sections of the city experienced flooding due to breaches in the levees[15] along the Gabras River. These breaches resulted from substantial runoff originating from the southern and western hills, exacerbated by the condition of the river and levee maintenance. The breaches in the dyke system led to extensive damage to the irrigation infrastructure.

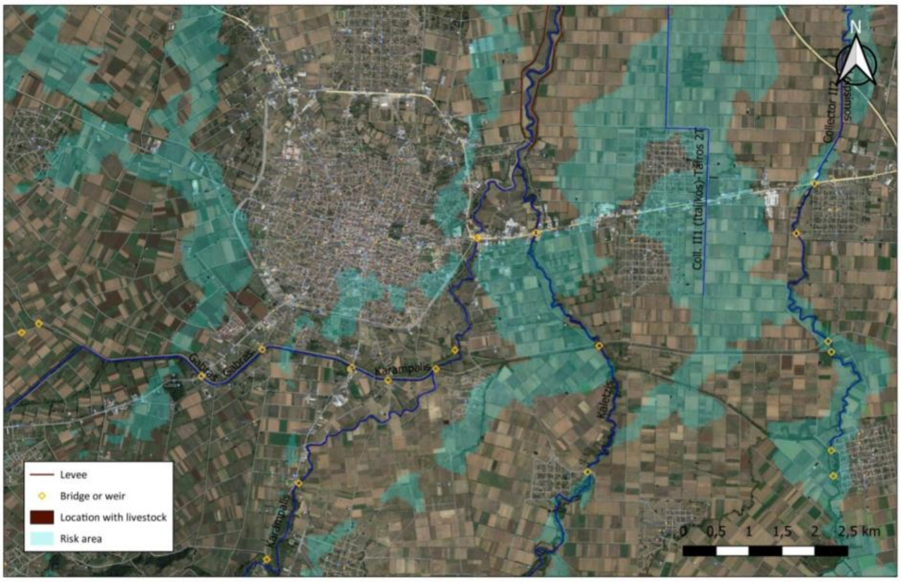


Figure 13: Flood defense Karditsa City and surroundings

At least the northern levee along the Gabras River must be strengthened, as it nearly broke again during the Storm Elias that occurred a few weeks after Daniel (see Figure 14). As the levees in the Karditsa area have far from uniform heights they must be repaired, raised and levelled.

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[15] The levees are not visible on the map

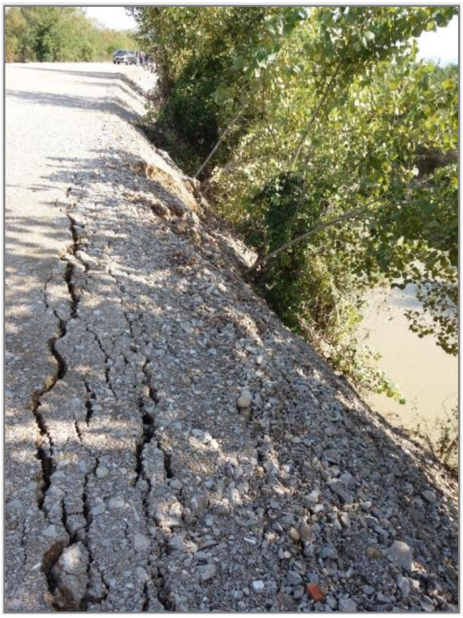


Figure 14: Vulnerable dyke south of Karditsa City

The stream east of the village Mavrikas, situated southeast of Karditsa, requires remodeling at its outlet. During Storm Daniel, backwaters from the stream were induced by the railway, resulting in the inundation of the village.

It is imperative to conduct a comprehensive assessment of the hydraulic properties of bridges, with particular focus on the two bridges east of Karditsa. This scrutiny is essential, given that inundations occurred just upstream of these bridges during the storm event.

Eastern part of Karditsa and Stavros

The inundations observed between the Karampalis and Kaletzis rivers, east of Karditsa, indicate a malfunction in the field drains system. While backwaters from the confluence of the Kaletzis and Karampalis rivers may have contributed, the primary impediment to the discharge of excess rainwater appears to be the road from Karditsa to Stavros. To address this, both the field drains and the floodplains of the Karampalis and Kaletzis rivers require clearing. Additionally, the discharge locations of the field drains must undergo scrutiny and potential improvement.

A parallel situation occurred further east, where the road acted as a barrier, causing inundations in the southern part of Stavros. In this context, the drains running east of the town need clearing, and an assessment of the state and size of the road crossing is necessary. If deemed necessary, enlarging the crossing by installing larger or additional culverts may be a viable solution.

The two collector drains running north between the Kaletzis and Orgozinos rivers lack sufficient capacity to handle excess rainwater. It is imperative to clear and possibly resize these drains to safeguard the villages of Myrina and Gorgovites, the aerodrome, and the irrigated lands. Notably, one of the collectors runs partially through a natural stream (Leipsimos), requiring special attention to ensure effective drainage.

Kaletzis River

Figure 15 shows the downstream portion of the Kalentzis River (and the Megas) with inundated areas. Seeing the extent and depths of the inundations choices need to be made about the areas that will be protected and areas that will not be protected and thus remain subject to inundations during extreme meteorological events.

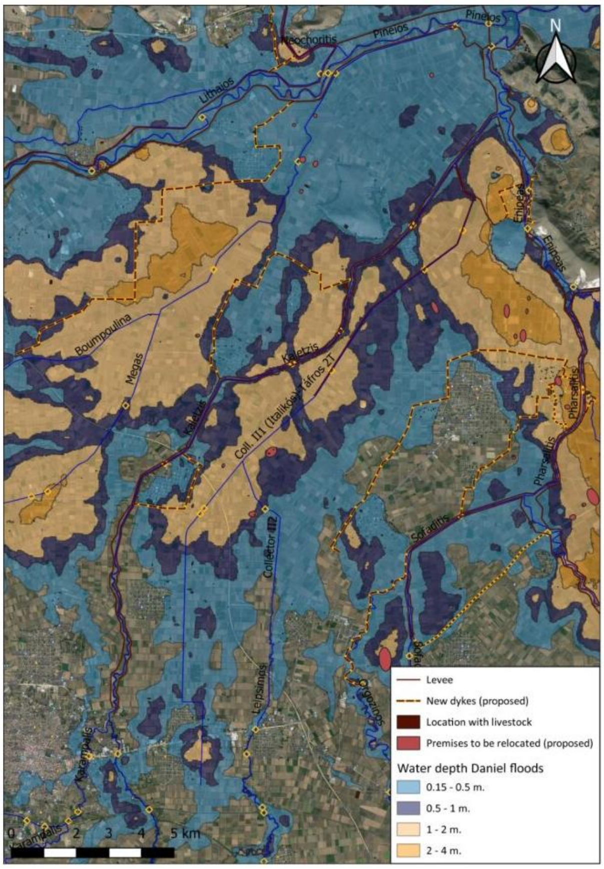


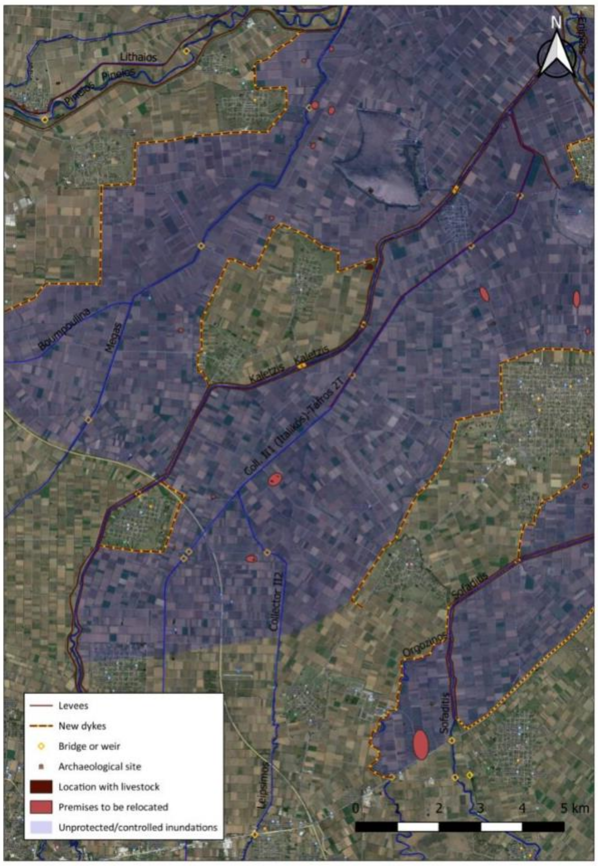
Figure 15: Flood situation Kaletzis and Megas

East bank

The confluence of the two collectors east of the Kaletzis River, occurring east of the village of Makrychori, resulted in extensive inundation during Storm Daniel. This phenomenon was primarily attributed to water impoundment at their discharge point. The combined accumulation of water from these collectors, along with another collector drain further north, the Kaletzis River itself, and local rainfall, led to widespread inundations. These inundations affected the village of Metamorfosi, exacerbated flooding in Vlochos, and posed a threat to the City of Palamas.

In the Master Plan, a section of this area has been identified as a zone where temporary inundations during extreme floods are unavoidable. Given the limited number of premises in this designated area, and considering the likelihood of substantial damage, it is recommended not to rehabilitate these structures. Instead, relocation is advised for the affected premises (Figure 16).

Both Palamas and the village of Markos need protection by an inland levee, which should be constructed west of the



residential areas (

Figure 16: Flood defense Kaletzis and MegasFigure 16).

The dyke west of Vlochos should be raised. It is expected that Makrychori also needs additional protection by a dyke east of the village.

Due to the inherent challenges in effectively protecting the village of Metamorfosi and the absence of viable evacuation options, a strong recommendation is made to seriously consider the abandonment of the entire village. Relocating the residents to safer areas, particularly after implementing protective measures in Palamas, is highly advisable. This proactive approach prioritizes the safety and well-being of the community, mitigating the risks associated with the vulnerable location of Metamorfosi.

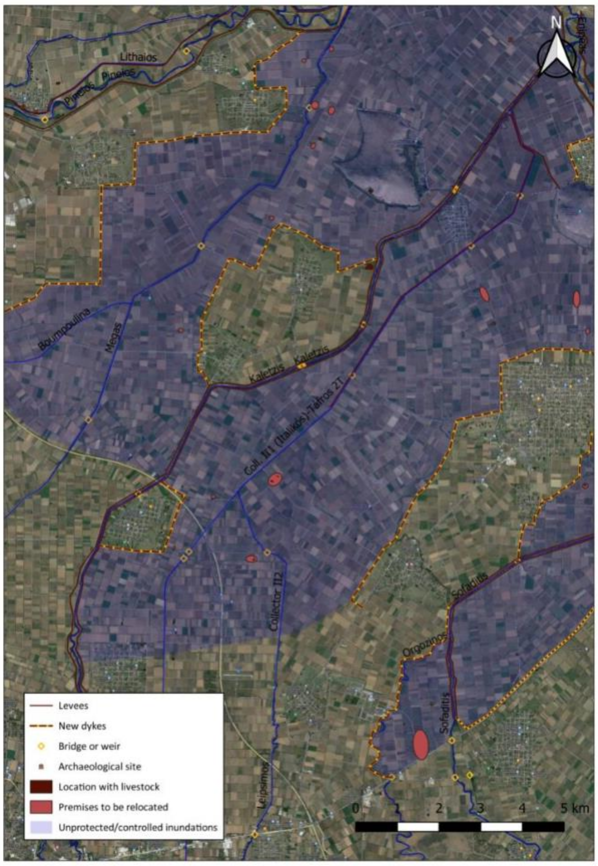


Figure 16: Flood defense Kaletzis and Megas

The hydraulic properties of bridges must be thoroughly assessed, with particular emphasis on those spanning the Kaletzis River at Makrychori. Special attention is warranted for the newly constructed bridge, adjacent to the ancient structure near Psathochori and Koskinas (Figure 17). Additionally, the bridge near Psathochori and Koskinas, situated in the floodplain, demands careful examination due to indications of breaches in the levees caused by the presence of an ancient structure.

In instances where the hydraulic perimeter is deemed insufficient based on the model's evaluation, measures such as riverbed excavation or bridge remodeling may be imperative. Comprehensive floodplain management is essential, necessitating the removal of obstructive elements, sediments, debris, and vegetation at various locations to ensure optimal functionality and resilience against potential hydraulic challenges.

Figure 17: Bridge near Psathochori and Koskinas

West bank

To the north of Makrychori village, areas along the Kaletzis and Megas rivers are designated as zones where temporary inundations during extreme floods are inevitable (refer to the next paragraph for further details). Psathochori village requires protective measures such as dykes. Similarly, the village of Koskinas may necessitate dyke protection, although a serious consideration should be given to the alternative option of relocating residents to safer areas. In such a scenario, adjustments to the inland dyke may be feasible.

In the unprotected zones, only a few structures remain, likely heavily damaged. Rather than rehabilitation, relocation of these premises is recommended.

North of Metamorfosi, the western levees along the Kaletzis River should be equipped with gates to facilitate water release into the temporary inundation zone during the risk of dyke breaches due to high water levels in the Enipeas River. If abandonment of Metamorfosi is contemplated, a similar approach should be applied to the eastern levees. Comprehensive planning is crucial to address potential risks and ensure the safety and resilience of the affected areas.

Megas

In the northern lands of Karditsa, the majority of excess rainwater is channeled through a drainage system towards the Megas River. Unfortunately, during Storm Daniel, the lands along the Megas experienced severe inundation, with water depths reaching 2-4 meters. This inundation disrupted the drainage system, causing overflow into lands along the main drains north of Karditsa, ultimately reaching the village of Artesiano. The drainage channels exhibit significant vegetation that requires urgent removal.

The determination of whether the Megas River's discharge capacity is insufficient in this region necessitates model calculations. It remains unclear whether this section of the Megas is impacted by water backing up due to elevated levels at the Boumpoulina tributary and Pineios River. Protecting this area poses challenges, especially given the presence of numerous structures between Karditsa and the Megas River. Prioritizing maintenance and clearance efforts is crucial. Simultaneously, a comprehensive investigation and optimization of the Megas River's discharge capacity are imperative.

Depending on the assessment results, the village of Artesiano and potentially the northern part of Karditsa may require additional protection through the construction of a dyke ranging from 1-2 meters in height. Given the Megas River's low elevation in the valley and its predominantly agricultural water source, constructing levees north of Karditsa is deemed impractical and not considered a viable solution.

Boumpoulina

At the confluence of the Megas and Boumpoulina rivers, downstream areas experienced extensive inundation, encompassing the entire region between the Upper-Pineios and Kalentzis-Enipeas due to water impoundment at discharge locations.

The villages of Proastio, Marathea, Pedino, Servota, and Korda, situated between the Boumpoulina and the Pineios River, can be safeguarded by constructing an inland dyke to shield them from inundations originating from the lower section of the Megas. Evaluation suggests the possible necessity of heightening the dyke along the Pineios to prevent northward inundations.

A significant portion south of these villages is designated as an area where temporary inundations during extreme floods are unavoidable. Given the likely extensive damage, it is recommended not to rehabilitate but relocate the few existing structures in this zone.

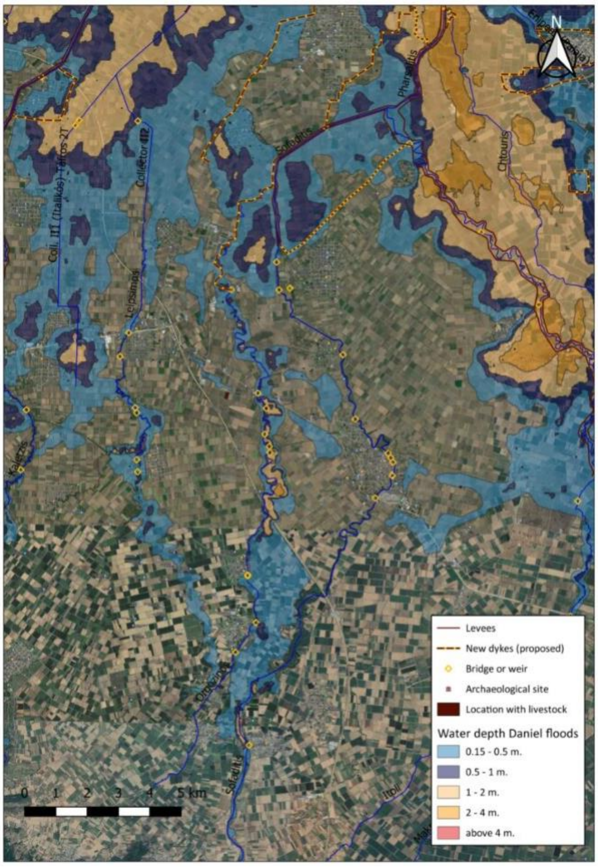
The situation in the villages of Agnandero Karditsas, Pamisos, Kalogriana, and Paleochori is intricate, as these areas are influenced by three rivers—Pamisos, Boumpoulina, and Pineios. Model calculations are essential to identify protection options for these villages, taking into account interventions in their respective river basins. The town of Megala, positioned between the Pineios and the Pamisos, may benefit from protection by an inland dyke, which could also create a broader floodplain for the Pamisos. Careful consideration and strategic planning are crucial for effective flood mitigation measures in these complex scenarios.

Sofaditis and Orgozinos

Upstream portions: Figure 18 illustrates the river basin of the Sofaditis and its tributary Orgozinos. During Storm Daniel, the area north of the village Filia experienced inundation, leading to the flooding of the small village Anogio (refer to Figure 17: Flood situation Sofaditis). To address inundations along the upper Sofaditis, optimizing the operation protocols of the Smokovo Dam is recommended to align with flood management requirements. This optimization aims to contribute to a more effective flow regime for the Sofaditis during flood events.

Implementation of improved protocols should prioritize clear communication between dam operators and observers stationed at downstream locations along the river during flood occurrences. Enhanced coordination and information exchange are vital components for proactive flood mitigation strategies in the Sofaditis river basin.

Figure 18: Flood situation Sofaditis



The inundations in the upstream sections of the Orgozinos are likely a result of the stream's restricted discharge capacity. Undertaking maintenance and clearance work in the affected areas presents a viable solution to alleviate the situation. By addressing these factors, the flow capacity of the Orgozinos can be enhanced, mitigating the risk of inundations and contributing to improved overall flood management in the region.

Downstream portions: Near the confluence of both rivers the water became impounded and areas at the confluence and east of the Sofaditis became inundated.

By constructing a dyke west of the Orgozinos the village Markos can be protected (Figure 19: Flood defense Sofaditis. The levee west of the Sofaditis has to be equipped with a few (1 or 2) gates that can be opened during and after flood events to discharge water from inundated areas north of Palamas. In normal conditions these gates will be closed.

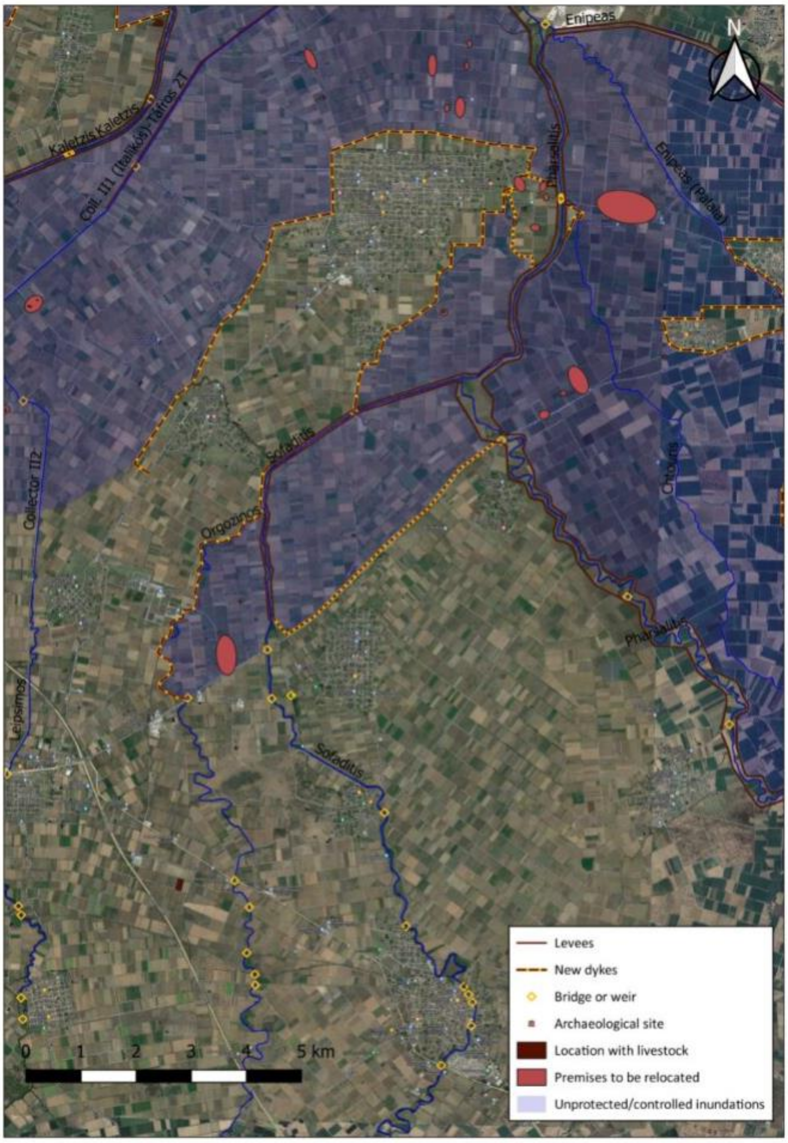


Figure 19: Flood defense Sofaditis

The storage company located north of the Karditsa-Larissa road (south of Markos) experienced inundation after Storm Daniel. Given the absence of additional structures in the area between this road and the confluence and considering the likelihood of significant damage to the premises, it is advisable not to pursue rehabilitation. Instead, relocating the company is recommended. Furthermore, redesigning the area to facilitate temporary water retention is advisable, recognizing that the current drainage capacity of ditches and rivers falls short of accommodating peak discharges. This approach aims to enhance resilience and mitigate the impact of future extreme weather events on the affected area.

East of the Sofaditis, just north of the Karditsa-Larissa road, the confluence of the river Sofaditis and the Sofaditis stream resulted in inundations that pose a potential threat to the village of Mataragka. To address this, it is recommended to thoroughly clear or even excavate the bed of the Sofaditis at this location, particularly since the levees restrict the floodplain to approximately 90 meters (Figure 19: Flood defense Sofaditis). The area north of the road is designated as a zone where temporary inundations during extreme floods may occur. While the road acts as a barrier to water flow towards the village of Mataragka, the construction of a small levee north of the road and/or an interceptor drain may be necessary. This strategic intervention is essential for crisis management and evacuations, while also enhancing the capacity to temporarily store floodwaters from the Sofaditis or Pharsalitis rivers.

The zone north of the confluence of the Sofaditis and Orgozinos is similarly designated as an area where temporary inundations during extreme floods may occur, excluding the city of Palamas and the village of Markos. These areas should be safeguarded by the construction of an inland dyke, potentially requiring a height of up to 5 meters northeast of Palamas. To the east of Palamas, where a few premises are located, relocation or the construction of another dyke for protection is advised. Provisions should be made to enable water discharge between the two areas through the gully towards the north. Furthermore, premises north of Palamas should be considered for relocation (see Figure 19: Flood defense Sofaditis). Comprehensive planning and implementation of protective measures are crucial to enhance the resilience of these vulnerable areas against potential flooding risks.

Pharsalitis

Upstream portions: During Storm Daniel, extensive areas in the upstream sections of the Pharsalitis and the Kakara tributary, including the village Neo Ikonio and parts of Stavros, experienced inundation. The probable cause of these inundations is the limited discharge capacity of the two rivers. Implementing maintenance and clearance work is a recommended measure to mitigate the situation. Additionally, the construction of extensive flood retention structures in the mountains can further reduce the risks of inundations in the upper regions of the Pharsalitis River and its tributary, Kakara.

Further downstream, water impoundment occurred near the confluence of the Pharsalitis and the Makryrema River. While there are hardly any premises in this area, any damaged structures should not be rehabilitated but rather relocated. Despite the sparse development, the inundations reached the town of Stavros. Decisive answers regarding the sufficiency of maintenance works and check dams in the mountains to protect the town should be provided through detailed model calculations. This analytical approach is essential to accurately assess the level of protection required for Stavros and to inform future flood mitigation strategies in the region.

Downstream portions: After the confluence of the Pharsalitis with the Apidanos Tampakos, the entire valley through which the Pharsalitis and Chtouris rivers flow experienced severe inundation following Storm Daniel, with water depths reaching up to 4 meters. These inundations were triggered by impoundments downstream at the confluence of the Pharsalitis with the Sofaditis, shortly thereafter at the confluence with the Enipeas, followed by the confluence with the Kaletzis, and ultimately at the Pineios River. These major rivers, originating in the mountains with relatively large catchments, converge in a small area, each capable of discharging substantial water volumes during storm events. Inevitably, inundations at the confluences of these rivers are unavoidable in the event of extreme meteorological occurrences like Storm Daniel. Decisions need to be made regarding areas that will be protected and those that will remain susceptible to inundations during such extreme events.

The Chtouris serves as the principal drainage course for the agricultural lands between the Pharsalitis and Enipeas. During Storm Daniel, it was unable to discharge its water into the Pharsalitis, resulting in flooding in the adjacent areas. Given its role as the main drain in the region, the construction of levees along the Chtouris is deemed impractical, as it may lead to more inundations rather than mitigating them. Strategic choices and planning are necessary to strike a balance between protecting vulnerable areas and acknowledging the inevitable inundations at the confluences of major rivers during extreme meteorological events.

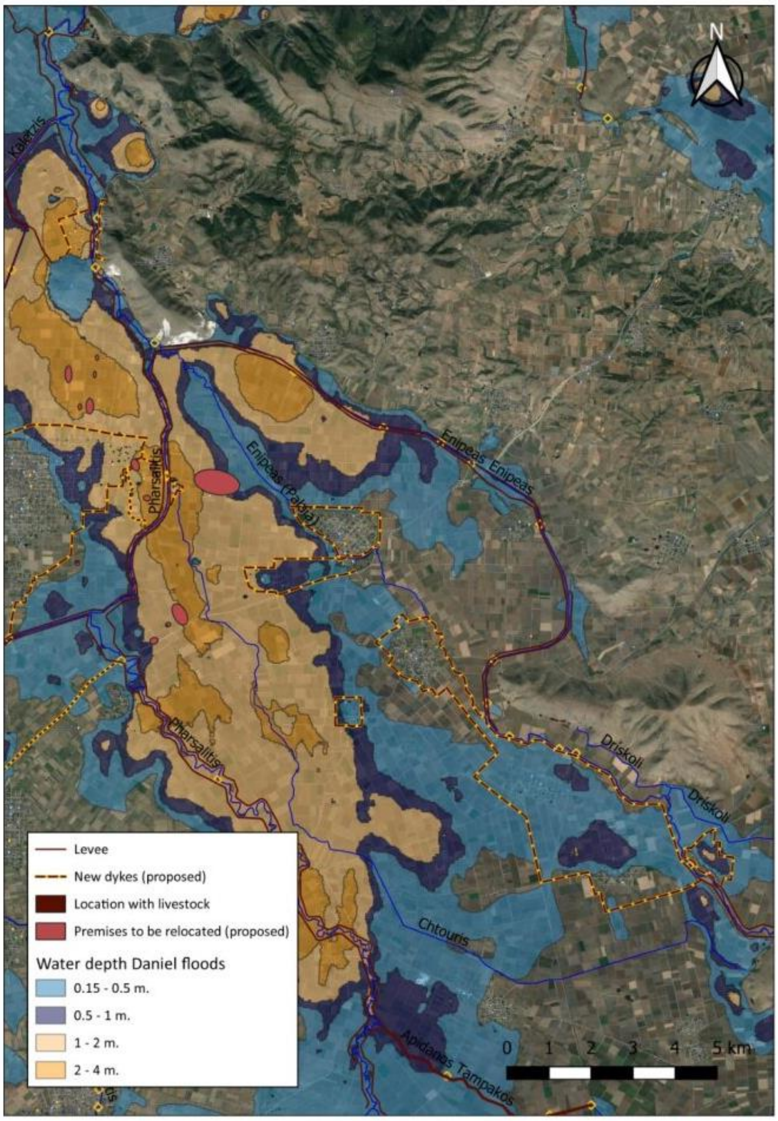


Figure 20: Flood situation Pharsalitis and Enipeas

As it will not be possible to protect the entire downstream areas of the Pharsalitis (and Enipeas) against extreme events such as the Storm Daniel temporary inundations have to be accepted for part of the area. Almost the entire area situated north of Chtouris is designated as zone where temporary inundations may occur. Except from the villages Astritsa, Ampelonas, Itea and Fyllo there are hardly any premises in this area. The four villages will have to be protected by dykes (Figure 21) and access and evacuation routes secured. It is, however, noted that Astritsa and Ampelonas are difficult to protect. During severe floods these villages will become fairly isolated places in the inundation areas ("islands"). Evacuations may become cumbersome without significant additional evacuation structures, for example more elevated access roads. It may therefore be considered to abandon these villages and relocate the people to safer places. Within the protected villages the urban drainage system should function optimally, and provisions must be made to discharge the water outside the diked area. It may be necessary to use (mobile) pumps during floods.

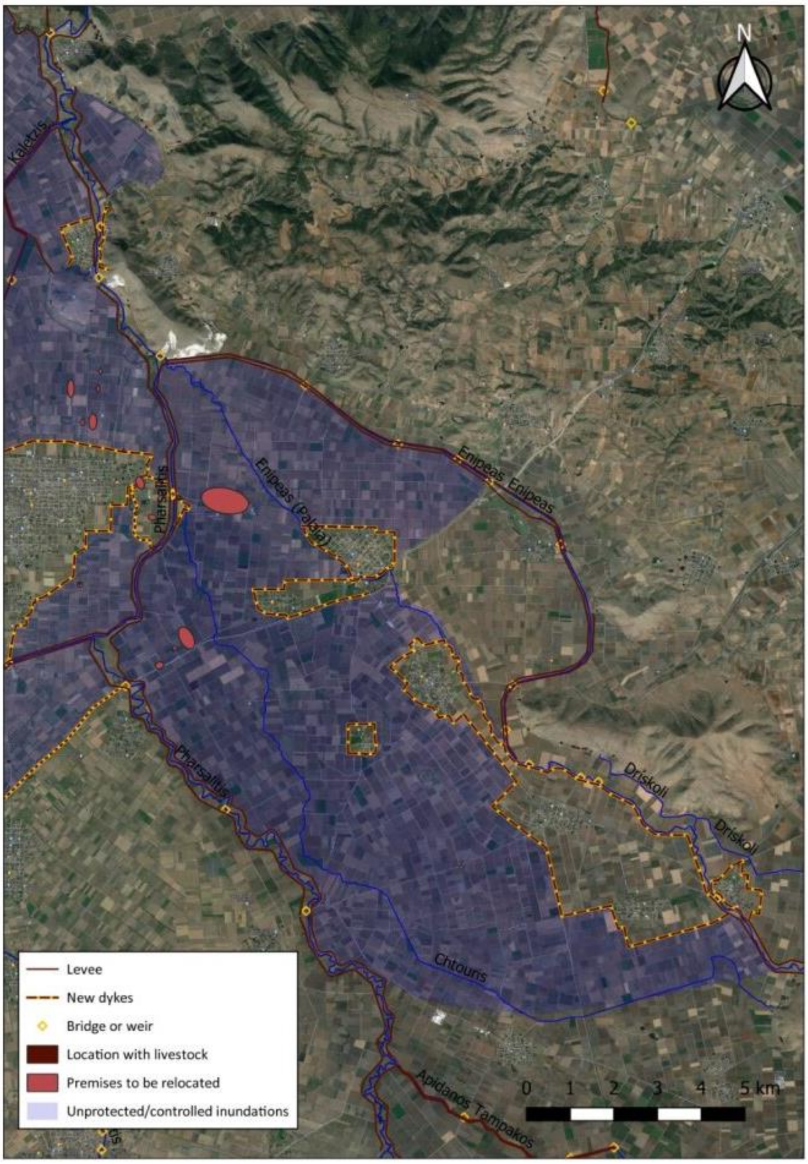


Figure 21: Flood defense Pharsalitis and Enipeas

North of Palamas the levees along the Pharsalitis may need to be provided with gates in order to facilitate the release the water to the temporary inundation zones at both sides of the river, in the case of the risk of dyke breaches due to high water levels in the Enipeas River.

Enipeas

The Enipeas river basin, encompassing approximately 3.200 km2, stands as the largest river basin in the Karditsa prefecture. Alongside its tributary basins, the Kaletzis and Pharsalitis, the Enipeas River plays a pivotal role in draining excess rainwater from nearly one-third of the Pineios River Basin. As the largest of the three rivers, the Enipeas River basin extends across vast mountainous areas.

In order to manage the runoff effectively, similar to the catchments of the Kaletzis and Pharsalitis, it is imperative to construct extensive flood retention structures in the mountains. A study conducted by the University of Thessaloniki (Karachaliou, 2023) identified the most favorable locations for 40 small dams to optimize the hydrographic network of Enipeas in Thessaly. Although these specific locations are not depicted in Figure 10: Selected locations for water retention in mountainous areas of Thessaly, it is noteworthy that a significant development has occurred. It has recently been decided to construct a large dam, the Enipeas Dam, east of the village Skopia. While the Enipeas Dam will undoubtedly have a substantial impact, the potential benefits of constructing additional small dams in catchments downstream of this major dam should be thoroughly assessed.

Initiating discussions about discharge protocols for the new Enipeas Dam is strongly recommended at the earliest opportunity. Establishing effective protocols is crucial to enhance the flow regime of the Enipeas River during floods. These protocols should encompass robust communication procedures between dam operators and observers situated at downstream locations of the river, facilitating real-time information exchange.

Comprehensive maintenance works for the entire riverbed are imperative. Coupled with optimized dam operation, these measures will collectively contribute to mitigating the risks of inundations in the upper regions of the river, extending down to the village of Megalo Efidrio (not on the map).

Further downstream, extensive areas experienced inundation due to water impoundment near the confluence of the Pharsalitis (as discussed in the previous paragraph). To prevent the flooding of the village Enipeas, enhancing the levee at the south bank of the Enipeas between the villages Pirgakia and Lofos is recommended. Strengthening this levee infrastructure is vital to provide effective protection for the village and surrounding areas, minimizing the impact of future flood events.

North of the village of Iperia, it is recommended to construct or improve a dyke along the south bank of the river to safeguard the villages of Orfana and Lefki. Additionally, an inland dyke is essential for optimal protection of these villages. Considering the lack of premises outside the villages, relocation is advised for any existing structures in these areas.

The village of Iperia itself requires protection by a dyke, given its proximity to the outflow of the Driscoli drain into the Enipeas. In instances of high water levels in the Enipeas, the area is susceptible to inundations, making the dyke a crucial safeguard.

In the most downstream portions of the Enipeas River, it is recommended to raise the levee protecting the village of Vlochos and connect it to the proposed new dyke north and west of the village. Another dyke on the opposite side of the river may also be necessary. Sizing these dykes requires detailed calculations of the peak discharges from the Enipeas River and its tributaries, considering the timing of peak occurrences. Fine-tuning measures such as check dams in the mountains and controlled inundations further downstream is essential to prevent amplification of peak discharges. A reliable, detailed hydrological model is imperative for optimizing these measures. It is crucial to note that constructing dykes to protect Vlochos may create a bottleneck in the Enipeas River, narrowing the floodplain to only 150 meters. Model calculations should definitively determine if a combination of measures can alleviate pressure on this bottleneck; otherwise, the unfortunate alternative may be to abandon the village.

At the very downstream portion, the village of Keramidi will likely require a higher dyke. The water passage along the ancient stone bridge south of the village should be assessed and potentially remodeled to enhance flood resilience. Comprehensive planning and meticulous execution of protective measures are essential to ensure the safety and resilience of these vulnerable areas along the Enipeas River.

Neochoritis

In the downstream portion of the Neochoritis, which serves as a northern tributary to the Pineios River, the village of Oichalia Trikala experienced extensive inundation during Storm Daniel. This was attributed to excessive water volumes cascading down from the mountains. Proposed check dams in the mountainous areas are recommended to mitigate inundation risks for the village and protect the surrounding monuments.

The impounding of water just upstream of the levees was likely a consequence of the small spacing between the levees, causing a narrowing down of the floodplain to approximately 60 meters. To prevent such issues in the future, it is advisable to extend the levee on the west bank over a maximum length of approximately 3 km. This extension will help enhance the floodplain's capacity and improve the overall flood defense system, reducing the likelihood of inundations and safeguarding the village and its cultural heritage. Strategic planning and meticulous execution of these levee extensions are essential for long-term flood resilience in the Neochoritis area.

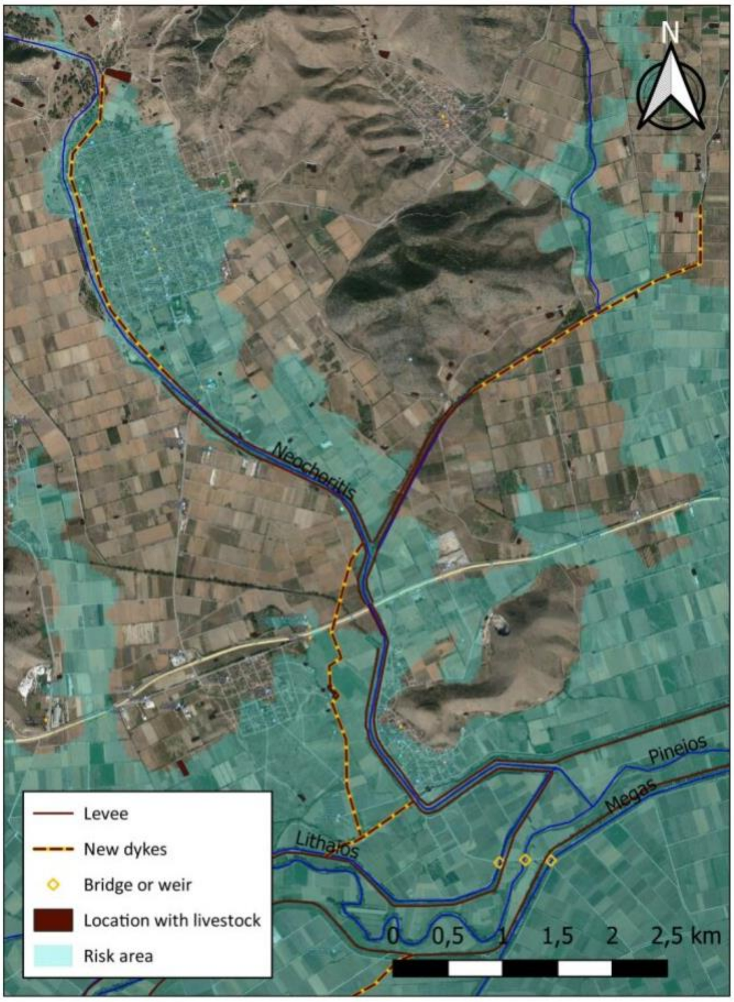


Figure 22: Flood defense Neochoritis

Considering the potential flood risks, it may be necessary to consider the construction of a new dyke on the south bank of the eastern branch of the Neochoritis to protect the village of Farkadona.

After the confluence between the two branches, the existing levees continue in close proximity. To enhance protection for the villages of Klokotos and Georganades, it will likely be necessary to relocate the western levee to a greater distance from the river. This relocation can be coordinated with the relocation of the dyke along the northern bank of the Pineios River, connecting with this new dyke just south of Klokotos. These measures aim to provide more space for the Pineios and Neochoritis rivers, reducing impoundments near the confluences.

The land currently cultivated with fodder and cotton in this area appears suitable for such purposes, and since there are no assets and no boreholes present, it facilitates the implementation of these measures to enhance flood defense. Comprehensive planning and coordination are crucial to optimize these levee relocations and ensure effective flood management in the Neochoritis region.

Upper and middle Pineios

Upstream portions: In the upper portion of the Pineios River, which drains a substantial mountainous area, local inundations were observed north of the bridges at Dialekto (Figure 23). It is recommended to conduct a thorough investigation into the hydraulic properties of this area to understand and address the factors contributing to these inundations.

Further north, local inundations were caused by a dam or another obstructing element in the riverbed. Implementing water retention structures and clearing the riverbed are expected to contribute significantly to mitigating flood risks in these areas. Although the volume of water downstream in the Pineios River will still be considerable, the implementation of these measures is anticipated to slow down the flow, resulting in lower maximums and reducing the overall flood impact in the affected areas.

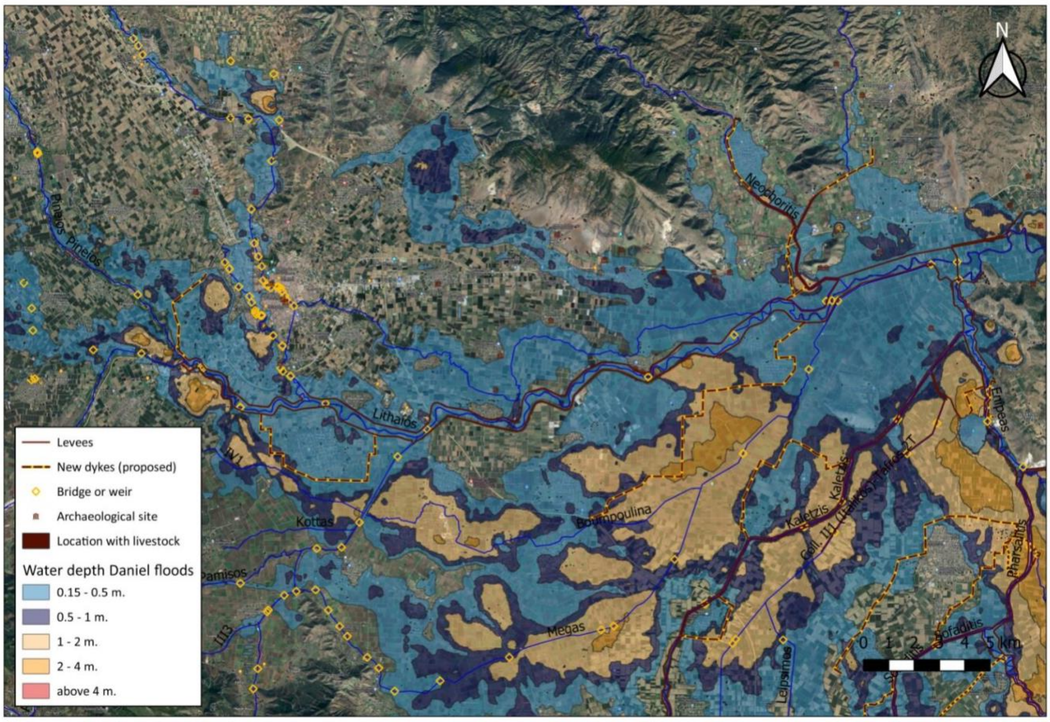


Figure 23: Flood situation Upper and Middle Pineios

North of the Portaikos tributary the villages Dendrochori and Kallidendro became inundated because the Portaikos Potamos drain could not discharge the excess water This drain needs clearance to increase its drainage capacity.

Valley of the Pineios River

Close to the confluence of the Portaikos and the Pineios River vast areas became inundated after the Storm Daniel.

Figure 24 shows that the area is highly developed with many industries and residential areas. The same applies to the entire valley of the Middle Pineios, from the outlet of the Portaikos down to the outlet of the Enipeas River. In this section of the Pineios a large number of major tributaries discharge their water into the river. The interactions between the Pineios River and its tributaries, and particularly the impacts of the possible interventions in the tributaries on the Pineios cannot be properly assessed without a detailed hydrological model.

Irrespective of the wide range of measures that are proposed in the tributaries it will be a huge challenge to make the Middle Pineios safe, as in this region huge volumes of water will accumulate during extreme rainfall. This is illustrated by the previously calculated peak discharges of the tributaries at their discharge point into the Pineios (according to the existing flood management plan). Although that these values are indicative, whereas the proposed directions of interventions will largely attenuate the peak discharges, the data show that the Pineios River will have to accommodate huge volumes of water during extreme events.

River basin[16]	**Peak discharge at outlet Return period of 100 years (m^3/s)**	**Peak discharge at outlet Return period of 1000 years (m^3/s)**
Upstream mountains	3178	6106
Portaikos	3171	6669
Agiamoniotis/Trikala	448	770
Pamisos	2128	4208
Neochoritis, Lithium and Lithaios	1524	3430
Megas	1252	3095
Kalentzis	3310	6124
Sofaditis	1610	3297
Pharsalitis (excluding Sofaditis)	1085	2465
Enipeas (excluding tributaries)	2291	3596

Table 5: Peak discharge per River Basin

The basins of different tributaries exhibit distinct physical characteristics, resulting in varied peak discharges reaching the Pineios River at different times. Furthermore, the implementation of retention

[16] Flood Management Plan of the River Basins of the Water Department of Thessaly. Stage 1, Phase 3 (December 2018).

measures in mountainous areas and controlled inundations serves to mitigate these peak flows. To ensure the most favorable hydrographs at the outlets of the tributaries, it is crucial to harmonize and optimize measures across the various basins. This synchronization aims to attenuate peak discharges in the Pineios River to the maximum extent possible. Achieving this objective constitutes a complex task necessitating a thorough evaluation through the utilization of a hydrological model. Without such an assessment, it is not possible to provide meaningful recommendations for interventions in the Middle (and Lower, as discussed in the next chapter) Pineios.

Pineios River downstream of the Enipeas confluence

Downstream of its tributaries, the Pineios River flows into a wide valley with a width of 1-2 km, extending further east into the Kalamaki Canyon towards the city of Larissa. The valley, particularly downstream of Enipeas, experienced complete inundation following Storm Daniel. This region serves as the natural floodplain of the Pineios. With the exception of a few structures that are challenging to safeguard, one noteworthy area is the southern part of the village Piniada, which could potentially be protected by the construction of a dyke (Figure 24).

According to data from the Greek government, numerous archaeological sites are situated in this region. It is imperative to conduct a thorough investigation into the locations and conditions of these sites. Given that the sites are situated in an area susceptible to floods, their vulnerability might be relatively low. However, it is crucial to acknowledge that safeguarding these archaeological sites from floods, particularly those triggered by events like Storm Daniel, is practically unfeasible in this specific area.

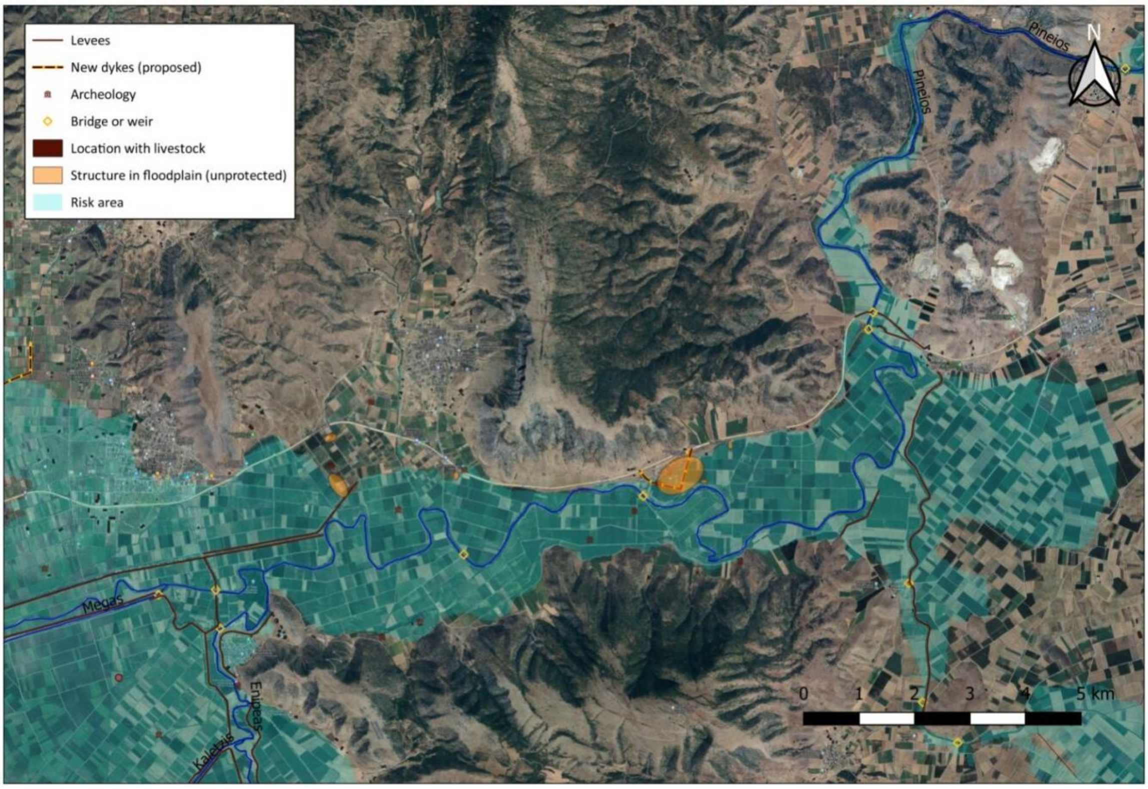


Figure 24: Flood defense Pineios downstream of Enipeas confluence

Implementation

The following box presents a summary of the steps for implementation of flood defense structures in the Trikala and Karditsa prefectures:

Immediate actions (6-9 months):

- Data collection, field surveys and construction of a hydrological model for the planning and preliminary designs of flood defense structures.
- Investigate damage, especially in the future unprotected areas and the willingness to relocate premises and residential zones.
- Investigate the situation of archaeological sites east of the confluence between the Pineios and Enipeas.
- Evaluate and refine the proposed flood defense structures and potential alternatives with the aid of the hydrological model (feasibility study).
- Investigate the local availability of materials for dyke construction.
- Assess and document archaeological values of all bridges.
- Mobilize investment funds.
- Conduct activities specified in Chapter Development strategy for flood defense infrastructure .

Follow-up actions (9-24 months):

- Liaise with stakeholders and financial experts to discuss and agree on proposed measures.
- Remodel bridges and other hydraulic infrastructures.
- Conduct detailed designs of (existing and new) dykes, gates, bridges, detour canals, road- and railway crossings and other structures.
- Determine the bill of quantities.

Follow-up actions (2-5 years):

- Tendering and construction.
- Continuous monitoring of progress and quality (by Task Team).

Flood defense infrastructure in the Larissa area

The flood defense structures and measures implemented in the Trikala and Karditsa prefectures have direct implications for the safety of the city of Larissa and its surrounding areas. This interconnectedness implies that certain protective measures for Larissa must be implemented in the Trikala and Karditsa prefectures. Conversely, actions taken in the Larissa area also have repercussions on the Lake Karla basin.

These interrelationships became evident during the occurrence of Storm Danie illustrates that Larissa largely escaped significant damage from the floods, primarily due to the (unintended) inundations resulting from dyke breaches in upstream areas and the intentional breaching of dykes in the downstream area near Gyrtoni. It is worth noting that these dyke breaches, while contributing to the flooding of the Lake Karla area, played a crucial role in preventing the likely flooding of the city of Larissa. Without these interventions, Larissa would have been more susceptible to flooding.

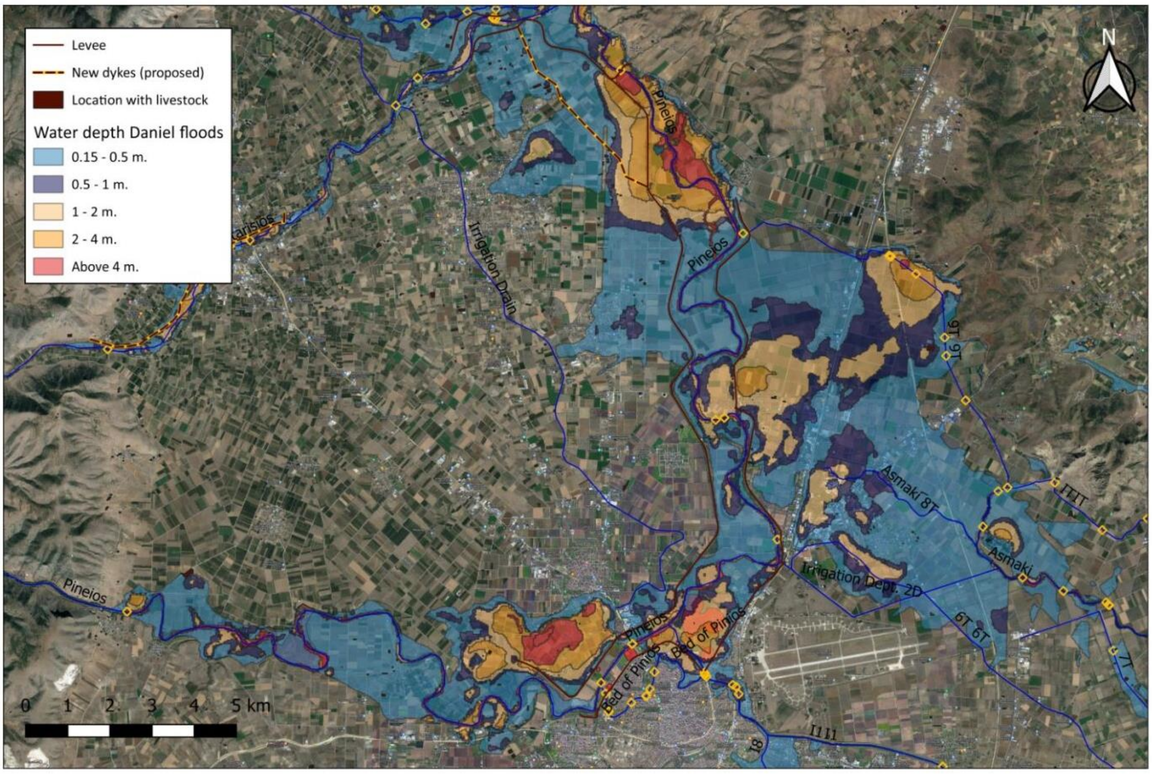


Figure 25: Flood situation Larissa Area

The area of Larissa is surrounded by mountains. The construction of check dams in these mountains, in combination with nature-based solutions, will reduce the flood risk, particularly in the Titarisio river basin. These measures alone are not sufficient, as the area has two other major sources for flooding, namely the Pineios River, which discharges the excess water from the Trikala and Karditsa areas, and the Pineios Potamos (Kousbasaniotis basin).

In the following paragraphs area-specific measures for 5 sub-areas will be elaborated:

- Area West of Larissa City
- Larissa City
- Area North of Larissa City
- Titarisio area
- Valley west of Tempi

Area west of Larissa City

To the west of the city of Larissa, the Pineios Valley expands after the narrow gorge of the Kalamaki Canyon. Subsequently, the Pineios River traverses a small forested area surrounding a meander in the river. Notably, during Storm Daniel, this meander and the accompanying forested region acted as impediments, slowing down the river flow. Consequently, this contributed to the inundations east of the canyon, extending to distances ranging from 500 to 750 meters from the river bed (Figure 25).

The region west of the forest, however, holds the potential for flood attenuation development. The Master Plan proposes exploring the creation of a natural retention area between the canyon and the forest, featuring expanded agriculture and nature, particularly forested areas (Figure 26). A total area of 600 hectares is identified for potential development as a retention area. From a flood management perspective, there are no restrictions on crop selection for farming in this designated area. Given the imperative to minimize the risks of losses due to floods, viable farming options should be collaboratively explored with the farmers in this locality.

It is important to note that the development of a retention area entails agreements and the payment of compensations to property owners, considering the presence of a few premises in this region[17]. Additionally, regardless of the decision to develop a retention area, any structures damaged due to Storm Daniel should not be rehabilitated; rather, relocation is recommended, considering the potentially high cost of protection measures.

[17] The identified assets were taken from satellite images. A field survey should complete this inventory.

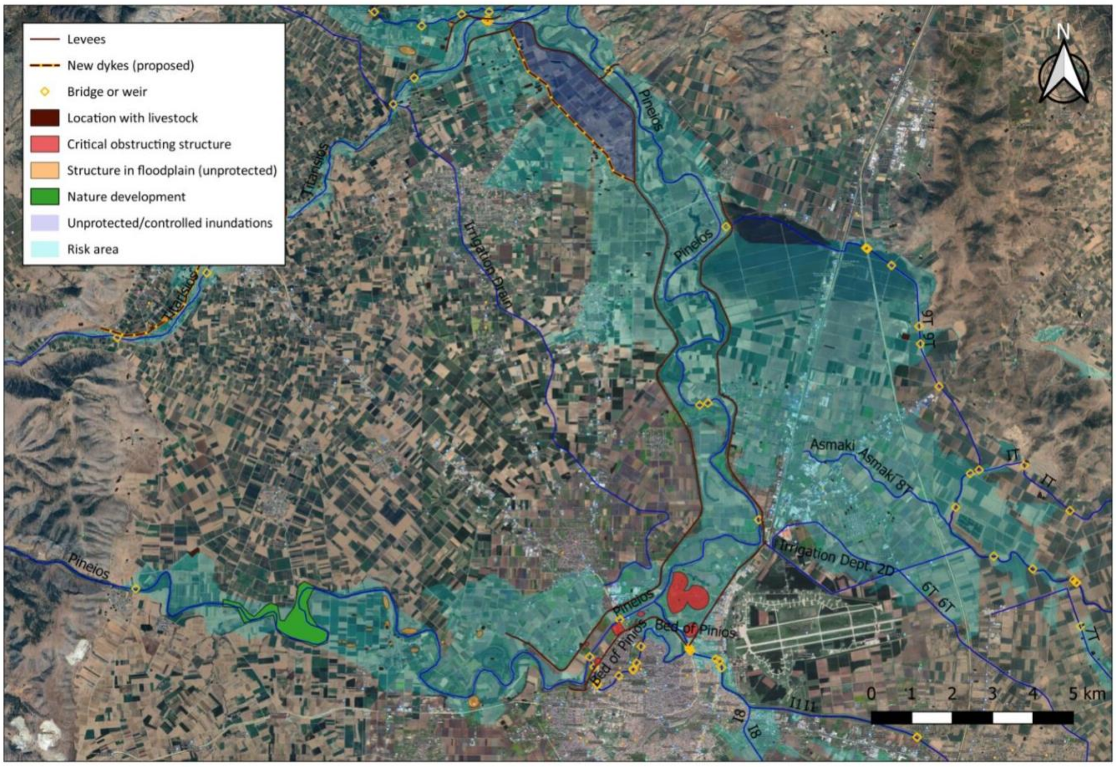


Figure 26: Flood defense Larissa Area

The area between the meander and the start of the levees is presently not protected. Particularly the area south of the Pineios River is vulnerable[18]. Figure 26 shows that quite a few premises and livestock locations are situated in this area. It will be very difficult to protect the area, as it forms part of the natural floodplain of the Pineios. The feasibility of two options should be investigated, which both require the use of the hydrological modelling:

1. Construction of a dyke along the south bank of the Pineios, in combination with the extension of the northern levee, in order to create a floodplain north of the Pineios River. This solution would require the construction of up to 10 km of dykes, in addition to the relocation of the premises north of the Pineios River.
2. Relocate all premises and (partly) develop the area as retention area for the better protection of the city of Larissa.

[18] The inundated areas north of the Pineos were largely due to the situation in Larissa City

Both options are quite drastic and involve elevated costs. Any rehabilitation works should therefore be postponed until the hydrological modelling work is completed and decisions on the development of the area are taken.

Immediate actions (3-6 months):

- Inventory of structures in the area between Kalamaki Canyon and the meander with the forest.
- Explore the willingness and involved costs to remove assets and to convert land.
- Investigate required adaptations in farming in the case of increased inundation risks in this area.
- Investigate nature based solutions.
- Inventory of structures east of the meander and the options and costs to relocate them, and/or to construct dykes.

Follow-up actions (9-12 months):

- Investigate (by modelling) the feasibility of a dyke system to manage the floodplain of the Pineios River west of the city.
- Conduct a detailed design of dyke system.

Follow-up (1-3 years)

- Start relocations and/or construction works.
- Start implementing land conversion (if agreed).

Larissa City

Figure 25 and 26 show that the city of Larissa is principally protected by levees. The floodplain situated between the levees exhibits a width ranging from 550 to 600 meters along the city and approximately 1600 meters after the Pineios Potamos tributary joins.

The precise volume of water that the system needs to discharge is currently insufficiently known and requires determination through hydrological modelling.

Considering the existing flood management plan, it is evident that peak discharges from the tributaries of the Pineios can vary significantly. For a return period of 100 years, these peak discharges range from approximately 500 to 3800 m^3/s, while for a return period of 1000 years, they range from 800 to over

7500 m^3/s. Given these variations, it becomes apparent that the Pineios River must be equipped to handle substantial volumes of water[19].

Therefore, it is of utmost importance to create optimal conditions for the rapid and secure discharge of large volumes of water through the river.

The discharge capacity of the Pineios at Larissa City is basically determined by 4 factors:

- The width of the riverbed and its adjacent floodplain;
- The slope (gradient) of the riverbed and the floodplain;
- The maximum depth of the water (determined by the height of the levees);
- The composition of the riverbed and floodplain.

Interventions to increase the discharge capacity can be made at 3 levels:

- Maximizing the width of the floodplain by remove all obstructing elements (including the re-dimensioning of poorly designed bridges)
- Maximizing the maximum water heights by increasing the level of dykes and/or excavation of the floodplain
- Maximizing the flow velocities by reducing the roughness of the floodplain.

Removal of obstructing elements

Figure 26 highlights critical obstructing elements in the floodplain that significantly diminish the discharge capacity of the Pineios River. The Fact Finding Report specifically identifies the built-up area along the road from Larissa to Giannouli as a notable barrier to the river's discharge. This site constricts the floodplain from around 550 meters to 340 meters, resulting in a substantial reduction in the discharge capacity of the river by approximately 38%. The built-up area acts as a serious bottleneck, playing a significant role in the extensive damages and inundations witnessed in the region west of Larissa during Storm Daniel. Addressing this bottleneck is crucial for enhancing the overall flood management and resilience of the area.

Raising dyke levels and/or excavation of the floodplain

[19] These values have to be recalculated with a more accurate model that includes the proposed directions for interventions upstream. The presented data from the flood management plan are largely indicative.

The maximum water heights can be increased by raising the level of the dykes and by lowering the level of the floodplain by excavation and the removal of accumulated sediments and debris. The following table presents the estimated effect of increased dyke levels and/or flood plain lowering:

Maximum water height of river (m) (difference between dyke level and -weighted- average of river bed and floodplain)	**Discharge capacity (%)**
5	Reference (100%)
7,5	195%
10	315%
12,5	450 %

Table 6: Overview of maximum height of river and discharge capacity

By raising the dyke levels the discharge capacity thus increases sharply (more than proportional). The same is valid for lowering the floodplain. The excavation of 1 meter will already increase the discharge capacity by 15%.

Roughness of the riverbed and floodplain

The land use and state of maintenance of the flood plain has also a great impact on the river flow. The floodplain should be as smooth as possible. For natural water courses such as the Pineios River, the floodplain should ideally consist of pastureland with short grasses. Other land uses will result in lower discharges. The following table gives an indication of the impact of the composition of the flood plain.

Land use in floodplain	**Discharge capacity (%)**
Pasture (short grass)	Reference (100%)
Irrigated or rainfed crops	≈ 75 %
Shrubs, thickets	≈ 60 %
Dense forests	≈ 3 %
Stones with some vegetation	≈ 60-75 %
Fruit trees	≈ 40 %
Wetlands	≈ 75 %

Table 7: Land use in floodplains and discharge capacity.

The table supports the recommendations in the Fact Finding Report, stating that trees and vegetation are serious obstacles that should as much as possible be removed from the flood plain.

Required interventions

The built-up areas and the current state of the floodplain, especially the trees immediately downstream of the bridge, along with other vegetation, have significantly reduced the discharge capacity of the Pineios River from its potential. To address this, doubling the current discharge capacity can be achieved by eliminating obstructive elements and implementing essential maintenance on the floodplain. Additional improvement can be realized by removing sediments. A strict prohibition on any further constructions in the floodplain needs immediate enforcement.

Evaluation of bridges and culverts for their hydraulic properties is essential, and if necessary, redesigning them is crucial. A comprehensive survey of the existing levees is required to identify damages and low spots, with subsequent repairs.

Assessing the need for dyke raising using a hydrological model is imperative. Adequate space exists on both sides of the river for dyke raising, totaling approximately 32 km from the city of Larissa to the Gyrtoni Barrage. The actual design discharge capacity of the system remains unknown. The water level gauge north of the city indicates a riverbed depth of 3-3.5 meters, with the levees accommodating an additional 5 meters of water. Assuming an average water height of 6 meters, the discharge capacity of the Pineios River along the western edge of the city of Larissa could range from 4,500 to 5,000 m^3/s, provided there are no obstructions and the floodplain is well-maintained.

Confluence with Pineios Potamos

North of the Pineios Potamos tributary, the floodplain expands significantly. Assuming a maximum water height of 6 meters and a well-maintained floodplain, the discharge capacity could surpass 10,000 m^3/s. However, the existing flood management plan, designed for a return period of 100 years, calculated peak discharges from the Pineios Potamos ranging from 2,000 to 3,000 m^3/s, and for a return period of 1000 years, it estimated 4,000 to 7,000 m^3/s. The current urban infrastructure and buildings in the floodplain, including two wastewater treatment plants, pose challenges. During Storm Daniel, the area experienced severe inundation, reaching almost 4 meters, with structures exacerbating the flooding.

Clearing and recovering the floodplain may be a daunting task, but protecting these developments while ensuring sufficient river discharge capacity to safeguard the city presents an equally formidable challenge. Given the extent of urban development, a detailed local study is imperative for future area planning and floodplain reconstruction. While clearing part of the floodplain may be unavoidable to prevent unacceptable water levels in the Pineios River during floods, an immediate ban on further constructions in the floodplain is essential.

Developing retention areas in the Pineios Potamos catchment could alleviate pressure on Larissa, although suitable areas appear limited. Exploring this option, even as a last resort, is crucial. Considering the risks and potential high impacts of floods on the City of Larissa, the restructuring of the floodplain between the levees demands serious attention.

Implementation:

Immediate actions (3 – 6 months):

- Inventory of all structures in the floodplain and costs of their removal.
- Survey of the state and heights of levees. Make repairs and ensure uniform heights.
- Immediate ban on any further developments between the levees.
- Detailed mapping of the urban developments in the floodplain north of the tributary.
- Protect the wastewater treatment plant (in the case of severe damage: move the plant to the other side of the levee).
- Conduct activities specified in Chapter Development strategy for flood defense infrastructure .

Follow-up actions (9-18 months):

- Dismantling or relocation of obstructing elements.
- Investigate (by modelling) the required levels of the dykes.
- Conduct detailed designs.
- Investigate (by modelling) potential retention areas in the Pineios Potamos river basin.

Follow-up actions (2-3 years):

- Evaluate and discuss retention in the Pineios Potamos river basin
- Start dismantling and construction works.

Area North of Larissa City

Figures 25 and 26 show that the region between the city of Larissa and the confluence of the River Titarisio is predominantly safeguarded by levees. The northeastern sector abuts the mountains, forming a floodplain typically 1000 to 1500 meters wide, with a minimum width of around 800 meters. Positioned approximately 11 km north of Larissa, the Gyrtoni Barrage plays a crucial role, creating a 5 million m^3 buffer for irrigation water supply to the Lake Karla basin. Spanning 115 meters, the barrage's gates have a reported discharge capacity of 5,000 m^3/s, but during Storm Daniel, accumulated debris curtailed this capacity, turning the Gyrtoni Barrage into a bottleneck. The absence of a spillway resulted in breached upstream dykes, causing inundations east and west of the levees and flooding towards the Lake Karla basin.

Unlike large dams such as the Smokovo Dam, the Gyrtoni Barrage lacks flood mitigation capabilities during extreme events, filling up rapidly without a spillway. The urgent need for a spillway, along with other associated measures, is evident. Additionally, the road southwest of the barrage poses an obstruction in the floodplain and must undergo remodeling, incorporating culverts and/or dedicated overflow areas. Detailed road design specifications should be determined through hydrological modeling.

Storm Daniel led to severe inundations north and northwest of the Gyrtoni Barrage, likely due to the narrowing of the floodplain to approximately 550 meters. Reassessment of the location and height of the existing western levee is imperative using modeling. Expanding the floodplain or creating a second one north of the Gyrtoni Barrage, possibly through the construction of a second dyke (approximately 5 km in length), is proposed in Figure 26. This dyke would add agricultural land to the floodplain without structures. The need and specific design of the dyke will depend on design discharges determined through modeling work.

While the described measures are anticipated to mitigate flood risk east of the levee between Larissa City and Gyrtoni, a reassessment of the required levee heights is essential.

Immediate actions (3-9 months):

- Inventory of all structures between the levees and costs of their removal
- Survey of the state and heights of levees. Make repairs and ensure uniform heights
- Conduct activities specified in Chapter Development strategy for flood defense infrastructure .

Follow-up actions (9-12 months):

- Investigate (by modelling) the size of a spillway at the Gyrtoni Barrage.
- Investigate (by modelling) the required levels of the dykes in combination with the construction of a second, new dyke.

Follow-up actions (1-3 years):

- If a new dyke needs to be constructed, assess any required adaptations in farming .
- Design and construction of a spillway at the Gyrtoni Barrage.
- Start construction works (existing and new dykes).

Titarisio

Figure 27 shows the downstream portion of the Titarisio catchment. The check dams in the mountainous areas, will reduce the peak floods and the associated defense infrastructure, but not make them unnecessary.

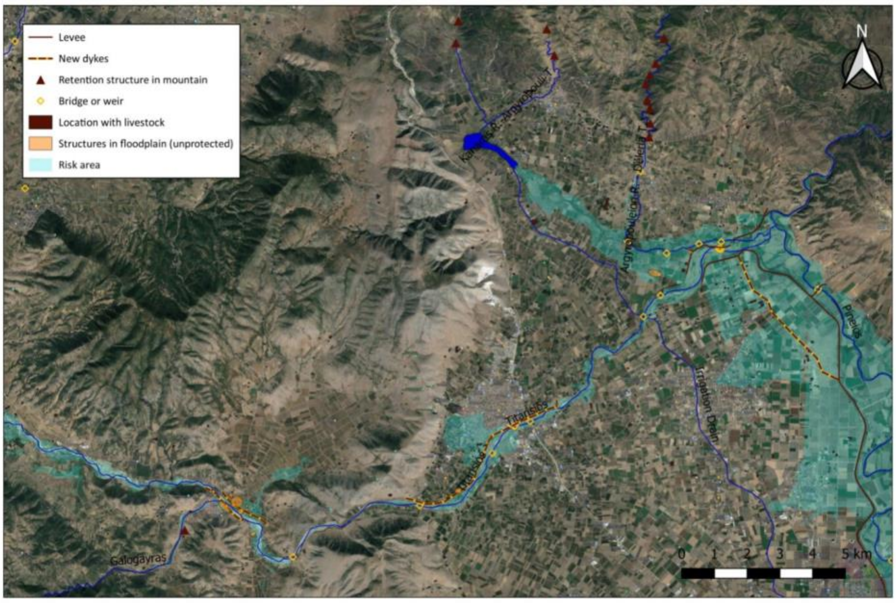


Figure 27: Flood defense Titarisio

In the upstream regions, specific measures are not outlined, except for Damasi, where numerous structures near the river pose a risk. The decision to relocate these premises should be carefully weighed against the option of safeguarding them through dykes on both sides of the river. The estimated length of the required dykes would be approximately 3 km.

Moving downstream, the town of Tyrnavos faced inundations from the Titarisio River, particularly affecting low-lying southern residential areas. A proposed dyke of around 6 km along the northern bank of the river would protect these areas, as well as numerous premises southwest of the town. The sizing of this dyke requires further assessment through hydrological modeling. It is crucial to evaluate whether constructing a dyke on the northern bank would pose increased risk to premises on the southern bank.

Existing structures downstream in the floodplain may only be shielded by local measures or, alternatively, relocated to safer areas. Bridges in and around Tyrnavos need a thorough assessment of their hydraulic properties, and the removal of sediments and debris is essential.

According to the existing flood management plan, peak discharges at the Titarisio outlet range from 4,000 to 6,000 m^3/s for a 100-year return period and 7,500 to 13,000 m^3/s for a 1000-year return period. These are substantial volumes of water. While the most downstream areas are protected by levees, they proved insufficient to contain the floods from Storm Daniel. Further evaluation and potential reinforcement of levees in these areas are necessary to enhance resilience against extreme events.

Figure 27 shows that the valley downstream of the Argyropouliou Lake became flooded during the storm Daniel. In the most downstream portion quite a few premises were constructed in the inundated areas. They were constructed behind the levees that protect them from flooding from the Titarisio River, but these premises are apparently not sufficiently protected from the waters coming from the Argyropouliou Lake and the Argyropouleion Rema - Deleria Tyrnavou stream coming from the mountains. It will be complicated and costly to protect this area. There are 3 options that need to be investigated, namely:

- Increase of the capacity of the Argyropouliou Lake (by constructing a dam)
- Redesign and increase of the dyke system near the confluence
- Relocation of premises

Such assessments (together with the proposed check dams in the Argyropouleion Rema - Deleria Tyrnavos stream) must be done with the detaled hydrological model.

Implementation:

Immediate actions (3 - 6 months):

- Inventory of all structures and costs of their removal in Damasi, the areas outside the proposed dyke at Tyrnavos, and in the risk areas near the confluence
- Conduct activities specified in Chapter Development strategy for flood defense infrastructure .

Follow-up actions (9-12 months):

- Investigate (by modelling) the adequacy and sizing of proposed dykes
- Investigate (by modelling) the options of a dam at the Argyropouliou Lake, and the construction of dykes near the confluences

Follow-up actions (1-2 years):

- Detailed designs (dam or dyke system).
- Start construction works (new dykes, and possibly a dam).

Valley west of Tempi

Figure 28 shows the valley west of the town of Tempi. After the gorge the valley widens. During the Storm Daniel the valley became inundated up to distances of 1 km from the riverbed. The waters did not cross the highway.

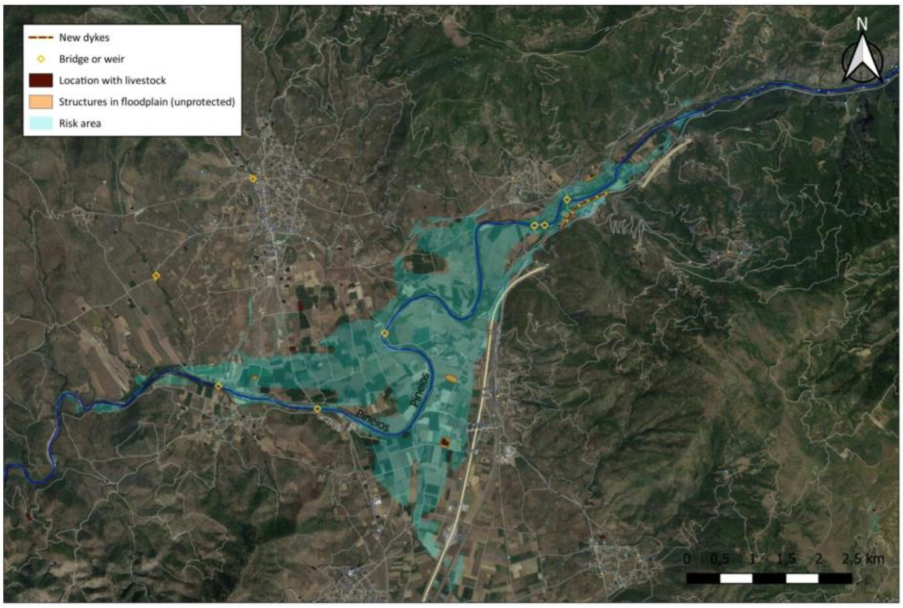


Figure 28: Flood defense Tempi

Considering the limited number of premises and livestock locations in this area, it is advisable not to rehabilitate damaged assets but to relocate them instead. The primary crops in this region are forage and cereals. Therefore, the existing irrigation systems should undergo an assessment for their resilience against inundations, and necessary adaptations should be made.

As the valley narrows towards the town of Tempi, the floodplain of the Pineios River is confined between the railway and the highway to the east of the town. In order to protect the town of Tempi effectively, it is recommended to construct a dyke with an approximate length of 1 km. Due to the anticipated difficulty and costliness of protecting premises between the railway and the highway, it is advised not to rehabilitate them but rather to relocate them to safer areas. This strategic approach aims to ensure the long-term safety and sustainability of the affected communities and infrastructure in the face of potential future flood events.

There are several bridges in the area, some of which have been damaged and require evaluation of their hydraulic properties. Satellite images reveal a buildup of debris in the vicinity of the central section of the valley, posing a potential threat of inundation. It is imperative to address these conditions by clearing debris at all bridges. Additionally, sites with destroyed bridges must undergo thorough clearance measures.

Implementation:

Immediate actions (3-6 months):

- Inventory of all structures and costs of their removal the risk area.
- Conduct basic maintenance on the floodplain: Remove trees, vegetation and accumulated sediments and debris, including destroyed bridges.
- Assess bridges and culverts on their hydraulic properties.

Follow-up actions (9-12 months):

- Investigate (by modelling) the adequacy and sizing of the proposed dyke at Tempi.

Follow-up actions (1-2 years):

- Design and construction works (new dyke at Tempi).

Flood defense infrastructure in the Lake Karla area

Figure 29 illustrates the Lake Karla basin and the areas that experienced inundation following Storm Daniel, resulting in the flooding of over 17,000 hectares of land. Due to the small artificial outlet in the catchment, the inundated area decreases gradually. It is anticipated that it may take approximately 1.5 to 2 years for the affected area to fully dry again. The long recovery period emphasizes the significant impact of the storm on the region and underscores the need for comprehensive flood mitigation measures to enhance resilience in the face of such events.

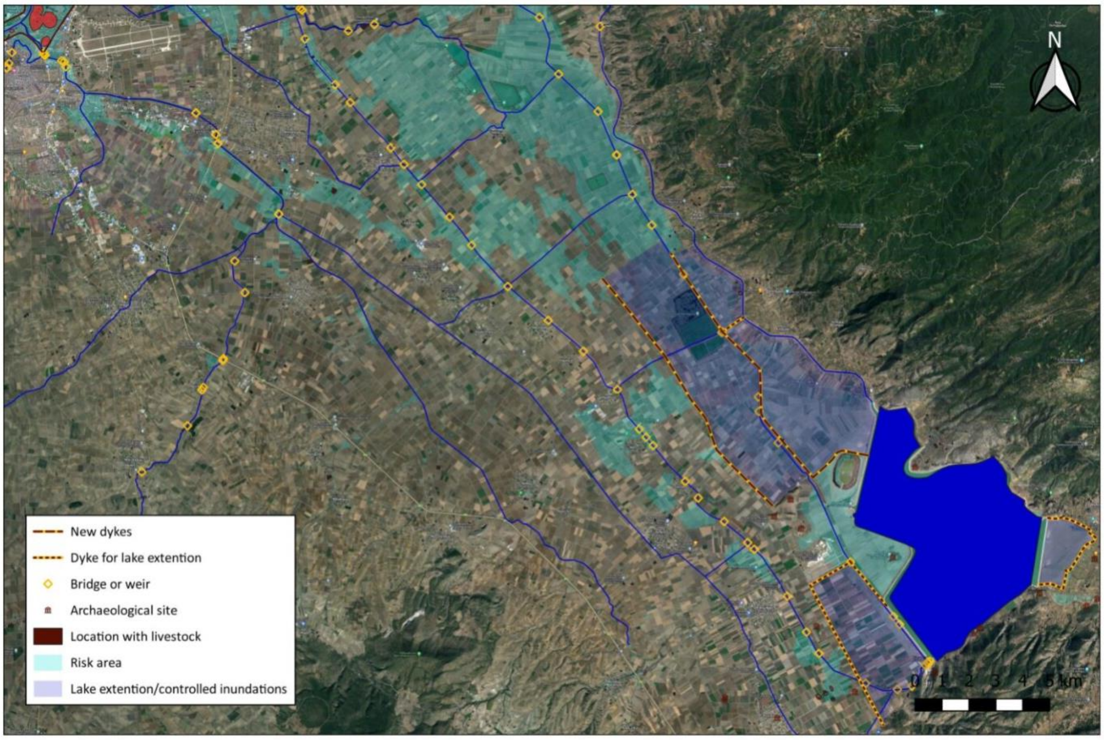


Figure 29: Flood defense Lake Karla Area

The floodwaters originated, in part, from rainfall in the Lake Karla Basin and, in part, from water breaching the dykes in the Pineios River Basin. In the future, it will be essential to prevent the latter through adequate flood defense measures. Managing rainfall in the Lake Karla Basin, on the other hand, requires internal control.

In order to address excessive rainfall, it is crucial to discharge water through the existing network of drains, including the interceptor drain along the eastern side of the valley, leading towards Lake Karla. The water is stored in Lake Karla and subsequently pumped into the farmers' irrigation system in the Stefanovikio area. However, it is important to note that Lake Karla primarily functions as a buffer storage. The annual water usage by farmers for crop irrigation, along with evapotranspiration losses, surpasses the amount of rainfall. To compensate for this deficit, water is conveyed from the Pineios River Basin to Lake Karla.

In instances of heavy rainfall during the rainy season, the buffer capacity of Lake Karla may occasionally prove insufficient to contain all the water. In such cases, excess water is discharged to the Pagasetic Gulf through a man-made tunnel. Under normal conditions, the combined capacity of Lake Karla and the tunnel is adequate to manage the inflow of high water volumes. However, during Storm Daniel, the rainfall amount (approximately 365 million m^3 [20]) exceeded Lake Karla's buffer capacity by more than 300%. The typical buffering capacity of Lake Karla is 80 million m^3 and, in extreme rainfall events, can be increased to a maximum of 125 million m^3. Consequently, Lake Karla cannot accommodate the water volumes experienced during Storm Daniel.

The discharge capacity of the tunnel outlet (8.5 m^3/s or 734,400 m^3/day ≈ 22 million $m^3/month$) is significantly inadequate for timely emptying the substantial volumes of water resulting from rainfall caused by a medicane like Storm Daniel.

Addressing such substantial rainfall volumes presents limited options: either the buffer capacity of Lake Karla must be increased, involving an expansion of the lake, or retention capacity needs to be developed on existing lands in the valley. Drastically enhancing the tunnel's discharge capacity or constructing an additional tunnel is not a viable standalone option. Buffering the water, which can eventually be utilized for irrigation, proves considerably more cost-effective and has lower environmental impacts.

In order to manage excess rainwater on the scale experienced during Storm Daniel (365 million m^3), a lake with three times the capacity of the current Lake Karla would be necessary[21]. For this purpose, Option 1 involves extending the lake to meet the required capacity. Figure 28 outlines three preselected potential areas for extension (a detailed study is required to confirm the most suitable locations).

Alternatively, these areas could evolve into nature reserves or extensive agricultural zones (once the current water has drained and dried up). Lake Karla would continue to be managed as it is currently, with the adjacent areas designated for controlled inundation as part of the management strategy for extreme flood events. The northwestern area for controlled inundation is positioned south of the interceptor drain, extending to the village of Kato Amigdali.

It is likely that an additional area for controlled inundations will need to be established south of this region (Figure 29). This second retention area will only be inundated if the capacity of the northern

[20] This volume does not include the water volumes from the Pineios River dyke breaches.

[21] Estimate only, stipulating the order of magnitude.

area proves insufficient during extreme events. This option implies dedicating a relatively large area to flood management. Unlike areas in the Trikala and Karditsa prefectures, the areas designated for controlled inundation in the Lake Karla basin will remain out of production for a relatively extended period. This is because the Lake Karla Basin lacks a natural outlet, and all water must either evaporate, be used for crop irrigation, or be discharged through the drainage tunnel. If prolonged inundations are deemed unacceptable for economic or health reasons, consideration might be given to increasing the capacity of the drainage tunnel.

Expanding Lake Karla and designating areas for controlled inundations necessitate investments in dykes and discharge systems, including pump stations, along with compensation for landowners and lessees (refer to Annex 2. Evacuation protocols in case of an upcoming flood). The investments in flood defense structures and occasional compensation payments to landowners affected by inundations in the Lake Karla area are likely to be recouped, as they prove more cost-effective than the "no intervention" option (present state).

Short-term actions

A substantial portion of the Lake Karla Basin remains submerged at present, and it is estimated to take 1.5 to 2.0 years for the water to fully recede, presuming no additional extreme rainfall occurs during this period.

Given that the primary means of drainage is through the drainage tunnel from Lake Karla, it is advisable to conduct a measurement to ensure that the tunnel's discharge capacity has not been compromised over the years. This verification can be achieved through a one-time discharge measurement at the tunnel's outlet in the Volos area, utilizing calibrated flow meters. Such measurements will identify any obstructions or sedimentation at the intake point. If the discharge is significantly less than the design discharge (8 m^3/sec), maintenance work should be undertaken.

Suggestions to enhance the discharge capacity of the drainage tunnel with pumps for faster drainage of the current pooled water are not recommended, as they would yield minimal time savings and involve unjustifiably high costs.

As a short-term intervention, an alternative approach involves modifying the water conveyance system that pumps water to the farming areas in Stefanovikio. The system has been inactive since September when parts of the pumping stations became inundated. Disconnecting the currently submerged section of the system and connecting the operational part to provisional pipes would enable farmers to irrigate their land while concurrently contributing to the more rapid drainage of the inundated area.