FACTA UNIVERSITATIS
Series: Architecture and Civil Engineering Vol. 22, Nº 3, 2024, pp. 175-183
https://doi.org/10.2298/FUACE230630036S

Original Scientific Paper

FOSTERING FLOOD CONTROL POLICY MEASURES AT BASIN SCALE HYDROSYSTEMS WITH THE USE OF GEO-SPATIAL TECHNOLOGIES

UDC 627.51:004.65(495)

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Abstract. *The increased rate of floods occurrence during the last few decades, which is mainly attributed to climate change and mankind pressures on the hydrosystems, results on large scale horizontal flood control and protection policies. At European Union (EU) scale, the Directive on the Assessment and Management of Flood Risks of the year 2007 aims, after implementing sequential processes which amongst other include remote sensing and hydraulic modeling coupling, at proposing specific measures for mitigating the flood risks and the derived socioeconomic devastating impacts. The current research demonstrates the usefulness of geo-spatial technologies for assessing the operationality of the current anti-flood infrastructures together with the historic flood events and the necessity of maintaining the infrastructures. For doing so, all the flood control structures in the case study area were mapped in a geographic information system (GIS). Additionally, information regarding the floods' spatial and temporal placement were used to populate the GIS database, while the repeatability of the works regarding the maintenance and/or restoration and/or failure recovery of the flood control structures was attributed in monetary terms to evaluate the feasibility of the projects. The case study area is the Greek part of the Struma/Strymonas transboundary river basin, which is shared between Bulgaria and North Macedonia and Greece. The outputs of the research demonstrated the usefulness of the current flood protection projects, however, there were particular cases where the annual maintenance cost necessitates the promotion of new and more financial independent solutions.*

Key words: *hydrosystems, floods, geographic information system, anti-flood structures, Strymonas River Basin, Greece.*

Received June 30, 2023 / Revised August 1, 2023 / Accepted August 15, 2023
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*Selected paper presented at the International Conference Sinarg 2023 held in Niš, Serbia on 14-15 September 2023.

1. INTRODUCTION

Floods are among the most devastating extreme events. During the last 50 years 44% of the weather-related disasters are flood-triggered [1]. The floods have direct impacts on human lives, with approximately 6.8 million human losses to be connected to terrestrial floods during 20th century [2], on national and regional economy, with the direct financial damage of 2002 floods in Prague and Dresden, for example, to be around €20 billion [3], while there are also significant indirect economic effects, such as the cost of economic recovery after a flood [4], on the environment [5], and on the cultural heritage which is either exposed to the outside environment or being part of the interiors of historical buildings [6]. It should be noted that although flood genesis is a natural based process, the imposed radical interventions to the natural environment by humans, e.g. alteration of land uses, technical constructions within flood zones, and river courses alterations, do also play an important role to the increase of floods particularly in urban and peri-urban environments.

Although large-scale floods occur almost every year, it is expected that climate change will increase the frequency and magnitude of these events. Based on the latest Sixth Assessment Report (AR6) on climate change, the more optimistic climate scenario which corresponds to a temperature's increase of 1.5 °C (irrespectively of the utilized model and the socio-economic scenario) foresees more than 50% growth in human losses, approximately 160–240 % of direct flood damage and welfare reduction between 0.23 and 0.29 % [7]. According to the same authors [7], in a 2.0 °C world, a 50% rise of all the negative impacts is expected in comparison to the 1.5 °C estimations. At the same time, the Mediterranean basin is designated as a hot-spot in terms of climate change impacts. The projected temperature increase together with the precipitation spatiotemporal anomalies, i.e. rainfall volume decrease but high-intensity rainfall in short time, is projected to facilitate the occurrence of flash floods, which are characteristic Mediterranean type of floods mainly occurring during autumn in small watersheds and urban areas [8].

The response of the European Union (EU) on the current and projected increased large-scale floods impacts was conducted through the Directive on the Assessment and Management of Flood Risks, commonly known as the Floods Directive (FD). FD aims at reducing and managing the risks of potential floods to human health, environment, cultural heritage and economic activities, and it is implemented through sequential methodological steps, which include the coupling of historical significant flood events with terrain slope characteristics and hydrologic and hydraulic modeling, to produce the Flood Risk Management Plans (FRMPs) [9]. These strategic documents integrate the produced information and propose a list of protection measures that will absorb the flood risk. FRMPs are redeveloped every 6-years to take into consideration any new information and data that could jeopardize the hydrosystem in terms of floods, and to investigate the progress achieved through the adoption of anti-flood measures on designated flood prone areas. At this point it should be mentioned, that although the hydraulic modelling process considers various important hydraulic structures such as bridges, dams, weirs, and diversions, other important anti-flood structures such as culverts, irrigation networks and drainage channels, and gabions, are not evaluated during the simulation process.

At the same time, mature technologies such as satellite remote sensing together with emerging technologies such as the Geographic Information Systems (GIS) have boosted the applicability of hydrological and hydraulic models. GIS, among its other capabilities, combines the storage of descriptive and observational information with coverage characteristics. It can, thus, take advantage of remote sensing products, such as Digital Elevation Models or Landsat images, to provide unique spatial information, as for example the topographic characteristics and the land uses percentage within a basin respectively. These outputs thereafter can be used to define the appropriate hydrological model parameters responsible for the representation of surface runoff the infiltration processes. Currently, both open source and commercial GIS tools are being routinely used, not only for advanced geoprocessing functions but for sharing data across the web via the commonly known WebGIS platforms [10].

The object of the research is to investigate the operationability of anti-flood constructions at a river basin scale through the use of GIS technology and of the Flood's Directive implementation process outputs. For this purpose, flood and water related information, i.e. the historical floods locations, the flood protection structures' locations, and the hydrographic network, together with socioeconomic data, i.e. inhabitant, agricultural and environmental protected areas and related information, were collected, stored and analyzed within an open source GIS environment. Both the inherent analysis of the anti-flood construction figures as well as the spatial analysis of system's features revealed a) the feasibility of the current infrastructures, b) the necessity for supplementary solutions for minimizing the cost of maintenance of the existing flood protection works. The proposed methodology provides a clear and direct assessment on watersheds' flood protection status and can be implemented at basins of various scales.

2. METHODOLOGY

2.1. Case study area

The Greek part, namely the Strymonas watershed, of the transboundary river basin Struma/Strymonas that is shared between Bulgaria, North Macedonia (upstream countries) and Greece (downstream riparian) is the case study area, Figure 1. Administratively, the Strymonas basin belongs to the River Basin District (RBD) of Eastern Macedonia (EL11) and in terms of land uses 52% of the basin is covered from forests and semi-natural areas, wetlands and water cover about 6% of the total area, while the percentage of agricultural areas coverage is also important (42% of the area). Strymonas basin hosts approximately 400.000 inhabitants, with most of them to work on the primary sector, mainly because of the large fertile and irrigated plains of the region [11]. The river flow is regulated by the Lake Kerkini which is located less than 20 km downstream of the borders. This artificial lake was constructed in 1932 as a massive downstream flood protection project, followed till recently by several large-scale land reclamation projects for the irrigation of the basin's plains.

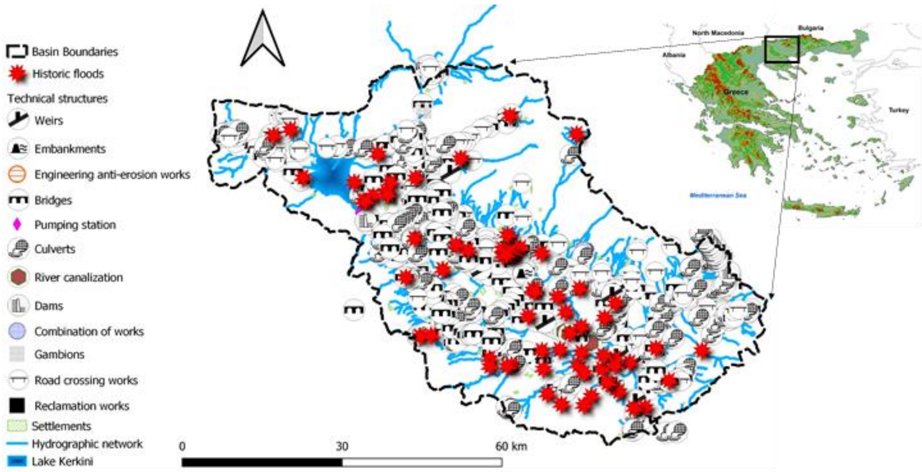

Fig. 1 The Strymonas basin case study area overlayed by the historic floods (red stars) and the flood protection structures.

In terms of water characteristics and floods occurrence, the RBD covers an area of 7,320 km2 and the hydrographic network is consisted of 84 River Water Bodies (RWBs). The Strymonas basin is the larger basin of the RBD covering approximately the whole RBD, thus in the research the Strymonas basin coincides with the RBD extent. The average RWBs' length equals 9.96 km, a length which is very close to the national average length of the designated RWBs, Table 1. Regarding the flood events, the data is separated in two time periods. The first period is up to the year 2011 and includes a limited number of floods, i.e. 93 events at the Strymonas basin and 1627 at national scale, since the national official database for floods' recording and mapping was launched in the year 2012, thus a large number of historic floods is missing. On the other hand, all flood events i.e. 43 events at basin scale, which occurred during the period 2012-2018 have been recorded in the database [9].

Table 1 River water bodies and flood events in the Strymonas basin

RBD	Extent (km^2)	No of RWBs	Average length (km)	Total length (km)	Floods (until 2011)	Floods (2012-2018)
EL11	7,320	84	9.96	837.1	93	43
Greece	131,995	1.317	10.21	13,162	1,627	210

2.2. The QGIS tool and spatial analysis techniques

In the research the development of the platform hosting our spatial database was accomplished with the use of the open-source Quantum Geographic Information System (QGIS) environment. QGIS is a publicly available, open-source, cross-platform and scalable GIS software, which facilitates the development of customised tools, namely plugins, in Python and C++ programming languages [10]. The QGIS operation adopts the standards set by the Open Geospatial Consortium (OGC) and integrates the geospatial data abstraction library (GDAL), which allows it to read and process a large number of raster files of different formats, as well as QGIS supports a variety of vector data formats e.g. PostgreSQL-PostGIS, ESRI shapefiles, GeoJSON, KML, Autocad DXF [11].

Spatial analysis, which is facilitated by GIS platforms, is conducted by coupling techniques of statistics on information that integrate a spatial component, i.e. they have coordinates and are spatially georeferenced. Within GIS by setting the spatial location of an object, the spatial and descriptive relationship between objects, e.g. which antiflood constructions are in a specific distance from an historical flood location and were built after or before a specific time period, were identified. In the research we make use of the aforementioned concept, i.e. we built a number of queries that responded on the spatial and temporal relationship of the floods and on the characteristics of flood protection structures.

2.2.1. Data mining

For the population of the GIS database that we constructed, to perform the spatial analysis techniques and identify the problematic regions in terms of floods, we collected various types of data through various sources as demonstrated in the followings:

Hydrologic/hydraulic data: They correspond to the hydrologic network, the historic floods, the basin and sub-basins boundaries. They are derived from the corresponding River Basin Management Plan and the Flood Risk Management Plan [12-13].

Land uses and environmentally protected areas: The data are related with the types of land and the designation of the areas that have environmental significance. The data are coming from online sources, namely the CORINE land cover programme of 2018, and the Natura 2000 sites designation, respectively.

Flood protection structures and works: The flood protection structures correspond to the geographic locations of the anti-flood structures. The flood protection works corresponds to the number of works that have been accomplished for the maintenance or enhancement of the existing infrastructures. The flood protection works are divided in the following seven categories: 1) weirs cleaning and maintenance, 2) embankments reinforcement, 3) removal of flood-created islands within the river main course, 4) cleaning of bridges' piers from sediments, 5) riverbed deepening, 6) removal of deposits, and 7) other type of maintenance. The data comes after a detailed survey on the flood protection procurement contracts repository of the Water Directorate of the case study region.

3. RESULTS

3.1. Analysis of infrastructure structures and works

The analysis of the survey data regarding the technical structures of the case study area revealed that within the Strymonas basin there have been constructed 649 anti-flood structures. Table 2 depicts both the structures' type and the number of each construction. Most of the structures, i.e. 41.9% or 272 out of 649 projects, are bridges, followed by 185 culvert' constructions, which represent 28.5% of the structures. The third more common flood protection structure, i.e. 17.1% of the structures, is related to road crossing works, while other constructions such as, weirs, dams, and gabions, account for about 2.0%-3.0% of the projects.

Table 2 Recorded technical flood protection structures

Type of structure	Number of structures
Weirs	24
Embankments	2
Engineering anti-erosion works	1
Pumping station	1
Bridges	272
River canalization	6
Reclamation works	18
Construction of gabions	9
Diversions	2
River bed reinforcement	1
Small mountainous dams	3
Culverts	185
Road crossing works	111
Dams	12
Combination of works	2
SUM	649

Most of the anti-flood protection works, as shown in Table 3, are linked to the cleaning of bridges' piers from sediments (55.0%, or 138 out of 253 works). When the repeatability of the works is taken into account, i.e. how many times the same work for the same structure has been repeated throughout the years, the specific percentage is equivalent to 62.0% (431 out of 692 works). The works the removal of the deposits constitute the 11.0% of the total works, with or without considering the repeatability. The analysis of the further data demonstrated that the percentage of the other works is equal to 10.0% or less. The last column of Table 3 presents the average cost per work type, as it was identified (when it as available) in the records of the authorities responsible for the implementation of the specific works.

Table 3 Recorded technical works that are related to the maintenance of enhancement of the existing flood protection structures in the Strymonas basin

Type of anti-flood works	Number of works	Number of works included repeatability	Averaged cost per anti-flood work (€)
Weirs' cleaning and maintenance	4	10	49,750
Embankments reinforcement	16	17	430,870
Removal of flood-created islands	19	19	85,714
Cleaning of bridges' piers from sediments	138	431	49,750
Riverbed deepening	21	44	74,054
Removal of deposits	27	75	47,250
Other work's type	28	96	41,270
SUM	253	692	

3.2. Developed GIS platform

The population of the custom developed geo-referenced system integrated all the collected information, as presented in Table 2. In parallel, a cloud-based version of the geo-reference system (https://gis.consortis.gr/strimonas/) integrating and illustrating all the datasets was also created.

The analysis of the data demonstrated the density of the anti-flood structures, i.e. in which way the structures are distributed within the basin and in which locations the majority of the structures is gathered, Figure 2. Moreover, the overlaying of the historic floods demonstrated the areas which are more flood prone, as well as depict the correlation between floods occurrence and the existence or not of flood protection constructions. The further analysis of the vulnerable areas to floods, i.e. the areas where floods phenomena are frequent, together with the locations and figures of flood protection works revealed the correlation between works and inundation occurrence.

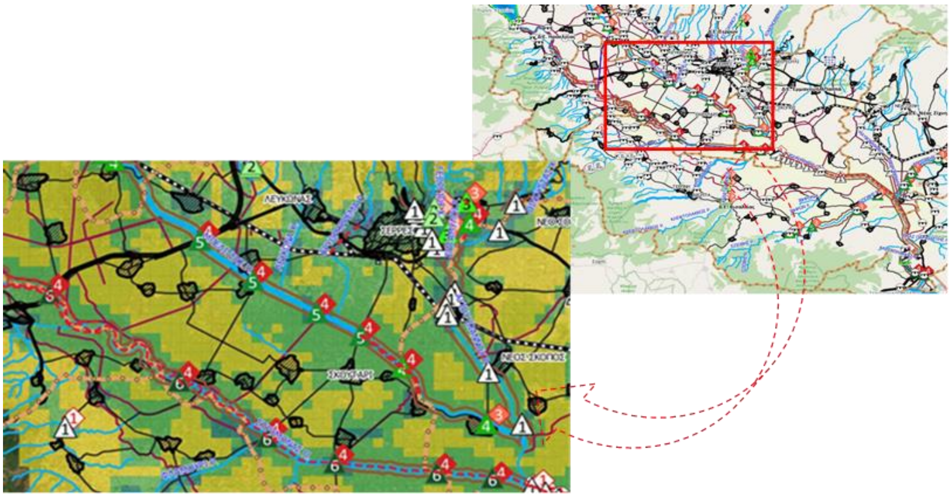

Fig. 2 Case study area as produced within the QGIS environment and zoom in regions with numerous flood protection works (e.g. red triangles and green squares attributes the works of the removal of deposits, and cleaning of bridges' piers from sediments).

4. Discussion and Conclusions

Flood protection plans should not only consider policy frameworks and directives, but also evaluate tangible figures, such as the flood incidences together with the operationality of the anti-flood structures, to assess the necessity of enforcing (or not) the current anti-flood structures and systems. The literature proposes the prioritization of anti-flood works based not only on the financial cost of the structure but also on the coverage of social and environmental prosperity and security respectively [14]. Motivated from the above necessity for sustainable management of floods, the research demonstrated, through the proposed methodology of spatial analyzing flood related elements, such as those gathered and presented in Table 2, that GIS technology can foster the applicability of policies related to flood protection.

The outputs of the research depicted, as expected, that specific regions, within the case study area, with limited flood protection structures had more flood incidents than the ones which were better protected. Moreover, numerous inundations have occurred before the construction of flood protections structures, such as in the case of the region around the Lake Kerkini. Additionally, the research established the operationality of the anti-flood constructions, since the construction of these structures in areas with historic flood events demonstrated that no new floods occurred afterwards.

On the other hand, the analysis of the flood protection works, i.e. actions related to the maintenance or the enhancement of structures and of the hydrographic network, demonstrated the large amount of works that took place in various part of the hydrosystem. Especially, we recorded 253 flood protection works, while by considering the repeatability of specific works, i.e. works that are frequently repeated such as every year or after a significant flood event, we recorded 692 works. This reveals that the average repeatability of the works is up to +153.63%.

Additionally, it was identified that the works have been implemented in 24 river water bodies located within the Strymonas basin. Focusing on the water bodies themselves, it was identified that in the Strymonas River main course have taken place 57 flood protection works. When the repeatability of some tasks is included, the total works amount to 170 works, i.e. a repeatability of +150.44% is presented. In the Aggitis River, which is the larger tributary of the Strymonas River and drains the eastern part of the basin, 36 flood protection works have been carried out. When the repeatability is included, the total amount of work equals 133 tasks, i.e. a repeatability of +137.11% was presented. Finally, in the Belitsa and Krousovitis steams, which are the second most important tributaries of the hydrosystem and practically have the same length, it was revealed that 30 works were carried out in each stream case. However, when the repeatability forms part in the analysis, it was found out that 107 and 90 works have been implemented in each stream respectively, an issue meaning that the anti-flood structures in the Belitsa stream required more often restoration works.

To conclude, as the financial figures of Table 3 demonstrate, there are high annual costs, such as for example the cleaning of weirs and of bridges' piers that account for 7.960.000. The proposal of more permanent and feasible solutions in terms of maintenance, thus, is conceived as the tangible output of the current research. Particularly, the identification of hot spot areas in terms of repeatability of works and high cost for the maintenance of these works, provides useful insights on the management of the flood protection infrastructure.

Acknowledgement. *The research was funded by the INTERREG V-A European Territorial Cooperation Program "Greece-Bulgaria 2014-2020 "Flood Protection-Cross Border Planning and Infrastructure Measures for Flood Protection".*

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RAZVIJANJE MERA POLITIKE KONTROLE POPLAVA NA HIDROSISTEMA SLIVA UZ UPOTREBU GEOPROSTORNIH TEHNOLOGIJA

Povećana stopa pojave poplava tokom poslednjih nekoliko decenija, koja se uglavnom pripisuje klimatskim promenama i pritiscima čovečanstva na hidrosisteme, rezultira horizontalnom kontrolom poplava i politikama zaštite velikih razmera. Na nivou Evropske unije (EU), Direktiva o proceni i upravljanju rizicima od poplava iz 2007. godine ima za cilj, nakon implementacije sekvencijalnih procesa koji između ostalog uključuju daljinsko detekciju i spajanje hidrauličkog modeliranja, da predloži specifične mere za ublažavanje rizika od poplava i posledičnih razornih socioekonomskih uticaja. Sadašnje istraživanje pokazuje korisnost geoprostornih tehnologija za procenu operativnosti postojećih protivpoplavnih infrastruktura zajedno sa istorijskim poplavnim događajima i neophodnošću održavanja infrastrukture. Za to su sve strukture za kontrolu poplava u oblasti studije slučaja mapirane u geografskom informacionom sistemu (GIS). Dodatno, informacije o prostornom i vremenskom rasporedu poplava korišćene su za popunjavanje GIS baze podataka, dok je ponovljivost radova na održavanju i/ili restauraciji i/ili sanaciji kvarova objekata za kontrolu poplava data u novčanom smislu za procenu izvodljivosti projekata. Područje studije slučaja je grčki deo prekograničnog sliva reke Struma/Strimonas, koji dele Bugarska i Severna Makedonija i Grčka. Rezultati istraživanja su pokazali korisnost trenutnih projekata zaštite od poplava, međutim, bilo je posebnih slučajeva gde je godišnji trošak održavanja zahtevao promociju novih i finansijski nezavisnijih rešenja.

Ključne reči: *hidrosistemi, poplave, geografski informacioni sistem, strukture protiv poplava, sliv reke Strimonas, Grčka.*