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Assessment of climate change impacts on the central coastal collector of Athens, Greece, based on a novel index

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Abstract: In the present work the impacts of climate change on the Central Coastal Collector (CCC) of Athens, Greece, are assessed utilizing a newly proposed index, called Index for Reliability of Urban Drainage Adaptation (IRUDA). The main aim of the present work is to evaluate flood hazard and determine rainfall return periods associated with flooding phenomena. In addition, the study assesses the projected climate change impacts in the Central Coastal Collector. Storm Water Management Model (SWMM) software was utilized for modeling the sewer network of the study area. Observed hydrometeorological data and Future Intensity Duration Frequency (IDF) curve were utilized. The future sub-hourly IDF curves were developed using rainfall data from different global and regional climate models and scale-invariance theory. Calibration indices confirmed the model's reliability, aligning observed and simulated flow data effectively. Results indicated that flooding phenomena in limited nodes of the sewer network occurs during extreme rainfall events, particularly along Poseidonos Avenue. IRUDA index indicated that under varying climate scenarios a significant increase in flood risk under extreme conditions, emphasizing the need for infrastructure upgrades. Effective Rainfall Derived Inflow and Infiltration (RDII) management is crucial to mitigate overflows and ensure future reliability of the drainage system under varying conditions. Flood mitigation strategies may include targeted rehabilitation of both public and private sewer components and implementing sustainable runoff mitigation measures. Overall, the present work underpinned the importance of integrating advanced hydraulic modeling and climate projections in urban drainage planning to enhance resilience against future climate extremes.

Key words: Water resources management; hydraulic modeling; SWWM software; climate change.

1. INTRODUCTION

Nowadays, more than fifty percent of the world's population lives in urban and semi-urban areas. In addition, projections of climate change, urbanization and growing population are expected to augment the pressure on the environment and as well as on human infrastructure, and moreover, challenge water resources sustainability (Bayazit 2015, Dubey Sharma 2018, Kourtis and Tsihrintzis 2021; 2022, Alehu and Bitana 2023).

Rainfall Derived Inflow and Infiltration (RDII) can have severe operational impacts in sanitary sewer systems and in wastewater treatment plants. Intensity-Duration-Frequency (IDF) curves constitute one of the most commonly adopted tools for planning, design and operation of a wide range of water resources related projects (e.g., dams, storm sewers etc.). As a result, update of Intensity-Duration-Frequency curves under climate change is essential for the adaptation of water-related structures to climate change.

Carriço et al. (2017) investigated the impact of RDII on the performance of a sanitary sewer system. They utilized field data collected during various rainfall events. They modeled the sewer network, using the SWMM software, in order to analyze RDII contributions to the total flow of the sewer system. Assessment of RDII contribution took place based on the produced flow hydrographs and the overall capacity of the drainage network during wet weather flows. Their results revealed that the contribution of RDII is significant during extreme weather events, which stressed the sewer system and increased the risk of overflows. Key infiltration points were linked to aging infrastructure and improper connections. Overall, they highlighted the need for targeted infrastructure upgrades and improved management practices to mitigate RDII and enhance sewer system reliability during extreme weather events. Zhang et al. (2022) studied the interaction between stormwater infiltration and RDII using a physically-based hydrologic model. They used a surface-subsurface hydrological model that integrated rainfall-runoff processes and soil infiltration dynamics. Simulations were validated using observed data. Their results revealed that stormwater infiltration exacerbates RDII by increasing soil saturation, leading to greater inflow into pipes during prolonged storm events. As a result, they emphasized the need of taking into account stormwater infiltration during RDII assessments and advocated for integrated water management mitigation measures to balance surface drainage and sewer system performance.

The main aims of the present work are: (i) to assess flood hazard at the Central Coastal Collector, in Athens, Greece; (ii) to investigate rainfall return periods for which flooding phenomena are observed; and (iii) to assess the main impacts of climate change on the Central Coastal Collector based on a recently proposed index, namely IRUDA (Kourtis et al., 2021). The future sub-hourly IDF curves recently proposed by Kourtis et al., 2023 were utilized in the present work. The aforementioned curves were developed based on a novel framework, using both the Generalized Extreme Value, and the Gumbel theoretical distributions considering an ensemble of future climate projections and scenarios, various General Circulation Models (GCMs), various Regional Climate Models (RCMs), five bias correction and one temporal disaggregation approach. Furthermore, scale-invariance theory was utilized in order to establish a relationship between hourly and sub-hourly rainfall intensities. Finally, the Central Coastal Collector was modelled using the well-known and widely used Storm Water Management Model (SWMM5.1) of the U.S. Environmental Protection Agency (EPA; (Rossman and Huber, 2016). For modeling RDII SWMM uses a synthetic, triangular unit hydrograph defining the rainfall proportion and the time at which the rainfall enters the sanitary sewer system.

2. MATERIALS AND METHODS

The methodological framework includes three major parts. In the first part all available data are collected, stored and processed. The second part is associated with the development of the hydraulic model, utilizing Storm Water Management Model (SWMM) software, of the Central Coastal Collector of Athens and the calibration of the developed model. The third and last part of the proposed methodological framework is associated with the assessment of the flood hazard in the study area and the projected impacts of climate change. Figure 1 presents the flowchart of the proposed methodology.

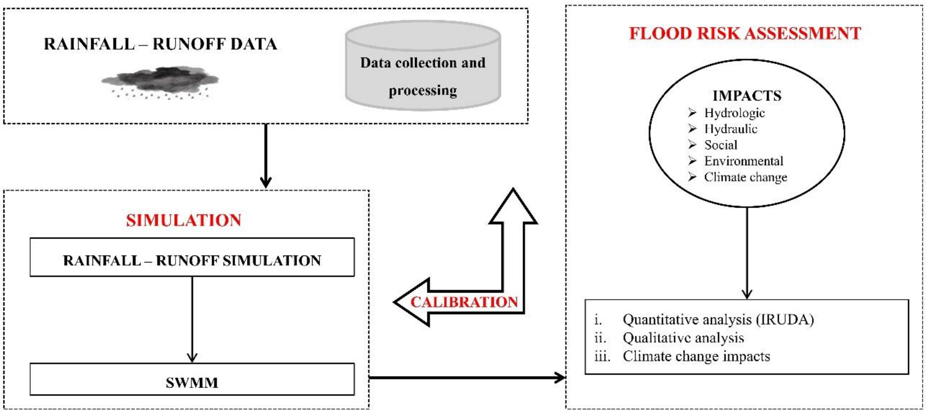


Figure 1. Proposed methodological framework

2.1 Study area

The examined drainage network (Figure 2) consists of 220 nodes and 243 sewers with a total length of about 18 km. The drainage system comprises egg-shaped conduits with depths ranging from 0.9 m to 1.65 m, and circular conduits with diameters ranging from 0.5 m to 0.9.

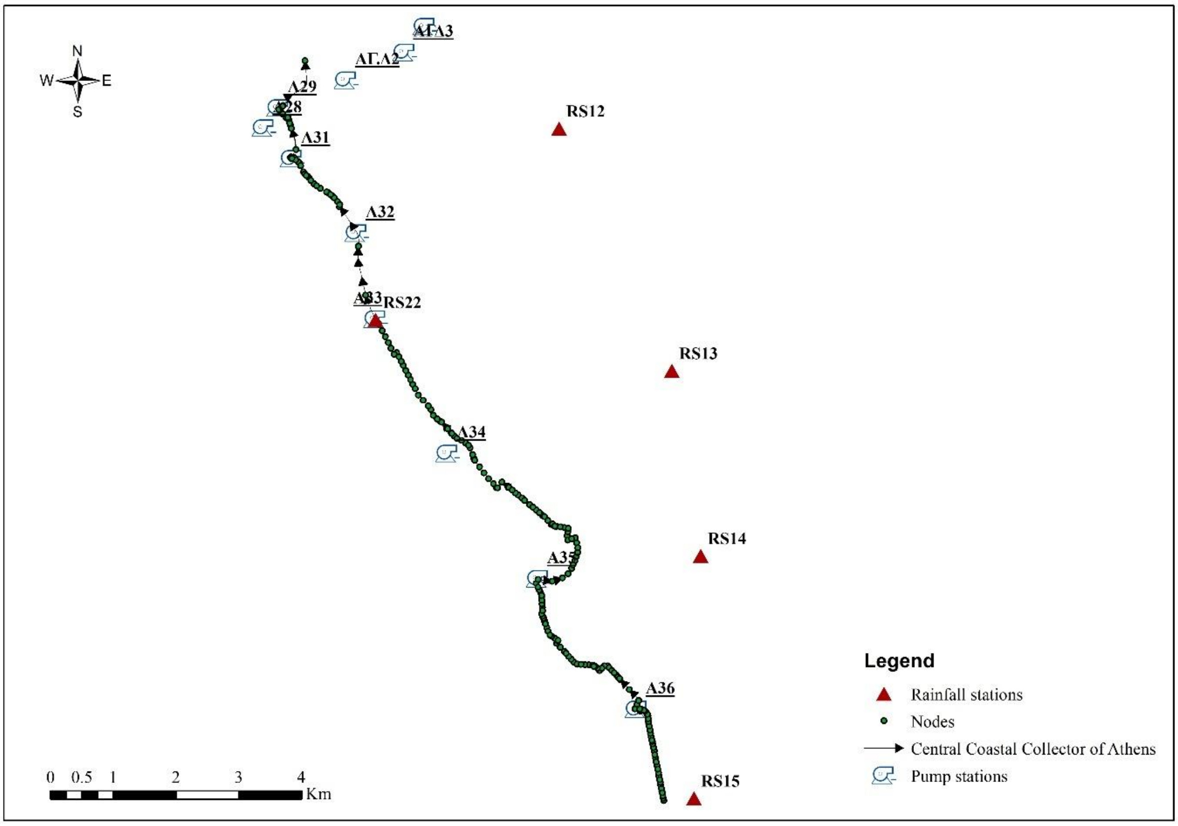


Figure 2. Study area

2.2 Hydrometeorological data

The meteorological stations located in the study area are presented in Table 1. The time resolution of the data is 5min. At this point it is necessary to mention that the time span of the aforementioned data, approximately 10 years, is relatively short for the development of reliable IDF curves as data for at least 30 years are required. To this end, it was chosen not to develop IDF curves for the aforementioned data presented, but to use the IDF curve from the Elliniko station (Eq. 1). The IDF curve is available for the Attica River Basin District (RBD; EL06) according to the Directive 2007/60/EC. Table 2 presents the rainfall depth (mm) for the Elliniko station for different return periods and various rainfall durations. Rainfall distribution was undertaken employing the Alternating Block Method (e.g., Kourtis et al., 2020).

Table 1. Rainfall stations

a/a	Code	Name	X (EGRS'87) m	Y (EGRS'87) m
1	RS12	Ilioupoli	478391.76	4196553.72
2	RS13	Glifada – Terpsithea	480191.03	4192690.42
3	RS14	Voula	480647.90	4189739.37
4	RS15	Kavouri	480540.56	4185873.00
5	RS22	Agios Kosmas	475464.56	4193503.29

Table 2. Rainfall depth based on the Elliniko IDF curve for different durations and return periods

Rainfall depth (mm)					
***T* (years)**	**5**	**10**	**25**	**50**	**100**
Time (h)	***d* (mm)**	***d* (mm)**	***d* (mm)**	***d* (mm)**	***d* (mm)**
0.25	12.9	16.1	20.6	24.4	28.4
1	25.9	32.5	41.7	49.2	57.4
2	34.9	43.7	56.1	66.2	77.2
3	41.2	51.6	66.2	78.2	91.1
6	54.2	67.9	87.1	102.8	119.9
12	70.9	88.8	113.9	134.5	156.8

Table 3 presents the rainfall data used for the calibration of the developed model. Rainfall-Runoff data were available for a single extreme rainfall event.

Table 3. Rainfall (mm) data used for calibration

	Ilioupoli	**Glifada – Terpsithea**	**Voula**	**Kavouri**	**Agios Kosmas**
26/02/2024	62.4	51.6	56.0	58.4	46.4

Finally, Figure 3 presents the observed discharge (m^3/s) in three pump stations of the sewer network. It can be observed that the hydrograph presents three peaks, same as the rainfall event, with the maximum observed discharged estimated at approximately 1.7 m^3/s.

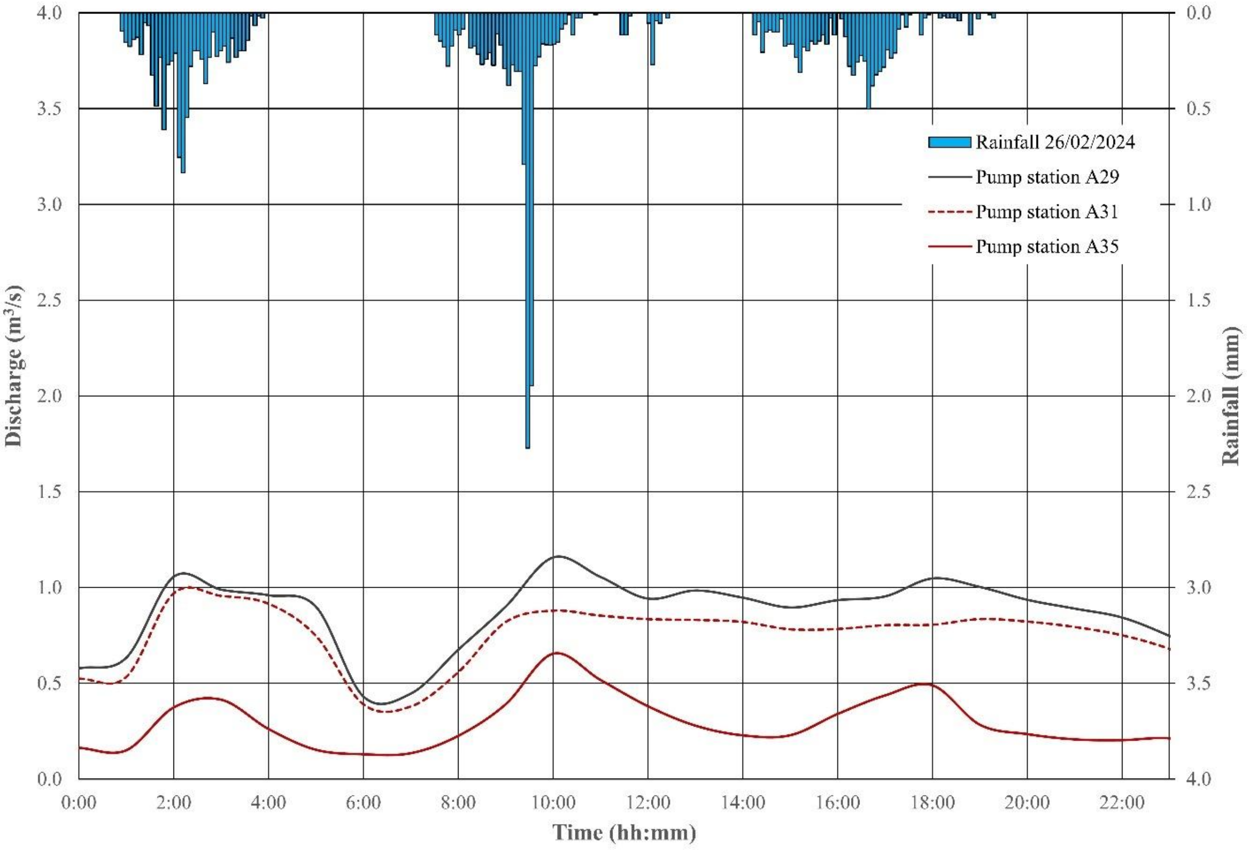


Figure 3. Observed discharge (m^3/s) in three pump stations of the sewer network

2.3 SWMM model

The Storm Water Management Model (SWMM) software was developed in 1971 by the US Environmental Protection Agency (EPA). It is a fully dynamic rainfall-runoff model suitable for simulating, qualitatively (Tsihrintzis and Hamid 1998) and quantitatively (Rossman and Huber, 2016, Bellos et al., 2017, Kourtis et al., 2017a, b; 2020), both individual and continuous rainfall events and is used primarily in urban areas. SWMM software, today, finds wide application all over the world for planning, analysis and design problems related to both stormwater runoff and stormwater runoff. The software provides the capability to simulate various hydrological processes, the main ones being: rainfall, evaporation, surface retention, infiltration, etc. In addition to hydrological processes, the software offers the possibility to simulate various hydraulic processes such as: various shapes of closed and open pipes as well as natural channels, simulation of pumping stations, spillways, retention tanks, simulation of external inflows, etc. One of the advanced capabilities offered by the SWMM software is the simulation of the Rainfall Derived Inflow and Infiltration (RDII) process. This process refers to the inflow of stormwater and groundwater into the sanitary sewer system. These inflows are due to illegal connections, inflows from the underground aquifer and inflows due to the poor condition of the network. These inflows cause an increase in flows in the sewerage system both during and after heavy rainfall events.

2.4 Calibration

For the calibration procedure the communication between an optimization algorithm and the SWMM model took place using the MATLAB computing environment (Goldberg 1989). For more information the interesting reader is referred to Kourtis et al. (2017b). The Nash-Sutcliffe coefficient (NSEE), (Eq. 1), was used as the objective function for the calibration. The results were further assessed using additional efficiency criteria (i.e., metrics) including Root Mean Squared Error (RMSE) (Eq. 2), the Mean Absolute Error (MAE) (Eq. 3), Coefficient of Determination (R^2) (Eq. 4), and the Normalized Objective Function (RMSE-observations standard deviation ratio-RSR; Eq. 5; Nash and Sutcliffe 1970; Krause et al. 2005; Muleta et al. 2012, Moriasi et al 2007).

$$\mathrm{NSE}=1-\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(O_i-S_i)^2}{\sum_{\mathrm{i}=1}^{\mathrm{n}}(O_i-\overline{O})^2} \tag{1}$$

$$R\mathrm{MSE}=\sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(Q_i-S_i)^2} \tag{2}$$

$$\mathrm{MAE}=\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}|S_i-O_i| \tag{3}$$

$$\mathrm{R}^2=\left(\frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}(O_i-\overline{O})(P_i-\overline{P})}{\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(O_i-\overline{O})^2}\sqrt{\sum_{\mathrm{i}=1}^{\mathrm{n}}(P_i-\overline{P})^2}}\right)^2 \tag{4}$$

$$\mathrm{RSR}=\frac{\mathrm{RMSE}}{\overline{O}} \tag{5}$$

where: O_i is the observed discharge at time i; S_i is the simulated output at time i; $\overline{O}$ is the average of the observations; $\overline{P}$ is the average of the simulations; and n is the number of observations.

Index for Reliability of Urban Drainage Adaptation (IRUDA)The IRUDA (Index for Reliability of Urban Drainage Adaptation; Eq. 6) index was recently proposed by Kourtis et al (2021) aiming to help scientists, practitioners and decision makers to assess the total reliability of a drainage network in terms of hydraulic, temporal and volumetric reliability. Values of IRUDA close to zero represent better reliability of the drainage network. The IRUDA index represents: (i) the percent of time during which the pipes of the drainage network are able to convey the produced runoff operating based on a predefined level (i.e., filling ratio <0.8); and (ii) the ratio of water volume conveyed safely through the drainage system to the total runoff volume generated from precipitation.

$$IRUDA = \left(\frac{1}{C}\sum_{C=1}^{C}\left(\frac{1}{t}\sum_{i=1}^{NC}T_i\right)\right) + \left(\frac{1}{C}\sum_{C=1}^{C}\left(\frac{1}{t}\sum_{j=1}^{NC}V_j\right)\right) + \left(\frac{1}{TV}\sum_{k=1}^{NF}FV_k\right) \tag{6}$$

where: C is the count for conduits, t is the duration of the operation period, NC is the total number of conduits of the drainage system, i is the count for the number of times the filling ratio is greater than 0.8, T_i is the number of times filling ratio is greater than 0.8, j is the count for the number of times velocity is greater than 6 m/s or less than 0.6 m/s, V_j is the number of times velocity is greater than 6 m/s or less than 0.6 m/s, NF is the total number of system failures, k is the counter for system failures, FV_k is the volume of water surcharged from the drainage system during failure mode k, and TV is the total volume of storm water runoff generated by the given rainfall.

2.5 IDF curves under climate change conditions

In the literature, the number of studies dealing with the hydrological impacts of climate change on urban and/or rural basins is increasing. Most studies focus on the risks from increased and/or decreased river flows. The number of studies focusing on the impacts of climate change on urban stormwater drainage systems is relatively limited. A key reason is the requirement for high spatial (1 - 10 km^2) and temporal resolution (5 min – 15min) of the required data (e.g., rainfall; Kourtis et al., 2023). The spatial and temporal resolution of General Circulation Models (GCMs) is quite coarse, with spatial scales ranging between 100 and 500 km and daily or monthly time scales; thus, prior to using them for hydrological-hydraulic impact assessment studies, there is a need for spatial downscaling and temporal disaggregation. The main spatial scale downscaling techniques are (i) dynamic downscaling using Regional Climate Models (RCMs) and (ii) scale downscaling using statistical methods. Different regional climate models driven by the same global climate model may produce completely different results as they are based on different solution schemes (Kourtis et al., 2023). In the present work, we utilized the future IDF curves recently proposed by Kourtis et al. (2023). The IDF curves (Eqs. 7 to 8) were developed based on the Generalized Extreme Value (GEV) distributions, with parameters estimated using the L-Moments method and with the 95% uncertainty band estimated employing the bootstrap approach.

$$(IDF\ \ Mean)\ i = 34.52\frac{T^{0.397}}{(d+0.783)^{0.861}} \tag{7}$$

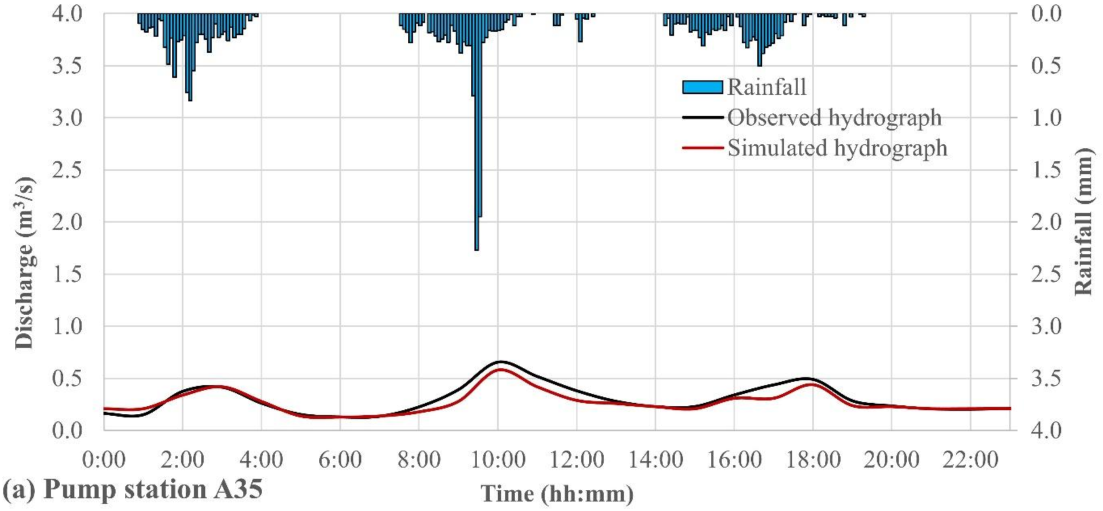
$$(IDF\ \ Upper)\ i = 62.94\frac{T^{0.448}}{(d+0.799)^{0.783}} \tag{8}$$

$$(IDF\ \ Lower)\ i = 20.59\frac{T^{0.350}}{(d+0.767)^{0.865}} \tag{9}$$

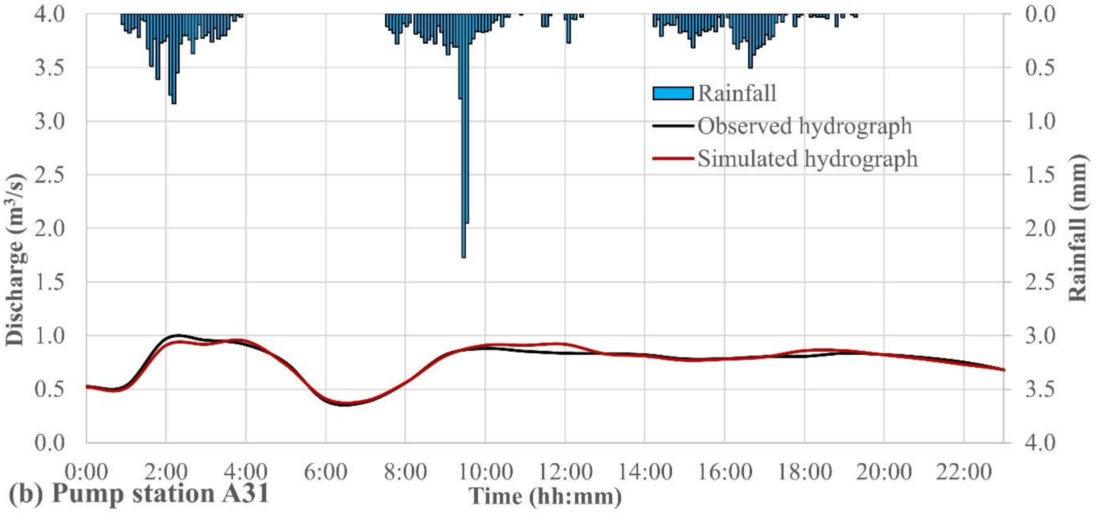
3. RESULTS AND DISCUSSION

3.1 Calibration

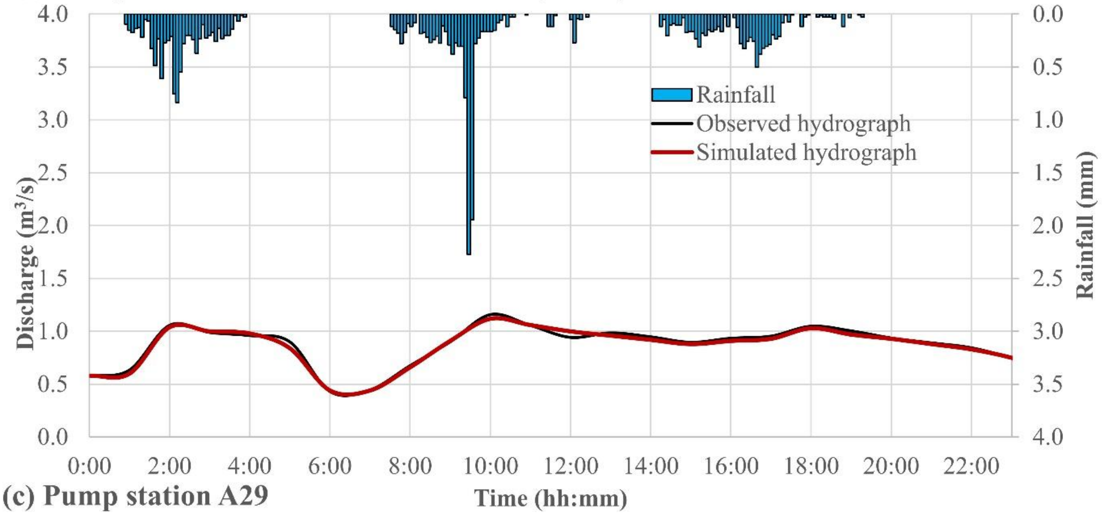
Figure 4 presents the discharge time series for both the observed and the simulated data. The calibration metrics are presented in Table 4. The results indicated that the simulated time series, for the one rainfall event that was available, closely match the observed flow values. In addition, the developed model is able to represent dry weather runoff fairly well. However, some minor discrepancies can be observed between the observed and simulated results. Overall, the calibration results (Figure 4 and Table 4) are found to be fully satisfactory (Moriasi et al., 2007) and as a result the developed hydraulic model can be used for flood risk assessment. According to Moriasi et al. (2007), the NSE and the RSR values of the calibrated model reveal a very good performance of the model for the calibration period.



(a) Pump station A35



(b) Pump station A31



(c) Pump station A29

Figure 4. Calibration results for pump stations (a) A35, (b) A31, and (c) A29

Table 4. Simulation metrics

Index	PC29	PC31	PC35	Index	PC29	PC31	PC35
Correl =	0.99	0.98	0.95	**R^2 =**	0.99	0.96	0.91
NSE =	0.98	0.96	0.85	**RSR =**	0.13	0.19	0.39
RMSE =	0.02	0.03	0.05	**PBIAS =**	1.22	-0.49	8.44
MAE =	0.02	0.02	0.04				

3.2 Flood hazard assessment

For the assessment of the flood hazard in the study area, the calibrated model SWMM model of the study area was used. The analysis was carried out for rainfall events with return periods of 5, 10, 25 and 50 years and rainfall duration of 6 h based on the IDF curve from Elliniko station. The results indicated that for all the scenarios examined, for rainfall events greater than 50 mm, flooding phenomena occur at the nodes of the network. The nodes of the network where flooding phenomena occur are located on Poseidonos avenue and more specifically between Alimos and Amfitheas Avenues. Figure 5 indicatively present the discharge in a sewer of the drainage for a 6h rainfall event and for various return periods (i.e., 5, 10, 25 and 50 years).

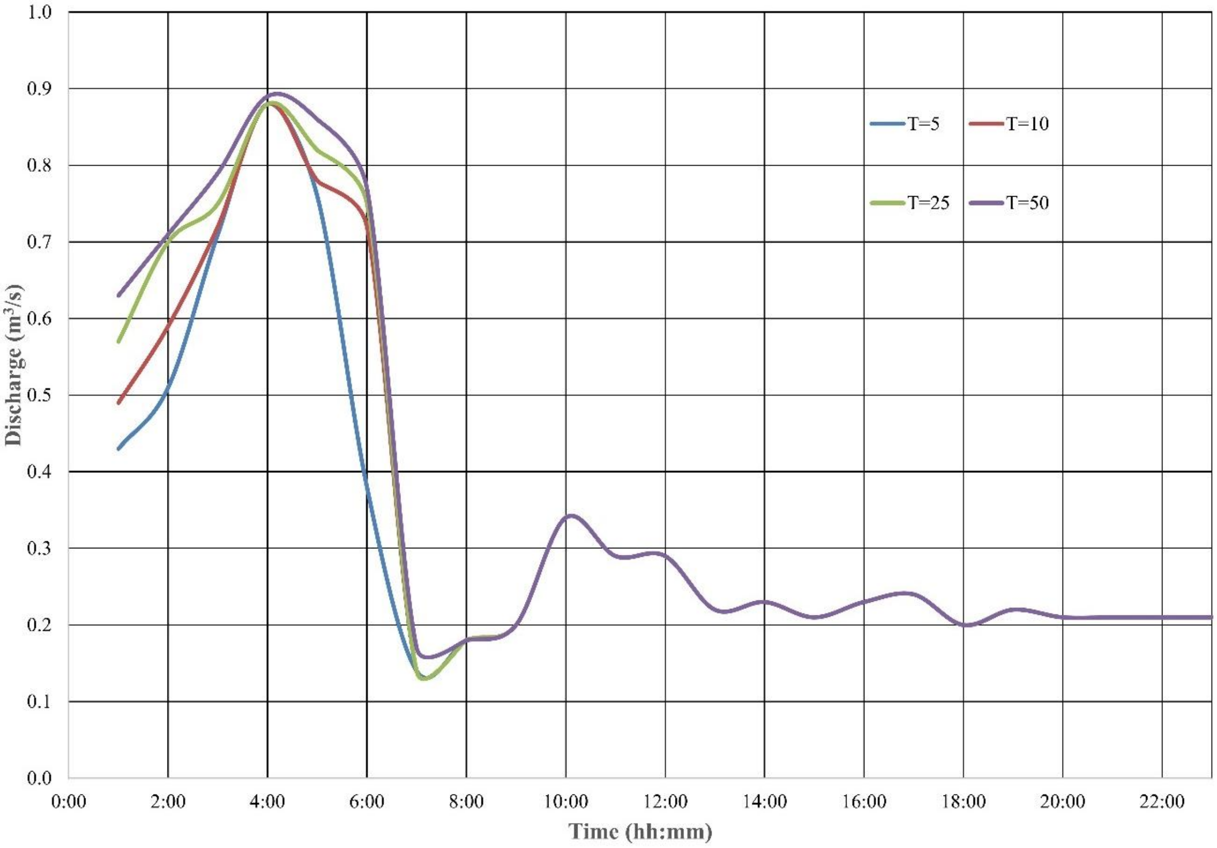


Figure 5. Indicatively results in a sewer of the drainage network

Finally, the results of the IRUDA flood risk assessment index are presented in Table 5. Based on the index for the upper climate scenario, the flood risk in the study area may increase significantly, as for all the return periods under consideration, the value of the index is almost doubled compared to the existing conditions. Based on the lower climate scenario, the flood risk may decrease by approximately 20%. Finally, based on the average climate scenario, the flood risk may slightly increase in the study area, by approximately 14% on average. In summary, based on the results of the flood risk assessment under climate change conditions, some interventions are needed in the network so that it operates smoothly.

Table 5. Flood hazard assessment results

		Rainfall (mm)	IRUDA index
IDF curve Elliniko	**T=5**	54.23	0.33
	T=10	67.88	0.36
	T=25	87.06	0.44
	T=50	102.84	0.49
Climate change Mean scenario	**T=5**	64.04	0.36
	T=10	80.39	0.42
	T=25	108.58	0.51
	T=50	136.29	0.58
Climate change Lower scenario	**T=5**	39.77	0.25
	T=10	48.69	0.28
	T=25	63.62	0.35
	T=50	77.90	0.41
Climate change Upperscenario	**T=5**	151.61	0.62
	T=10	196.07	0.72
	T=25	275.45	0.85
	T=50	356.22	0.87

4. CONCLUSIONS

The control of sewer overflows in wastewater networks is a key issue for both network operators and decision-makers due to the risks it poses to public health and environmental protection from water pollution. Wastewater sewerage networks are capable of providing an adequate level of service during dry weather conditions. However, during extreme weather events, with extreme rainfall, some nodes of the system experience flooding. This could lead to damage (e.g., vehicles, backflow, basement flooding) with significant economic losses.

The present work analyzed the flood hazard in the Central Coastal Collector of Athens Greece as well as to estimate the return period of rainfall for which overflow phenomena are observed at the nodes (water flow on the ground surface) of the central sewage collector of the Saronic coast.

Addressing and/or mitigating RDII phenomena can reduce and/or eliminate overflows, ensure drainage capacity in the sewer network for future development and reduce the negative consequences of the phenomenon on the network's pumping stations and wastewater treatment plants. However, before intervening and taking measures to address the phenomenon, it is crucial to conduct a field survey for an appropriate period of time (e.g., one hydrological year and or more if it is possible) in order to collect data that will be used for the integrated simulation of the system.

There are several options for reducing RDII inflows, including simple rehabilitation of manholes, repair or replacement of sewers, with or without repair of the lateral connection up to the property line, repair or replacement of only private sewers, and repair or replacement of all sewers, both public and private. There are also a number of approaches to address the problem from the perspective of private sources.

In the international literature, the results of various studies of similar projects have revealed that ignoring private sources may expose utility authorities to the risk of not significantly reducing peak RDII flows. Connected roof gutters and inflows from other sources (e.g., foundations, illegal connections, etc.) should, of course, be disconnected if identified. In addition, runoff mitigation measures such as Low Impact Development practices should also be considered in order to avoid runoff entering directly into the drainage system.

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