A Climate Change Impact Assessment of the Irish Road Drainage System

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ABSTRACT: As climate change becomes an increasingly pressing issue, Ireland is expected to experience a rise in infrastructure failures caused by flooding. This puts significant stress on the country's drainage system, which is designed to efficiently channel rainfall. To address this issue, it is crucial to assess the impact of climate change on the Irish road drainage system and adjust strategies accordingly. This study focuses on the effect of intensive rainfall events on the drainage system, using a typical system consisting of pipes, manholes and an attenuation pond as a case study. A probabilistic model is developed to simulate system performance using Monte Carlo simulation, and intensive rainfall events are derived under various climate scenarios. (i.e. historical scenario for 1976-2005, and future emissions scenarios RCP 4.5 and RCP 8.5 for 2071-2100). The performance of the system is analyzed using the SWMM software as a basis for the probabilistic assessment under various climate scenarios. The results indicate that climate change will increase system inflow and lead to more severe flooding. Model variability will influence the occurrence probability of system flooding. The impact of intensive rainfall was found to be greater under RCP 8.5 than RCP 4.5 or the historical one, and pipes and the pond showed different levels of resilience under the design allowance of 20%.

1. INTRODUCTION

Climate change is a reality that has been acknowledged by the IPCC and is evident in the shifting temperature and weather patterns observed globally (IPCC, 2021). The effects of climate change, such as flooding, extreme weather, catastrophic storms, and rising sea levels (Abbass and Qasim, 2022), pose significant threats to our critical infrastructures across the world (Krogstrup and Oman, 2019; Diffenbaugh and Burke, 2019).

In Ireland's oceanic climate, there is a high likelihood of flooding. Irish institutions such as the Office of Public Works (OPW) and Met Éireann have warned of increased occurrences of failures, particularly flood risk, across various sectors due to climate change (National Adaptation Framework, 2018; Climate Action and Low Carbon Development Act, 2021; Nolan, 2015; Nolan, Sullivan, and McGrath, 2017). The OPW has created flood maps for flood management, highlighting the potential for flood events in the future (OPW, 2021). The risk of flooding from intense rainfall in rural and urban areas in Raphoe, Co. Donegal, Co. Cork, and Dublin City has been deemed potentially significant (NIFM, 2020). Researchers have noted a clear increase in annual mean precipitation in Ireland under future climate scenarios, with winters having increased rainfall (O'Brien and Nolan, 2023). This increase may put significant pressure on, and potentially overload the existing drainage system, leading to failures of the system. Given the serious consequences of flooding on society's normal functioning, it is important to examine the performance of the Irish road drainage system under various climate scenarios through risk analysis.

Despite development over the years, it remains a significant challenge to design an effective functioning drainage system for collecting and conveying stormwater under the climate change background (Zhou, 2014). Fear surrounding the impact on Irish road drainage systems has led to a 20% allowance factor being included in the design stage to account for climate change. It is, however, unclear whether this is overly conservative, or if with this factor the designed drainage system will meet future demands. This paper aims to examine the impact of climate change on the performance of Irish road drainage systems subjected to intensive rainfall events under various climate scenarios. The study focuses on a typical drainage system designed in accordance with the Transport Infrastructure Ireland (TII) standards in Ireland. A probabilistic model of the system is created using the Storm Water Management Model (SWMM) incorporating uncertainty and variability. The simulation of the system's performance under intensive rainfall events is conducted under historical and future climate scenarios (RCP4.5 and RCP8.5), which are derived from the rainfall records collected at the meteorological stations located all over Ireland. The performance of the drainage system is analyzed and evaluated, and results of the study highlight the potential impact of climate change on Irish road drainage systems.

2. DRAINAGE SYSTEM

For this study, a simplistic but representative typical road drainage system was established in

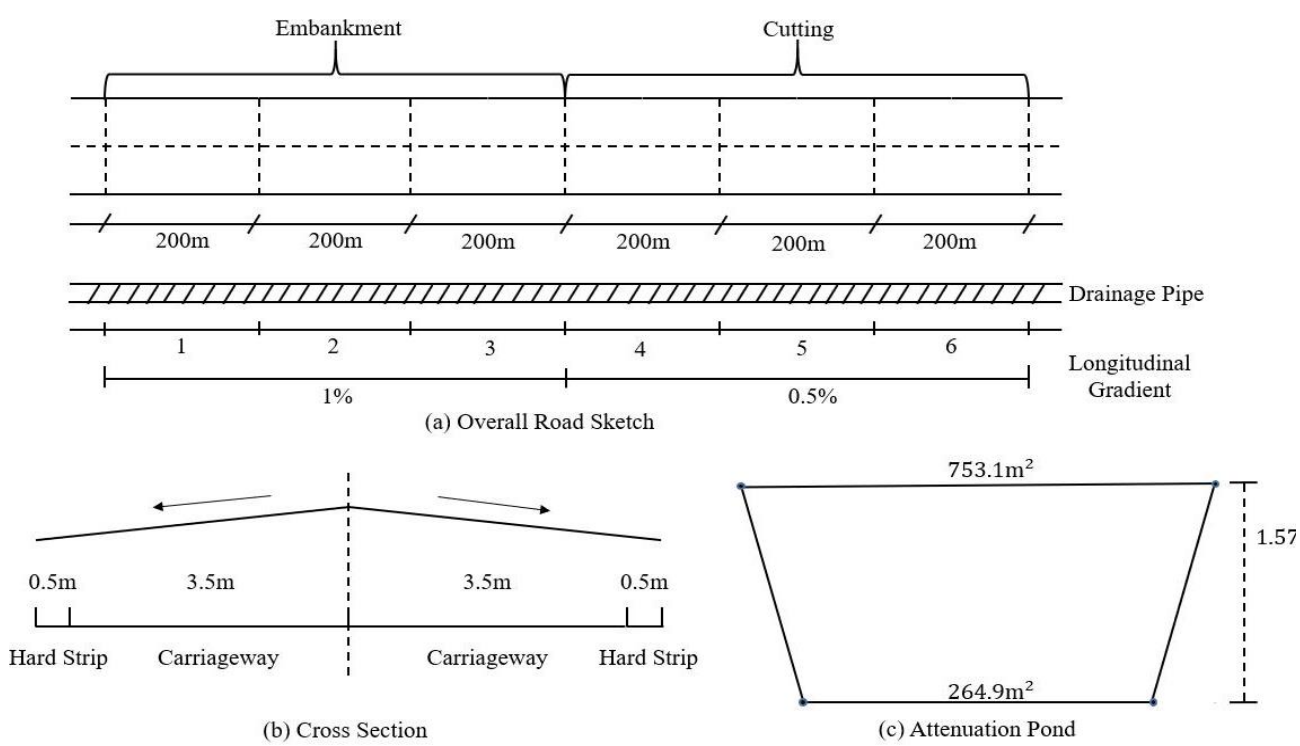

Figure 1: Sketch for the road and drainage system

Ireland (motorway or national route) through extensive consultation with industry stakeholders (TII and Arup Consulting Engineers). The selected road drainage system extends for 1.2 km and is designed in accordance with TII standards (TII, 2015). The design for County Cork in the south of Ireland serves as the first case study, and additional locations will be considered later in the ongoing project to account for regional variability. The drainage system studied consists of manholes connected by pipes, and an attenuation pond at the terminal before the free outfall of the rainwater. The catchment has an impermeable road footprint area of approximately 1.055 ha and an average annual rainfall depth of 1230 mm (https://www.met.ie/climate/available-data/monthly-data). The soil type is classified as Type 4, with a soil index of 0.45, as determined by the Flood Studies Report (TII-DN-DNG-03068, 2015). The meteorological data, including the characteristic rainfall metrics, was collected from Met Éireann. The road under consideration is 8.0-meter-wide, with a 7.0-meter-wide carriageway and two 0.5-meter-wide hard strips, and runs on a 1% gradient embankment before transitioning to a 0.5% gradient cutting (Department of Translate, 2022). The flow in the pipes was calculated using the Modified Rational Method, and the pipe sizing was performed using the Colebrook-White Equation (Kellagher, 1981). The size of the attenuation pond was determined by comparing the development runoff rate and greenfield runoff rate for various rainfall durations (TII-DN-DNG-03066, 2015). A sketch of the road and drainage system is presented in Figure 1(Department of Translate, 2022; National Roads Authority, 2000).

3. DEVELOPMENT OF PROBABILISTIC MODEL

As mentioned above, the impact of climate change on the road drainage system is evaluated through numerical simulations using the open-source software SWMM. The abovementioned system is modeled to represent its performance under intensive rainfall events for both historical and projected future climate scenarios. The model simulation is carried out in five steps, including information preparation, model creation, parameter setting, running the simulation, and results analysis.

The numerical model of the physical drainage system was built, as depicted in Figure 2. In this system, rainfall routed to the sub-catchments (S1-S6) is collected by the corresponding manholes (J1-J6) and transmitted inside the pipe networks (C1-C7) along the road sections to the terminal portal of the attenuation pond (Sto1), and finally discharged to the surrounding environment through outfall structures including an orifice (Orifice 1) and a weir (Weir 1). To accurately model the drainage system, appropriate values for the parameters were assigned. Varied ranges of important parameters are listed in Table 1. Monte Carlo simulations were used to account for variability in the model by generating a large number of model samples with varied parameters that follow appropriate distributions. The variability of intensive rainfall events is taken into account by combining various climate scenarios (historical, RCP 4.5, and RCP 8.5 for the future period 2071-2100) and return periods, creating different rainfall events as the hazard input. The kinematic wave model was chosen as the routing calculation method, and the total simulation time was set to 24 hours. To balance simulation accuracy and efficiency, the control timestep was set to 10 s. The creation of the model samplings can be achieved through the batching process of the information files (.inp) using Matlab and running the SWMM solver through the command prompt. The process is clarified in Figure 3. It is noted that while the uncertainty of the model is incorporated herein, for this iteration of the analysis the uncertainty associated with the climate change projections is not incorporated. Work is however ongoing to capture the uncertainty associated with climate change projections for intense rainfall events in Ireland. This aspect will thus be incorporated into the model in the coming months.

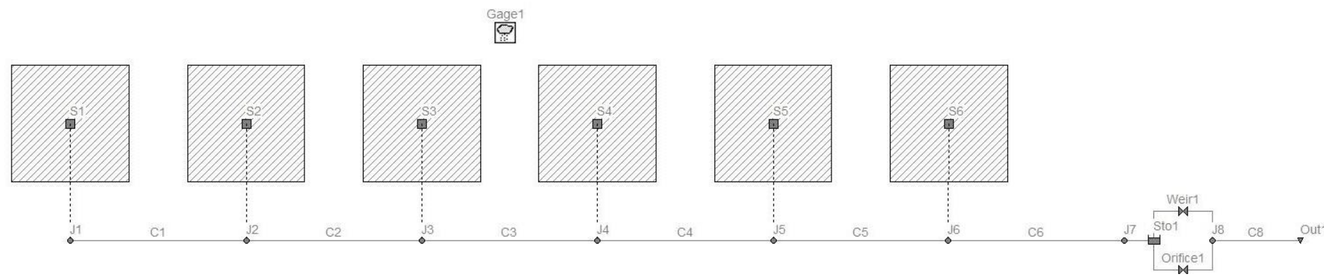

Figure 2: Numerical model of the drainage system using SWMM

Table 1: Varied numerical model parameters

Variables	*Distribution*	*Range*		*Source*
Manning Coefficient for Subcatchment	*Uniform*	*[0.011,0.013]*		*(EPA,2022)*
Pipe Roughness	*Uniform*	*[0.011,0.017]*		*(EPA,2022)*
Depression Storage Depth (mm)	*Uniform*	*[1.27,2.54]*		*(EPA,2022)*
Pipe Diameter (mm)	*Normal*	*Mean*	*Variance*	*(TII-DN-DNG-03066,2015)*
		225,225,300,375,450,450,225	*0.05*	

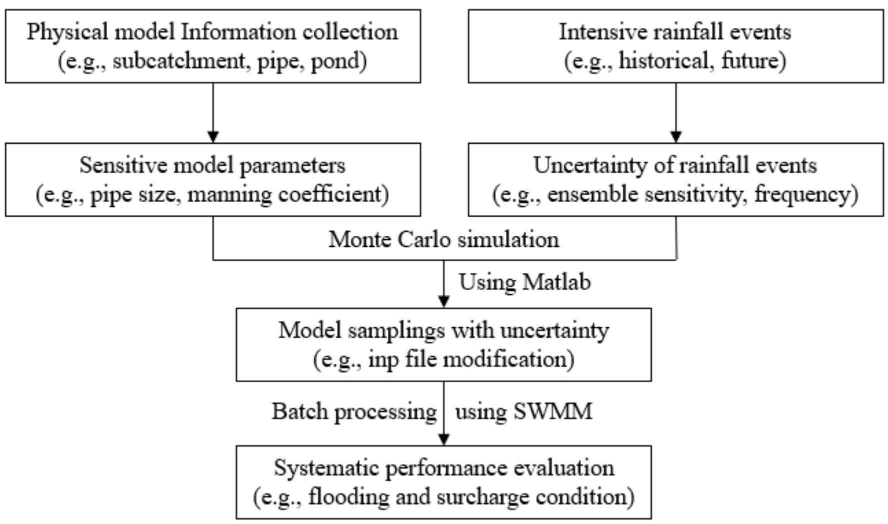

Figure 3: Process of the numerical simulation considering climate change uncertainty

4. CREATION OF INTENSIVE RAINFALL EVENTS

To successfully carry out the numerical assessment, rainfall events with 2-hour durations are projected as the hazard input for both historical and future climate scenarios. Rainfall records of nine metrics (e.g. r4in15, r5in30) from more than 30 stations across Ireland have been gathered by Met Éireann. These metrics have been represented in peak over threshold format, where "r4in15" refers to rainfall depth exceeding

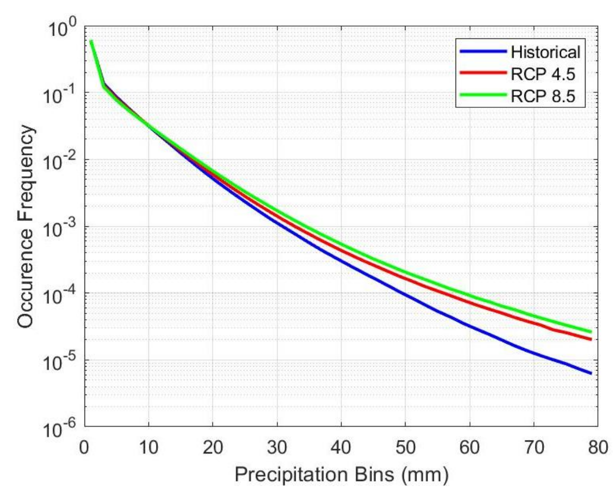

Figure 4: Ratio of frequency for daily rainfall events between historical and future climate scenarios

4 mm in any 15 mins period. For this paper, the aggregated rainfall records of 23 stations for the historical period of 1976-2005 located all over Ireland were utilized as the data source. Statistical methods were employed to convert infrequent events into yearly frequency distributions. Specifically, the occurrence frequency of rainfall events for the record time period of every metric is obtained. Generalized Pareto Distribution was utilized to describe the exceedances of these events. Then, the depth-duration-frequency relationship for the historical period can be obtained through comprehensive consideration of the occurrence frequency of every metric and its corresponding Pareto Distribution. Besides, the quantile mapping method was employed to link the frequency of historical daily rainfall intensity with future daily rainfall intensity, and the frequency ratios for various simulated ensembles between the historical period and future climate can be calculated. There were 27 and 35 ensemble results projected for RCP 4.5 and RCP 8.5 during the time period of 2071-2100, respectively. Figure 4 showed the mean value of various ensemble results.

There are various ways to consider the ratio of frequency between the historical period and future climate scenarios. One idea is to consider the influence of different metrics and find the corresponding frequency ratios of all the ensemble members according to various occurrence frequencies of each metric, then adopt suitable distributions for every metric to derive the rainfall depth-duration-frequency relationship for the future climate. The other one is to adopt the ratio of frequency for all the ensemble results using the design return period of the pipe network. Research is still underway as to which approach is more appropriate.

Table 2: Maximum intensity for intensive rainfall events considered

Return Period(year)	*5*	*10*	*50*	*100*
Historical(mm/h)	*23.00*	*35.85*	*100.52*	*156.71*
RCP4.5(mm/h)	*25.74*	*40.29*	*113.99*	*178.40*
RCP8.5(mm/h)	*28.08*	*44.06*	*125.40*	*196.75*

In this paper, the frequency ratios corresponding to the occurrence frequency of various metrics were adopted. Generalized Extreme Value (GEV) distribution was selected as the best fit for the simulated ensemble results. With the randomly created frequency ratios based on the fitted GEV distribution, the rainfall depth-duration-frequency relationships under various future climate scenarios were developed. This is the basis of deriving the intensity hyetograph for intensive rainfall events using the 'Alternating Blocks Method' extended from the Chicago synthetic storm pattern proposed in the reference (Keifer and Chu, 1957). It is important to note that this paper listed the preliminary results at the moment. As research goes on, a much more suitable method to derive the ratios of frequency between the historical period and future climate scenarios will be proposed and adopted.

In this study, rainfall events with a 2-hour duration and various return periods (5-year, 30-year, 50-year, and 100-year) were considered and created by possible rainfall scenarios. Table 2 lists the maximum intensity for simulated rainfall events under various climate scenarios. It shows that the peak intensity for simulated rainfall data (2071-2100) under RCP 4.5, compared to the historical reference period (1976-2005), increases by 2.74 mm/h to 21.69 mm/h for return periods of 5-year to 100-year, respectively. The total increase in rainfall depth is from 1.21% to 2.94%. Meanwhile, the peak intensity for projected rainfall data (2071-2100) under RCP 8.5 compared to the historical period (1976-2005) increases by 5.08 mm/h to 40.04 mm/h for return periods of 5-year to 100-year, respectively. The total increase in rainfall depth per hour is approximately from 2.26% to 5.16% for RCP 8.5 when compared to the 1976 to 2005 period. These preliminary results indicate that climate change does affect the intensity and depth of intensive rainfall events. Both values show significant increases, with the historical scenario having the lowest values, followed by RCP 4.5, and the highest values for RCP 8.5. This increase could have significant consequences for the performance of the drainage system and may result in more severe flooding conditions, highlighting the need for analyzing the performance of drainage systems under intensive rainfall events considering climate change.

5. PERFORMANCE ASSESSMENT OF DRAINAGE SYSTEM SUBJECTED TO INTENSIVE RAINFALL EVENTS

The behavior of the system and key performance indicators, including flooding and surcharge conditions, are analyzed in this section. Figure 5 describes the percentage increase of system inflows for RCP 4.5 and RCP 8.5 compared to the historical period along with their standard deviations considering varied model parameters. Results indicate that the system inflow increase as the climate scenarios change from the historical period to the end of the 21st century under RCP 4.5 and RCP 8.5, which coincides with the increase of rainfall intensity and depth as described in Section 4.

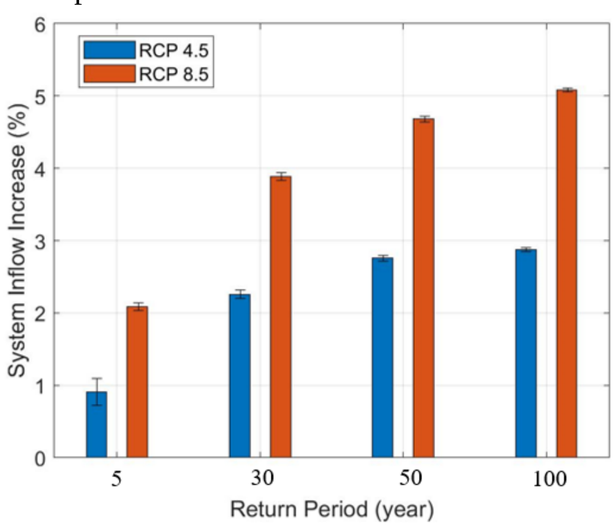

Figure 5: System inflow increase of RCP 4.5 and RCP 8.5 compared to the historical period (Note: "whiskers" in the Figure show plus and minus one standard deviation)

As an important component, the performance of the attenuation pond has been examined and it has been found that no flooding occurs under all climate scenarios, despite the observation of the flooding at manholes and surcharge in pipes. However, the maximum water depth does show an increase with the severity of climate scenarios (Figure 6). It is noted that the entire drainage system is designed under the same 20% allowance specified by the infrastructure owner to account for the impacts of climate change (TII- DN-DNG-03022, 2015). Regardless, the results indicate that the pond is much more resistant when subjected to intensive rainfall events compared with the pipe network, highlighting the difference in the resilience of components within the system.

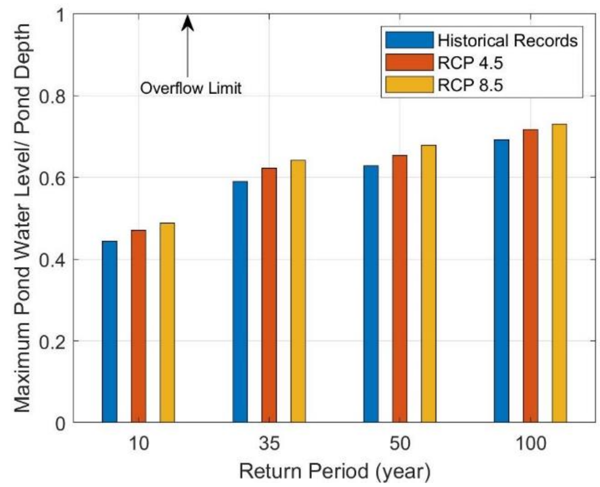

Figure 6: Ratio between maximum water depth and pond depth under various climate scenarios

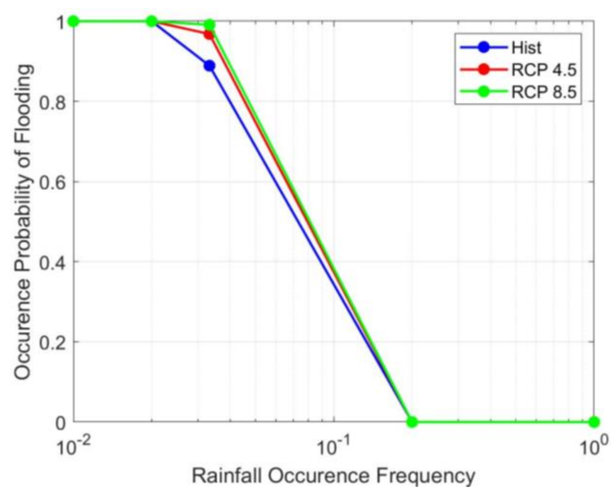

Figure 7: Occurrence probability of system flooding under various climate scenarios

Figure 7 shows the occurrence probability of system flooding under various climate scenarios considering the uncertainty of varied model parameters. It indicates that varied parameters have an impact on the flooding probability of the drainage system, which displays a higher occurrence probability of flooding under RCP 8.5 and RCP 4.5 by the end of the century, and flooding will definitely occur under intensive rainfall events with a smaller occurrence frequency such as 0.01.

6. CONCLUSIONS

This study investigates the impact of climate change on road drainage systems in Ireland, with a specific focus on a length of road located in the County Cork. A probabilistic model is developed using Monte Carlo simulation to account for model variability, and various climate scenarios and return periods are considered for intensive rainfall events. The system performance is analyzed and evaluated. The findings of the study reveal that the impact of climate change on the drainage system may be significant. It is essential to consider model variability for deriving the occurrence probability of flooding. As a result of the projected increased rainfall intensity and rainfall depth, system inflow is likely to rise, as the climate evolves from the historical period to the end of the century under RCP 4.5 and RCP 8.5, respectively. This increase leads to a rise in the likelihood of flooding conditions including manhole flooding and pipe surcharge. This impact highlights the need for research to effectively manage flood risk in a changing climate. Moreover, despite using the same allowance factor in the design process of Irish drainage systems, varying resilience among components was observed. This paper only considers the uncertainty from the drainage model. Work is however ongoing, and the uncertainty of different climate scenarios, and regional and seasonal variability under climate change impact across Ireland are planned to be considered in the future.

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