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Ahmed Nasr
*Technological University Dublin*, ahmed.nasr@tudublin.ie

Zeinab Bedri
*Technological University Dublin*, zeinab.bedri@tudublin.ie

Loreta Ramanauske
loreta.ramanauske@mydit.ie

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# Prediction of Flood Hydrograph in Small River Catchments Using System Modelling Approach

Ahmed Nasr[1], Zeinab Bedri[1], Loreta Ramanauske[1],
[1]School of Civil and Structural Engineering, Dublin Institute of Technology, Bolton Street, Dublin 1
email: ahmed.nasr@dit.ie, zeinab.bedri@dit.ie, loreta.ramanauske@mydit.ie

ABSTRACT: Floods remain to be one of the natural catastrophic disasters with serious adverse social and economic implications on individuals and communities all around the world. In Ireland, frequency of flood events have increased dramatically during the last forty years and is expected to continue to rise primarily due to changes in rainfall and temperature patterns as a result of the global climate change. Small river catchments are usually vulnerable to different types of flooding particularly those associated with "monster" rainfall events, which are characterised by short durations and high intensities. Therefore accurate prediction of flood hydrographs resulting from these rainfall events are vital for issuing timely and detailed warning to competent authorities in order to allow for efficient preparedness in the affected catchment and other downstream areas. The current study assess the performance of Unit Hydrograph model in predicting flood hydrograph due to extreme rainfall storms at three small river catchments with different physical and hydrological characteristics. Results suggest that the UH model is more powerful in simulating flood hydrographs at natural rural catchments than in urban catchments. The artificial drainage settings of the urban catchments could be the main reason for hindering the UH from simulating the characteristic behaviour of such type of catchments.

KEY WORDS: Flood prediction; Small catchments; Unit Hydrograph; Hydrology.

## 1 INTRODUCTION

Floods are one of the most significant water-related natural disasters, causing serious property damage and loss of lives [1]. The distinctive topography of Ireland and its relatively high precipitation are the major causes of flooding. Moreover human activities, particularly those associated with changes in land uses e.g. rapid urbanisation and the destruction of natural resources, are also contributing to the severity of most of the unprecedented extreme flood events [2]. Such extreme flooding is often triggered by localised extreme rainfall events in small sub-catchments and subsequently propagate downstream to inundate lowland areas in the catchment. A "small catchment" in the context of this paper is a drainage basin with surface area usually less than 25 km$^2$ and with defined natural and topographic boundaries.

In response to increasing flooding incidents, a call has been issued for the development and implementation of mitigation measures to reduce the impact of flooding. One of such measures encompasses the use of operational flood forecasting systems, the use of such systems have been highlighted as a best practice in flood risk management [3]. The growing necessity of these operational systems gives impetus to the development of rainfall-runoff models which may be used to estimate the magnitude and frequency of peak discharges resulting from extreme rainfall events over a catchment. Estimation of these variables in a catchment provides crucial information used in managing flood disasters by designing and constructing essential flood defence and relief structures. For this purpose, a large numbers of models have been developed ranging from simple lumped empirical data-based models to more complex and sophisticated physically-based numerical systems. Application of these models in large-scale Irish catchments is well-documented in the literature; however, few studies are available for modelling hydrological behaviour of small catchments. The current study contributes to bridging this gap in knowledge through evaluating the performance of the Unit Hydrograph rainfall-runoff modelling approach in predicting flood hydrographs in small river catchments.

## 2 STUDY CATCHMENTS

Three small catchments were selected for the purpose of the current study. The catchments are the River Slang (Co. Dublin), the Lough Ennell Tributary River (Co. Westmeath) and the River Big (Co. Louth). The catchments differ in their main physical characteristics and this in turn enables testing the model under a diverse range of hydrological behaviours.

The River Slang catchment is a 5.5 km$^2$ sub-catchment (Figure 1) of the River Dodder catchment (Co. Dublin). This sub-catchment is heavily developed with residential and industrial land uses and it is anticipated that urban land cover in this sub-catchment will continue to grow in the future years [4]. In terms of topography, the Slang catchment rises at the Three Rock Mountain at an elevation of approximately 430 m OD. The Slang stream is approximately 8 km in length and falls at an average gradient of 1 in 20. In terms of bedrock geology, the lower reaches of the Dodder catchment, including the Slang sub-catchment, predominately consist of carboniferous limestone.

The Lough Ennell Tributary River catchment is a 10.77 km$^2$ small catchment (Figure 1) in county Westmeath and it is a part of the Brosna sub-catchment in the Shannon River Basin. Agriculture is the principal activity in this River Basin (73% of total area) with pasture being the dominant land use [5]. There are also some significant areas of wetland (12%) consist mainly of peatland. The soils of Lough Ennell Tributary River catchment are dominated by a mixture of well-drained soil and peat, together with some poorly drained soil.

River Big is a small sub-catchment of the Neagh Bann River Basin in Co. Louth (Figure 1) and covers an area of 10.4 $km^2$. The dominant land use in the Neagh Bann River Basin, including the River Big sub-catchment, is agricultural with some small areas of forestry and peatland. The River Big sub-catchment is predominantly covered by peat bogs and pastures. The soil types that characterise this catchment is predominantly deep well drained mineral podzols with interspersed deep well drained lithosols. Peaty podzols and scree are also located on Carlingford Mountain, which is a part of the River Big sub-catchment. Poor aquifer is dominating the sub-catchment.

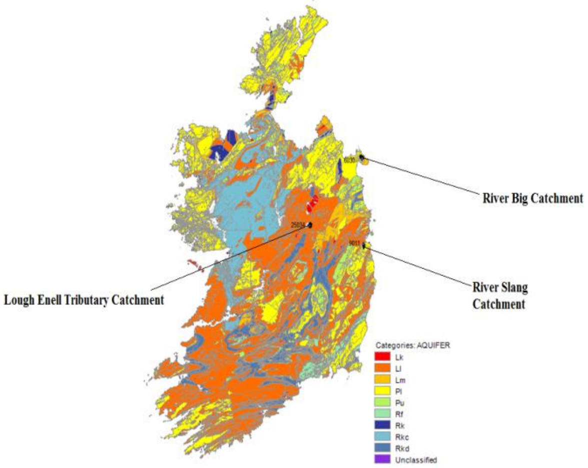


Figure 1. Study Catchments.

## 3 METHODS

The Unit Hydrograph (UH) was developed originally by Sherman (1932) and it is defined as the hydrograph of direct surface runoff resulting from a unit depth of effective rainfall (usually 1 cm) falling over the catchment area at a uniform rate during a specified period of time. Hence it can be categorised as a lumped model for transforming effective rainfall obtained after subtracting rainfall losses through various processes (e.g. interception, infiltration) into direct surface runoff. This single transformation model normally uses a spatially averaged effective rainfall event as an input and converts it into an output runoff hydrograph. Despite of the simplistic assumption of the unit hydrograph theory, the model generally gives modelling results that are widely acceptable for practical purposes [6].

Calibration and validation of the UH model requires two sets of data; namely rainfall and river flow data. For the current study, the rainfall data was obtained from the Irish Meteorological Services, Met éireann, website, (https://www.met.ie/climate/available-data/historical-data) while river flow data was obtained from Hydronet, the Environmental Protection Agency hydrometeric website (http://www.epa.ie/hydronet/). Six historical significant rainfall events in terms of duration and intensity have been identified and used in calibrating and validating the UH model. These storm events were selected based on the availability and quality of rainfall and flow data. The six events are Event 1 - August 1986 (Hurricane Charley), Event 2 - August 2008, Event 3 - November 2009, Event 4 - October 2011; Event 5 – February 2014 (Storm Darwin); and Event 6 - August 2017.

The six selected rainfall events were split into two groups for the purpose of calibration and validation of the model. Events 3 and 4 were used to calibrate/derive the UH model while the rest of events were used in validating the derived UH model in all three study catchments.

Before using storms Events 3 and 4 for calibration of the UH model, it was necessary to pre-process both the rainfall and flow data. Rainfall data was analysed in order to produce the Effective Rainfall Hyetograph (ERH). In this analysis the total rainfall was partitioned into infiltration losses and ERH. A number of rainfall separation models are available in the literature e.g. the Horton infiltration model [7], the Soil Conservation Service Curve Number method [8], and the percentage-based method of rainfall separation [9]. In this study, the Φ-index method [10] was chosen due to its simplicity and effectiveness.

Similarly, the existing flow data was analysed in order to derive the Direct Runoff Hydrograph (DRH) from the observed stream flow hydrograph. This was performed using a baseflow separation routine (SWATBFLOW) of the SWAT model [11].

The direct runoff hydrographs and effective rainfall amounts resulting from the pre-processing stage were then used in the derivation of the unit hydrographs. The derivation of the unit hydrographs for Storms 3 and 4 for each catchment was conducted using the Ordinary Least-Squares Regression Method [12]. The Unit Hydrographs derived from Storm 3 (UH3) and Storm 4 (UH4) were then averaged to obtain a third Averaged Unit Hydrograph (Average UH).

Following the calibration stage, the three resulting unit hydrographs were then used for predicting the direct runoff hydrographs of the remaining selected storm events (Storm 1, Storm 2, Storm 5, and Storm 6). The predicted direct runoff hydrographs were then compared with the actual flow hydrographs in order to validate the performance of the UH model. In addition, the fit between the predicted and observed hydrographs was evaluated using two statistical criteria; Coefficient of Determination ($R^2$) and the Nash Sutcliffe Efficiency (NSE). Finally an inter-comparison of the results of the three study catchments was undertaken in order to elicit the relationship between the hydrological responses of the catchments and their physical characteristics.

## 4 RESULTS

### *4.1 Derivation of the UH model*

The derived Unit Hydrographs for the River Slang Catchment, Lough Ennell Tributary River Catchment, and the River Big Catchment are shown in Figures 2, 3, and 4 respectively. It is obvious from Figure 2 that at the River Slang Catchment, the UH3 produced a higher peak (by almost 30%) and quicker falling limb than UH4, indicating a “more flashy” response than UH4. At the Lough Ennell Tributary River Catchment (Figure 3), the derived unit hydrographs yielded approximately similar peak flow magnitudes but with the

UH3 showing a quicker recession hydrograph than UH4. At the River Big Catchment, the UH3 and UH4 have displayed an identical behaviour (Figure 4).

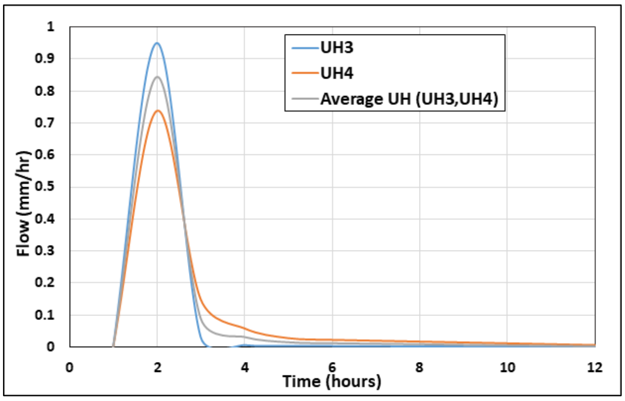


Figure 2. Comparison of three UHs at the River Slang Catchment.

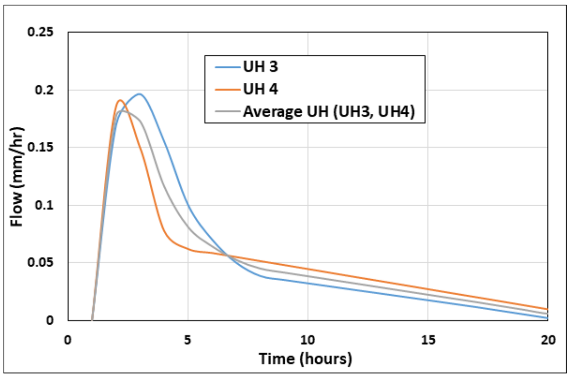


Figure 3. Comparison of three UHs at the Lough Ennell Tributary River Catchment.

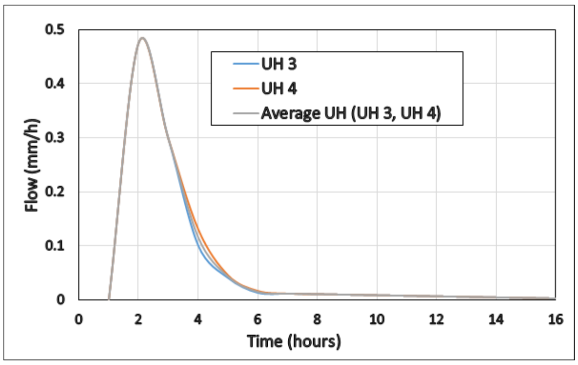


Figure 4. Comparison of three UHs at the River Big Catchment.

### *4.2 Validation of the UH models*

The resulting unit hydrographs (in Section 4.1 above) were then used for predicting the direct runoff hydrographs of the remaining selected storm events (Storm 1, Storm 2, Storm 5, and Storm 6). For the purpose of this paper, the results of two storm events Storm 2 and Storm 5 are presented and discussed below.

Figure 5 demonstrates the performance of the three UHs (UH3, UH4, and the average UH) in predicting flood hydrographs for Storm Events 2 and 5 at the River Slang sub-catchment. The figure clearly shows that the timing of the peak of Storm 5 has been reasonably captured by the three UHs whereas the opposite has occurred for Storm 2. In terms of the magnitude of the peaks, the three UHs have overestimated the observed peak of Storm 5. For Storm 2, UH3 has overestimated the actual peak while UH4 underestimated it and this has resulted in producing good predictions by the average UH. Generally for the two storms the rising limb and recession limb of the simulated hydrographs are steeper than the actual hydrographs. Also the three UHs have responded well to the second rainfall event in Storm 2 and the first rainfall event in Storm 5 while the actual hydrograph shows no response.

This behaviour may be attributed to the fact that the River Slang catchment is an urban catchment and therefore will likely undergo quick artificial drainage following storm events. This manifests itself as a lack of response to smaller rainfall events or smaller peaks of resulting flood hydrographs.

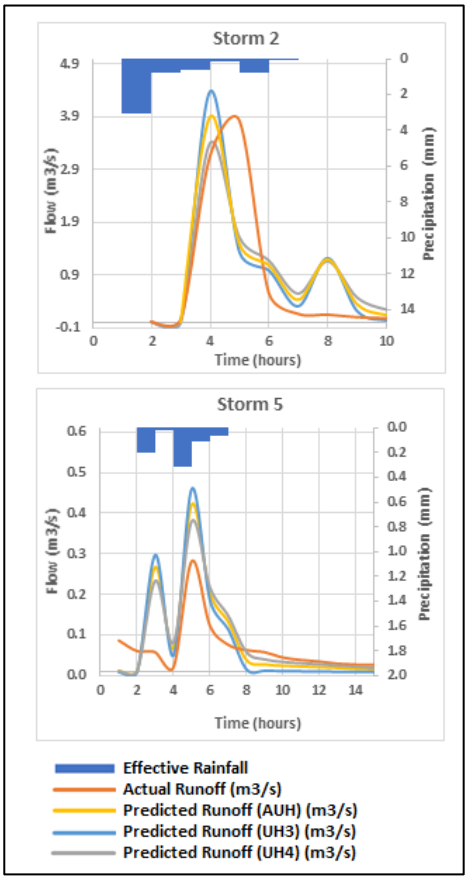


Figure 5. Predicated and actual flow hydrographs for the River Slang Catchment.

In Lough Ennell Tributary River Catchment, the three UHs have generally given good prediction to the actual hydrographs of Storm 2 and 5 (Figure 6). The predicated shape and peak magnitude of the flow hydrograph of Storm 2 are comparable to the actual ones. For Storm 5, the predicted shape of its flow hydrograph is matching the actual one; however, there is an underestimation to the actual peak magnitude by all UHs.

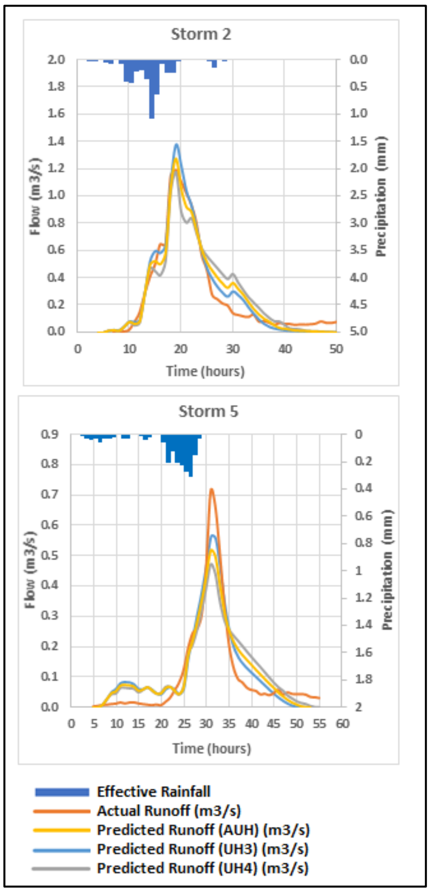


Figure 6. Predicated and actual flow hydrographs for the Lough Ennell Tributary River Catchment.

Figure 7 shows that the predicted hydrographs of Storm 2 gave a very good fit to the observed hydrograph in terms of both shape and peak magnitude in the River Big Catchment. Results of Storm 5 demonstrated a good fit between the actual and predicted magnitude of the first peak, but showed inconsistency with the second peak. This response may be due to two reasons. Firstly the River Big is a steep catchment and therefore may drain quickly particularly following small rainfall events. Secondly, the event-based nature of the Unit Hydrograph model implies that the model handles rainfall events on an isolated discrete basis; i.e. the system has a short memory to account for the antecedent moisture condition which resulted from one storm event and affecting a subsequent event following immediately the first one. When comparing the hydrographs of Storm events 2 and 5 it is noteworthy that there is a dry spell of approximately 5 hours between the two rainfall events of Storm 2 as opposed to 1.5 hours on Storm 5. Also the amount of rainfall during Storm 5 is significantly less than that of Storm 2.

The model predictions of the three catchments demonstrated that the Lough Ennell Tributary River and the River Big Catchments which are both agricultural catchments, performed better than the River Slang Catchment. Such an outcome may indicate that the Unit Hydrograph model performs better in catchments that exhibit natural damped drainage system than urban catchments with artificial drainage system such as the River Slang Catchment.

Topography of the catchments is another important factor influencing the catchment response to rainfall. Both River Slang and River Big catchments are steep, implying a flashy response and quicker drainage than the Lough Ennell Tributary River Catchment which lies in a low-land area.

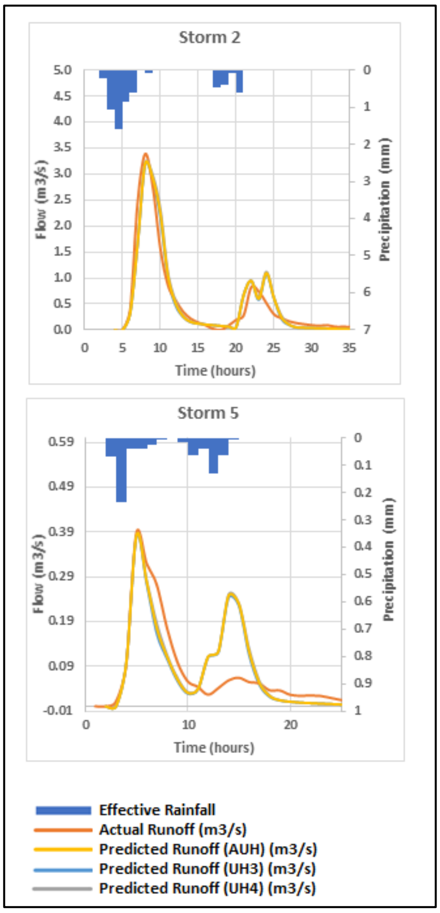


Figure 7. Predicated and actual flow hydrographs for the River Big Catchment.

The results of statistical efficiency are presented in Tables 1 to 4 below. In this study both the Coefficient of Determination ($R^2$) and Nash-Sutfcliffe Efficiency (NSE) were calculated to assess the fit between the predicted and actual flow values for the two validation storms (Storm 2 and 5).

The range of NSE lies between 1.0 (perfect fit) and $-\infty$. An efficiency of lower than zero indicates that the mean value of the observed time series is a better predictor than the model.

The range of $R^2$ lies between 0 and 1, which describes how much of the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation.

The NSE values for Storm 2 and 5 at the River Slang catchment (see Tables 1 and 2) were negative suggesting that the mean value of the observed time series is a better predictor than the UH model. This finding is also confirmed by the low values of $R^2$ which range between 0.061 and 0.70 (Tables 3 and 4).

The UH model gave a remarkably better fit between the actual and the predicated flow values at the Lough Ennell Tributary River as demonstrated by both the NSE (0.795 – 0.957) and $R^2$ (0.842 – 0.967) values.

Results at the River Big catchment also showed a good fit between the observed and predicted flow values. The NSE values for this catchment ranged between 0.612 and 0.923 while the $R^2$ ranged between 0.657 and 0.924.

Table 1. Comparison of the predicted and actual hydrographs of Storm Event 2: Nash-Sutfcliffe Efficiency (NSE).

| Catchment | UH3 | UH4 | AUH |
|---|---|---|---|
| River Slang | -0.45 | -0.01 | -0.22 |
| Lough Ennell Tributary River | 0.96 | 0.88 | 0.94 |
| River Big | 0.92 | 0.91 | 0.92 |

Table 2. Comparison of the predicted and actual hydrographs of Storm Event 5: Nash-Sutfcliffe Efficiency (NSE).

| Catchment | UH3 | UH4 | AUH |
|---|---|---|---|
| River Slang | -0.78 | -0.07 | -0.36 |
| Lough Ennell Tributary River | 0.91 | 0.80 | 0.87 |
| River Big | 0.61 | 0.61 | 0.61 |

Table 3. Comparison of the predicted and actual hydrographs of Storm Event 2: Coefficient of Determination ($R^2$).

| Catchment | UH3 | UH4 | AUH |
|---|---|---|---|
| River Slang | 0.061 | 0.151 | 0.097 |
| Lough Ennell Tributary River | 0.97 | 0.88 | 0.94 |
| River Big | 0.92 | 0.91 | 0.92 |

Table 4. Comparison of the predicted and actual hydrographs of Storm Event 5: Coefficient of Determination ($R^2$).

| Catchment | UH3 | UH4 | AUH |
|---|---|---|---|
| River Slang | 0.70 | 0.70 | 0.70 |
| Lough Ennell Tributary River | 0.92 | 0.84 | 0.90 |
| River Big | 0.66 | 0.68 | 0.66 |

The results of the statistical analysis demonstrated that the best fit between predicted and actual flow was achieved at the River Big Catchment, followed by the Lough Ennell Tributary River Catchment, while the least accurate fit was obtained at the River Slang Catchment.

## 5 CONCLUSIONS

Accurate prediction of flood hydrographs due to localised extreme rainfall events in small river catchments provides essential information used in designing necessary measures for managing floods at various scales. Unit Hydrograph (UH) model is considered one of the simplistic types of hydrological models which reasonably predicts the hydrological behaviour of small catchments. The current study evaluated the performance of the Unit Hydrograph rainfall-runoff modelling approach in predicting flood hydrographs at three small Irish catchments with different physical and hydrological characteristics; namely the River Slang (Co. Dublin), the Lough Ennell Tributary River (Co. Westmeath) and the River Big (Co. Louth).

Hydrographs due to six historical significant rainfall events in terms of duration and intensity have been selected and used in calibrating and validating three variants of a UH model at the three catchments. Two of the six storms were used in calibrating the UH model while the remaining four storms used in validating the same model. Performance of the UH model in predicting the actual flood hydrographs was assessed based on visual inspection and goodness of fit statistical criteria.

Comparison between the actual and the predicted flow hydrographs demonstrated that the UH model was successful in simulating the principal hydrograph parameters such as shape, base time, and magnitude and timing of the peak in the two rural catchments (River Big catchment the Lough Ennell Tributary River catchment). Simulation of the same parameters in the urban catchment (River Slang catchment) was not as good as those of the rural catchments.

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