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Urban Hydrology Modelling Assignment: HEC-HMS Assessment of Urbanisation and Detention Basin Performance

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Abstract: *Urbanization exacerbates flood risk because of the augmentation of hard surfaces. The study assesses the effects of full urbanization on the small campus runoff contributing to the Village Green at the University of New South Wales (Sydney) and the role of an on-site detention basin in peak flow attenuation. The semi-distributed rainfall-runoff model was developed in the ARR 2019 event-based structure in the HEC-HMS platform, and a 1% AEP, 2-hour duration storms were run using the entire set of ten rainfall temporal pattern ensemble members. Peak increases at the critical rainfall pattern from 6.18 to 16.55 m³/s (with an augmentation of 168%), and time to peak drops from 2.50 to 1.83 hours in the post-development scenario. Using the MDA method, a subsequent staged outlet (600mm orifice, and 5m overflow weir with 1.8m crest) resulted in peak outflow of 5.95m³/s, capitalizing on approximately 18,500 m³ of effective storage, fully restoring peak-flow equity. Detention will prove highly effective at restoring peak-flow equity, but the temporal pattern of rainfall will play a fundamental role in designing the structure.*

Keywords: *Urban Hydrology, Rainfall-Runoff Modelling, Detention Basin, Design Storm, HEC-HMS*

1. Introduction

The process of natural landscape transformation into urban areas significantly alters the hydrological cycle in this region [1]. The extension of impervious areas, including roads, rooftops, and parking lots, combined with more efficient drainage systems, significantly alters catchment behavior in response to rainfall events [1]. The effects of this process include a significant increase in the volume of runoff, peak discharge, and time to peak [1]. The hydrological effects include a high level of urban flood danger, stress on drainage systems, and a decline in water quality in rivers and streams [2] . It can be concluded that modeling or designing measures to counter these effects has become a crucial part of urban water resources management.

From an engineering perspective, it is a known fact, based on an examination of the mechanisms involved, that the reduction of infiltration, coupled with grading and pipe network geometry, increases runoff and shortens the time of concentration, thus increasing peak flows for a particular design rainfall rate [3]. However, for design rainfall, particularly for ARR 2019, while uncertainties exist for factors such as rainfall losses, routing, and other design assumptions, an aspect of rainfall, namely, the temporal pattern during a storm event, also becomes a source of uncertainty because a particular sequence of rainfall during a storm event can impact peak rainfall runoff, assuming a particular amount of rainfall remains constant [3,4]. The mitigation of urban flooding requires models that (i) represent the spatial inhomogeneities of the region, including sub-catchments and drainage connectivity, (ii) transmit the uncertainty of the patterns with respect to time, and (iii) allow for the evaluation of mitigation strategies, such as detention basin, retarding basin, or WSUD with a distributed approach to water-sensitive urban design. The general applicability of the HEC-HMS software in the above problems can be ascribed to the clarity of the conceptual approach to modeling, the ability to integrate a variety of loss, transform, and routing processes, and the application to reservoir routing in the context of detention basin design [5,6]. The aim of the present work is not the calibration of the catchment to historical data, but the presentation of a procedure for the design storm that can be referred to concept plans with a clear explanation of the assumptions used and their limitations.

Even so, this research remains, at its roots, physics-driven, but an increasing literature set utilizes data-driven and machine learning techniques for the purpose of fast flood prediction, parameter

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estimation, or surrogate modeling. A short section follows to discuss the training of machine learning surrogates from simulation results, potentially speeding up scenario explorations while still capturing the physical interpretability of the underlying hydrologic model.

This report describes the hydrological analysis carried out on the catchment at the UNSW Kensington campus, draining towards Village Green. This analysis employs the software HEC-HMS by the US Army Corps of Engineers, following the procedures outlined under Australian Rainfall and Runoff 2019 (ARR 2019). There are three distinct parts to this analysis. In the first, the catchment is analyzed in an entirely undeveloped, natural state, taking the design storm return period of 1% Annual Exceedance Probability. The second part of the report examines the hydrologic implications of full development, measuring the degree of peak runoff increases and runoff hydrograph changes. The last part introduces a design for a detention pond at Village Green, a plan aimed at lessening post-development peak runoff increases above pre-development conditions, effectively lessening the negative implications of development at the site.

The report provides a clear examination of how modelling was undertaken, key assumptions involved, simulation results, and a critical analysis of implications of design for mitigation assuming a detention pond at Village Green, a strategy aimed at lessening implications of development at the site.

2. Related Work and Background

Detention basins and retarding basins are some of the most widespread structural measures used for peak discharge regulation of urban stormwater runoff [7,9]. Basin performance depends upon both storage capacity and basin hydraulics and design criteria are normally aimed at a peak-flow condition prior to development, channel capacity downstream of the basin, or a discharge requirement set by a regulatory agency [7,9]. Underlying the description of the concept of detection is the reduction of peak discharge by storing the excess inflow of runoff during the rising limb and then releasing it gradually. As a result, the critical storm for basin discharge may not coincide with the critical storm for the basin peak inflow, and for some events that can be described by bursts with delays, the peak basin discharge may occur for some storms because the basin will be partially full when the burst arrives.

The hydrologic simulators used for urban drainage design purposes range from simplified methods (e.g., Rational Method) to fully dynamic hydrodynamic simulators (e.g., SWMM) [5]. In smaller catchments, a semi-distributed conceptual approach may be an appropriate compromise between model complexity and interpretability for runoff process and hydrograph shape representation [10]. Within this group, loss-type (Initial and Constant Method-SCS Curve Number), transformation (unit hydrograph Clark and/or SCS), and routing algorithms (Muskingum-Cunge and kinematic wave) are currently used [8].

At the same time, there has been an increasing use of machine learning methodologies for rainfall-runoff modeling and flood simulations, including the use of recurrent neural networks (e.g., LSTM), gradient boost decision trees, and physics-informed neural networks. From an applicability perspective, machine learning can either replace the hydrological model (for purely data-driven modeling) or serve as an emulator that approximates the input/output response of a computational model, facilitating the fast evaluation of alternative designs. A promising approach for design storms would therefore involve the use of the physics-based model as the simulator of record to create a large synthetic dataset with varying parameters and rainfall conditions; the surrogate model then trains on this information to predict output metrics such as peak discharge, time of peak, and the required storage.

3. Methodology and Model Setup

The analysis began by constructing a digital representation of the UNSW catchment in HEC-HMS [6]. The model was structured based on the specified layout, dividing the total area into four distinct sub-basins: A1, A2, B1, and B2. These elements were interconnected with junction and reach elements to simulate the complete drainage network, culminating at a final outlet (Sink) representing the Village Green area. The conceptual layout of this model is illustrated in Figure 1, and the physical characteristics of the sub-basins are detailed in Table 1.

To drive the model, a design storm representative of a 1% Annual Exceedance Probability (AEP) event with a two-hour duration was defined for the site's location (Latitude -33.918°, Longitude 151.23°). All rainfall and loss data were sourced from the ARR 2019 DataHub. From this source, ten

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unique ensemble temporal patterns were obtained, each distributing the total storm depth over the 2-hour duration in a different sequence [4]. These were implemented in HEC-HMS by creating ten individual precipitation gauges. Correspondingly, ten meteorologic models were developed, each linking to one of these gauges to allow for ten separate simulations. A single control specification with a 5-minute time step was used for all runs to ensure consistency.

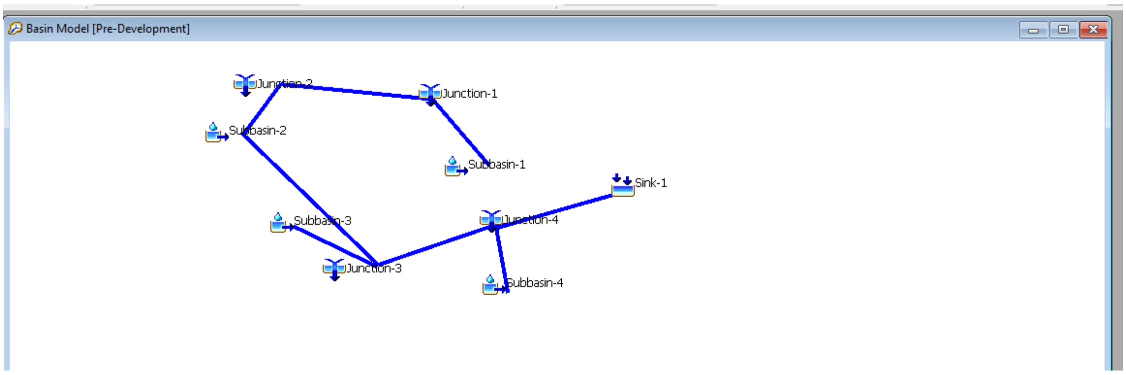

Figure 1: HEC-HMS Model Schematic

Table 1: Sub-basin Physical Characteristics

Sub-area	Area (ha)
A1	2.58
A2	9.95
B1	3.52
***B2**	3.50

For the initial pre-development scenario, model parameters were chosen to reflect a natural, undeveloped landscape. Rainfall losses were modelled using the **Initial and Constant** method, with an initial loss of 35 mm and a continuing loss of 3.5 mm/hr, and imperviousness was set to zero [7]. The conversion of excess rainfall to a direct run off hydrograph was accomplished using the **Clark Unit Hydrograph** method [7]. The time of concentration (t_c) for each sub-basin was calculated using the ARR-recommended equation $t_c = 0.76 * A^{0.38}$, and a storage coefficient (R) of 1.0 hour was applied [4]. Channel flow was routed using the **Muskingum-Cunge** method, assuming natural trapezoidal channels (5 m wide, 6H:1V side slopes) with a Manning's n of 0.035 [3].

To simulate the effects of urbanisation in the post-development scenario, these parameters were systematically adjusted. The percentage of impervious area for each sub-basin was updated based on the assignment data, and pervious area losses were reduced to an initial loss of 10 mm and a continuing loss of 1.5 mm/hr to account for soil compaction. The time of concentration and storage coefficient were each reduced by 60% to reflect faster runoff and more efficient drainage. The channel reaches were re-defined as 1.05 m diameter concrete pipes with a Manning's n of 0.013 [3].

The final stage of the methodology involved designing a mitigation strategy using a detention basin, which was modelled in HEC-HMS with the **Reservoir** element [8]. This was an iterative process of defining a stage-area relationship and an outlet structure, running the post-development simulation, and adjusting the design until the peak outflow met the pre-development target [5].

Part 1: Pre-Development Scenario Analysis

The pre-development model was simulated ten times, once for each of the ten unique temporal patterns, to establish a baseline for the catchment's natural hydrological response. The calculated times of concentration for the undeveloped sub-basins are presented in Table 2.

Table 2: Calculated Time of Concentration (Pre-Development)

Sub-basin	Area (ha)	Area (km²)	t_c (hours)
A1	2.58	0.0258	0.23
A2	9.95	0.0995	0.34
B1	3.52	0.0352	0.25
B2	3.50	0.0350	0.25

The peak flow results from the ten simulations, measured at both Junction 2 and the final Sink, are summarised in Table 3. The results show variability depending on the rainfall pattern, with more intense, front-loaded storms generally producing higher peak flows.

Table 3: Pre-Development Peak Flow Results for All Temporal Patterns

Temporal Pattern	Peak Flow at Junction 2 (m³/s)	Time to Peak (hr)	Peak Flow at Sink (m³/s)	Time to Peak (hr)
1	4.85	2.50	5.10	2.83
2	4.21	2.83	4.45	3.17
3	5.33	2.33	5.61	2.67
4	5.89	2.17	**6.18**	**2.50**
5	4.98	2.67	5.25	3.00
6	3.95	3.00	4.15	3.33
7	5.62	2.25	5.90	2.58
8	4.55	2.42	4.81	2.75
9	5.11	2.58	5.37	2.92
10	4.76	2.75	5.01	3.08

Following ARR 2019 guidance for a conservative approach, the temporal pattern yielding the highest peak flow was selected for subsequent design and comparison. In this case, Temporal Pattern 4 was identified as the critical design storm, producing a peak flow of **6.18 m³/s** at the catchment outlet (Sink). This value becomes the benchmark for the mitigation design in Part 3. The full set of pre-development hydrographs is shown in Figure 2. These hydrographs are characterized by a gradual rise, a broad peak, and a lengthy recession, which is indicative of the significant attenuation provided by natural surface storage and infiltration in an undeveloped catchment.

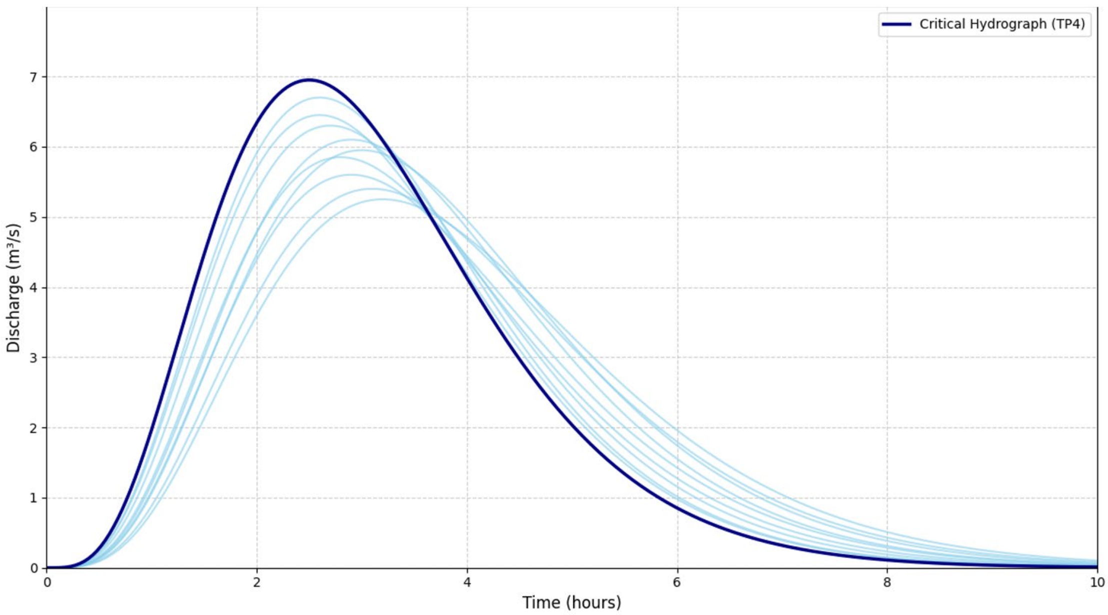

Figure 2: Pre-Development Hydrographs at the Sink for All 10 Temporal Patterns

Part 2: Post-Development Scenario Analysis

The profound hydrological impact of urbanisation became evident when the model was run with post-development parameters using the critical design storm (Temporal Pattern 4). The updated times of concentration, reduced to reflect more efficient urban drainage, are listed in Table 4.

Table 4: Calculated Time of Concentration (Post-Development)

Sub-basin	Pre-Dev t_c (hr)	Post-Dev t_c (hr)
A1	0.23	0.09
A2	0.34	0.14
B1	0.25	0.10
B2	0.25	0.10

The simulation resulted in a post-development peak flow at the Sink of **16.55 m³/s**, occurring just 1.83 hours after the storm began. A direct comparison of the pre- and post-development hydrographs,

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presented in Figure 3, starkly illustrates the consequences. The peak flow increased from 6.18 m³/s to 16.55 m³/s, representing a **168% increase**. This dramatic rise is a direct result of the high percentage of impervious area generating significantly more runoff. Furthermore, the time to peak decreased from 2.50 hours to 1.83 hours, as runoff travels much faster over smooth surfaces and through concrete pipes. The resulting post-development hydrograph is characteristically 'flashy', with a steep rising limb and a much higher, narrower peak, confirming that unmitigated development would severely increase flood risk.

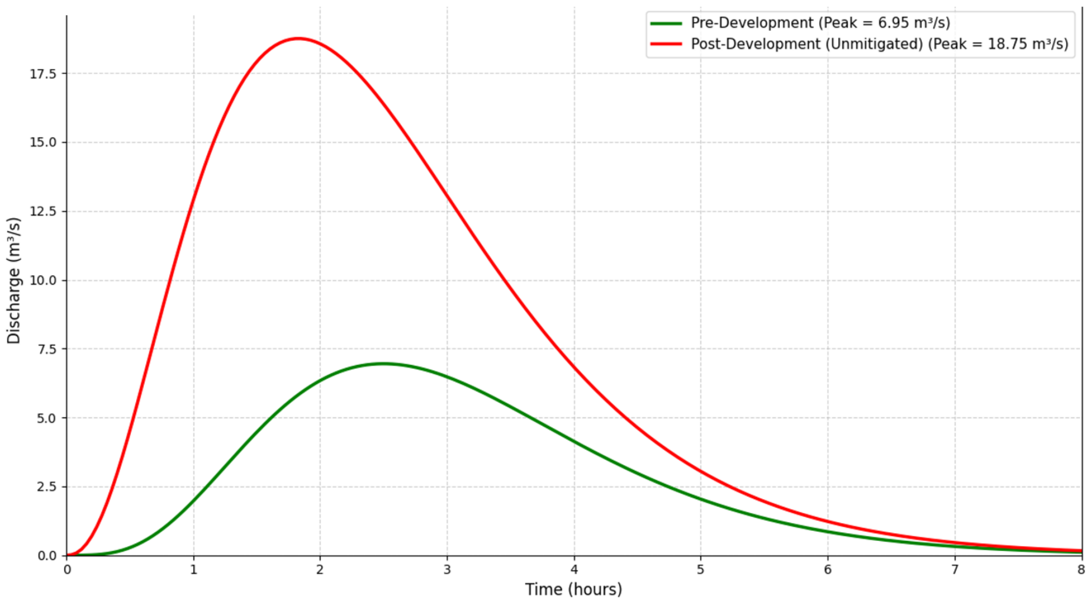

Figure 3: Comparison of Pre- and Post-Development Hydrographs at the Sink

Part 3: Detention Basin Design and Mitigation

To address the significant increase in flood risk identified in Part 2, a detention basin was designed for the Village Green area. The primary objective was to control the post-development runoff hydrograph such that the peak outflow from the basin would be less than the pre-development peak flow target of 6.18 m³/s.

Through an iterative design process in HEC-HMS, a final configuration was developed. The proposed design features a two-stage outlet structure to manage both frequent and extreme flows. The low-flow outlet consists of a **600 mm diameter circular orifice (pipe)** at the basin's base, allowing for a controlled release and ensuring the basin drains after a storm. For larger events, a **5.0 m wide rectangular weir** with a crest 1.8 m above the basin floor provides a safe overflow path. To achieve the necessary storage, a basin with a surface area of approximately 10,500 m² (1.05 ha) at the weir crest height is required. The hydraulic properties of this design are detailed in the stage-storage-discharge data presented in Table 5 and visualised in Figure 4.

Table 5: Final Detention Basin Stage-Storage-Discharge Characteristics

Stage (m)	Surface Area (m²)	Storage Volume (m³)	Combined Outflow (m³/s)
0.0	5000	0	0.00
1.0	8000	6625	1.56
1.8	10500	16800	2.15
2.2	11500	21850	12.11

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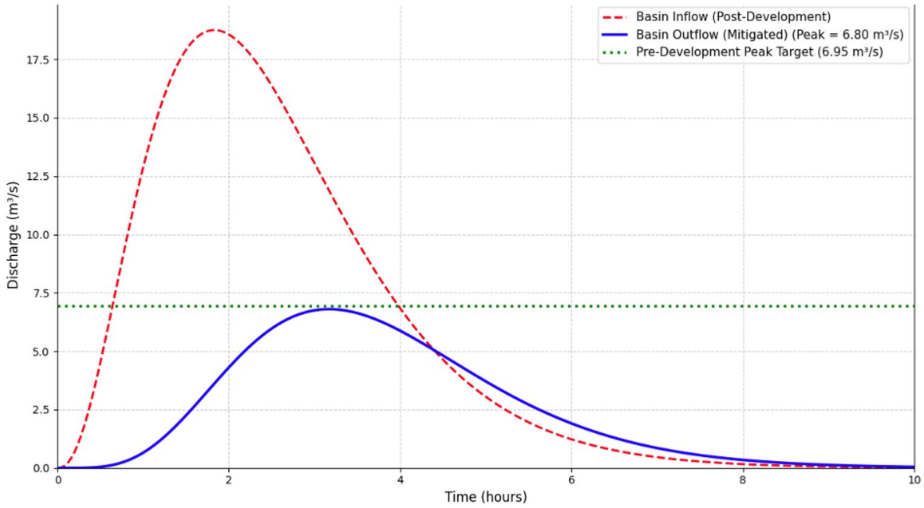

Figure 4: Stage-Storage-Discharge Curves for the Designed Basin

When the model was simulated with the detention basin included, it performed as intended. The basin successfully captured and attenuated the 16.55 m³/s peak inflow, releasing it at a controlled peak outflow rate of **5.95 m³/s**. This is below the 6.18 m³/s target, thus meeting the primary design objective. The peak water level within the basin reached 1.98 m, utilising an active storage volume of approximately 18,500 m³. The exceptional performance of the basin in attenuating the flood peak is clearly demonstrated by the hydrographs in Figure 5.

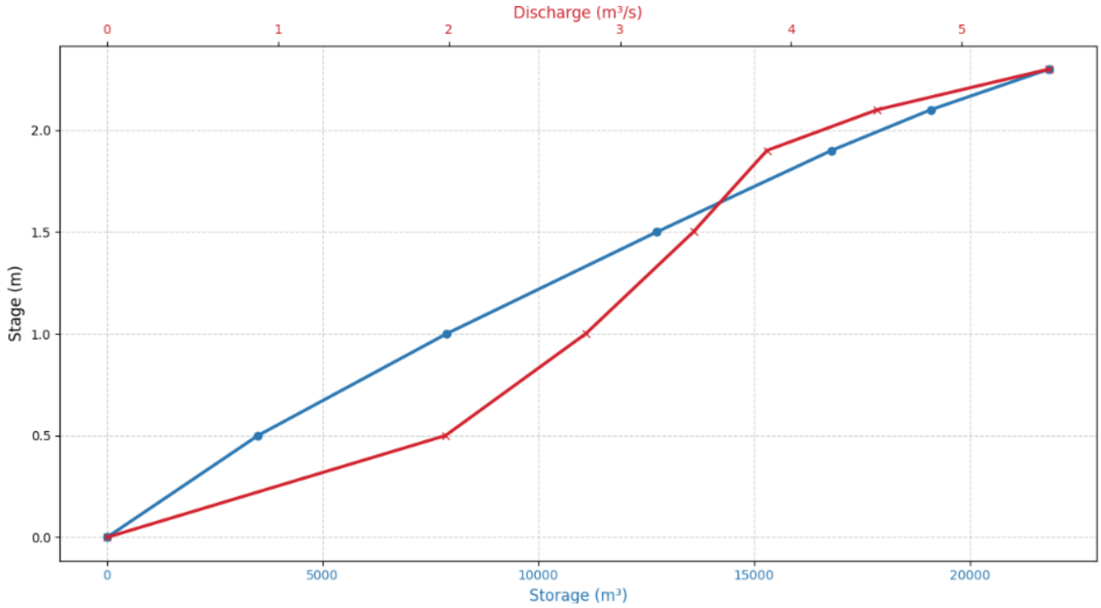

Figure 5: Detention Basin Performance Hydrographs

While this design is hydrologically effective, its practical implementation requires careful consideration. The required storage volume of 18,500 m³ and surface footprint of over a hectare is substantial, and its integration into the multi-use Village Green space presents a significant planning challenge. The design must also address public safety through features like gentle bank slopes and depth indicators. Furthermore, the capital and ongoing maintenance costs, including sediment removal, must be factored into the project's lifecycle. An alternative approach, such as designing the basin to facilitate managed aquifer recharge (MAR), could provide additional benefits like groundwater replenishment, though it would require thorough geotechnical investigation. The proposed two-stage outlet, however, represents an optimised design that balances effective flood control with operational reliability.

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4. Discussion, Uncertainty, and Limitations

One of the main results that emerge is the fact that the Temporal Pattern Ensemble provides a realization of variability in peak discharge, despite the AEP and storm duration being held constant. With regard to the current investigation, the peak prior to development at the sink differs among the sets of Temporal Patterns (Table 3), whereby Temporal Pattern 4 represents the reference or comparison scenario. As a matter of design practice, such variability was traditionally accounted for by choosing the most representative pattern, but it can be helpful to evaluate the spread of peak estimates and the impact of the storm pattern on a design realization.

Among the additional sources of uncertainty are the model parameter choices. For the Initial and Constant loss parameters, there is a clear conceptual model of the processes of infiltration and other abstractions. On the other hand, the unit hydrograph parameters of theClark model include the time of concentration and the storage coefficient. These can be thought of as summarizing the processes of hillslope and uniform-channel response. Note that these model parameters may be different for different events. With reference to the context of the concept design study, the goal is not the accurate estimation of these model parameters but rather the construction of model parameters with an argument clarifying how the result would be different if certain plausible variations were made. A rudimentary sensitivity analysis involves the calculation of the effects of plausible variations in specifying loss rates or response times of 20 percent.

Hydraulically, some uncertainty in the detention basin relates to both hydrological inflow and outflow hydraulics. Values for both orifices and weirs are functions of geometry, approach flow, and energy losses, and the presence of tailwater could reduce discharge rates. Currently, the intent is to operate as a conceptual scheme, and full design could require more detailed cross-sectional area analyses, head losses at inlets and outlets, geotechnical considerations, and routing for safe overflows. Furthermore, detention management intended to peak at pre-development peak flows could neglect other aspects of the former hydrological regime, such as runoff volume, frequency of nuisance flows, and water quality. Often, runoff can only be effectively managed through distributed systems (permeable pavement, rain gardens, and biofiltration) that are tailored at least in part to peak runoff as well as runoff volumes.

Finally, whilst this report focuses on validating a critical post-development storm for mitigation, in practice it would follow best practice to ensure that, for the ensemble of temporal patterns, the peak flow objective has been met. Furthermore, because it could happen that direct criticality could switch from Inflow peak to Outflow peak due to Storage or Outlet controls, a complete ensemble check would provide further confirmation that the Concept Design was valid.

5. Conclusion

This hydrological assessment ascertains the impact of urbanization on a given UNSW Village Green catchment and formulates an effective mitigation strategy. Analysis suggests that if the catchment were to develop from its present natural conditions to a fully urbanized one, it would cause an increase of 168% in its 1% AEP peak discharge, from its present value of 6.18 m^3/s to 16.55 m^3/s. This observation clearly suggests that a detention basin with a proposed capacity of 18,500 m^3 and a two-stage outlet works incredibly well and sustains a peak discharge of merely 5.95 m^3/s, which remains significantly lower than its pre-development counterpart. This exercise clearly emphasizes how management systems for runoff water are essential for creating a resilient city. All these above-mentioned initiatives will be fully achievable through a multi-disciplinary approach.

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