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Muskingum optimisation used for evaluation of regionalised stormwater detention

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Abstract

Strategies for flood mitigation are compared within an urbanising watershed. An approach for modelling and evaluating placement of detention in a developing watershed is presented. Effect of regionalised detention upon required detention volume is compared with localised detention. The study compares the effect of detention basins placed within the completely urbanised watershed by generating models of both the overall watershed and detailed sub-basins. For planning within a developing watershed, this requires modelling the ultimate developed condition, with and without detention. From a watershed having 114 sub-basins, detailed models of five selected sub-basins are generated, representing the ultimate urbanised condition with and without local detention. Hydrologic Engineering Center – Hydrologic Modeling System optimisation is used to estimate parameters of Muskingum routing reaches resembling the effects of localised detention. Next, using Muskingum routing to replicate those effects in other sub-basins, detained hydrographs are generated for the other sub-basins throughout the watershed. Thus, a model of the entire watershed with localised detention is generated. The original watershed model is modified yet again, with detention applied only at selected regional sites. Regional basins are designed to reduce peak flow to values comparable with that achieved by localised detention. Regional versus localised detentions are evaluated by comparison of total required detention volume.

Introduction

Urbanisation has a profound effect upon the hydrologic characteristics of a developing watershed, exacerbating natural flow volumes and peaks. To mitigate effects primarily upon storm flow peaks, the practice of stormwater detention has been widely adopted, attenuating post-urbanisation run-off rates to pre-urbanisation levels. Although methods vary, in general, this effort has relied heavily upon placement of small basins on a development-by-development scale.

Alternatively, regional detention schemes employ fewer basins of greater size placed at strategic locations in the watershed. Thus, regional basins can reduce the total storage capacity needed and lessen costs. However, to plan an effective detention scheme, it is necessary to assess placement options and compare alternatives. The purpose of this study was to investigate a technique for generating hydrologic models of the Caulks Creek watershed, both for localised and regional detention, so that the benefit of differing placement schemes could be evaluated.

Background

Previous studies have compared the benefit of regional versus onsite localised stormwater detention basins (Brown *et al*., 1986; McCuen and Moglen, 1990; George and Hartigan, 1992). Notably, some studies (Traver and Chadderton, 1992; Emerson *et al*., 2005; Goff and Gentry, 2006) have found that onsite detention systems could, in fact, adversely affect downstream flow peaks. The peak run-off produced in these cases was actually greater than that produced without the basins, as peak discharges from adjacent sites entered the drainage system at approximately the same time and combine to exceed peak non-detained developed run-off rates.

Because regional detention basins are designed to attenuate flows on the watershed scale, they are found to be better than onsite detention basins at restoring both the timing and peak of the flow to natural conditions (McCuen, 1974; Emerson *et al*., 2005). This also helps in achieving basin-wide water quality, as longer detention residence time allows the settling of particulates (George and Hartigan, 1992).

Onsite detention basins are constructed as a particular area is being developed. This is often not a coordinated effort; consequently, the localised system may not be effective in reducing peak flows for the entire watershed (Traver and Chadderton, 1992; Emerson *et al.*, 2005). Regional detention basins (and the stormwater conduits connecting them) are specifically designed to handle larger basin-wide storm events. The location and sizing of a regional detention basin plays a major role in its efficiency (James *et al.*, 1987; Sloat and Hwang, 1989; Fulton and O'Toole, 1990; Chase and Ormsbee, 1992). In addition to programs such as Engineers Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) and others useful for hydrograph and routing computations, several authors have developed programs to optimise basin dimensions, cost and downstream water quality (Bennett and Mays, 1985; Cheng *et al.*, 1987; Chao-Hsein and Labadie, 1997; Behera *et al.*, 1999). Still, the appropriate combination and placement of detention storage is largely determined by trial and error.

The maintenance of a large structure and the cost of land in an urban area are major limitations of regional detention basins. However, onsite detention basins have also been wrought with maintenance problems. This study shows that the volume required by regional detention is less than that needed for onsite detention.

Study area

The Caulks Creek watershed comprises a 49.73 km^2 area in the northwestern part of the Saint Louis County, Missouri, and drains from the south to the north directly into the Missouri River approximately 54.71 km upstream of its confluence with the Mississippi River. The watershed consists primarily of residential and undeveloped land, with a commercial corridor along the western boundary. Presently, about 60% of the watershed is developed, beginning from the south and east, and spreading towards the northwest. Its topographic features include moderate slopes (2%–10%), with few isolated steep slopes (20%–45%). Based upon the US Geological Survey (USGS) topographic maps, the region has been delineated into six principal subregions and 114 sub-basins. The total length of the watercourse from the discharge point to the uppermost boundary is 12.23 km. Delineation of the basin boundaries is shown in Figure 1.

Method of study

The objective of this study was to model the hydrologic responses of the future fully developed subject area under alternate detention approaches, first by considering a localised development-by-development scheme and then by placing basins regionally. These responses were used to compare and evaluate the benefit of implementing a regionalised detention plan, as opposed to the localised practice. A significant component of this study was the methodology used to generate the first scenario, a model of a very large basin with localised development-by-development detention.

A hydrologic model of future fully developed land use conditions on the Caulks Creek watershed was developed using the US Army Corps of HEC-HMS program (Feldman, 2000). The watershed was divided into tributary areas that overall have similar hydrologic characteristics. The 114 sub-basins shown in Figure 1 represent the extent of that delineation. Figure 2 presents the display of that same watershed in the HEC-HMS model. Each of the sub-basins is described in the model by the physical characteristics of the area, soil conservation service (SCS) curve number and percent imperviousness for hydrograph computations by the SCS Triangular Unit Hydrograph Method. The model began as a representation of the current field conditions, drawing upon surveys, topography and aerial photos. The model was calibrated to USGS stream flow values.

Next, the calibrated HEC-HMS model of current conditions was modified to represent the anticipated ultimate urbanised land use. Values of SCS curve number and percent imperviousness were carefully adjusted in a pattern consistent with anticipated land use. This was accomplished by using regional zoning maps, development plans and direct information from local planning officials to estimate the ultimate urbanised watershed conditions.

However, the representation of these conditions did not include the placement of detention structures. It was not feasible to incorporate the details of localised stormwater detention systems into the model of such a large area prior to its actual development. The watershed in the HEC-HMS model is delineated only at the sub-basin level; to represent each detention basin at every possible development within all 114 sub-basins would require significantly finer detail and physical information for even smaller sub-basin delineations. Because much of the area is undeveloped, it would have been necessary to forecast the placement and estimate design details of as many as 200 or more detention basins. Then, if each of the 114 sub-basins were to be individually modelled, the details of ultimate urbanisation (roadway locations, residential layout, storm sewer placement, etc.) would also have been needed.

Therefore, a more feasible means for utilising the HEC-HMS Caulks Creek watershed model was implemented. It seemed more direct to estimate the effects of detention on some sub-basins, and then simulate that effect for the other sub-basins in the watershed. This was accomplished by first studying several individual sub-basins distributed throughout the watershed. Detailed models were generated representing the ultimate urbanised condition, both with and without local detention. By comparing the resulting hydrographs, the effects of localised detention were quanti-

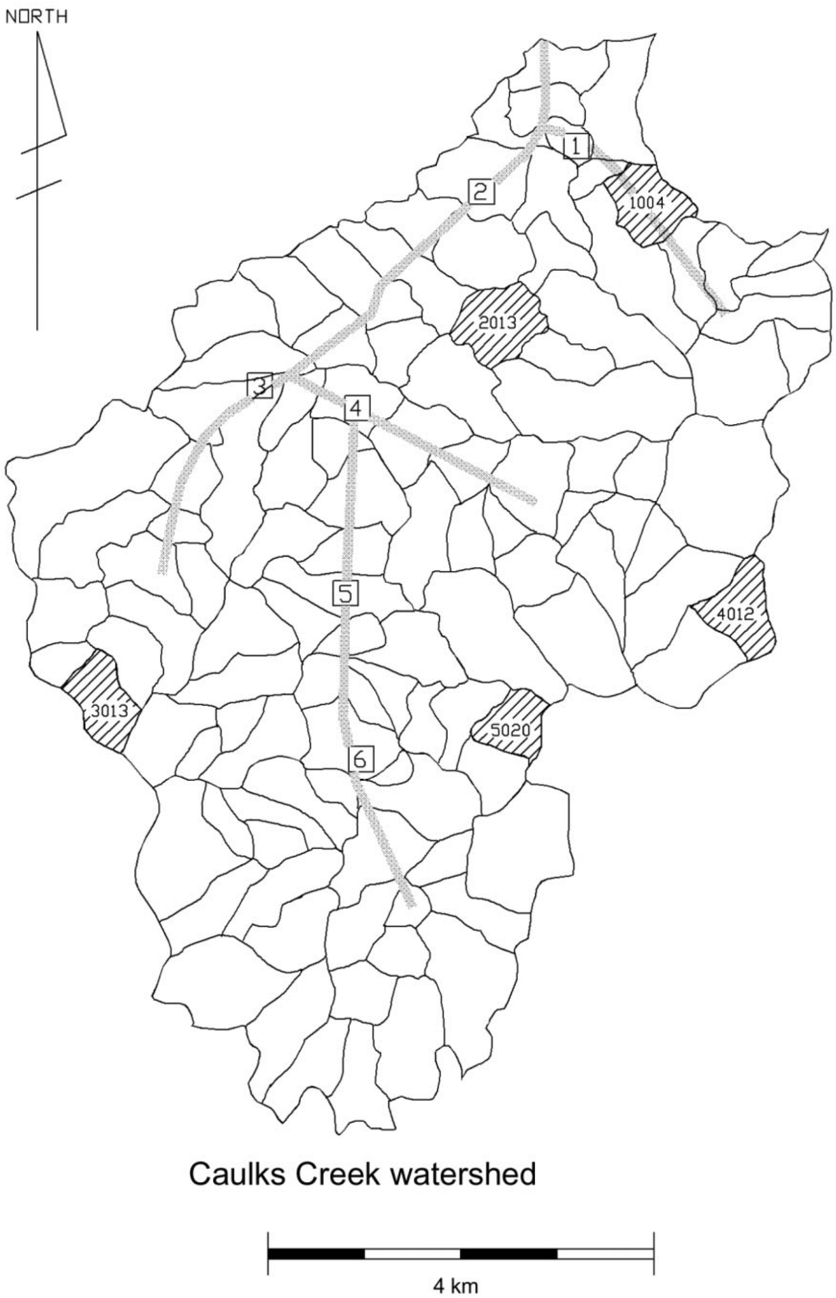

Figure 1 Watershed map of Caulks Creek. Solid lines denote topographic boundaries. Cross-hatched sub-basins were study areas for detailed modelling with ILUDRAIN program. Numbered boxes denote locations chosen for regional detention. Shaded lines denote drainage path.

fied. Then by simulating those effects in other sub-basins, it was possible to estimate detained hydrographs for other sub-basins without undergoing the rigour of specifically modelling each of the detention basins. Using this approach, the HEC-HMS model of the fully developed Caulks Creek watershed with localised detention was generated.

Next, the initial HEC-HMS model of fully developed land use conditions on Caulks Creek watershed was again modified, this time with larger scale detention basins applied only at selected regional sites. These regionalised basins were designed to reduce peak flow rates to values comparable with those accomplished by the use of localised detention. By comparing the total required detention storage volumes needed to achieve the reduction of the urban storm flow peaks resulting from these alternative models, the effectiveness of localised versus regional stormwater detention was evaluated.

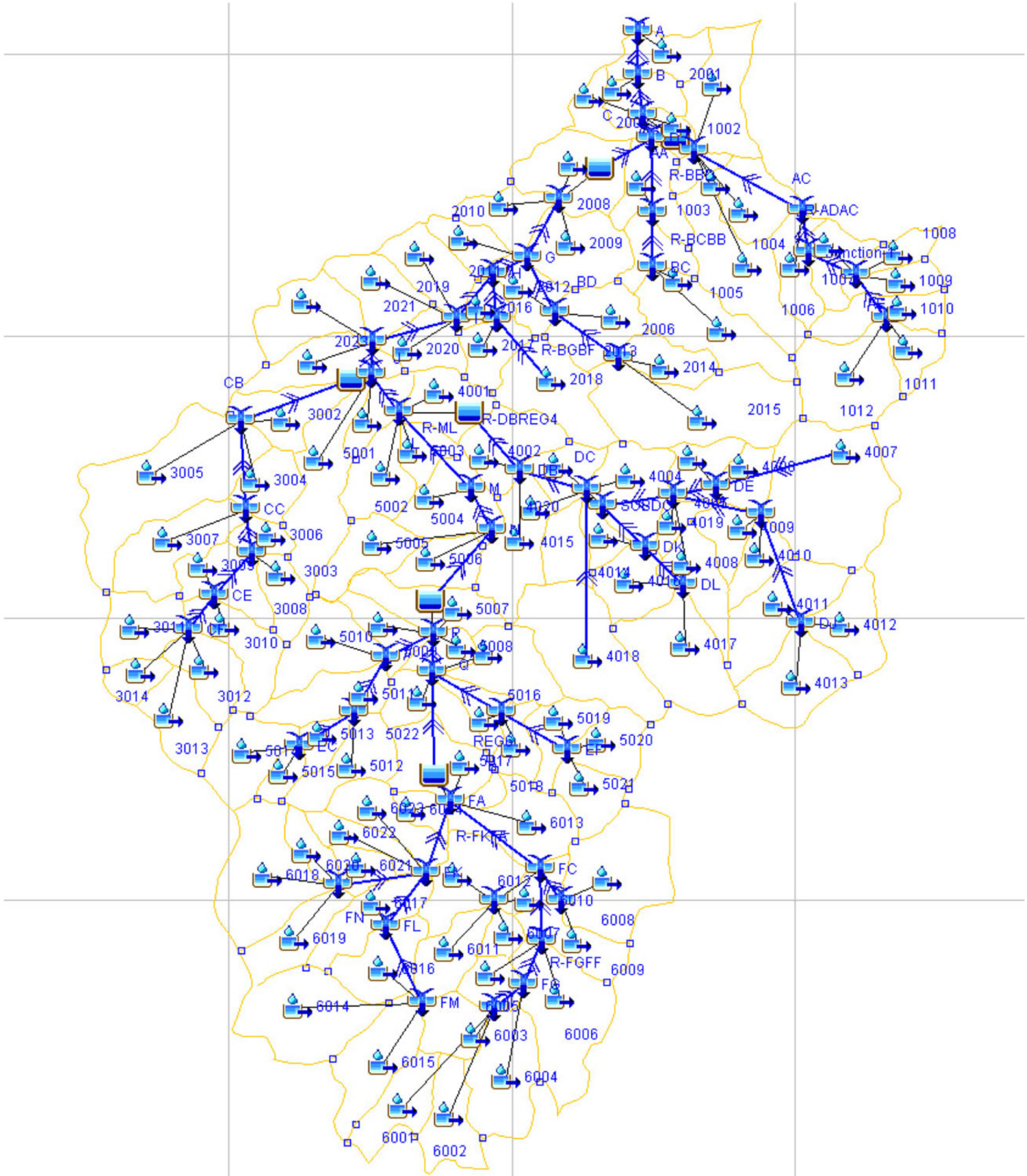

Figure 2 Display of model for Caulks Creek watershed generated in HEC-HMS program. Yellow lines denote topographic boundaries. Blue icons and numbering represent computational segments.

Localised detention modelling

As stated earlier, the initial HEC-HMS model of the Caulks Creek watershed provided an estimate of the basin-wide run-off response for anticipated ultimate urbanised land use conditions without detention. To reflect the application of localised detention for each of the 114 sub-basins, five sub-basins were selected and modelled in detail using a computer program specifically designed to model the hydrologic response of urban development. For each of these, two cases were represented: (1) the urbanised condition showing the hydrologic elements of the sub-basin with as much detail as possible and (2) the same urbanised condition with local detention. Thus, for each of these sub-basins, hydrographs of the urbanised area with and without detention were produced. From those five specific sub-basins, a general relationship was determined to estimate the effect of detention on storm run-off hydrographs. Using that relationship, estimates of the detention effects were incorporated into the HEC-HMS model for all 114 sub-basins.

The rainfall event adopted for use in this study has a 15-year recurrence interval with duration of 20 min. This reflects standards that have existed in St. Louis County and is representative of the design standards for which detention systems have been regularly designed. The National Weather Service document HYDRO-35 (US Weather Bureau, 1977) provides point rainfall values allowing interpolation of rainfall depth for a 15-year, 20-min duration event; this value was found to be 4.07 cm of precipitation. The rainfall pattern has been arranged by the Huff distribution (Huff, 1967), which was developed in Illinois and adopted due to Saint Louis County's proximity to Illinois. The time increment used for this distribution is 1 min. The final pattern for the applied rainfall is listed in Table 1.

Table 1 Distributed rainfall pattern

Distributed rainfall pattern	
Time interval (min)	Precipitation (cm)
0	0.000
1	0.505
2	0.584
3	0.551
4	0.437
5	0.338
6	0.229
7	0.188
8	0.152
9	0.122
10	0.122
11	0.097
12	0.097
13	0.086
14	0.086
15	0.081
16	0.081
17	0.076
18	0.076
19	0.076
20	0.076

Although the selection was somewhat subjective, an effort was made to choose basins that generally reflected the range of conditions in the Caulks Creek watershed, based upon surface area, length, average slope, principal soil type and general potential for development. Following an established index scheme, the sub-basins chosen were 1004, 2013, 3013, 4012 and 5020, shown cross-hatched on Figure 1. Physical characteristics of the respective sub-basins are presented in Table 2. An enlarged detail of sub-basin 5020 is presented in Figure 3 showing the individually delineated tributary areas.

The program used to model these five respective sub-basins is the Illinois Urban Drainage Area Simulator, called ILUDRAIN (Terstriep and Stall, 1988), chosen for its specific adaption to urban modelling. It is a single storm event model that can handle a detailed storm sewer system. The data input structure is especially conducive to representing the elements of an urban development, such as curb and gutter sections, inlets, and storm sewer configurations.

Aerial photography was the first information source used to create the ILUDRAIN sub-basin models. County and municipal records also provided access to original plans for development that had progressed in the Caulks Creek watershed. Although not all records of the local development could be retrieved, a considerable amount of information was available. Most significant were records showing proposed and final grading, placement of storm sewer systems, roadway culvert plans, and detention basin details. For portions of sub-basins that had not yet been urbanised, existing data such as zoning, topography and surrounding development were used to evaluate what the fully developed conditions were likely to be. In all cases, the generated models represented full urban development.

Sub-basins were delineated to the smallest feasible scale for the measurement of surface area (both pervious and impervious), drainage lengths (directly and not directly connected) and average cross-slopes. The predominant hydrologic soil group was SCS soil type B. Some type C soils also exist in the area, but these were much less prevalent. Infiltration losses were determined through a Newton–Raphson solution of the Horton equation (Terstriep and Stall, 1988). Rainfall losses due to depression storage and paved initial abstraction were assumed to be 0.51 cm and 0.25 cm, respectively. The run-off hydrograph from each tributary surface element was determined by the British Road Research Laboratory method, as described in the ILUDRAIN User's Manual. From the physical data for the sub-basin, an area-

Table 2 Sub-basin characteristics

Sub-basin characteristics							
Sub-basin	Area (hm^2)	Length (m)	%IMP	CN	Ratio L/A	Soil	Slope
1004	19.38	944.9	23.72	76.67	29.81	B	1.61
2013	21.27	914.4	15.50	77.44	24.00	B	3.67
3013	17.77	990.6	28.44	82.91	32.31	B	3.38
4012	18.07	990.6	25.08	77.49	32.50	B	2.15
5020	13.04	823.0	21.29	80.59	38.07	B	2.59

CN, curve number; %IMP, percent imperviousness.

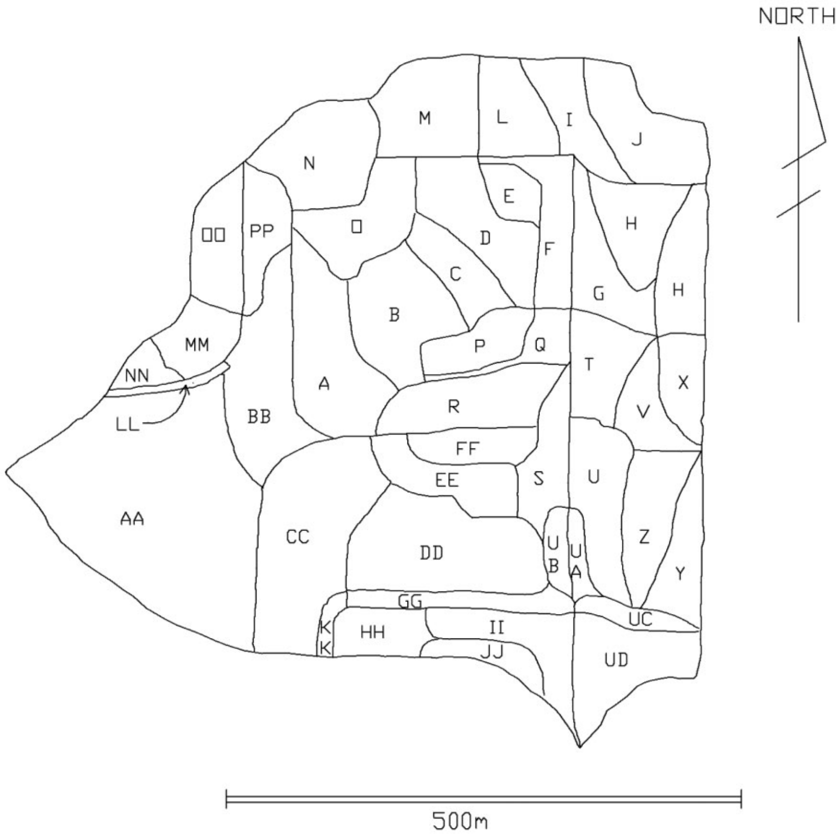

Figure 3 Delineation map of sub-basin 5020 used for detailed modelling. Labelling identifies individual tributary areas. Total area is 13.04 hm^2. Average tributary area is 0.68 hm^2.

time curve was established. By combining the area-time curve with the design storm hyetograph, the run-off hydrograph was produced.

Drainage system details were based upon information provided by development plans. Many elements of the systems could also be identified using aerial photos, which, along with topographic maps, were useful for supplying information not provided by the development plans. For areas in which development was not yet complete, open spaces were examined for possible future land use arrangements. A layout of roads and homes that could complete the development was forecast, including placement of the remaining storm sewer system. A schematic diagram representing the final drainage network of sub-basin 5020 is shown in Figure 4.

Routing was performed using an option for time-lag shifting of the hydrograph based upon the velocity of the hydrograph peak. This was compared with an implicit solution for linear approximation of the continuity equation for in-channel storage. However, the sub-basins typically contained smaller storm sewer laterals, with moderate storage capacity having only a small effect in the routing of the stormwater discharges. Consequently, the computation difference between these approaches was negligible.

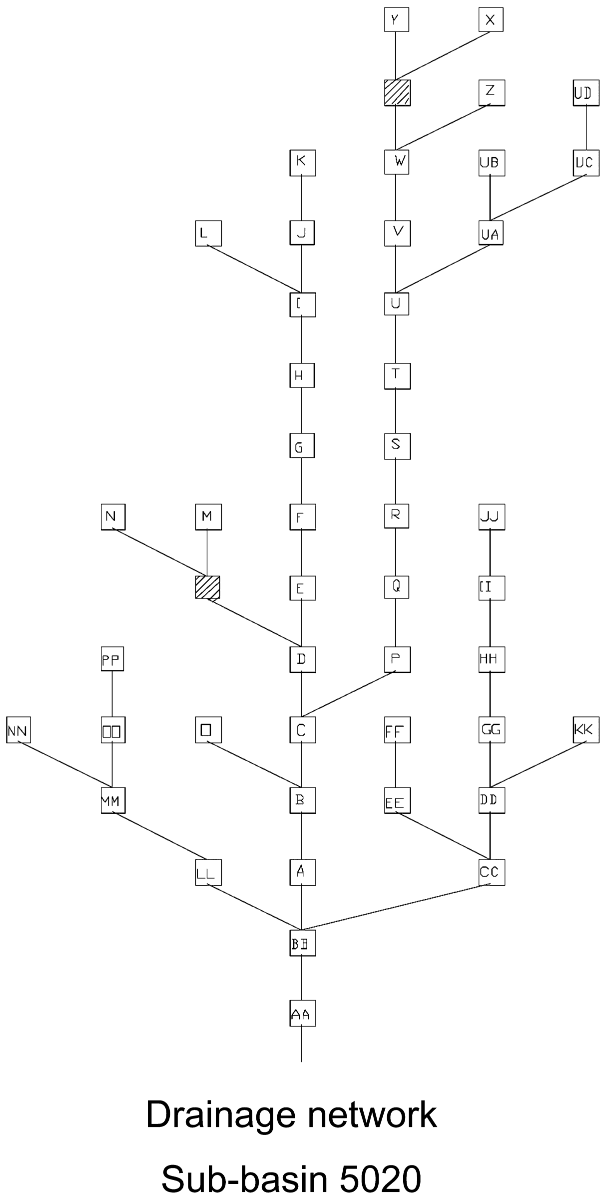

Figure 4 Drainage network for sub-basin 5020. Lettered elements represent tributary areas.

When the detailed modelling of fully urbanised conditions for the five selected sub-basins was complete, results from the ILUDRAIN sub-basin models were compared with the values that had been previously generated by the HEC-HMS model of fully developed conditions. Direct comparison of the ILUDRAIN sub-basin models to field observations was not possible because these are models of anticipated future conditions. As a proxy for future field observations, the ILUDRAIN models were compared with values generated by the HEC-HMS model of fully developed future conditions. As mentioned earlier, that model was adapted from an initial HMS model of the watershed, which

Table 3 Comparison of hydrographs

	Comparison table Undetained hydrograph parameters, ILUDRAIN and HEC-HMS			
	Peak discharge (cm)		Time to peak (min)	
Sub-basin	ILUDRAIN/HEC-HMS		ILUDRAIN/HEC-HMS	
1004	3.85	4.05	17	14
2013	3.61	3.20	13	15
3013	3.62	3.79	14	16
4012	4.82	5.10	9	16
5020	4.90	4.33	17	14

HEC-HMS, Hydrologic Engineering Center – Hydrologic Modeling System.

had been fully calibrated to USGS flow measurements under current conditions. The comparison of those results in Table 3 confirms that the two models yielded similar results. The small range of variation between the two models suggests that the HEC-HMS model was acceptable for use in further modelling of the whole Caulks Creek watershed.

After generating the detailed ILUDRAIN model for fully urbanised conditions at each sub-basin, the next step was to prepare another version of these five models, adding localised development-by-development detention structures to the storm drainage systems. The placement of these basins again required some subjectivity. It began with the full preliminary design of a detention basin to be located at an actual development, following requirements applicable in that governance. These stipulated that the peak discharge rate from a development should be no greater than the peak discharge rate produced by the same area in its undeveloped condition for a 15-year, 20-min duration event.

To calculate basin volumes, the undeveloped peak run-off rates were subtracted from the developed peak run-off, factored by a duration of 30 min. Using this regulatory standard, the allowable peak discharge and required detention volume was computed for each development within the five ILUDRAIN sub-basin models. Varying assumptions of basin geometry and outlet structure were tried to ascertain the effects of the curvature of the respective storage/discharge relationships. Although it was desirable to select a realistic storage/discharge curve as possible, the models were not highly sensitive to variations in the design assumptions.

Figure 5 presents the storage/discharge curve derived for sub-basin 2013, typical of curves used for Modified Puls detention routing at basins throughout each of the five sub-basins. The resulting hydrographs for sub-basin 2013 are presented in Figure 6, showing the rainfall run-off both with and without detention applied. These hydrographs are representative of the results produced for each of the sub-basins. The greatest peak run-off without detention was 4.89 m^3/s from sub-basin 5020. With detention applied, the greatest peak run-off was 1.47 m^3/s from sub-basin 2013. The shape of the detained hydrographs was as anticipated.

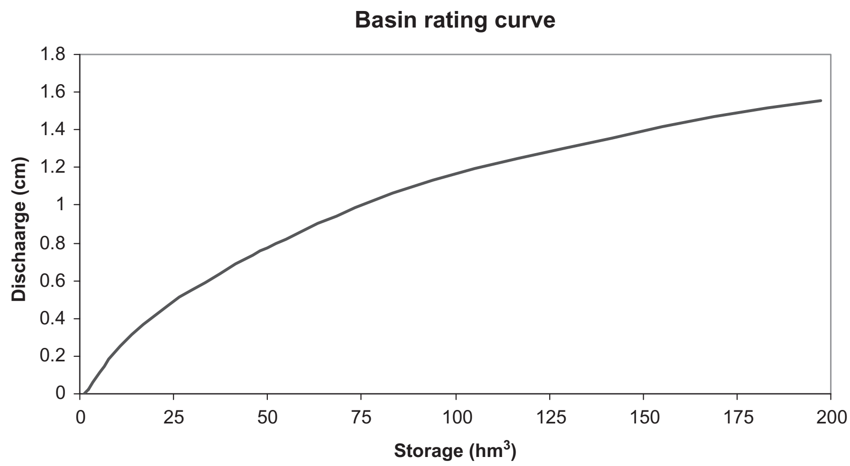

Figure 5 Detention basin rating curve for sub-basin 2013.

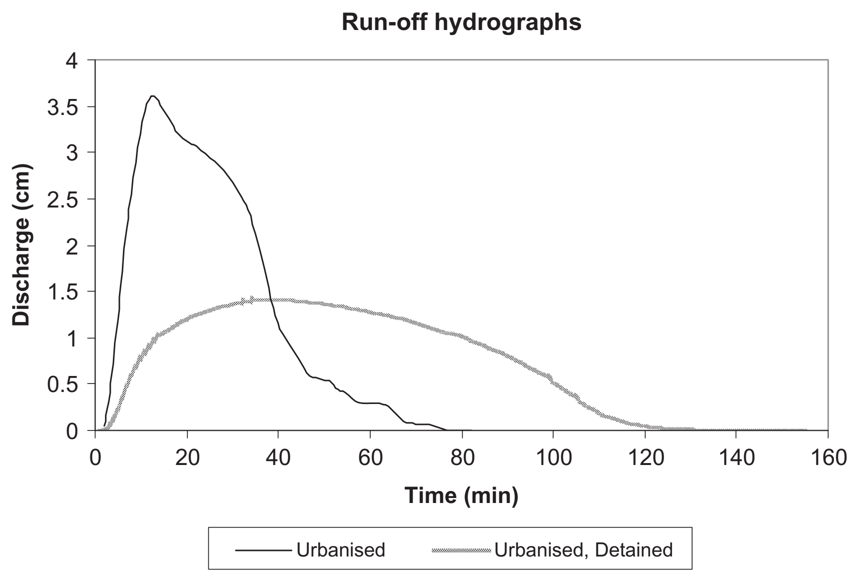

Figure 6 Hydrographs for sub-basin 2013.

The times to peak were all delayed by approximately 30 min, and the peaks were flat and broad. A comparison of the resulting hydrograph parameters with and without detention is presented in Table 4.

To determine the effect that the application of this localised detention practice would have on the entire Caulks Creek watershed, the effects of local detention illustrated by the ILUDRAIN models had to be incorporated into the HEC-HMS model of the fully developed watershed and applied to all of the 114 sub-basins. This was accomplished using a novel application of the optimisation capability of HEC-HMS.

Optimisation features of HEC-HMS include the ability to automatically derive (optimise) routing parameters for several hydrologic routing techniques, including the Tatum, Straddle-Stagger and Muskingum methods. Given both inflow and outflow hydrographs, the program uses an iterative error reducing scheme to determine routing parameters. This HEC-HMS optimisation capability can be directly

Table 4 Results of ILUDRAIN model

Comparison of values estimated by ILUDRAIN models				
	Peak discharge (cm)		Time to peak (min)	
Sub-basin	Developed	Detained	Developed	Detained
1004	3.85	1.19	17	32
2013	3.61	1.41	13	11
3013	3.62	1.19	14	47
4012	4.82	1.13	9	42
5020	4.90	0.77	9	32

applied to determine parameters of a routing reach that will produce an effect similar to the use of localised detention on the urbanised hydrograph. Once routing reaches with the appropriate parameters have been determined, they can then be written into the HEC-HMS model at a chosen sub-basin to produce results similar to those achieved through the placement of localised detention, without having to model specific details of the urbanised drainage system and detention structures.

As input for HEC-HMS optimisation, the ILUDRAIN output files were edited, deleting all data except for the ordinates of the final outflow hydrographs from the detained and non-detained models. These were merged into a single file for each respective sub-basin, producing five data sets. Using a tabulation interval of 1 min, routing optimisation was performed using the Muskingum method. Table 5 shows the results produced by HEC-HMS optimisation. The Muskingum K constant represents the travel time, in hours, through a routing reach. X is the Muskingum weighting factor for attenuation, which represents the relative importance of inflow and outflow upon storage. The resulting optimised values of X were 0 for each data set. As described earlier, routing with an X = 0 is representative of a linear, level-pool reservoir. The actual detention basins designed and built during the urbanisation of the study area are typically linear, level-pool reservoirs; therefore, these values appear to be appropriate.

Table 5 Results of HEC-HMS optimisation

Results of routing optimisation		
Basin	K	X
1004	0.83	0
2013	0.63	0
3013	0.88	0
4012	0.80	0
5020	1.02	0

Figure 7 displays the results for sub-basin 4012. The plot shows the urbanised hydrographs, both with and without detention, produced by ILUDRAIN. Then, the reconstituted hydrograph computed by HEC-HMS is also shown for comparison. Generally, the shape of the original hydrograph has been reproduced by the reconstituted hydrograph. The outflow hydrograph and the reconstituted outflow hydrograph match well. The difference in the time to peak of the two curves was less than 9 min. The peak discharges of both curves were within 0.23 m^3/s of each other. Also, the average flow rate of the observed outflow hydrograph was 0.51 m^3/s, while the average flow rate of the reconstituted

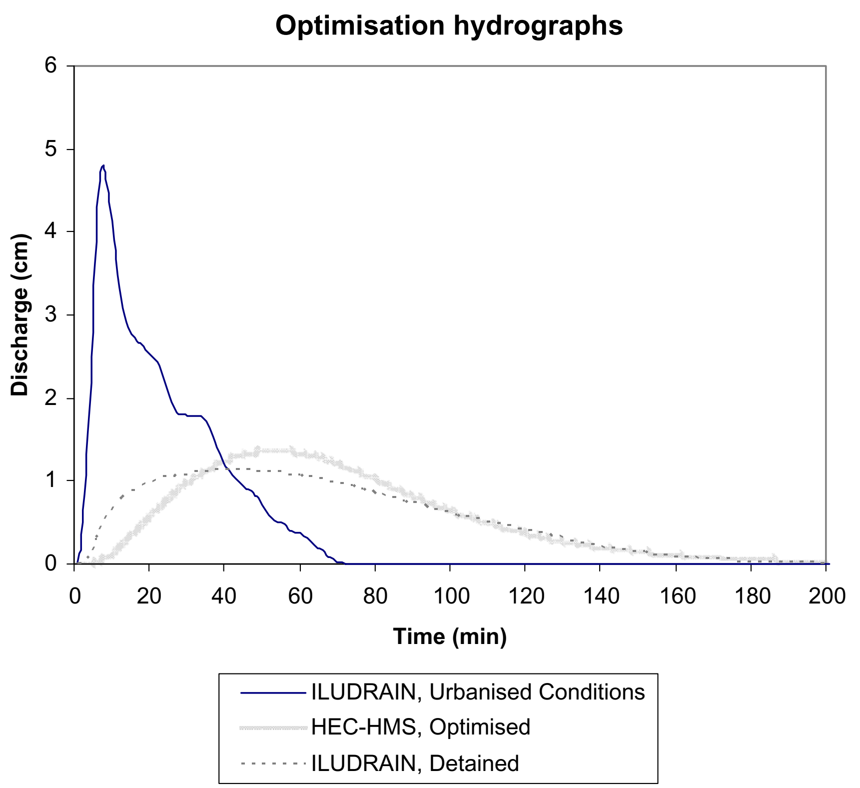

Figure 7 Hydrographs for sub-basin 4012. This includes the hydrograph generated using optimised M uskingum routing parameters in HEC-HMS.

Table 6 Comparison of detained peak discharges

Detained peak discharge, HEC-HMS and ILUDRAIN		
Sub-basin	Peak discharge (cm) ILUDRAIN	Peak discharge (cm) HEC-HMS
1004	1.189	1.218
2013	1.388	1.161
3013	1.189	1.104
4012	1.133	1.274
5020	0.765	0.765

HEC-HMS, Hydrologic Engineering Center – Hydrologic Modeling System.

hydrograph was 0.56 m^3/s, showing a difference of only 0.05 m^3/s.

Next, routing reaches using the optimised Muskingum parameters were inserted into the HEC-HMS model at the respective locations of those same five sub-basins. These routing reaches applied the effects of detention to the urbanised sub-basins in HEC-HMS without requiring either the introduction of more detailed sub-basin data or the design of specific detention basins. The resulting HEC-HMS hydrographs, with the new Muskingum routing reaches, provided a good match to those hydrographs originally produced by ILUDRAIN, with detention, for each respective sub-basin. The average deviation in peak discharge rates was only 0.096 m^3/s. For comparison, the results are listed in Table 6.

To complete the HEC-HMS model of the entire Caulks Creek watershed, placing localised detention within all 114 sub-basins, the preceding work was adapted so that appropriate Muskingum routing reaches could be estimated and applied throughout all of the remaining sub-basins within the watershed. This was done by determining a relationship between the physical characteristics of the five sub-basins that were first studied and their optimised Muskingum *K*-values. That relationship was then used to estimate Muskingum routing parameters appropriate for each of the remaining tributary sub-basins.

Regression analysis was used to determine Muskingum routing parameters for each sub-basin, based upon its physical characteristics. Ultimately, two expressions were developed to relate the criterion variable *K* to predictor variables area, percent imperviousness and length. The first was a multivariate linear expression, while the second was a multivariate non-linear power expression, listed as follows:

$$K = 1.8658 - 0.0062(AREA) + 0.0235(\%IMP) - 1.395(LENGTH) \quad (1)$$

and

$$K = 0.1289\left(AREA^{-0.144}\right)\times\left(\%IMP^{0.732}\right)\times\left(LENGTH^{-1.701}\right) \quad (2)$$

where *AREA* is drainage area (hm^2), *%IMP* is percent imperviousness and *LENGTH* is hydraulic length (km).

Multiple correlation coefficients of 0.9998 and 0.9996 were solved for the two equations, respectively. The difference between the observed *K*-values produced by HEC-HMS and those that were predicted by both of the regression equations were tabulated for both equations. The sum of the squares of the residuals was 2.74×10^{-5} and 5.40×10^{-7} for the first and the second equations, respectively. Thus, both equations were accepted as valid representations of the relationships exhibited by the measured data.

Using the regression equations and tabulated values of area, percent imperviousness and length, parameters for Muskingum routing reaches were then estimated for the remaining 109 sub-basins. The Muskingum *K*-value was computed for each using both of the regression equations. In nearly all instances, the *K*-values predicted by each equation were the same. The only noticeable difference occurred within isolated sub-basins where the ultimate percent imperviousness was very small. In that event, the first equation produced an erroneous negative *K*-value, so the value of the second equation was used. If the percent imperviousness was absolutely zero, the second equation would produce a *K*-value of zero. A Muskingum value of *K* equal to zero has the same effect as no detention at all. When a sub-basin is never expected to experience urbanisation, it is also expected not to have detention basins placed within it.

Using this approach, a Muskingum routing reach was placed just downstream of the normal outfall for each of the sub-basins within the original HEC-HMS model, representing the placement of localised detention throughout the Caulks Creek watershed. As expected, the results showed a substantial reduction of peak run-off rates. The overall effect was a reduction of the final discharge hydrograph at the northernmost point of the watershed from the non-detained peak flow rate of 52.94 m^3/s to the peak flow rate of 60.40 m^3/s. This represents a reduction of 22.54 m^3/s in the peak discharge rate.

Finally, the necessary storage volume was determined by comparison of the respective hydrographs both before and after each of the sub-basin routing reaches. By subtracting the incremental ordinates of the hydrographs before and after the routing reach for a given sub-basin, and totalling the sum of the differences until the outflow exceeded inflow, the total storage volume was computed. A FORTRAN routine was used to expedite the computations, reading the numeric ordinates of the individual hydrographs from the HEC-HMS output file, sub-basin by sub-basin, and summing the detention storage volume at each. The total volume of local detention required throughout the entire watershed was 0.455 hm^3.

Regional detention modelling

To implement and compare a regional detention scheme, the original HEC-HMS model of fully urbanised conditions on the Caulks Creek watershed was again used. Regional modelling did not include any of the Muskingum routing reaches from the localised modelling. To model regional detention, large storage basins were applied only at selected sites; each of these regional basins were designed to match the site-specific reduced peak flow rates, which would have resulted from the use of onsite detention determined by the localised HEC-HMS model.

The Caulks Creek watershed was examined to select appropriate locations for the regional basins, focusing on confluence points for significant portions of the drainage area, and taking into consideration the level of development downstream of large tributary sections. The proximity of development to reaches, which could potentially receive dramatic peak flow rates and incur substantial flood losses, guided the choices made in placing the regional reservoirs. Information from both the original HEC-HMS model and localised detention HEC-HMS model was used to assess potential flow rates at given locations and comparative values of the flow rate reduction that would be achieved if onsite local detention had been applied throughout the basin.

Six sites were chosen for the placement of the regional detention basins, indicated by boxes 1 through 6 on Figure 1. This is just one possible scheme. Considerations such as development, zoning, maintenance, property ownership, etc. could have resulted in alternate arrangements of more or fewer than six basins.

The computational method used for reservoir routing at each of the regional basins was the standard Modified Puls technique. Appropriate rating values were determined iteratively – the same means by which routing was accomplished for the onsite detention basins within the five ILUDRAIN sub-basin models – with a general rating curve similar to Figure 5. Peak discharge rates computed for the same locations in the previous localised detention HEC-HMS model were adopted as the maximum allowable release rate for each respective regional basin. As general discharge rating curves were created for each regional basin, that respective peak discharge rate was assigned to the uppermost point for each corresponding rating curve. The necessary amount of storage volume required for the uppermost rating curve value was determined iteratively. A preliminary number was assumed, and the remaining points on the rating curve were interpolated. The basins were all edited into the regional HEC-HMS model, which was then executed. All of the preliminary regional basins initially failed to provide adequate detention storage. The rating curves were then adjusted to allow for more storage, and successive runs were conducted. After iteration, the necessary storage volumes were ultimately determined, and the regional HEC-HMS model was complete. The outflow discharge rate at the northernmost point of the Caulks Creek watershed resulting from the completed regional HEC-HMS model was 59.44 m^3/s. This was slightly less than the 60.68 m^3/s value produced using localised detention. By summing the storage at each of the six basins, the total storage volume used by the regional approach was found to be 0.269 hm^3.

Results

Values from both the localised and regional detention models are listed in Table 7. Column 1 indicates the location within the Caulks Creek watershed of each regional detention basin corresponding to the numbered markers (1 through 6) on the watershed map in Figure 1. Column 2 shows the peak discharge rate computed at each of those sites by the original HEC-HMS model of fully urbanised conditions prior to the introduction of any form of detention. In Column 3, peak run-off rates are shown for the same locations with localised detention applied uniformly throughout the entire watershed. Values in Column 4 are the peak run-off rates yielded by detaining stormwater run-off only at the six regional sites. Columns 3 and 4 results are very similar. Comparable reduction of peak discharge rates have been accomplished by both of the detention schemes.

Table 7 Comparison of results

Comparison of results						
1	2	3	4	5	6	7
Location	Undetained discharge (cm)	Localised detention (cm)	Regionalised detention (cm)	Local detention (cu. hm.)	Regional detention (cu. hm.)	Volume reduction (cu. hm.)
Region 6000	106.370	42.225	39.620	0.173	0.129	0.044
Region 5000	90.907	46.841	40.498	0.052	0.004	0.048
Region 4000	45.793	22.713	21.098	0.097	0.055	0.043
Region 3000	15.888	7.250	5.607	0.029	0.022	0.006
Region 2000	96.486	62.332	58.792	0.046	0.014	0.032
Region 1000	27.244	10.592	9.884	0.058	0.044	0.014
Total				0.455	0.269	0.186

Column 5 presents the sum of the individual storage volumes for localised detention, which accumulated from sub-basin to sub-basin at each detention structure upstream of the respective numbered locations on the watershed map. Column 6 shows the storage volume used by each of the regional detention basins. In Column 7, the amount is shown by which the detention volumes have been reduced through the regional detention scheme. The difference between these values is significant and underscores the efficacy of regionalised detention. The total volume of detention storage has been reduced from 0.455 hm^3 to 0.269 hm^3, representing a savings of 0.186 hm^3. The reduction of storage throughout the basin is 41%.

Demonstration of alternatives

A single regional plan may not be sufficient given the commercial interests surrounding development, the governance needed to plan regional systems and other practical constraints upon constructability. It may be necessary for planners to choose a regional scheme from among several options. Therefore, two additional scenarios have been prepared using the HEC-HMS model of fully developed conditions. Both scenarios are again guided by reference peak flow rates determined by the HEC-HMS Muskingum-enabled model of uniform applied localised detention.

The first alternate model again exclusively used regional detention. The locations were similar to, but fewer than, the original regional model. In this case, regional basins were sited at the same locations as Regional Basins 1, 2, 4 and 6 shown in Figure 1. Regional Basins 3 and 5 were omitted. This could reflect many practical contexts that simply prohibit the implementation of Regional Basins 3 and 5.

It is still possible with this alternate arrangement to achieve reduced peak flows at Regional Basins 1, 2, 4 and 6 that match flows from the uniform localised detention approach. As expected, the required volume of regional storage necessary at basins 1, 4 and 6 were again 0.044 hm^3, 0.055 hm^3 and 0.129 hm^3, respectively. Due to the absence of detention in the Region 3000 and 5000 sections of the watershed, the storage capacity of Regional Basin 2 had to be increased. The resulting maximum stormwater volume stored at this site now increased to 0.098 hm^3. The combined regional detention volume resulting from this scenario is 0.326 hm^3. Although this needed storage volume has increased from the six regional basin scheme, it still represents a 28% reduction from the 0.455 hm^3 storage volume associated with a uniform local detention approach.

The second alternative model explores the context of combining and targeting the assignment of both localised and regional systems in different areas of the same watershed. Here, regional detention is kept in the Region 1000, 2000, 3000 and 4000 sections of the watershed. However, the Regional Basins 5 and 6 are eliminated. Instead, the Muskingum reaches from the HEC-HMS local detention model were copied into this hybrid model for each sub-basin of Regions 5000 and 6000. Peak flows matching the reference flow rates from the earlier uniform local detention model were again maintained at all control points 1 through 6. Storage volumes for regional detention at Basins 1, 2, 3 and 4 remained very close to the values presented in column 6 of Table 7. However, the storage volumes associated with Regions 5000 and 6000 reverted to the levels previously listed in column 5. The summed storage volume resulting from this hybrid scheme was 0.36 hm^3, yielding a 21% reduction from the storage volume associated with an entirely uniform local detention approach.

Conclusions

This study demonstrates a novel approach to analysing detention alternatives for a watershed undergoing urbanisation. Without exact knowledge of final development, it was nevertheless possible to mimic the use of localised detention via optimisation of Muskingum routing parameters. Regression analysis was then used to apply Muskingum reaches as a synthetic form of localised detention throughout all the sub-basins of the greater watershed. The resulting model provides the information needed for an engineer to compare and analyse one or more scenarios for regional detention. Results of the analysis demonstrated that a regionalised stormwater detention system, as compared with a localised detention scheme, mitigate the peak stormwater run-off rates caused by urbanisation on a basin-wide level.

It should be noted that those areas upstream of the regional basins where run-off may otherwise have been intercepted by a prior local detention basin will instead receive the non-detained urbanised peak run-off. However, the magnitude of these flows coming from the upper tributary areas is not of the scale experienced further through the watershed. And, as cited earlier, reliance upon those smaller localised detention basins could adversely affect the peak flows experienced at the immediately downstream adjacent areas due to coincidence of peak timing.

Comparison of the results produced by this study indicate that by implementing a regionalised detention plan on the Caulks Creek watershed, the volume of storage capacity that is dedicated to stormwater detention may be reduced by as much as 41%. That reduced storage volume will translate directly into monetary savings through land value, construction costs and maintenance expenses. Extension of these methods may be useful for evaluating detention alternatives for watersheds in other study areas as well. Future application of this approach should be useful not only for comparing localised to regional schemes, but also for exploring options to combine and target the assignment of localised and regional detention systems in different areas of the same watershed.

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