Predicting GIS-Based Spatially Distributed Unit-Hydrograph from Urban Development Scenarios

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Abstract:

A spatially distributed unit-hydrograph model was implemented using a Geographical Information System (GIS) in this study to investigate the effects of how increasing impervious areas influences surface runoff in urban areas. A distributed velocity grid was developed from a 10m Digital Elevation Model (DEM) using the kinematic wave approximation and Manning's equation. By estimating the cumulative travel time across each cell in the catchment along each flow path, a time-area histogram is developed to derive one-hour unit-hydrograph. The method was implemented using ArcGIS 9.1 software and used to study the effect of the increase in impervious area from 1996 to 2006 for the Calais Burn catchment in Fife. The historical unit-hydrographs developed show that an increase of 11 % in impervious area has increased the peak discharge of the area by 35% and has decreased the time to reach the peak flow by one hour.

Introduction:

Urbanisation leads to rapid changes in land-use/land-cover. This in turn can have significant impacts on the hydrological cycle and water quality of a catchment. This may result in flooding, and changes in groundwater and river regimes. Urban areas consist of complex land-cover types which are difficult to parameterise in hydrological modelling. In this study a distributed hydrological approach has been used to model the influence of changing land-use/land-cover (LU/LC) upon the hydrology of an urban area. Geographical Information System (GIS) is used to represent the distributed geomorphological and land cover parameters for the study. The objectives of this study are to

(1) Develop GIS based unit-hydrograph tool for assessing urban runoff for planners to assess the impact of development quickly.

(2) Compare and evaluate the effect of changes in LU/LC in urban settlements upon the hydrograph.

(3) Determine the effect of resulting increases in impervious surface area upon the peak of the hydrograph.

GIS store information on previous and present LU/LC and they are utilised in land use planning and development control planning applications. If a capability to estimate hydrological runoff could be added, these systems

would then allow a initial estimate to be made of how the change in impermeable areas may impact upon the peak flows and the potential flood risk. This would assist land use planners by allowing them to review the hydrological consequences of approving different types of planning applications where there are significant changes in existing land use. This type of information, which allows the consequences of land use changes to be much more directly linked to possible effects on the hydrological system, is likely to be required more often and in more detail as part of present moves to integrate land use and river planning under the requirements of the EU Water Framework Directive.
(http://ec.europa.eu/environment/water/water-framework/index_en.html)

Modelling Approach:

In this study, we explore how the technique of the unit-hydrograph can be implemented using existing GIS functionality and show how this technique can be roughly calibrated using historical land use changes and flow records for a catchment. The established method can then be used to simulate the likely changes in hydrology of a catchment under a range of future land development scenarios.

The basic modelling approach will be to use the raster GIS functions of ArcGIS version 9.1 to calculate the travel time of surface water flow from each point in the watershed to the outlet, by determining the flow path and the travel time through each cell along this path. The travel time through each individual cell along the flow path will be summed to estimate the cumulative travel time from the start of each flow path to the outlet. The model accounts for differences in overland slope, and land use. Runoff is routed over the surface using DEM. The total travel time to the outlet from each grid cell is then estimated based on the runoff pathway and the travel time through each grid cell along the path using the *path distance* function in ArcGIS 9.1 and ArcTool box.

The output from each analysis is a unit-hydrograph for each cell. This has been assessed for the same catchment from 1996 to 2006. The Spatially Distributed Unit-Hydrograph (SDUH) model will take into account the increasing impervious area in the different parts of the catchment each year. The distributed parameter estimation capability of the SDUH model helps to understand how the development in the different parts is affecting the hydrology in the catchment. This will help to understand the changes in the LU/LC and the relevant changing flow patterns in the study area.

Study Area:

The area under investigation in this study is the Dunfermline Eastern Expansion (DEX) area; location is shown in the Figure 1. Dunfermline is a town of 41,000 (2001, census) residents located in Eastern Scotland, and its eastern expansion area was identified in the 1994 Fife Structure Plan as the best area to accommodate the town’s expansion needs up to 2020. The Dunfermline Eastern Expansion area is located between the east of

Dunfermline and the M90 motorway covers an approximate area of 600 hectares. Three natural watercourses that flow into the Forth estuary drain the land. These are Pinkerton Burn, Calais Burn and Linburn. Prior to the start of development the area was agricultural land, including approximately forty hectares of woodland and thirteen hectares of natural wetland. In the past, the whole area was also mined for coal. It is planned that 4,500 homes, an 18 hectares leisure park, 300,000 square metres of manufacturing and industrial warehouse space, three schools and a district shopping centre will be built at the site by 2020.(Spitzer, 2005)

The study area in 2006 is partially urban and rapidly developing. This presented an opportunity to study the effects of increasing impervious surface on the unit-hydrograph for this watershed. The DEX site comprises three catchments Calais Burn, Linburn and Pinkerton Burn. The Calais Burn catchment has been subjected to continuous change of land-use. It is in a semi-urban stage with approximately 23% impervious area and the construction activities are gaining pace. For the current study the Calais Burn catchment has been selected to investigate how the rapid recent effects of urbanisation and increase of impervious area may have affected the catchment unit-hydrograph.

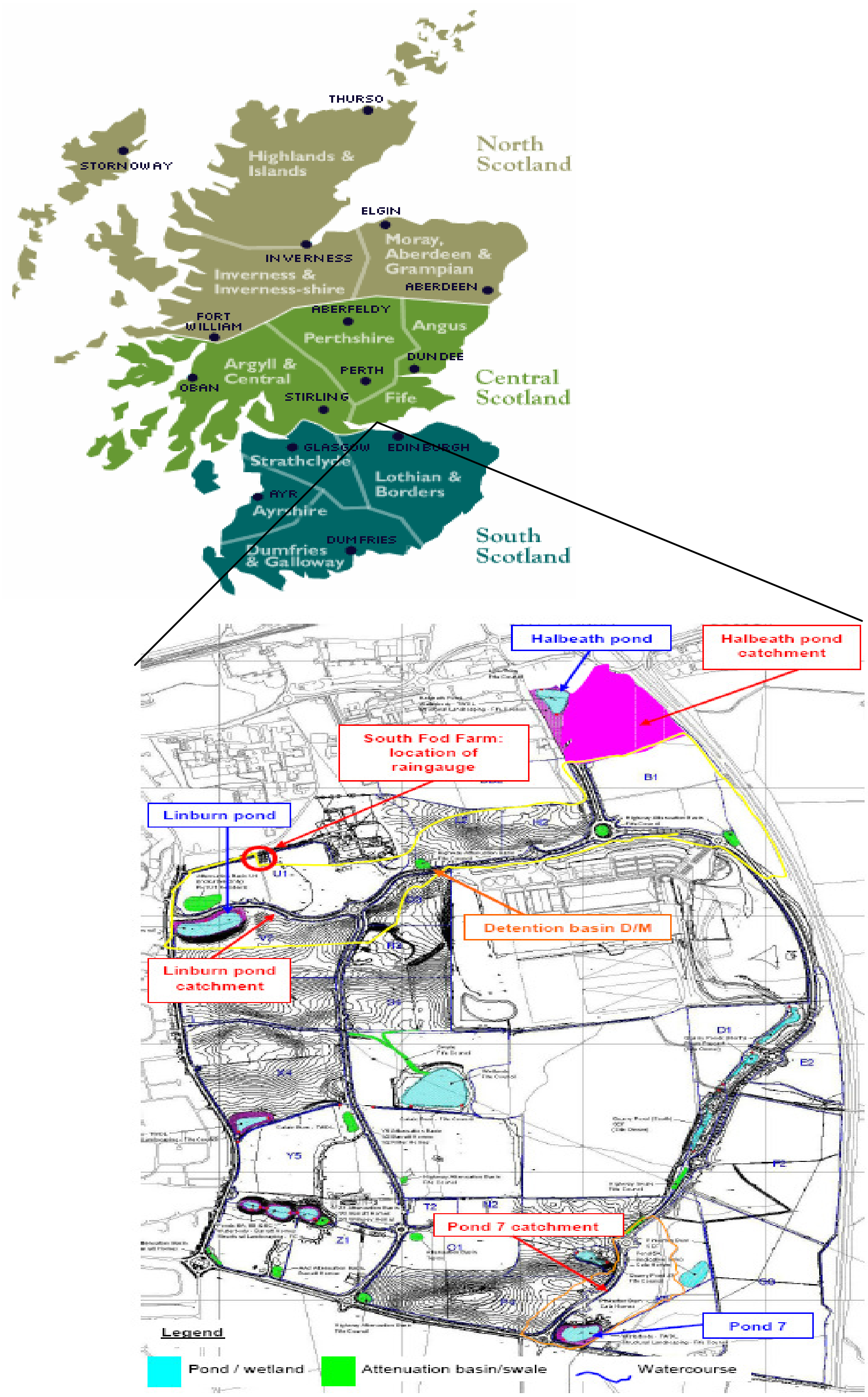

Figure-1, Location of Dunfermline Eastern Expansion Site (Adapted from Adolf Spitzer PhD Thesis.

Data and Methods:

In this study the time series land-use data for the area is extracted from Ordnance Survey (OS) MasterMap topographic layer which is available from 1996 to 2006. The MasterMaps are shown in the Figure-2, depicting the development taken place during 1997, 2003 and 2006. OS land-Form

PROFILE 1:10000 was downloaded from Digimap and converted to DEM of 10m resolution. Interpolated flow data at the Calais Burn outlet was provided by SEPA at 15 min intervals from 1997 to 2006. The rainfall data at South Fod Farm (Figure-1) from 2000 to 2003 was taken from Spitzer's PhD thesis. All the files were imported in Microsoft Excel using the import data option for further statistical calculations.

The recorded outflow for Calais Burn catchment (Figure-3) indicated an increase of 13 % from 1999 to 2000. However, a continuous decrease in the recorded outflow has been observed in the consecutive years till 2003. The average rainfall at the site remains more or less the same during 2000 to 2003.

However, after careful observation and consideration of the data collected from SEPA and Spitzer (2005), it was noted there were significant gaps in the datasets between 2000 and 2003.

Instead, the findings of the Adolf Spitzer PhD thesis are used for the study. Spitzer had collected rainfall, runoff outflow and individual storm event related data for the site from 2000 to 2003 with good continuity. From May 2000 to July 2002, 92.3% of all events were equal to or less than 5 mm in depth and 90% were equal to or less than 5 mm/h intensity. In terms of duration, 92% of all recorded events were less than three hours when an inter event time of 30 minutes was used. Analysis also showed that 92% of the inter event times were less than three days. Using these findings for the study area a rainfall event of intensity of 5mm/hr is assumed used to derive one hour unit-hydrographs for all the years.

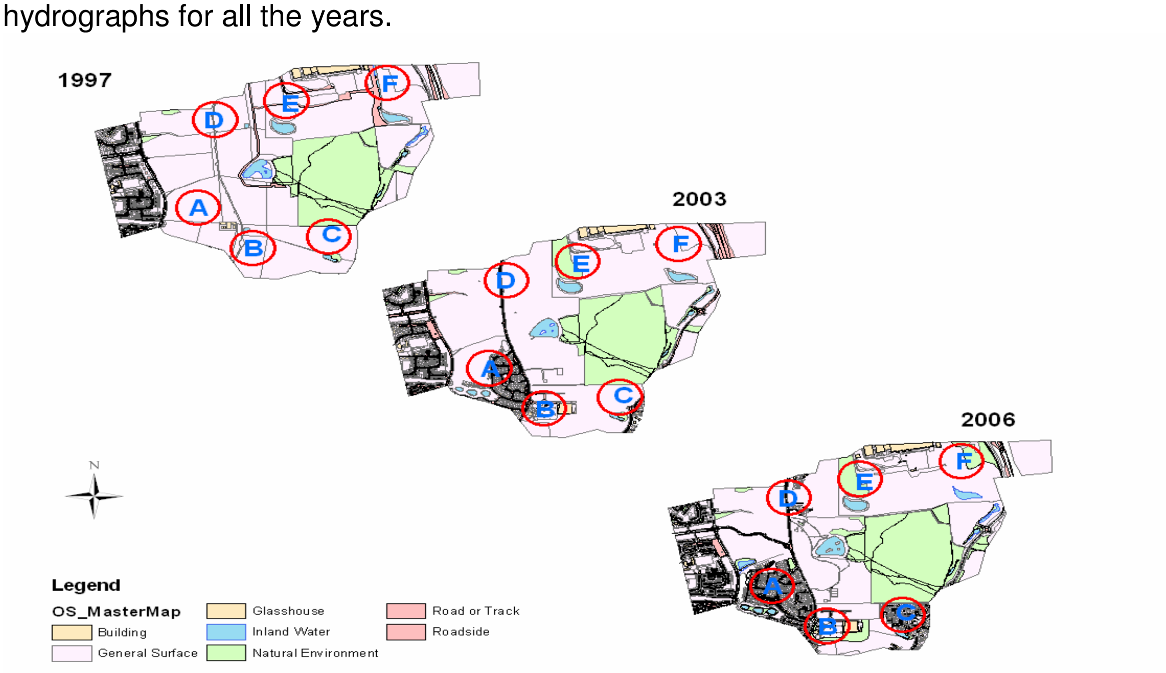

Figure-2, Increasing Development in Calais Burn catchment from 1997 to 2006

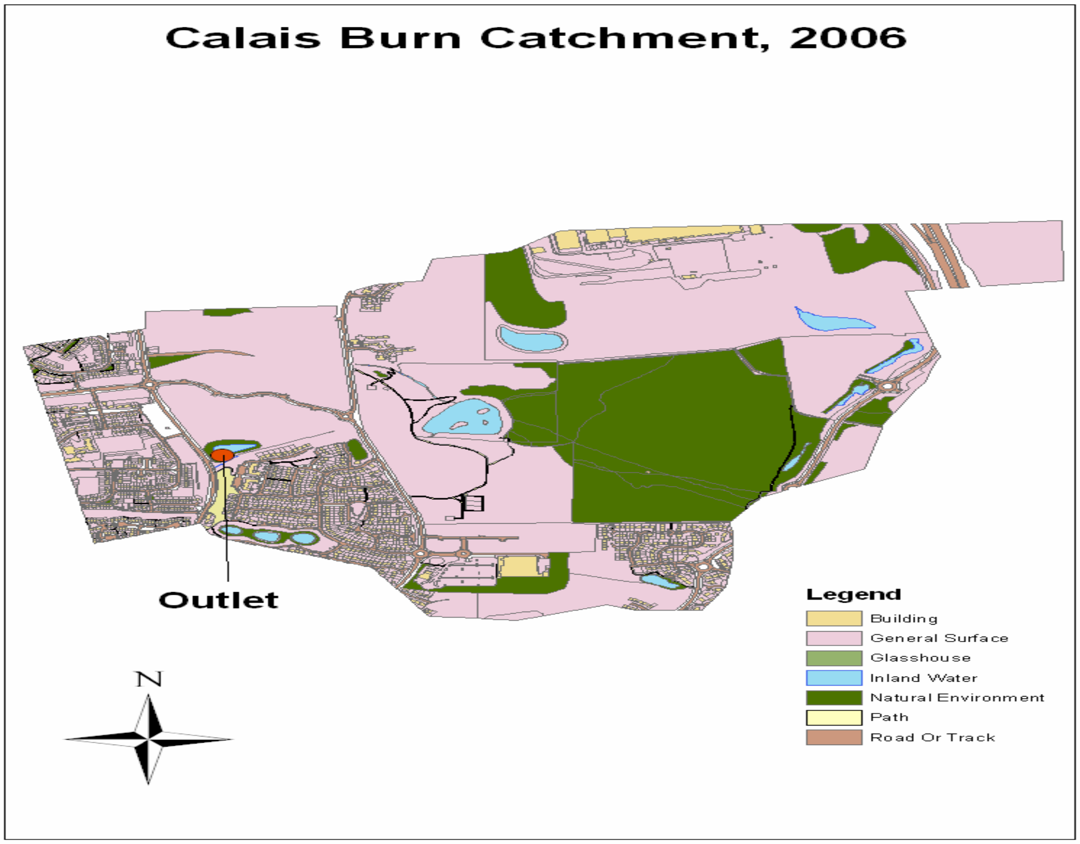

Figure-3, OS MasterMap, 2006, Calais Burn Catchment

Model Development:

Overview:

The GIS software ArcGIS 9.1 and ArcHydro extension developed by the Center for Research in Water Resources, University of Texas at Austin is used in this study. All calculations are made on raster grids developed from DEM. Watershed topographic properties needed in this study are derived from a 10m digital elevation model (DEM) derived from 1:10000, OS Land-Form PROFILE. The hydrologic model implemented here utilises the concept of the SDUH. This model is a rainfall-runoff transformation model where the time-area curve method is used for the purpose of generating the output hydrograph at the watershed outlet for a given storm. Spatial variability in the watershed response is accounted by analysing the topographic and land-cover on cell by cell basis in raster GIS. The methodology adopted is shown in Figure-4.

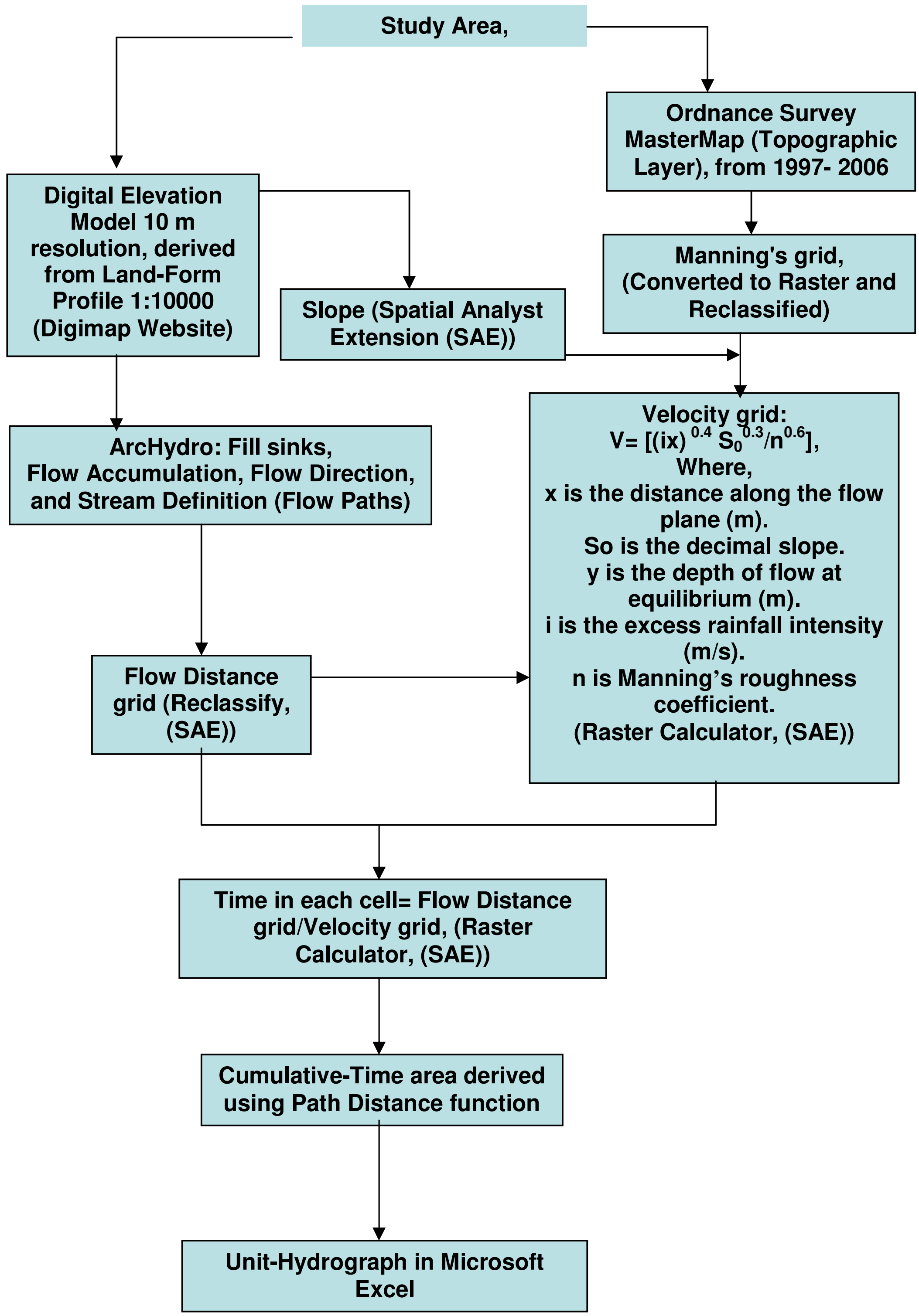

Figure-4, Flow chart of the methodology adopted

Manning's Grid

MasterMap data from 1997 to 2006 was clipped to extract the Calais Burn catchment and all the features were converted to raster grid of 10m by 10m using the descriptive group attribute (Figure-5). The attribute and cell count values were assigned with the Manning's roughness coefficient depending upon the land-use type adapted from Kilgore, (1997). The values assigned are presented in Table-1. It should be noted that only one land-use was set for each 10m by 10m grid cell. For the purpose of this study the majority of the land-use in each cell was adopted where there was more than one land-use present.

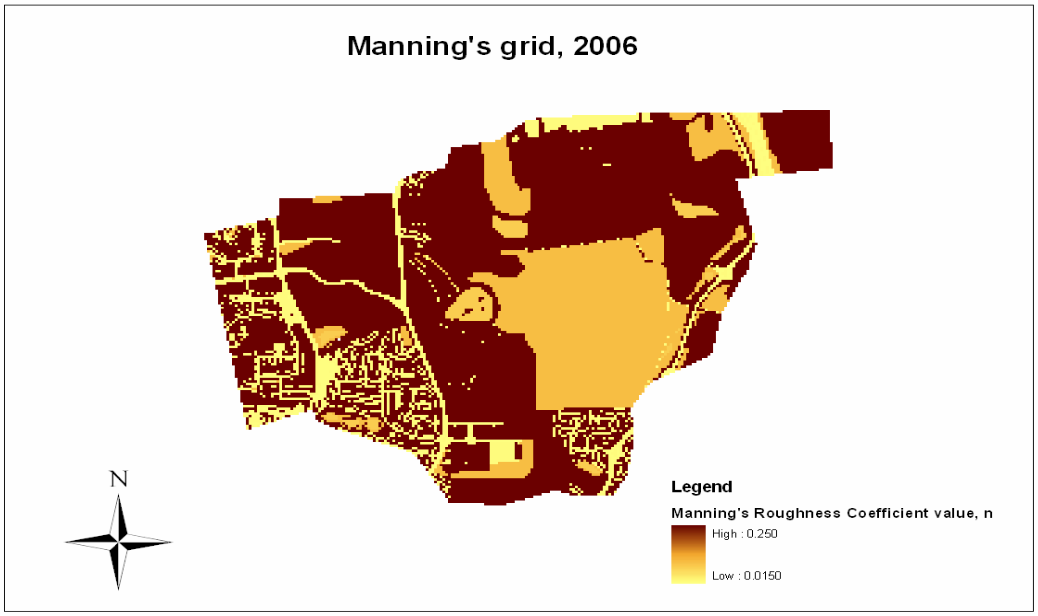

Figure-5, Manning's grid

Land-use Classification based on MasterMap	Manning's Roughness Coefficient, n
Buildings	0.16
General Surface	0.25
Inland Water	0.08
Road or Track	0.20
Natural Environment	0.015

Table- 1 Manning's Roughness Coefficient, adapted from Kilgore, 1997

Excess Rainfall:

The excess rainfall is the rainfall that becomes runoff after the initial and infiltration losses. The excess rainfall for all the years is assumed to be 5mm/hr and constant for a one hour duration. The Calais Burn catchment is small and partially urban with impervious areas hence this assumption is made. This means the runoff in each cell is equivalent to excess rainfall intensity of 5mm/hr and as the intensity is constant for one hour the excess rainfall intensity value in metres/second in velocity equation-2 remains the same. This excess rainfall intensity can also be taken as the depth of the flow in each cell when hydraulic radius parameter is to be calculated for velocity estimation in Manning's equation as there are no specific flow channels to collect the surface runoff and can be considered as wide channels in the study area.

Slope:
The slope for the study area is calculated using *spatial analyst* extension of ArcMap from DEM of 10 m resolution. The output is either in percent or a degree which has to be converted to decimal by dividing the raster output by a hundred which is used in equation-2.

Overland Flow Velocity:
Flow velocity is estimated by combining a kinematic wave approximation with Manning's equation. The depth of flow at equilibrium is given by (Overton and Meadows, 1976):

$$y= (nix/S_0^{0.5})^{0.6} \ldots\ldots\ldots\ldots\ldots \text{Equation-1}$$

Where:
x is the distance along the flow plane (m).
S_0 is the decimal slope.
y is the depth of flow at equilibrium (m).
i is the excess rainfall intensity (m/s).
n is Manning's roughness coefficient.
By substituting the depth of flow at equilibrium in Manning's equation, the velocity of overland flow can be calculated as:

$$V= [(ix)^{0.4} S_0^{0.3}/n^{0.6}] \ldots\ldots\ldots \text{Equation-2}$$

Where, V is the overland flow velocity (m/s).

Watershed Delineation:

Sinks:
Sinks (and peaks) are often errors due to the resolution of the DEM data or rounding of elevations to the nearest integer value. Sinks should be filled to ensure proper delineation of basins and streams. If the sinks are not filled, a derived drainage network may be discontinuous. In this study ArcHydro extension performs the filling of all sinks operation. The *Fill Sinks* function fills sinks in a grid. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The *Fill Sinks* function modifies the elevation value to eliminate these problems. In this study Z value of 2m is selected based on the field visit taken to the site. The fill operation may create large flat areas which may take time to drain to the outlet. This is overcome by increasing the gradient by 10% for flat areas.

Flow Direction and Flow Distance:
The direction of flow is determined by finding the direction of steepest descent from each cell to the neighbouring cell. This is calculated as:
Change in z-value / distance * 100

The distance is determined between cell centres. Therefore, if the cell size is 1, the distance between two orthogonal cells is 1, and the distance between two diagonal cells is 1.414. (See Figure-4)

In the present DEM of 10m resolution the direction can be 10m or 14.14m in diagonal direction as per the algorithm. Depending on the directions calculated from flow accumulation grid shown in the Figure-6, 10m and 14.14 m values were assigned to obtain the flow distance grid.

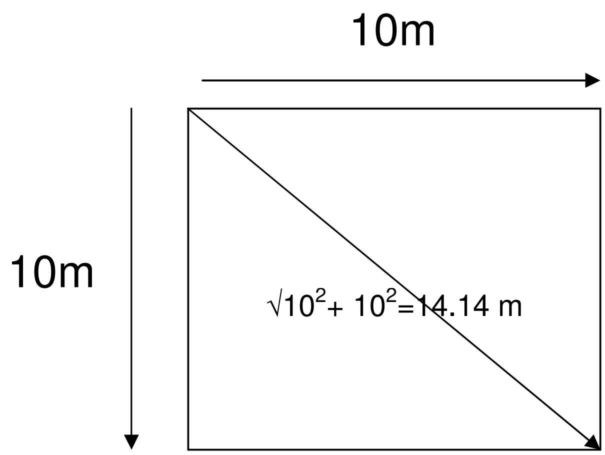

Figure-6, Distance travelled across each cell is either 10m or 14.14m having eight possible directions.

Stream Definition:
The *Stream Definition* function takes a flow accumulation as input and creates a Stream Grid for a user-defined threshold. This threshold is defined either as a number of cells (default 1%) or fraction of the drainage area in square kilometres.
In this case the watershed area is of 227 hectares hence threshold of $500m^2$ is considered and used to derive flow paths. See Figure-7.

Cumulative Time-Area Grid:
The distance grid is estimated by reassigning the flow direction grid with 10m or 14.14m values. The ratio of the distance grid to the velocity grid gives the time required by flow to travel in across each cell.

Time in each cell = Distance Grid/ Velocity Grid

The calculations are done in the raster calculator in the spatial analyst extension. The cumulative time required for each cell to reach outlet along the flow path can be estimated using *Path Distance* function in the ArcToolbox. See Figure-8. The time grid and outlet feature are given as inputs and the output is delivered as the cumulative time taken by each cell to reach the outlet. The grid can be reclassified using *symbology tab* to arrange the isochrones of 1-hr. The *histogram* function of spatial analyst is used to display the number of cells under each isochrone. The database file of the histogram is exported to *Microsoft Excel* for further calculations. The number of cells multiplied by the area of each cell (10m x 10m=100m^2) gives the area under the isochrone. These steps are repeated for every year and excess rainfall remains constant for all the years and Manning's grid being only the changing input to estimate the unit-hydrograph.

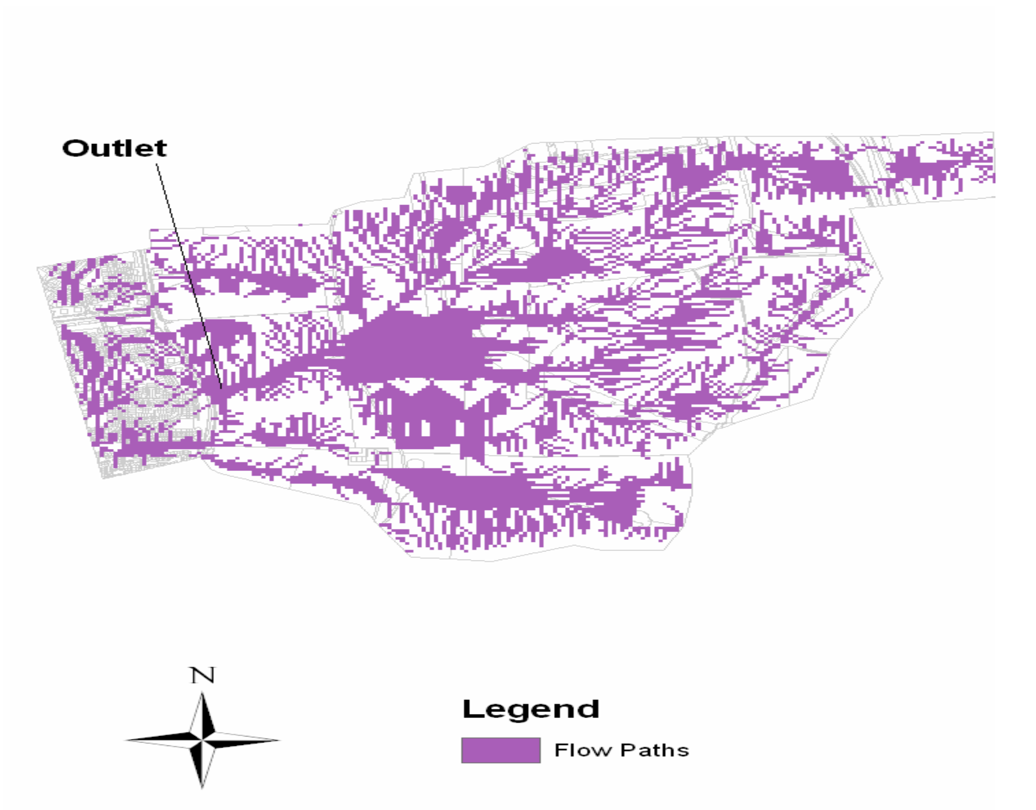

Figure-7 Flow paths in the Catchment derived from DEM for 500m^2 threshold area for the year 2006.

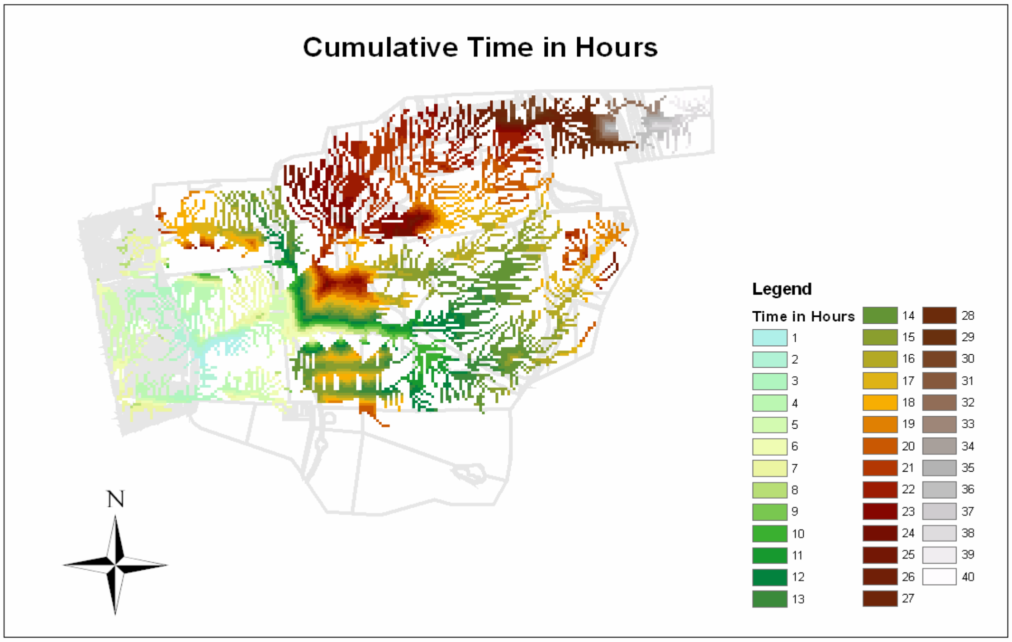

Figure-8 Cumulative time in hours to the outlet of the catchment for the year 2006.

Cumulative-Time Area Diagram:

The graph of time against area is plotted (Figure-7) in the Microsoft Excel for each year. The incremental area ordinates are then divided by the time interval to yield the unit-hydrograph ordinates. One-hour unit-Hydrographs from 1997 to 2006 are derived.

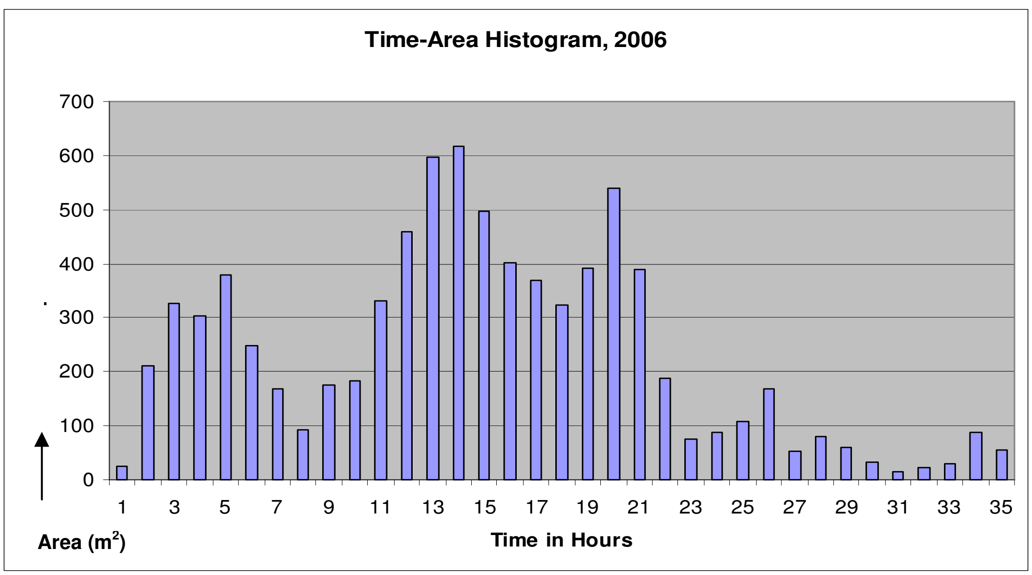

Figure-9 Time- Area Histogram for the year 2006

Results and Discussion:

Figure-10 depicts the decreasing cumulative time in the cells for surface runoff through time. The development taking place in the catchment is shown in red circles and the corresponding cumulative time is shown exactly below the respective year diagram. The cumulative time represented in Figure-10 is not along the flow path and not taken into account for the further analysis. Figure -10 demonstrates how impervious areas can decrease the time taken by runoff to the outlet. It can be seen in the Figure-10 that the green colour for 7-8 hours cumulative time is increasing and extending its coverage in 2003 and 2006 compared to 1997. This means the areas under the 8-9 and the 9-10 hour isochrones are reduced.

It should be noted that this analysis has only been undertaken for one storm event therefore may not be representative of all storm intensities and durations. Higher intensity rainfall may result in different flow pathways being utilised due to the increase in water depth at each cell.

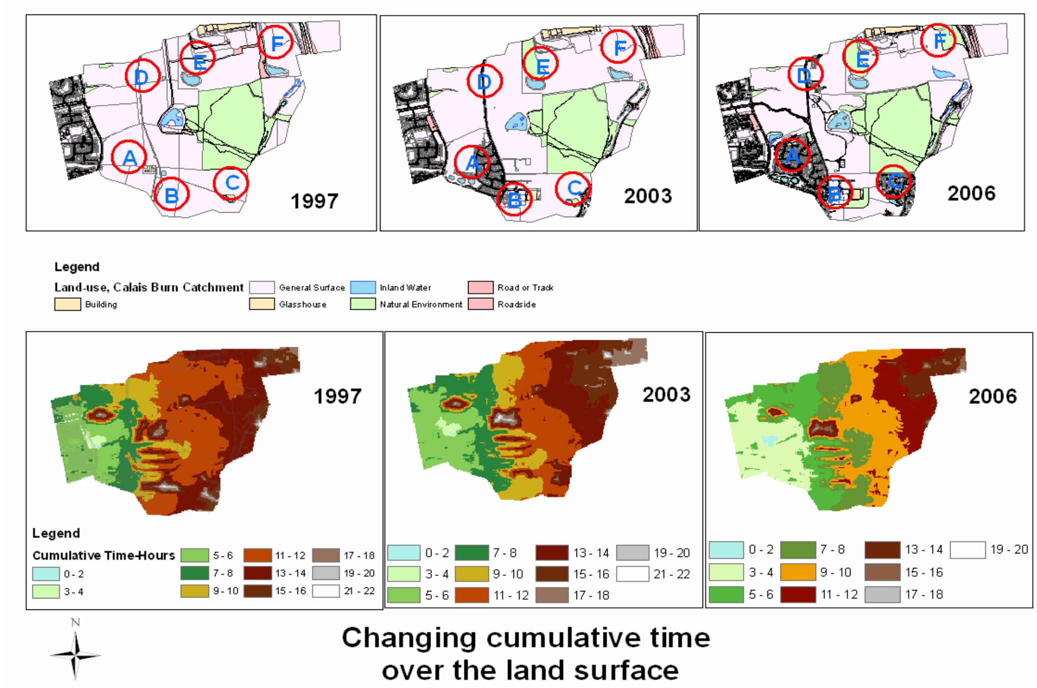

Figure-10

Unit-Hydrograph for 1997:

The one hour unit-hydrograph for 1997 (Figure-11) shows a peak ordinate of 7000 m^2 at 4 hours. At this period of time the development in the catchment was only at the initial stage of construction. The impervious area in the Calais Burn catchment was 12%. The hydrograph has three peaks, one (see annotations in Figure-11) of 7000m^2 at 5 hours, a second of 4400m^2 at 13 hours and third of 1000m^2 at 23 hours. The second and third minor peaks in the falling limb may be due to the depressions in the central area of the catchment which are more or less flat between the parts A and E shown in Figure-12 and start contributing only after 10 hour of time interval. This undulating nature of the unit-hydrograph may be due to the flatter areas in the catchment which are effectively captured at 10m resolution.

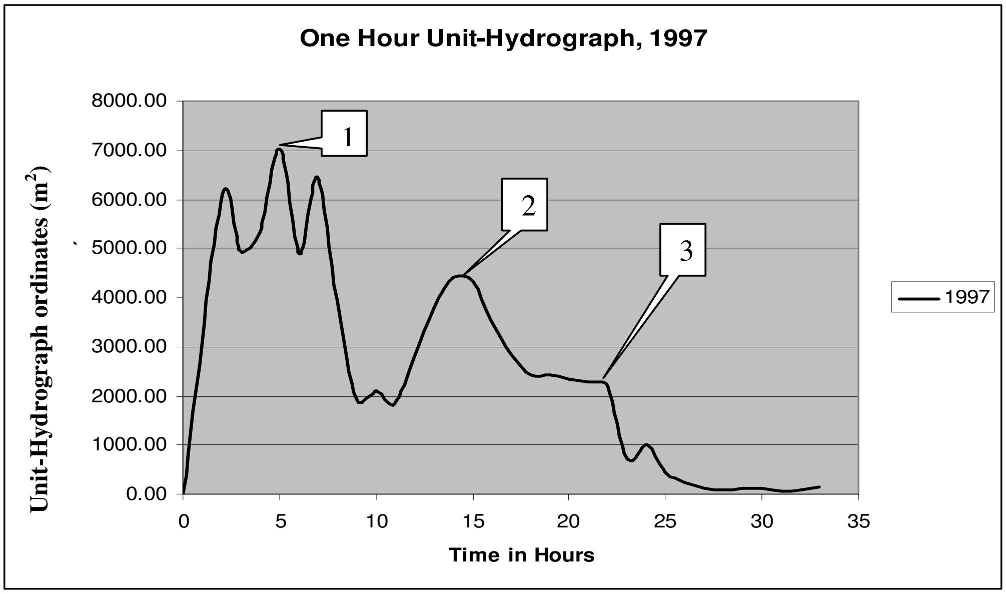

Figure – 11, Unit-Hydrograph, 1997

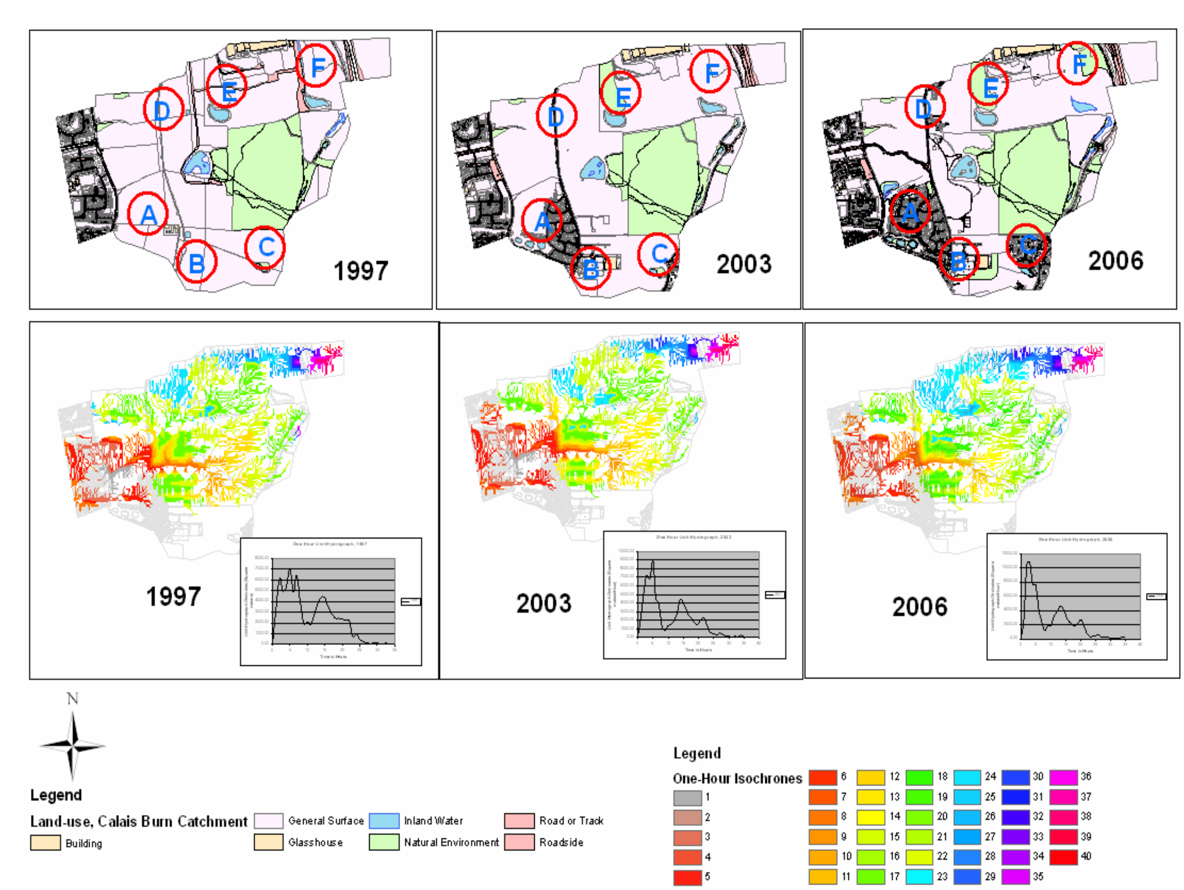

Figure-12, Increasing Development, cumulative-time and unit-hydrographs for Calais Burn Catchment.

Unit-Hydrograph for 2001, 2002 and 2003:

The Unit-Hydrograph of 2001 and 2002 shows (see Figure-13) an increased peak discharge of 8340m^2 and 8460m^2 respectively at 5 hours as compared to 7025m^2 at 4 hours in 1999. Increase of around 1300m^2 and a decrease of 1 hour for time to peak. The impervious area during this period of time is still around 12% which is not a marked increase but it has impact on the time to peak flow and peak discharge. The development in sectors B and C of the catchment shown in Figure-12 justifies the increase in the peak but delay in time to reach peak flow from 4 hours in 1999 to 5 hours in 2001 to 2003 was not anticipated. This may be due to the uneven velocities generated across the cells in the catchment representing fragmented development patches in the sectors A, B and C (Figure-12) and the artificial storage adopted during the construction resulting in delaying the surface runoff. Another reason for delayed time to peak may be due to the increase in vegetation cover between part C and E in the central part of the catchment.

The unit-hydrograph of 2003 shows a peak ordinate of 8880m^2 which is an increase of 1855m^2 when compared to 1997 and time to peak flow of 5 hours, 1 hour more than 1997. The impervious area has now reached 13% which is only a 1 % rise compared to 1997. However, this 1% rise in the impervious area is showing a notable difference on the shape of the unit-hydrograph. The approach of time-area diagram considers the distributed velocity fields and geomorphological characteristics of the catchment, such as slope, while arriving at the ordinate of the unit-hydrograph. The development away from the vicinity of the outlet is increasing the peak ordinate but not the time to peak. However, during this period the development has also taken place near the outlet in northern and western part of the catchment in part A (Figure-12) which should decrease time to peak, but they are on flatter areas thus, not increasing the time to peak.

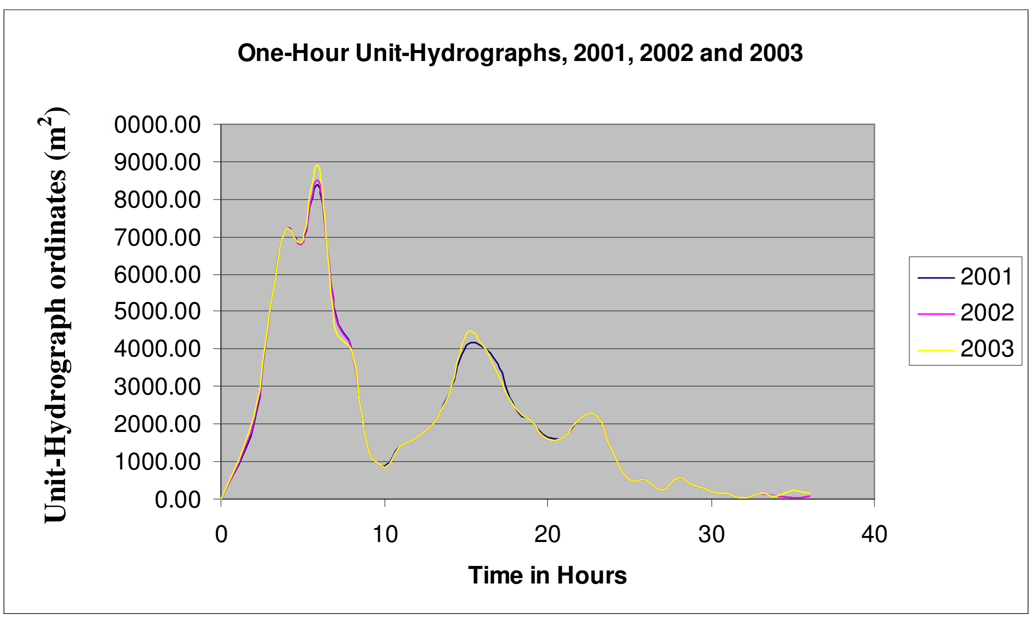

Figure-13 Unit-Hydrograph for the years 2001, 2002 and 2003

Unit-Hydrograph of 2006:
The 2006 unit-hydrograph shows (see Figure-14) the same characteristic and shape compared (see Figure-15) to previous ones but the peak ordinate has increased to 10,900m^2. This is an increase of 3875m^2 when compared to the 1997 peak area ordinate. The time to peak is only 3 hours which has decrease by 1 hour since 1997. The development in the catchment is in the third phase as per the plan of DEX site development in 2006. Most of the proposed area has now been developed and the impervious area has substantially increased to 23 % from 13 % in 2003 which is rise of 10 %. By 2006 the development in the catchment has taken place over all the sides of the catchment see sectors A, B, C, and D in Figure-12 especially near the outlet where housing have been constructed and sector B in which the shopping complex has been completed. This is thought to be primary reason for increased peak area ordinate and time to peak.

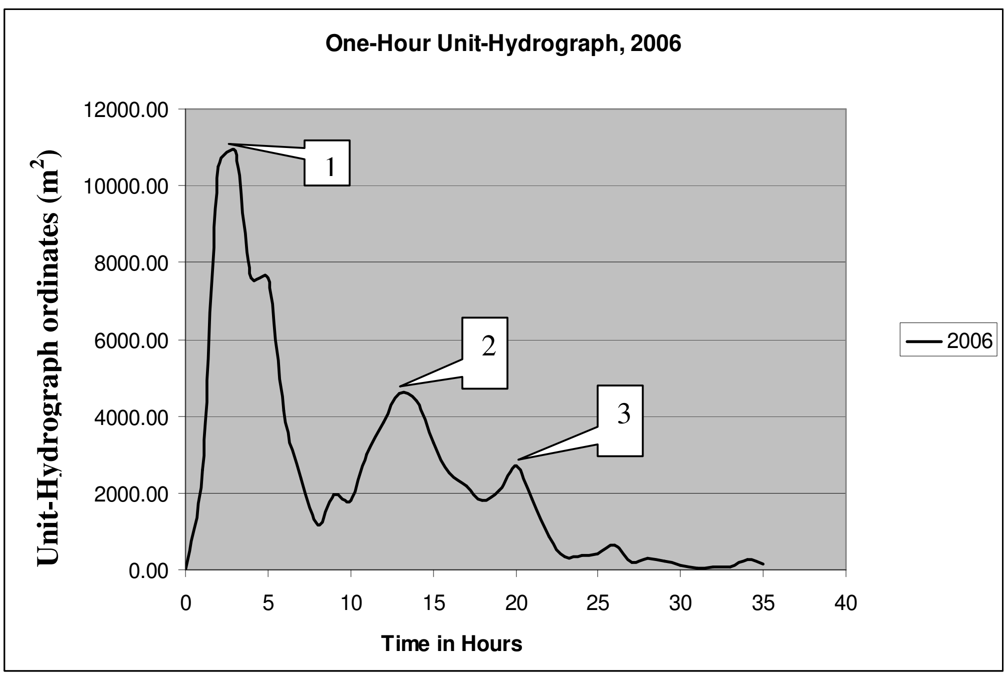

Figure- 14, Unit-Hydrograph, 2006

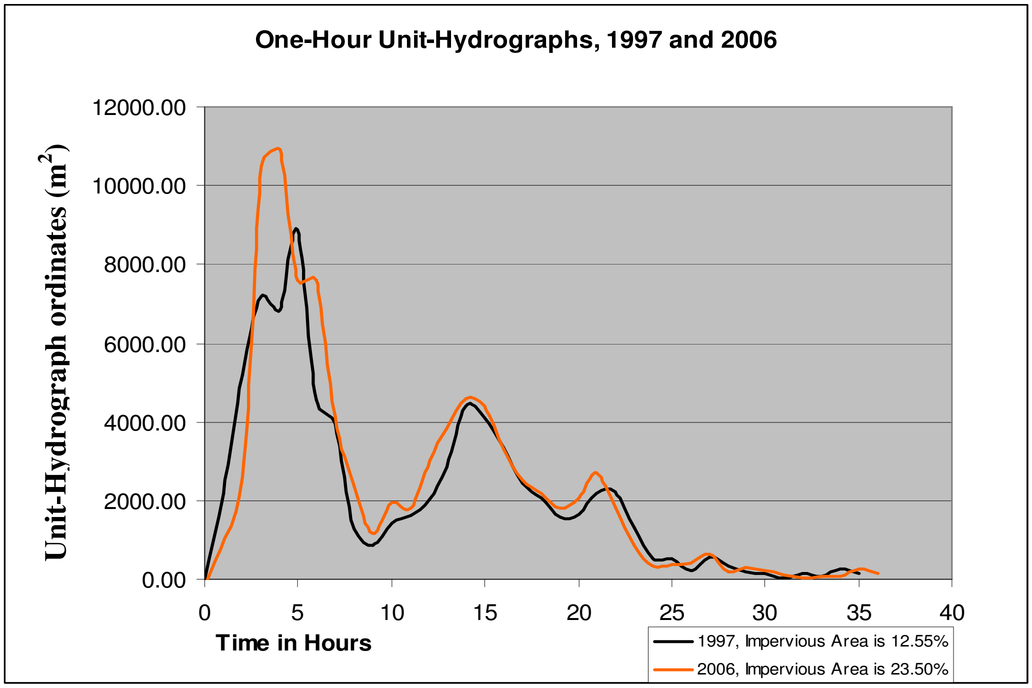

Figure -15, Unit-Hydrograph, 1997 and 2006

Table - 2 Comparisons of impervious area and peak area ordinate

Year	Impervious Area (%)	Peak Area Ordinate (m2)	Increased Peak ordinate in percent compared to 1997	Time to Peak in Hours
1997	12.55	7025	0	4
1998	11.04	7025	0	4
1999	12.59	7025	0	4
2001	11.75	8340	15.76	5
2002	12.52	8460	16.96	5
2003	13.08	8880	20.88	5
2006	23.50	10900	35.55	4

The increase of 10% in the impervious area from 1997 to 2006 has increased the peak discharge by 35.55% (see Table- 2) and decreased the time to peak by one hour (see annotations in Figure-12) by the areas contributing from the parts A, B C, and D. The linear regression analysis of impervious area to peak area ordinate for seven years gives reasonably strong r^2 value of 0.73. Spitzer, 2005 observed the rainfall to runoff relationship from 2000 to 2003 and found that the r^2 value between 0.50 to 0.70 for DEX site. However, to establish the relationship between impervious areas and peak discharge more values for consecutive years are needed of 20 to 25 years. This study for the Calais Burn showed no relationship between impervious area and time to peak and this may be due to the uneven and fragmented development, small size of the catchment and the artificial storage strategy adopted during the construction phase.

The common feature observed in all the unit-hydrograph is the sharp fall of the curve after the first peak. This may be due to the flat areas and the vegetation cover retained during the study period from 1997 to 2006 between sectors E and C (Figure-12) i.e. more or less central part of the catchment.

Model Assumptions:
SDUH model incorporates the unit-hydrograph assumptions which also form the limitations of the model. The assumption of uniform rainfall intensity does not hold true in practice as the rainfall intensity varies. However, the Calais Burn catchment is relatively small in the size, only 227 hectares, and this assumption may not have significant effect on the results. To overcome this limitation instantaneous unit-hydrograph can be developed from varying rainfall intensities for large catchments.

The model assumed that the rain falling on the catchment becomes 100% percent runoff; the assumption is made because the catchment is urbanised and small in area in this case majority of rainfall becomes runoff and reaches the outlet quickly. One of the challenges in the development of the model was the simplification and to make it programming free. The methods to determine the rainfall excess intensity like the SCS method can be added for other catchments but this will make the model more complicated.

Conclusions:

1. This is a quick alternative tool for an approximation of urban runoff to verify the potential impact on receiving water courses.

2. Future developments could be included to design SUDS and outline solutions.

3. The model can be used for planning and decision making to minimise the effect of urban development on the peak discharge in terms of urban land-use and land-cover but significant issues like rainfall simplification needs to be addressed.

4. The use of GIS data and raster grid analysis is suitable for identification and to represent the distributed parameters contributing to the change in shape of unit-hydrograph.

5. The sensitivity analysis of overland flow velocity was found to have a effect on the peak discharge and thus need to be carefully chosen.

6. Decomposition of velocity and area in to raster grid of 10m for 227 hectares of catchment area to represent the land-use using MasterMap provides finer details of the catchment for the study.

7. The application of SDUH model in this study in urban context as compared to recent studies in the agricultural and rural catchments shows the potential of the model to represent the dynamic change in land-use and land-cover.

8. To represent the fine details of the runoff rainfall process the storage effect may be taken in to account by introducing storage coefficient, particularly when the artificial storage is observed during construction phase.

9. The increase of velocity with the increase of flow in the main channel can be taken into account using equation-3 suggested by Maidment, (1996).

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