Comparison of Different Hydrograph Routing Techniques in XPSTORM Modelling Software: A Case Study

Fatema Akram, Mohammad Golam Rasul, Mohammad Masud Kamal Khan, Md. Sharif Imam Ibne Amir

Abstract—A variety of routing techniques are available to develop surface runoff hydrographs from rainfall. The selection of runoff routing method is very vital as it is directly related to the type of watershed and the required degree of accuracy. There are different modelling softwares available to explore the rainfall-runoff process in urban areas. XPSTORM, a link-node based, integrated stormwater modelling software, has been used in this study for developing surface runoff hydrograph for a Golf course area located in Rockhampton in Central Queensland in Australia. Four commonly used methods, namely SWMM runoff, Kinematic wave, Laurenson, and Time-Area are employed to generate runoff hydrograph for design storm of this study area. In runoff mode of XPSTORM, the rainfall, infiltration, evaporation and depression storage for subcatchments were simulated and the runoff from the subcatchment to collection node was calculated. The simulation results are presented, discussed and compared. The total surface runoff generated by SWMM runoff, Kinematic wave and Time-Area methods are found to be reasonably close, which indicates any of these methods can be used for developing runoff hydrograph of the study area. Laurenson method produces a comparatively less amount of surface runoff, however, it creates highest peak of surface runoff among all which may be suitable for hilly region. Although the Laurenson hydrograph technique is widely acceptable surface runoff routing technique in Queensland (Australia), extensive investigation is recommended with detailed topographic and hydrologic data in order to assess its suitability for use in the case study area.

Keywords—ARI, design storm, IFD, rainfall temporal pattern, routing techniques, surface runoff, XPSTORM.

I. INTRODUCTION

RAINFALL-RUNOFF processes can be explored either by physical watershed model in the laboratory or by numerical model using computers [1]. Temporal and spatial rainfall distributions are converted to runoff hydrographs by applying hydrodynamic laws and using various linear and nonlinear numerical schemes. Runoff routing procedures route hydrographs over land. Routing procedures are generally classified as hydrologic and hydraulic. Hydrologic models have a closed form of solution equation, while hydraulic models usually require some form of numerical integration with a finite difference approach. Hydrologic models are more commonly used which practice the continuity equation and

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mathematical relationships between discharge and storage. The discharge storage relationship can be either linear or non-linear. Hydrologic models are based on a hypothesized relation between outflow and water storage in the watershed, which is often modelled as a conceptual reservoir. Hydraulic models are based on approximations of the real physical rainfall-runoff process [2]. There are different types of unit hydrograph techniques available for the generation of runoff hydrograph. The routing procedure may produce more accurate result than unit hydrograph approach. As it becomes difficult to develop an adequate relationship between physical watershed parameters and the unit hydrograph shape [3].

With the advance in computer models and Geographic Information System (GIS) software, a trend of comparative study on different routing techniques is apparent. Syed et al. (2012) compared the efficiency of the kinematic wave and SCS unit hydrograph flow model to the observed flow data [4]. Basnayaka and Sarukkalige (2011) compared two surface routing approaches: hydrological and hydraulic 2D to represent the hydrological behaviour of an urban catchment and to assess the flood risk of an urban catchment using XPSWMM modelling software. Both the approaches were finally integrated with one dimensional (1D) hydraulic stormwater drainage network [5]. They found that both the approaches were suitable to represent urban catchment's hydrological behaviour, however hydrological surface routing produced more close result to observed data. For the assessment of flood risk they recommended to use the hydraulic approach as it calculates the flood depth by using both the surface runoff and excess water from pipe network. Saghafian and Shokoohi (2006) compared the time area method with the kinematic wave theorem for 1D flow and found better result from the kinematic wave theory [6]. Then they developed a revised time area algorithm that showed perfect agreement with the kinematic wave method. Xiong and Melching (2005) tested the accuracy of two routing techniques: Kinematic Wave and Nonlinear Reservoir for the routing of urban watershed runoff using some experimental data [7]. They found that the result based on Kinematic wave theory fit well in a surface flow generation.

Nowadays, numerous computer models are available which compute surface runoff from rainfall using different routing theories. For example XPRAFTS uses Laurenson hydrology technique to route runoff from rainfall. Dynamic Watershed Simulation Model uses a hydraulic routing method: Kinematic wave theory [7]. The nonlinear reservoir method is applied in

models such as the Stormwater Management Model (SWMM). About 40 to 60% projects of the U.S. Army Corp of Engineers are handled by the time-area method and its variants [6], [8].

XPSTORM is now becoming a widely used storm water modelling software worldwide [9]. It is capable of predicting stormwater flows for rural and urban catchments by adequately delineating sub-catchments. In the runoff module of XPSTORM, there are five major types of hydrograph generation techniques available. They are; i) SWMM Runoff /Non-linear Reservoir Method, ii) Kinematic Wave Method, iii) Laurenson Non-linear Method, iv) SCS Unit Hydrograph Method and v) Other Unit Hydrograph Methods (Nash, Snyder, Santa Barbara Urban Hydrograph, Alameda, Time-area, Rational formula). Besides, there are some more routing techniques available in XPSTORM that are suitable for specific location like UK, Florida, Chicago, Colorado etc. [9]. This research explores the performance of four hydrograph generation techniques inbuilt in XPSTORM for generating surface runoff hydrographs at a watershed scale. Among them two methods are non-linear hydrologic routing methods; Laurenson Hydrology and SWMM Runoff method, one is hydraulic routing technique: Kinematic wave and another one is the unit hydrograph approach: Time Area. The overall objective of this study is to provide an improved understanding of these four techniques of XPSTORM modelling software for the generation of peak surface runoff from design rainfall for a case study area, Golf course in Rockhampton, Central Queensland, Australia.

II. Model Descriptions

XPSTORM is one of many types of software of XP solutions that offers numerous software technologies and professional solutions worldwide to government agencies, engineering and environmental management organizations to plan, design, simulate and manage the physical and social environment. Actually XPSTORM and XPSWMM are essentially the same program, the exact same interface and functionality for everything except the sanitary (sewer) module. XPSWMM includes the Wastewater and Water Quality module which allows access to the Sanitary (sewer) module. The origin of XPSTORM is the program Stormwater Management Model (SWMM) that is originally produced by United States Environmental Protection Agency (EPA). It is primarily maintained by Wayne Huber (Huber et al., 1988) at Oregon State University, USA.

XPSTORM, a link-node based, integrated stormwater modelling software, can be used for the design, simulation and analysis of stormwater collection and conveyance systems. It can also simulate the natural flow systems of lakes, rivers, floodplains with groundwater interaction, etc. It can predict stormwater flows for rural and urban catchments by adequately delineating sub-catchments. In runoff mode, this model can simulate the complete hydrologic cycle, including rainfall, infiltration, evaporation, surface ponding, and ground surface water exchanges for each subcatchment and calculates

the runoff to collection nodes of those subcatchments. The fundamental laws that govern and describe fluid flow are described by the momentum equation (1) and the continuity equation [10], [11] as in

$$\frac{\partial y}{\partial x} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{1}{g}\frac{\partial v}{\partial t} = S_o - S_f \tag{1}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{2}$$

where; y is the depth(m); v is the velocity (m/s);x is the longitudinal distance(m); t is the time(sec); g is the gravitational acceleration (m/sec^2); So is the ground slope (m/m); S_f is the friction slope (m/m); Q is the flow rate(m^3/s); A is the flow area (m^2); q is the discharge per unit length(m^2/s).

The above two relationships are approximated by the Manning's equation and the continuity equation respectively as in

$$V = \frac{1}{n}R^{2/3}S_0^{1/2} \tag{3}$$

$$Q = VA \tag{4}$$

where, n is the manning's roughness coefficient; R is the hydraulic radius (m).

The subcatchments model parameters are surface roughness, depression storage, slope, flow path length; max/min rates for infiltration and decay constant. A study area divided into numerous individual subcatchments, all drains to a single point. Study areas can range in size from a small portion of a single lot up to thousands of acres. XPSTORM can handle hourly or more frequent rainfall data and can be run for the single event or continuous simulation for any number of years. In this study four commonly used methods used in XPSTORM, have been applied to generate runoff hydrograph for design storm and comparison has been made among them. The four methods are SWMM runoff, Kinematic wave, Laurenson, and Time-Area. A brief description of them is presented below.

A. SWMM Runoff / Nonlinear Reservoir

It is a popular routing procedure developed by the USA EPA as a deterministic approach to runoff hydrographs. It is also known as EPA runoff or Nonlinear reservoir method. Here Nonlinear Reservoir method is used where the catchment is considered as a very shallow reservoir. The discharge derived from this theoretical reservoir is assumed to be a non-linear function of the water depth of the reservoir. The subcatchments are described by the surface roughness and depression storage for pervious and impervious area. The subcatchment width is calculated based on the collection length of overland flow of the watershed area. The Nonlinear Reservoir method can be explained by Fig. 1.
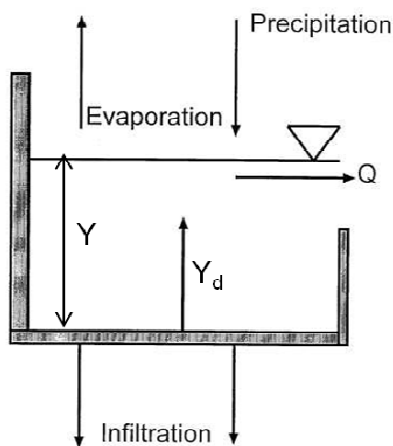
Fig. 1 Sketch defining Non-linear Reservoir Model

Fig. 1 shows a reservoir where inflow is rainfall rate and infiltration and surface discharge is outflows. Here y represents the average depth of surface runoff, and y_d represents the average depression storage in the catchment. In this method infiltration can be modelled by either Horton or Green Ampt equations or using a uniform loss rate. The Horton or Green Ampt loss is applied only to the pervious percentage of the subarea. The only loss applied to the impervious portion is through the depression storage defined for the impervious area. Depression loss can also be applied to the pervious component that will be an additional loss to the Horton or Green Ampt loss. In this routing procedure overland flow hydrographs are generated using Manning's equation and a lumped continuity equation. The continuity equation for this method is given as in

$$A\frac{dy}{dt} = A(I - f) - Q \tag{5}$$

where, A is the catchment area (m^2), I is the rainfall intensity (mm/hr), f is the infiltration rate (mm/hr) and Q is the discharge at the catchment outlet (m^3/s).

Based on the Manning friction relationship, the catchment discharge, Q is as in

$$Q = \frac{W}{n}(y - y_d)^{5/3} S^{1/2} \tag{6}$$

where, W is a representative width of catchment (m), n is manning roughness coefficient for the catchment, Y_d is average depth of depression storage (m), S = average surface slope (m/m).

Combining (5) and (6), a non-linear simple finite difference equation can be expressed as in

$$\frac{y_2 - y_1}{\Delta t} = \overline{I} - \overline{f} - \frac{CWS^{1/2}}{An}\left[\frac{y_1 + y_2}{2} - y_d\right]^{5/3} \tag{7}$$

where, Δt is time step increment (sec), Y_1 is depth at the beginning of the time step (m), Y_2 is depth at the end of the time step (m), I= average rainfall rate over the time step (mm), f is average infiltration rate over the time step (mm).

B. Kinematic Wave

Kinematic-wave is a commonly used hydraulic routing method, utilized by many models [7]. Overland flow from Kinematic wave method applies only the kinematic wave component of the St Venant shallow flow equations for momentum and continuity. Similar to the SWMM Runoff procedure the subcatchments are modelled as idealised rectangular areas with the slope of the catchment perpendicular to the width. The infiltration or rainfall excess model is developed here same as the SWMM runoff method. The data required for this method is similar to the EPA Runoff method including area, impervious %, subarea width and slope. The continuity and momentum equations for overland kinematic wave reduced to the below two equations as in

$$\frac{\partial y}{\partial x} + \frac{\partial q}{\partial x} = i - f = i_e \tag{8}$$

$$q = ay^m = \frac{1.49}{N}S_o^{1/2}y_o^{5/3} \tag{9}$$

where; y is depth of overland flow, q is rate of overland flow per unit width (m^2/s), i_e is net rainfall rate, a is a conveyance factor= $(1/N)S_o^{1/2}$ when obtained from Manning's equation, m=5/3 when obtained from Manning's equation, N is effective roughness coefficient, S_o is average overland slope, Y_o is mean depth of overland flow (ft).

C. Laurenson Hydrology

This method is developed by Laurenson in 1964 by routing runoff through non-linear catchment storage using separate hydrographs from pervious and impervious area [11]. In this method each sub-catchment is divided into two parts; pervious and impervious. The subcatchment width is by default not used here, but a non zero value need to be provided for this field in xpstom. Routing for a particular subcatchment is carried out using the Muskingum procedure. Each sub-area is treated as a concentrated conceptual storage. However the storage is a non-linear function of the discharge and the relationship is expressed by the nonlinear equation as given in (10);

$$S = BQ^{n+1} \tag{10}$$

where, S= Volume of storage (hrs x m^3/s); Q= Discharge (m^3/s) and n= storage non-linearity exponent; (default value = -0.285); B= storage delay time coefficient.

Each storage has a storage delay time and B for each storage is calculated by the above equation. The default procedure for infiltration calculation applies to either the Horton or Green Ampt loss to the pervious percentage of the

subarea, as defined by the % impervious data item. No loss is applied to the impervious component as the depression storage defined for the impervious area in the infiltration dialog in Laurenson is inactive. Besides, loss model can be developed using uniform loss method. In this method, values of the initial loss and continuing loss for both the pervious and impervious area can be provided separately. In this study both uniform loss model and Horton model have been used to estimate the excess rainfall and finally to get a runoff hydrograph.

D. Time Area

Time-area rainfall runoff transformation is one of the most widely applied unit hydrograph techniques of runoff routing. This method employs rainfall excess hydrograph with a time-area diagram to represent the progressive area contributions within a catchment in set time increments. In this method separate hydrographs are generated for the impervious and pervious surfaces within the catchment. To estimate the total flow, those two individual sub-catchment entries are combined. The time area method assumes a linear time area relationship for the subarea and is based on an input 'time of concentration is the time to travel flow from the most hydraulically remote point in the contributing catchment area to the point under study. It is assumed that the rainfall occurring during the time of concentration is directly related to flow rate [12].

The major similarities and dissimilarities found among these four techniques used are summarised at the Table I.

III. STUDY AREA

The case study area of this study is a Golf Course, located in Rockhampton city, Central Queensland, 40 km away from the coast on the Fitzroy river. The Rockhampton is situated at the Fitzroy Basin which is the largest basin of Queensland [13]. The location of Fitzroy basin at Queensland is shown in Fig. 2 (a). Fitzroy basin has six major subcatchments shown in Fig. 2 (b). Among these six subcatchments, the study area lies on Fitzroy sub-catchment which is bounded by the red line and the study area is pointed out by a red diamond in Fig. 2 (b). This sub-catchment is further divided into smaller sub-catchments. The area of the sub-catchment on which study area lies is 35 km^2. The enlarged view of the study area is shown in Fig. 2 (c). The area of the Golf course is around 50 ha.

IV. METHODOLOGY

The systematic method to generate surface runoff from subcatchment due to rainfall by any routing method can be summarized by the flowchart shown in Fig. 3.

A. Selection of Hydrograph Method

To make a comparison, four hydrograph methods were selected i.e., EPA Runoff, Laurenson, Kinematic Wave and Time Area Unit hydrographs method.

B. Selection of Design ARI (Average Recurrence Interval)

Design ARI need to be selected to estimate the design rainfall intensity. To estimate the flow, it is assumed that the design flow with a given ARI is produced by a design storm rainfall of the same ARI. Design storms are not typical of a complete storm; they are at best a representation of a possible design storm burst likely to be found within a real storm [14]. In this study 5year design ARI was selected to generate hydrographs using different routing methods. Besides, hydrographs for different ARI (1, 2, 5, 10, 20, 50, and 100) have been generated using Laurenson hydrology.

TABLE I
COMPARATIVE VIEW OF FOUR RUNOFF ROUTING METHODS IN XPSTORM

| Item	SWMM Runoff	Kinematic	Laurenson	Time Area
Data Needed	• Drainage Area, • Percent Impervious, • Basin slope & Width • Rainfall • Evaporation • Infiltration Method	• Drainage Area, • Percent Impervious, • Basin slope & Width • Rainfall • Evaporation • Infiltration Method	• Drainage Area(impervious & pervious) • Storage Delay Parameter • Manning's n • Slope • Rainfall	• Drainage Area(impervious & pervious) • Time of concentration • Rainfall
Basin Width	Subcatchment width is used	Subcatchment width is used	Subcatchment width is not used	Subcatchment width is not used
% Imperviousness	Imperviousness is expressed by % of area	Imperviousness is expressed by % of area	Subcatchment is divided into pervious and impervious area	Subcatchment is divided into pervious and impervious area
Storage-Discharge relation	Non-linear	Non-linear	Non-linear	Linear
Method	Non-linear Reservoir	Kinematic wave component of St. Venant shallow flow equations	Muskingum procedure	Unit hydrograph
Loss from impervious area	Loss from an impervious area can only be set by depression storage	Loss from an impervious area can only be set by depression storage	Depression storage for impervious area is not active	Depression storage for impervious area is not active
Limitation	Lumped Catchment Parameter	Lumped Catchment Parameter	Lumped Catchment Parameter	• Can over estimate peak runoff rate • Not valid for storm durations over 24 hours
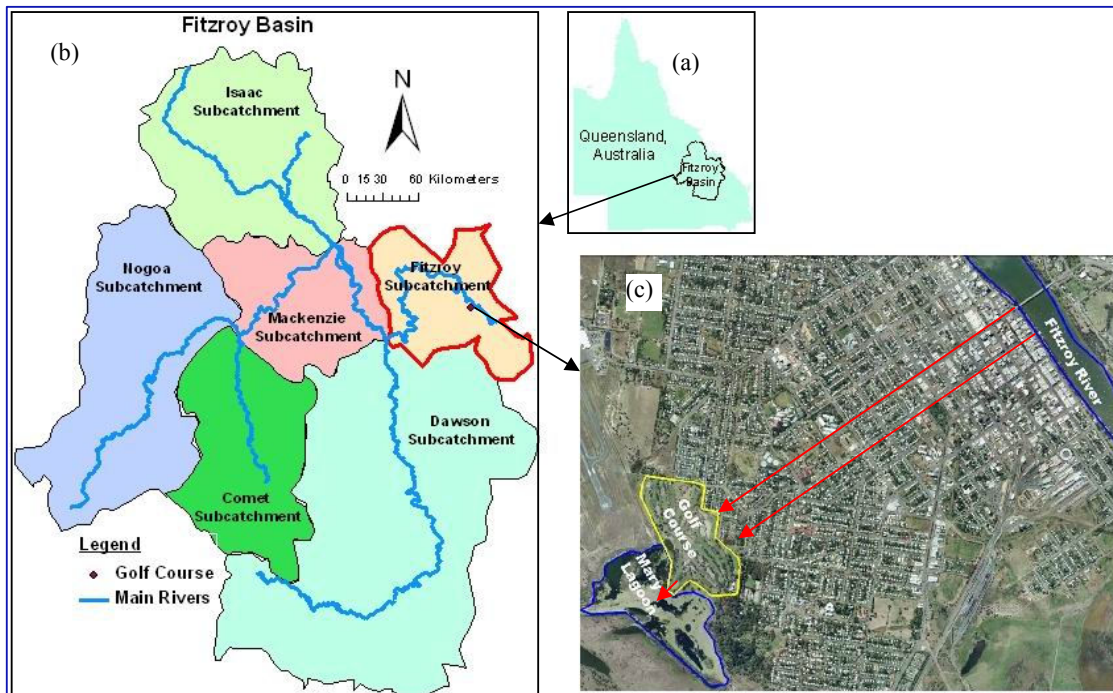
Fig. 2 Case Study Area: (a) Location of Fitzroy Basin in Queensland,(b) Location of Rockhampton in Fitzroy Basin, (c) Model Area in Rockhampton
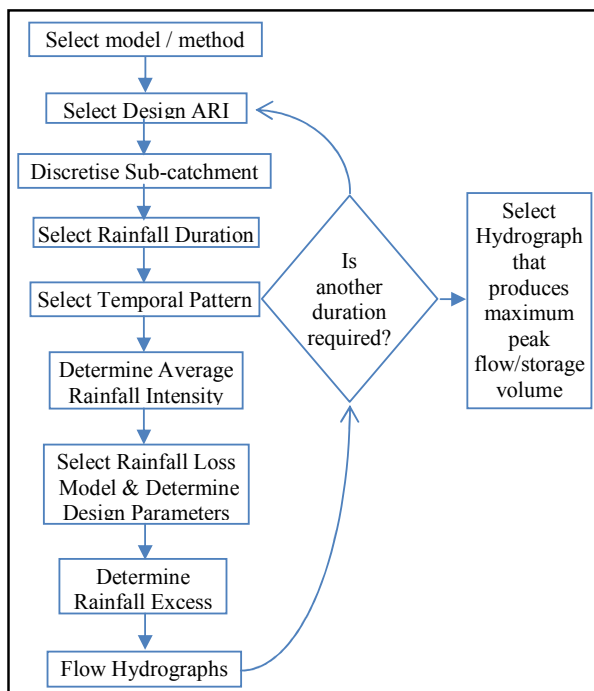

Fig. 3 General Flowchart for Generating Runoff Hydrograph for a Single Sub-Catchment

C. Subcatchment Delineation

This is one of the major steps of hydrological model development. In this study delineation of subcatchments were done with a digital terrain model (DTM) data using the spatial analysis tools of ArcGIS 10.1. Fatema et al. (2012) did a detailed study on subcatchment delineation in this region [15]. For the delineation of subcatchment the required parameters were;

i)   Tributary networks and
ii) Catchment topography (DEM data).

D. Design Rainfall Temporal Pattern

According to Australian Rainfall Runoff 1987 (ARR87) manual, Australia is divided into eight rainfall zones [16]. For each zone there are two temporal patterns. One is less than or equal to 30 years ARI and the other one is more than 30 years ARI. These are referred as Australian Rainfall and Runoff temporal patterns (ARR Temporal Patterns). ARR87 implemented the Method of Average Variability to derive design rainfall temporal patterns in Australia. It is expected that use of these temporal patterns along with other inputs of the rainfall runoff modelling are able to preserve the frequency of input rainfall depth in the final output of the model [17]. The eight zones of Australia for the design rainfall temporal pattern are shown in Fig. 4. According to Fig. 4 the study area is located in Zone 3.

ARR temporal pattern for 1 hour design storm derived from XPSTORM modelling software is presented in Figs. 5 (a) and (b). The time interval of these two bar charts is 5 minutes. Figs. 5 (a) and (b) represent the ARR temporal pattern of 1 hour design storm for the ARI less than or equal to 30 years and greater than 30 years respectively.
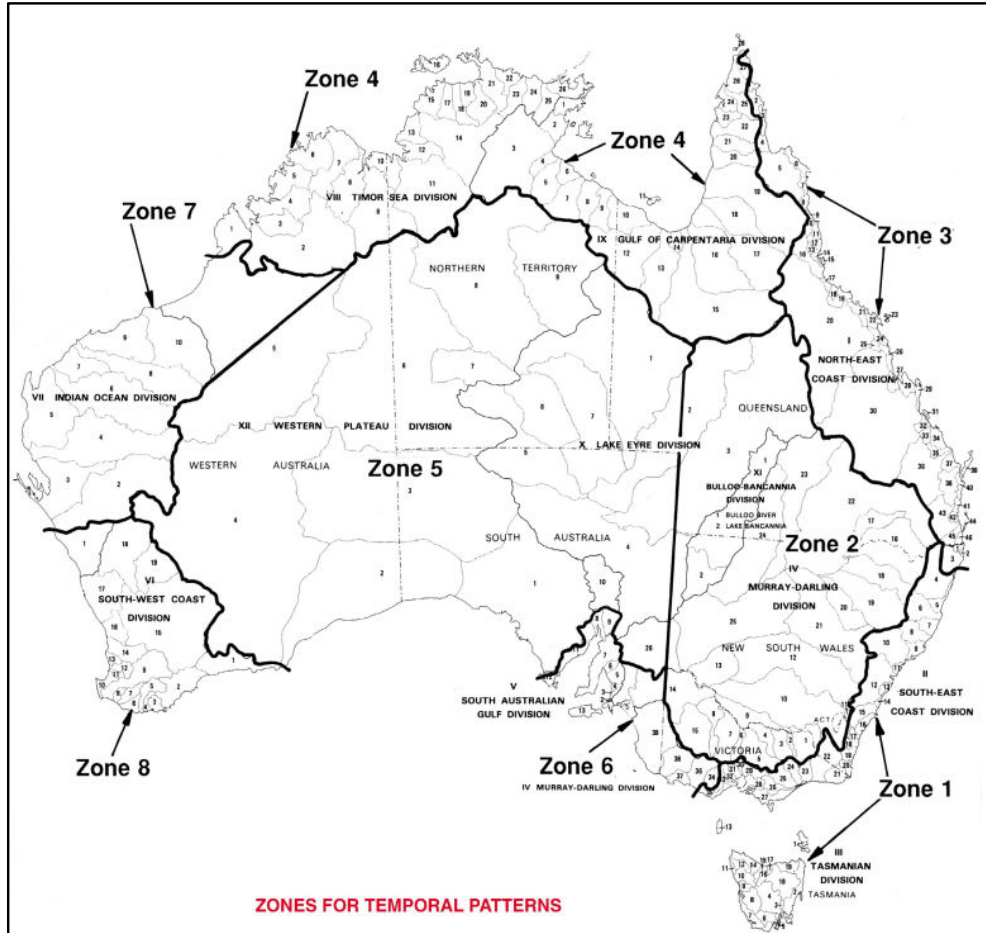
Fig. 4 Eight Zones of Australia for Design Rainfall Temporal Pattern– Source: ARR 1987, BOM
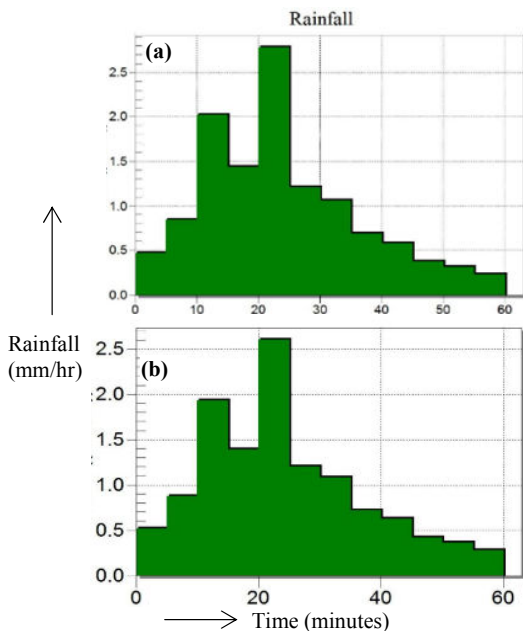

Fig. 5 Design Rainfall Temporal Patterns for Zone 3 for return period
(a) less than 30years; (b) greater than 30years

E. Average Rainfall Intensity

In the study area the nearest rainfall station is Rockhampton Aerodrome, collected from BOM. The rainfall station no. is 039083. The latitude of the station is 23.3753S and the longitude is 150.4775E. Putting the location of this rainfall station at the BOM website (http://www.bom.gov.au/hydro/has/cdirswebx/cdirswebx.shtml), the design rainfall intensity chart is found which is shown in Fig. 6.

The rainfall intensity (mm/hr) of Rockhampton Aero station for various durations and average recurrence interval are found from the intensity frequency duration Table II. The Polynomial coefficients Table for Rockhampton region is presented in Table III. The relation of coefficient with the rainfall intensity is shown as in

$$log_e(I) = A + Bx(log_e(T)) + Cx(log_e(T))^2$$
$$+ Dx(log_e(T))^3 + Ex(log_e(T))^4 \qquad (11)$$
$$+ Fx(log_e(T))^5 + Gx(log_e(T))^6$$

where T= time in hours and I= intensity in mm/hour

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From IFD table (Table II) it is found that the rainfall intensity for 5 year ARI and 1 hour duration is 55.2 mm/h. using the IFD tools of XPSTORM the processed value of rainfall intensity for 5 year ARI and 1 hour duration comes as 55.7 mm/hr which is shown in Fig. 7. Using the values from Tables II and III of BOM, rainfall intensities for different ARI and different rainfall duration can also be found from IFD tools of XPSTORM that is shown in Fig. 7.

Applying the same procedure, the average intensities estimated for 1 hour rainfall duration and 1, 2, 5, 10, 20, 50 and 100 ARI are presented in Table IV.

F. Infiltration/ Rainfall Excess Model

To calculate the infiltration and the storage of runoff in surface depressions, the XPSTORM uses four types of rainfall loss model, i.e. Horton, Green Ampt, Uniform Loss and SCS Curve Number. In this study, Uniform loss model have been used in four approaches of runoff estimation. Only Horton model was used at Laurenson method for better understanding.
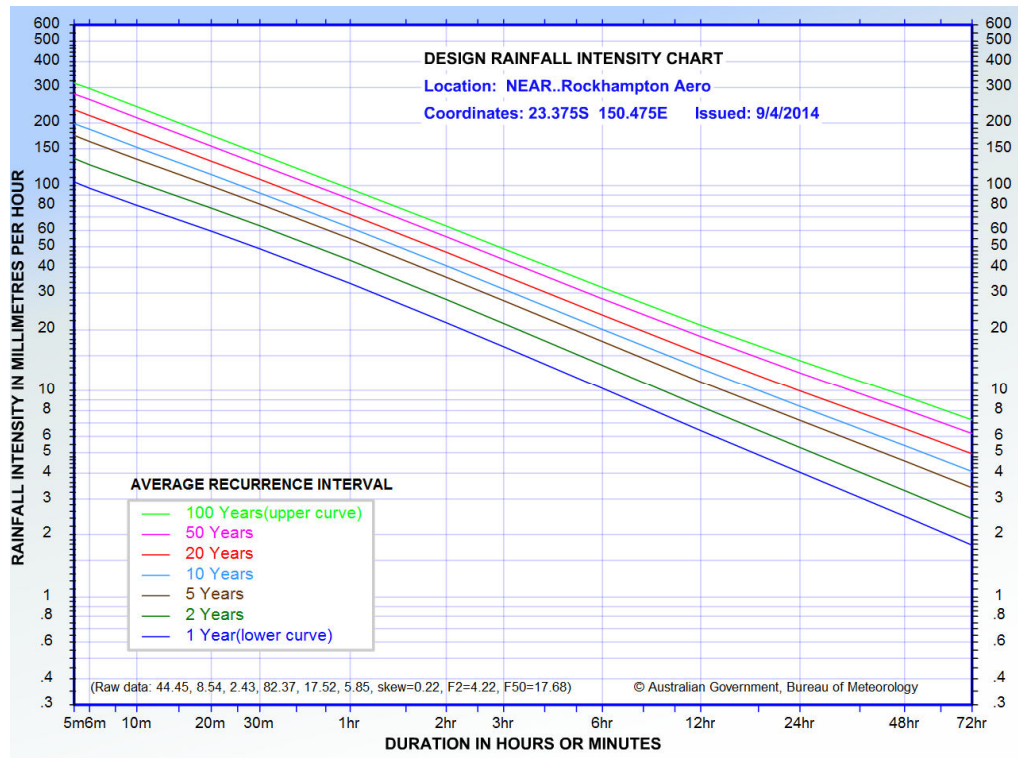

Fig. 6 Design Rainfall Intensity Chart for Different ARI and Duration of the rainfall station: Rockhampton Aero

TABLE II
INTENSITY-FREQUENCY-DURATION TABLE FOR ROCKHAMPTON AERO STATION

Duration	Return Period / ARI						
	1 year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	104	135	175	199	233	278	314
6Mins	96.9	126	163	187	218	261	295
10Mins	80.1	104	134	153	179	213	241
20Mins	60	77.6	99.3	113	131	155	175
30Mins	49.3	63.7	81.2	91.9	107	126	142
1Hr	33.5	43.3	55.2	62.5	72.4	85.8	96.3
2Hrs	21.6	28	35.9	40.8	47.4	56.4	63.5
3Hrs	16.5	21.4	27.6	31.4	36.6	43.7	49.3
6Hrs	10.3	13.4	17.5	20	23.5	28.2	32
12Hrs	6.41	8.39	11.1	12.9	15.2	18.5	21
24Hrs	4.02	5.3	7.19	8.42	10	12.3	14.1
48Hrs	2.46	3.28	4.56	5.43	6.55	8.14	9.44
72Hrs	1.78	2.39	3.38	4.06	4.94	6.19	7.22

TABLE III
POLYNOMIAL COEFFICIENTS TABLE FOR ROCKHAMPTON AERO STATION

| Year	A	B	C	D	E	F	G
1	3.51289	-5.9901059E-01	-5.5568531E-02	9.7454796E-03	2.1168243E-03	-5.6130806E-04	-4.3041270E-06
2	3.76775	-5.9715885E-01	-5.2933276E-02	9.2049837E-03	2.0445287E-03	-4.7874582E-04	-1.5410873E-05
5	4.01066	-5.9249353E-01	-4.5887981E-02	8.1669930E-03	1.7837485E-03	-3.0011070E-04	-3.7102625E-05
10	4.13459	-5.8963519E-01	-4.2022809E-02	7.5173997E-03	1.6455146E-03	-1.9903868E-04	-4.8562852E-05
20	4.28161	-5.8743805E-01	-3.8687054E-02	7.0206486E-03	1.5202044E-03	-1.1672596E-04	-5.8173704E-05
50	4.45151	-5.8440840E-01	-3.5089642E-02	6.2139770E-03	1.4342669E-03	4.8157800E-06	-7.5219315E-05
100	4.56766	-5.8270603E-01	-3.2522045E-02	5.8312542E-03	1.3348988E-03	6.8827040E-05	-8.2439008E-05
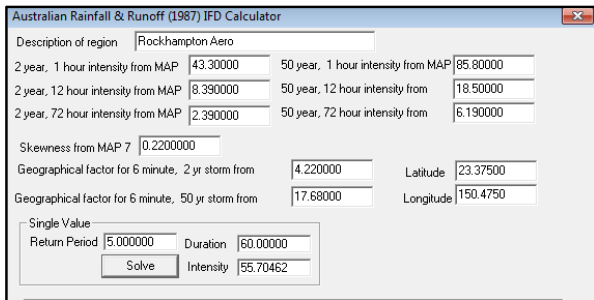
Fig. 7 IFD Tools of XPSTORM for Calculation of Design Rainfall Intensity

TABLE IV
AVERAGE RAINFALL INTENSITY IN MM/HR FOR 1 HOUR DURATION AND DIFFERENT ARI (1 TO 100 YEAR)

Name	Return Period (Years)	Average Intensity (mm/hr)
1Yr-1Hr	1	32.78
2Yr-1Hr	2	42.68
5Yr-1Hr	5	55.7
10Yr-1Hr	10	63.89
20Yr-1Hr	20	74.82
50Yr-1Hr	50	89.8
100Y-1Hr	100	101.71

Horton Model

Horton's infiltration model is the best known of all the infiltration equations. It is a three parameter empirical infiltration model, presented by Horton (1940) [18]. Horton's empirical equation gives infiltration capacity as a function of time as in

$$F_P = F_C + (F_O - F_C)e^{-\alpha t} \qquad (12)$$

where; F_p is infiltration rate into soil (mm/hr), F_c is minimum/asymtopic infiltration rate (mm/hr), F_o is maximum/initial infiltration rate (mm/hr), t is time from beginning of storm (sec), α is decay rate of infiltration (1/sec). This equation describes the familiar exponential decay of infiltration capacity which is shown in Fig. 8.

Different specific values of k are assigned to represent the proportional loss rate, initial and continuing loss rate, initial and proportional loss rate, or methods of infiltration. Horton's equation is only applicable when effective rainfall intensity, i_e is greater than F_c [19]. For continuous simulation the Horton infiltration model is normally used [9].
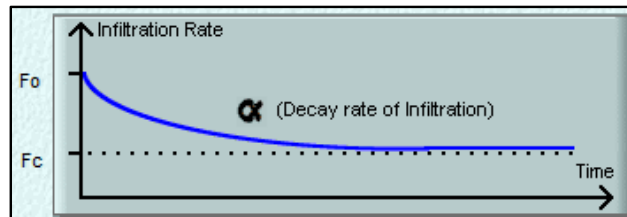

Fig. 8 Exponential Decay of Infiltration Capacity by Horton's Equation

Uniform Loss Model

The initial and continuing loss rate function is described mathematically as in

$$f(t) = I(t) \text{ for } P(t) < IA \qquad (13)$$

$$f(t) = I(t) - C \text{ for } I(t) > C\, P(t) \geq IA \qquad (14)$$

$$f(t) = I(t) \text{ for } I(t) \leq C \qquad (15)$$

where; f(t) is the loss rate; I(t) is the rainfall intensity, t is time; P(t) is the cumulative rainfall volume at time t from the beginning of rainfall; IA is the initial loss and C is the constant loss rate.

For the design storms, uniform loss model is normally used where the initial and continuing loss need to be provided (XPSTORM manual). It is possible to provide a proportional continuous loss, as a fraction of rainfall as well. Applying the catchment loss model, a rainfall excess hydrograph for each subcatchment have been calculated. The initial and continuing loss rate function is shown in Fig. 9.

Loss model has been set up for both the impervious area and pervious area. Infiltration from the pervious area is computed by (13), (14) and (15). Other parameters related to infiltration, required for impervious area are depression storage (mm), manning's roughness (n) and zero detention (%). The initial values of required parameters provided for setting up the loss model are given in Table V.
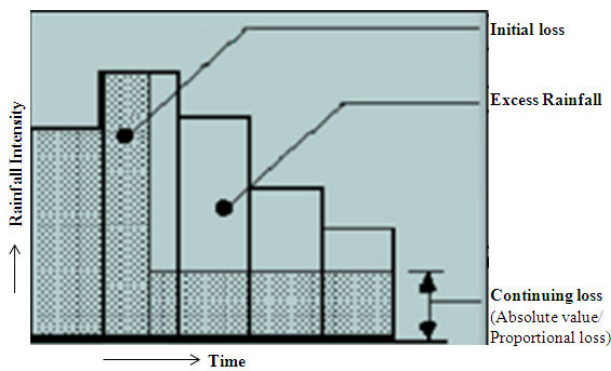
Fig. 9 Initial Loss and Continuing Loss (Source: [16])

TABLE V
THE INITIAL VALUES OF PARAMETERS FOR LOSS MODEL

Parameters	Impervious Area	Pervious Area
Initial Loss (mm)	1	25
Continuing Loss (mm/hr)	0	2.5
Depression Storage (mm)	4	12
Manning's" n"	0.014	0.03
Zero Detention (%)	25	

Note: Laurenson method does not use the value of depression storage for pervious area.

V. RESULTS AND DISCUSSIONS

To explore the comparative performance of the four techniques of runoff routing, all the hydrographs were generated by using XPSTORM models for the design storm of 5year ARI and 1 hour duration. The hydrographs are shown in Fig. 10.

Fig. 10 shows that the highest peak was gained in Laurenson method as well as the runoff ceases comparatively quicker in this method of hydrograph routing. It is apparent that in Laurenson method, initially the hydrograph is flat, but after a little period of time it rises very rapidly and the peak is much higher than other three hydrographs. Two types of infiltration model were used in Laurenson method: Uniform loss method and Horton method. In uniform loss method the maximum flow is 1482.6 m^3/s, whereas in Horton method the maximum flow is 1316.52 m^3/s. On the other hand the shapes of Laurenson hydrograph from two methods of infiltration have some difference. In Uniform loss method the hydrograph raises quite uniformly as the infiltration loss is uniform, while in Horton method a clear jump and down is shown according to the equation of Horton infiltration. The total infiltration generated by Laurenson using uniform loss and Horton method is 46.7mm and 43mm respectively which is a fair agreement. The total runoff in Laurenson for Uniform loss and Horton is 36.8 and 35.1 mm respectively which is a good agreement.

The peak flow generated by SWMM and Time Area methods are respectively 705.9 m^3/s and 754.2 m^3/s which are close. Total surface runoff found from SWMM and Time Area are 46.4 mm and 47.4 mm correspondingly i.e. very close. The lowest peak generated by Kinematic wave is 500.4 m^3/s, though the total surface runoff generated by this method is 48.4 mm which is maximum among all methods. Fig. 10 shows that the more the peak goes high, the quicker the runoff goes out of the catchment, i.e. the time of concentration is less.

For more understanding on runoff hydrographs, a model was simulated using Laurenson hydrology method for 1 hour duration design rainfall and for different ARI of 1, 2, 5, 10, 20, 50 and 100 year and the hydrographs is shown in Fig. 11.

All the models output found from simulation are presented in the Table VI.

TABLE VI
MODEL OUTCOME OF RAINFALL RUNOFF MODEL USING FOUR ROUTING TECHNIQUES

Routing Method	Infiltration Method	Total Rainfall (mm)	Total Surface Runoff (mm)	Max Flow (m^3/s)
SWMM	Uniform Loss	55.7	46.4	705.898
Time Area	Uniform Loss	55.7	47.4	754.237
Kinematic	Uniform Loss	55.7	48.4	500.405
Laurenson	Uniform Loss	55.7	36.8	1482.6
	Horton	55.7	35.1	1316.52

From the model outcome, it is apparent that the total surface runoff generated by the three methods except Laurenson hydrology method are quite close, therefore all of these methods could be used to develop runoff hydrographs of the study area with reasonable accuracy. Though the Laurenson hydrograph technique is widely acceptable surface runoff routing technique of Queensland (Australia), extensive investigation is recommended with detailed topographic and hydrologic detain order to assess its suitability for use in the case study area.

VI. CONCLUSIONS

Using XPSTORM modelling software, four runoff routing techniques (Non-Linear reservoir, Kinematic Wave, Laurenson and Time Area method) were applied to generate the runoff hydrographs of a subcatchment of Rockhampton, Queensland. The hydrographs were produced for design rainfall (5 year ARI and one hour duration). A comparison was done among the four methods which found that the total runoff produced by Non-Linear reservoir, Kinematic and Time Area methods are reasonably close. Therefore any of these methods can be used for developing hydrograph for study area. The Laurenson produces comparatively less amount of runoff. However, Laurenson produces noticeable high peak than other three methods which may be suitable for hilly area. For all the four simulation, Uniform Loss model was used for the calculation of infiltration. Only, for Laurenson method, both Horton and uniform loss model were used for the calculation of infiltration to ensure the calculation is right. It is to be noted that both Horton and uniform loss model produces close results for Laurenson method. However, further study is recommended with detailed hydrologic data of the case study area for using Laurenson method as only this method produces different results than others.
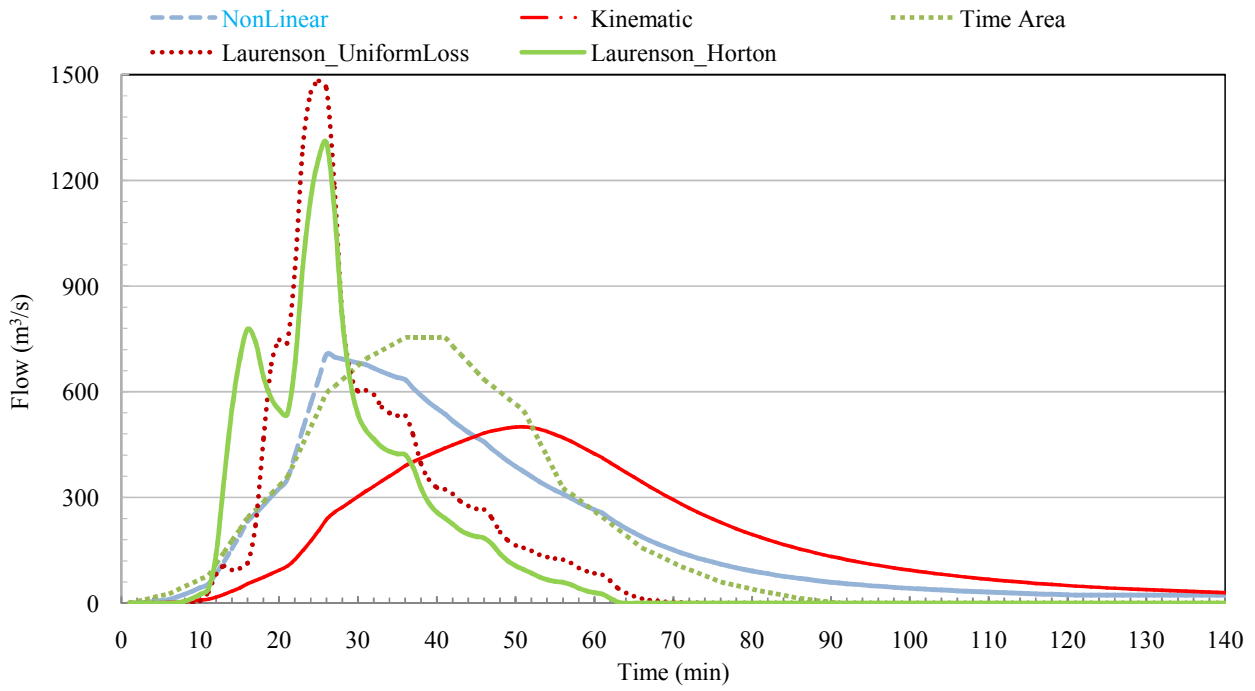
Fig. 10 Runoff Hydrographs generated by four different routing techniques of XPSTORM for the Design Storm of 5Year-1Hour
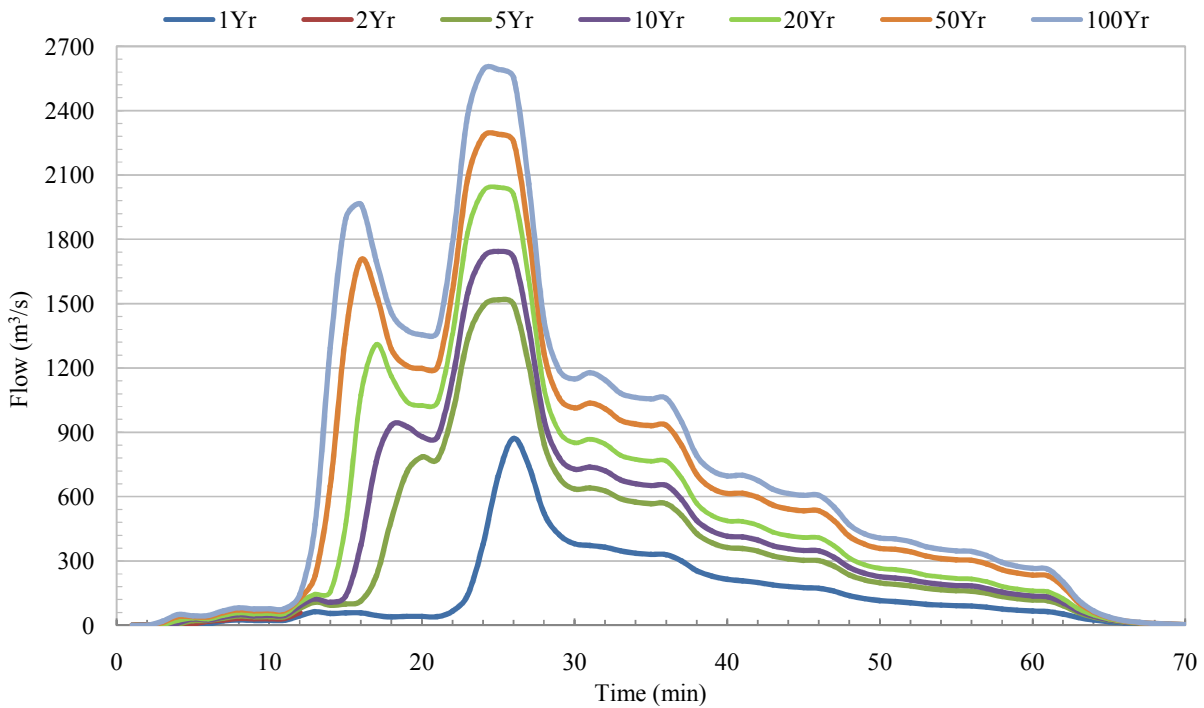

Fig.11 Runoff Hydrographs by Laurenson method for the different ARI and 1Hour rainfall duration

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