URBAN FLOODING: HEC-HMS

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1.0 Introduction

All major ancient civilisations were developed in the river valleys because river served as source of water, food, transportation and protection to the mankind. On contrary, nowadays even a small, slow-flowing stream or gentle river could cause severe damage to the people and their businesses by flooding. With the changing patterns of rainfall and global climate, floods are matter of greater concern now as it has enhanced damage potentials. Not only river plains are vulnerable to riverine or fluvial flooding but also places far away from the river are prone to surface water flooding due to heavy rainfall. Hydrological processes are extremely complex phenomena so as its accurate understanding & its quantification. However, with the advent of many hydroinformatics tools & technology, a fairly accurate rainfall-runoff analysis of a catchment is possible nowadays. Despite rapid advancement in computer processing technology, 2-dimensional flood flow simulation is not in practice on large scale catchment because of its massive computational requirements. Especially long computational time is the greatest limitation and therefore, 2-D models cannot be effectively utilised for the flood forecasting and other purposes where information is desired to be conveyed in much advance to reduce the impact of the flooding event. Considering this inherent fact of 2D modelling, a comparatively smaller zone is taken for 2D flow simulation. Therefore, 2D models are incapacitated for rainfall-runoff analysis or flood flow simulation of entire catchment and software like HEC-HMS is quite useful for this purpose. Rainfall-runoff analysis & flow-simulation of an urban catchment remains a challenge as it consists of building, roads, footpath, fences, hedges etc which affects the flow substantially. There is an urgent need to adopt a holistic modeling approach to address urban flooding problems.

2.0 Integrated Urban Water Modeling

A holistic modeling approach is essentially needed to be followed which includes rainfall-runoff model of upstream catchment, hydraulic model of the river & drainage network of the urban catchment and a coupled 2-D flow simulation model for flood analysis (Fig.1). The output of rainfall-runoff analysis of the upstream catchment serves as the input for the hydraulic model. Further, the drainage/sewage component also constitutes as the part of urban hydraulic model. In case of riverine or pluvial flooding, the water overflows out of river or drainage system is represented by the 2-dimensional flow simulation.

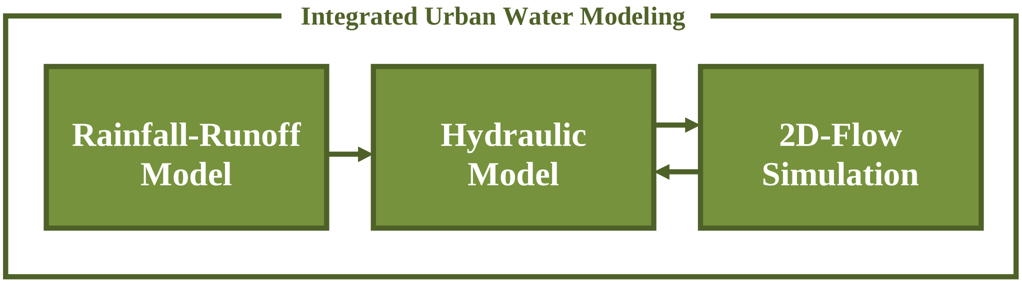

Fig 1: Schematic Diagram

The two arrows (incoming & outgoing, in Fig.1) between hydraulic and 2-D models signifies the flood wave in the flood plain and receding flood wave respectively. At the time of flooding water break the bank of river or urban drainage is insufficient to intake storm water. When flood recedes the water from flood plain drains back to river or drainage system.

3.0 Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS)

The Hydrologic Engineering Center (HEC) is the appex Center of Expertise for the US Army Corps of Engineers and works under the Institute for Water Resources. Its working domain include surface and groundwater hydrology, river hydraulics and sediment transport, hydrologic statistics and risk analysis, reservoir system analysis, planning analysis, real-time water control management and a number of other closely associated technical subjects. HEC-HMS is designed to simulate the rainfall-runoff processes of watershed systems. It is designed to be applicable in a wide range of geographic areas for solving a broad range of problems. This includes large river basin water supply and flood hydrology to small urban or natural watershed runoff. Hydrographs produced by the program can be used directly or in conjunction with other software for studies of water availability, urban drainage, flow forecasting, future urbanization impact, reservoir spillway design, flood damage reduction, floodplain regulation, wetlands hydrology, and systems operation.

3.1 Runoff Processes in HEC-HMS

The hydrological processes incorporated for Rainfall-Runoff analysis in HEC-HMS is shown below:

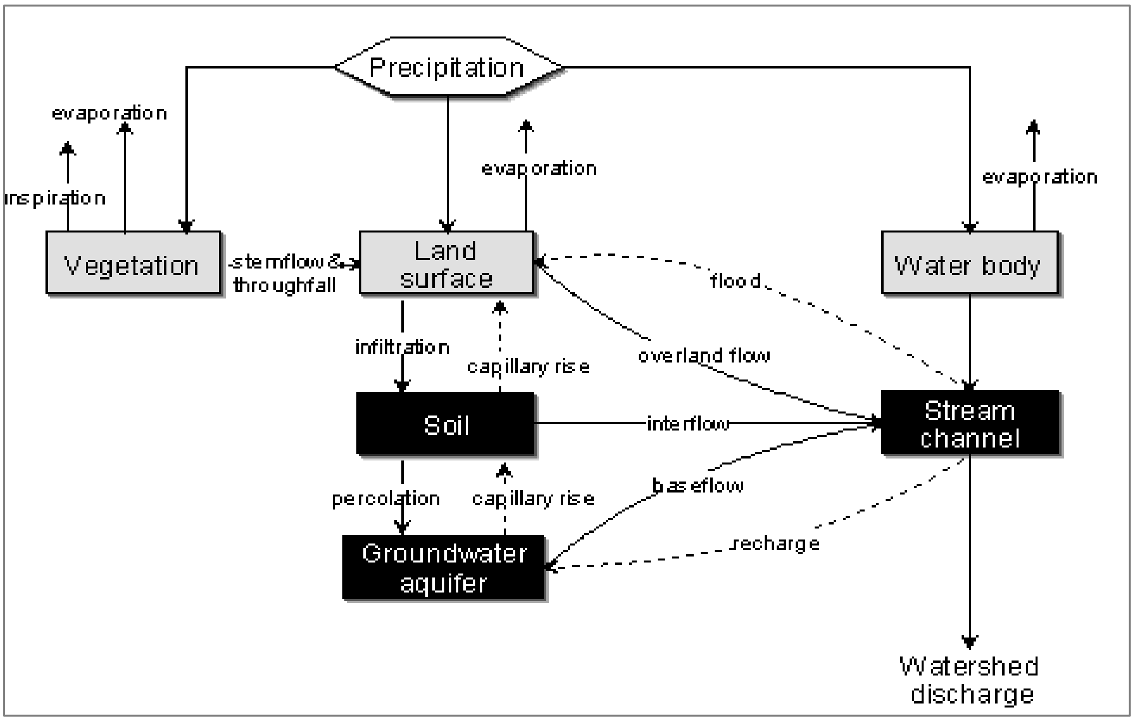

Fig 2: Natural Hydrologic Process

In the hydrological system, runoff depends on many factors such as soil type, ground cover, antecedent moisture, infiltration, evaporation from vegetation and other watershed properties. This infiltrated water is stored temporarily in the upper, partially saturated layers of soil. From there, it rises to the surface again by capillary action, moves horizontally as interflow just beneath the surface, or it percolates vertically to the groundwater aquifer beneath the watershed. The interflow eventually moves into the stream channel. Water in the aquifer moves slowly, but eventually, some returns to the channels as baseflow. Water that does not pond or infiltrate moves by overland flow to a stream channel. The stream channel is the combination point for the overland flow, the precipitation that falls directly on water bodies in the watershed, and the interflow and baseflow. Thus, resultant streamflow is the total watershed outflow.

3.2 Constituents of HEC-HMS

3.2.1 State Variables

These terms in the model's equations represent the state of the hydrologic system at a particular time and location. For example, the deficit and constant-rate loss model that is described in next section tracks the mean volume of water in natural storage in the watershed. This volume is represented by a state variable in the deficit and constant-rate loss model's equations. Likewise, in the detention model, the pond storage at any time is a state variable; the variable describes the state of the engineered storage system.

3.2.2 Parameters

These are numerical measures of the properties of the real-world system. They control the relationship of the system input to system output. Parameters are generally used as turning knobs of a model. The parameters are adjusted to accurately match the real life physical process. For example, the Snyder unit hydrograph model has two parameters, the basin lag, *tp*, and peaking coefficient, *Cp*. The values of these parameters can be adjusted to "fit" the model to a particular physical system. Different methods have different parameters used to calibrate the outcome of model vis-à-vis a measured data.

3.2.3 Boundary Conditions

Boundary conditions are the input/output of a model and these are the forces that act on the hydrologic system and cause it to change. The most common boundary condition in the HEC-HMS program is precipitation; applying this boundary condition causes runoff from a watershed. Another example is the upstream (inflow) flow hydrograph to a channel reach; this is the boundary condition for a routing model.

3.2.4 Initial Conditions

Initial conditions are the set of information describe the state before running a particular model. It affects significantly the initial time period of simulation but eventually its impact is comparatively less in the later time period of simulation.

3.3 Fundamentals of HEC-HMS Modeling

The program underneath HEC-HMS considers that all land and water in a watershed can be categorized as either:

- Directly-connected impervious surface
- Pervious surface

Directly-connected impervious surface in a watershed is that portion of the watershed for which all rainfall converted to runoff with no infiltration, evaporation, or other hydrological losses. Precipitation on the pervious surfaces is subject to losses. The following alternative models are included to account for the cumulative losses:

- The initial and constant-rate loss model
- The deficit and constant-rate model
- The SCS curve number (CN) loss model
- The Green and Ampt loss model

With each model, precipitation loss is found for each computation time interval, and is subtracted from the Mean Areal Precipitation (MAP) depth for that interval. The remaining depth is referred to as precipitation excess. This depth is considered uniformly distributed over a watershed area, so it represents a volume of runoff.

3.3.1 Initial and constant-rate loss model

The underlying concept of the initial and constant-rate loss model is that the maximum potential rate of precipitation loss, f_c, is constant throughout an event. Thus, if p_t is the MAP depth during a time interval t to $t+\Delta t$, the excess, pe_t, during the interval is given by:

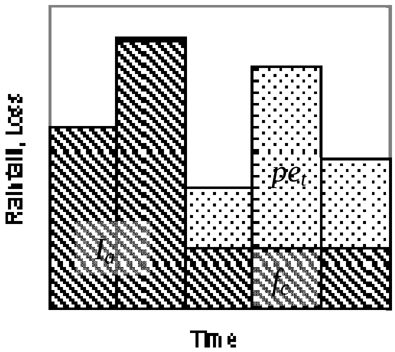

Fig 3: Initial & Constant rate loss

$$pe_t = \begin{Bmatrix} p_t - f_c & \text{if } p_t > f_c \\ 0 & \text{otherwise} \end{Bmatrix} \quad (1)$$

An initial loss, I_a, is added to the model to represent interception and depression storage. Interception storage is a consequence of absorption of precipitation by surface cover, including plants in the watershed. Depression storage is a consequence of depressions in the watershed topography; water is stored in these and eventually infiltrates or evaporates. This loss occurs prior to the onset of runoff. Until the accumulated precipitation on the pervious area exceeds the initial loss volume, no runoff occurs. Thus, the excess is given by:

$$pe_t = \begin{cases} 0 & \text{if } \sum p_i < I_a \\ p_t - f_c & \text{if } \sum p_i > I_a \text{ and } p_t > f_c \\ 0 & \text{if } \sum p_i > I_a \text{ and } p_t < f_c \end{cases} \qquad (2)$$

The initial losses are computed in HEC-HMS as per following table:

Table 1: SCS soil groups and infiltration (loss) rates (SCS, 1986; Skaggs and Khaleel, 1982)

Soil Group	Description	Range of Loss Rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.30-0.45
B	Shallow loess, sandy loam	0.15-0.30
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.05-0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00-0.05

3.3.2 The deficit and constant-rate model

The HEC-HMS program also includes a quasi-continuous variation on the initial and constant model of precipitation losses; this is known as the deficit and constant loss model. This model is different from the initial and constant loss model as the initial loss can "recover" after a prolonged period of no rainfall. This model is similar to the loss model included in computer program HEC-IFH (HEC, 1992). To use this model, the initial loss and constant rate plus the recovery rate must be specified. The moisture deficit is tracked continuously, computed as the initial abstraction volume less precipitation volume plus recovery volume during precipitation-free periods. The recovery rate could be estimated as the sum of the evaporation rate and percolation rate, or some fraction thereof.

3.3.3 SCS curve number (CN) loss model

The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \qquad (3)$$

where P_e = accumulated precipitation excess at time t; P = accumulated rainfall depth at time t; I_a = the initial abstraction (initial loss); and S = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Runoff is zero until the accumulated rainfall exceeds the initial abstraction.

Through analysis of results from many small experimental watersheds, the SCS developed an empirical relationship of I_a and S:

$$I_a = 0.2\,S \qquad (4)$$

Therefore, the cumulative excess at time t is:

$$P_e = \frac{(P - 0.2\,S)^2}{P + 0.8\,S} \qquad (5)$$

Incremental excess for a time interval is computed as the difference between the accumulated excess at the end and the beginning of the period. The maximum retention, S, and watershed characteristics are related through an intermediate parameter, the curve number (commonly abbreviated *CN*) as:

$$S = \begin{cases} \dfrac{1000 - 10\,CN}{CN} & \text{(foot} - \text{pound system)} \\ \dfrac{25400 - 254\,CN}{CN} & \text{(SI)} \end{cases} \qquad (6)$$

CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates. A table (called TR-55) is developed by SCS for obtaining CN according to the soil type, land use etc.

3.3.4 Green and Ampt loss model

The Green and Ampt infiltration model included in the program is a conceptual model of infiltration of precipitation in a watershed. The model computes the precipitation loss on the pervious area in a time interval as:

$$f_t = K\left[\frac{1 + (\phi - \theta_i)S_f}{F_t}\right] \qquad \textbf{(7)}$$

Where f_t = loss during period t; K = saturated hydraulic conductivity; $(\phi - \theta_i)$ = volume moisture deficit; S_f = wetting front suction; and F_t = cumulative loss at time t. Same as other models, the Green and Ampt model also includes an initial abstraction and computed in same manner.

3.4 HEC-HMS: Direct Runoff

HEC-HMS simulates the process of direct runoff of excess precipitation on a watershed using following two methods:

3.4.1 Empirical models (also referred to as system theoretic models)

These are the traditional unit hydrograph (UH) models. The system theoretic models attempt to establish a causal linkage between runoff and excess precipitation without detailed consideration of the internal processes. The equations and the parameters of the model have limited physical significance. Instead, they are selected through optimization of some goodness-of-fit criterion.

3.4.2 Conceptual model

The conceptual model included in the program is a kinematic-wave model of overland flow. It represents, to the extent possible, all physical mechanisms that govern the movement of the excess precipitation over the watershed land surface and in small collector channels in the watershed.

3.5 HEC-HMS: Modeling Channel flow, Routing

HEC-HMS routing models are based on the fundamental equations of open channel flow: continuity and momentum equation. Together the two equations are known as the St. Venant equations or the dynamic wave equations.

The continuity equation accounts for the volume of water in a reach of an open channel, including that flowing into the reach, that flowing out of the reach, and that stored in the reach. In one-dimension, the equation is:

$$A\frac{\partial V}{\partial x} + VB\frac{\partial y}{\partial x} + B\frac{\partial y}{\partial t} = q \qquad \textbf{(8)}$$

where B = water surface width; and q = lateral inflow per unit length of channel. Each of the terms in this equation describes inflow to, outflow from, or storage in a reach of channel, a lake or pond, or a reservoir. Henderson (1966) described the terms as $A(\partial V/\partial x)$ = prism storage; $VB(\partial y/\partial x)$ = wedge storage; and $B(\partial y/\partial t)$ = rate of rise.

The momentum equation accounts for forces that act on a body of water in an open channel. In simple terms, it equates the sum of gravitational force, pressure force, and friction force to the product of fluid mass and acceleration. In one dimension, the equation is written as:

$$S_f = S_0 - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \qquad \textbf{(9)}$$

where S_f = energy gradient (also known as the friction slope); S_0 = bottom slope; V = velocity; y = hydraulic depth; x = distance along the flow path; t = time; g = acceleration due to gravity; $\partial y/\partial x$ = pressure gradient; $(V/g)(\partial V/\partial x)$ = convective acceleration; and $(1/g)(\partial V/\partial t)$ = local acceleration.

- The momentum and continuity equations are derived from basic principles, assuming:
- Velocity is constant, and the water surface is horizontal across any channel section.

- All flow is gradually varied, with hydrostatic pressure prevailing at all points in the flow. Thus vertical accelerations can be neglected.
- No lateral, secondary circulation occurs.
- Channel boundaries are fixed; erosion and deposition do not alter the shape of a channel cross section.

Water is of uniform density, and resistance to flow can be described by empirical formulas, such as Manning's and Chezy's equation. The channel flow or routing models available in HEC-HMS include:

- Lag
- Muskingum
- Modified Puls
- Kinematic-wave, etc.

Each of these models computes a downstream hydrograph, given an upstream hydrograph as a boundary condition. This is obtained by solving the continuity and momentum equations.

3.5.1 Lag Model

This is the simplest of the included routing models. With it, the outflow hydrograph is simply the inflow hydrograph, but with all ordinates translated (lagged in time) by a specified duration. The flows are not attenuated, so the shape is not changed. This model is widely used, especially in urban drainage channels (Pilgrim and Cordery, 1993).

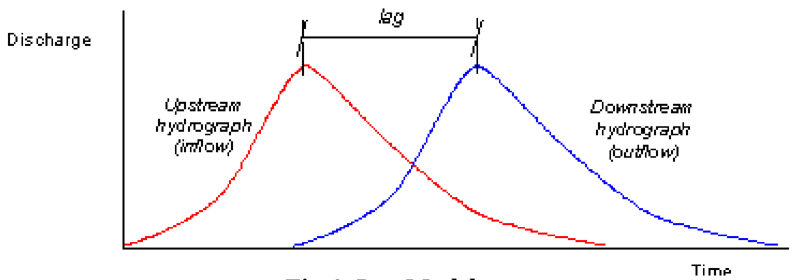

Fig 4: Lag Model

3.5.2 Muskingum Model

Storage in the channel-reach is modeled as the sum of prism storage and wedge storage. As shown in Fig.5, prism storage is the volume defined by a steady-flow water surface profile, while wedge storage is the additional volume under the profile of the flood wave. During rising stages of the flood, wedge storage is positive and is added to the prism storage. During the falling stages of a flood, the wedge storage is negative and is subtracted from the prism storage.

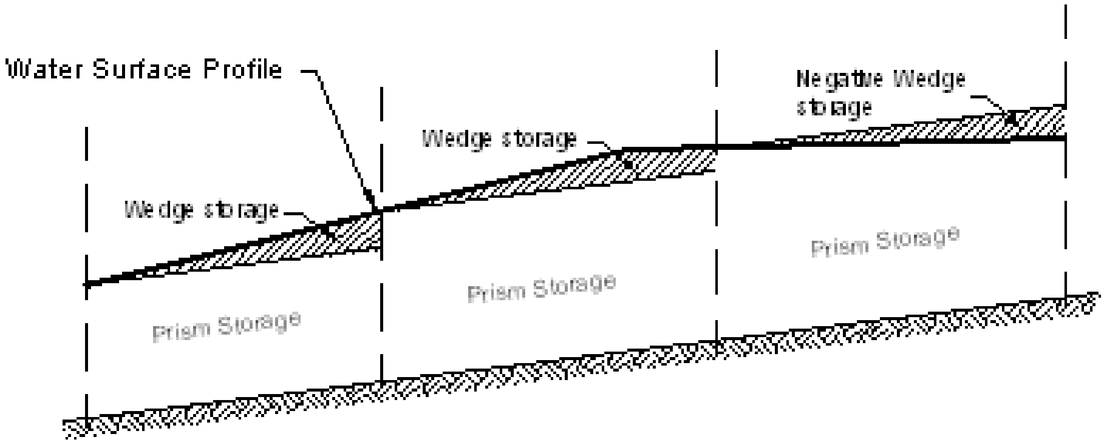

Fig 5: Muskingum Model

3.5.3 Modified Puls Model

The Modified Puls routing method, also known as storage routing or level-pool routing, is based upon a finite difference approximation of the continuity equation, coupled with an empirical representation of the momentum equation (Chow, 1964; Henderson, 1966). For the Modified Puls model, the continuity equation is written as

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

This simplification assumes that the lateral inflow is insignificant, and it allows width to change with respect to location. Rearranging this equation and incorporating a finite-difference approximation for the partial derivatives yields:

$$\overline{I_t} - \overline{O_t} = \frac{\Delta S_t}{\Delta t}$$

Where, I_t= average upstream flow (inflow to reach) during a period Δt; O_t= average downstream flow (outflow from reach) during the same period; and ΔS_t = change in storage in the reach during the period.

3.5.4 Kinematic Wave Model

Kinematic wave routing, the watershed and its channels are conceptualized as shown in Fig.6 below. This represents the watershed as two plane surfaces over which water runs until it reaches the channel. The water then flows down the channel to further downstream. At a cross section, the system would resemble an open book, with the water running parallel to the text on the page (down the shaded planes) and then into the channel that follows the book's center binding.

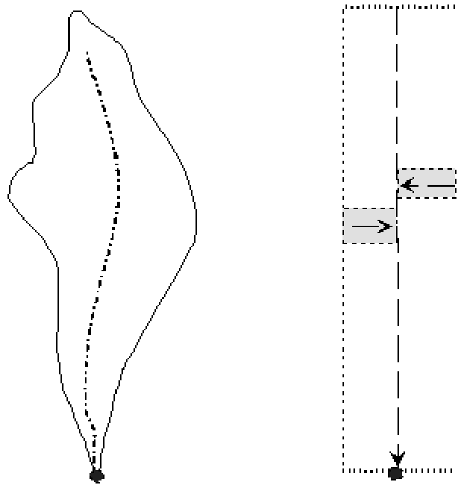

Fig 6: Muskingum Model

4.0 Conclusion

Rainfall- runoff analysis is a key component of urban flood analysis and HEC-HMS is an effective software tool for this purpose. However, accuracy will be definitely improved once 2-D models are employed for the same purpose. It'll also indicate fairly accurate pour-points of the runoff generated over the catchment. But huge computational requirement and availability fine grid-size GIS data remains a challenge for application 2-D modeling for rainfall-runoff analysis.