HYDROLOGIC MODELING SYSTEM (HEC-HMS): NEW FEATURES FOR URBAN HYDROLOGY

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Abstract Many cities have been built along large rivers. The rivers can provide a source of drinking water, act as receiving water for treated effluent, provide navigation for shipping, and other beneficial uses. However, the city must also be protected from flooding due to the close proximity to the river. Hydrologic analysis plays a crucial role in the development of plans for protecting a river city. Typical components of such an analysis include simulation of holding ponds and pump stations adjacent to river levees. Finally, heterogeneous soil conditions may require the use of distributed infiltration calculations.

INTRODUCTION

The Hydrologic Modeling System (HEC-HMS) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff. Hydrographs produced by the program are 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, and systems operation. The focus of this paper is the new or improved capabilities for representing hydrologic processes in urban environments.

RESERVOIR CULVERTS AND PUMPS

Storage Indication Routing The reservoir element included in the program can be used to represent natural lakes. A storage-discharge relationship is developed by the user that represents the outflow of the lake as a function of storage. An elevation curve may also be added to track outflow as a function of lake water surface elevation. The storage curve may itself be represented as an elevation-area curve with the conic formula used to compute storage. A level pool is assumed and the routing of inflow through the lake is simulated using the storage indication method. This method is also known as modified Puls routing (Chow, 1964). It is an excellent routing method for lakes, and possibly reservoirs or other types of water bodies, where changes in storage vary gradually and outlet control structures are not present. It may be possible to use storage-indication routing with outlet structures that have one and only one discharge for a given water surface elevation.

Mass Conservation Routing Urban areas are frequently protected in part by flood protection reservoirs. Such reservoirs provide storage for excessive inflow and release it at a later time, thus reducing the peak flow to a level that is safe. These reservoirs typically have one or more structures such as weirs or low-level outlets. Often these structures have gates that vary the amount of water exiting through each structure. The presence and movement of gates creates a complex hydraulic situation where many different reservoir outflows may occur for a given water surface elevation behind the dam. It is only possible to compute the outflow for a given water surface if the setting of the gates is known. Thus it is not possible to build a single storage-discharge curve and therefore storage-indication routing cannot be used.

In cases where outlet structures will be used to define the outflow characteristics of the reservoir, the program uses a direct solution of the conservation of mass equation. The equation as implemented in the program is given as:

$$\frac{dS(wse)}{dt} - I(t) + \sum_{n} O(wse,t) = 0$$

The equation states that the change in storage at some time $t=\tau$, minus the inflow at that same time τ, plus the sum of outflow through the n outlet structures at that same time τ, is equal to zero. The state variable for the equation is storage and it is a function of water surface elevation in the reservoir. Outflow through each outlet structure is also a function of water surface elevation and possibly other variables. The boundary condition is the combined inflow.

Solving the equation for each time step is a root finding problem, further there is only one root. It might be argued that without a formal proof, the existence of a single root cannot be guaranteed. However, qualitatively examining the reservoir system we see that for a given water surface elevation, there can be only one outflow. The presence of gates may lead to different outflow for the same water surface elevation. However, gate settings are required as part of the descriptive characteristics of the reservoir. While the flow through a structure may be subcritical or supercritical, which would result in different outflow, the flow cannot be both subcritical and supercritical simultaneously. Likewise, the depth of any tailwater submergence on outlet structures could lead to different outflows. However, since the calculation of outflow through each outlet structure considers the presence of tailwater, again there can be only one outflow and thus one root.

The root finding problem is solved for each time interval of the simulation using Brent's method (Press et al., 1988). It combines root bracketing, bisection, and inverse quadratic interpolation to converge on the root. It is well suited to reservoir problems because it can handle such discontinuities as pump cycling and gate movement. Finally, it does not depend on computing derivatives of the equation which actually change from one iteration to the next as changes in the water surface elevation cause individual outlets to change their properties. To date excellent results have been achieved using this solution technique.

Tailwater Submergence of Structures Calculation of tailwater submergence is a critical component of reservoir modeling. All of the different weir, overflow, culvert and other structure types include the calculation of unrestricted flow and reduced flow due to tailwater submergence. We have recently added to the program four different options for computing the tailwater depth used in submergence calculations. The first option is to ignore possible tailwater submergence. It is rare that a reservoir truly has no submergence restrictions. The second option is to consider only the reservoir outflow and combine it with a rating curve. For every iteration, the outflow is computed first and then the tailwater stage is computed from the rating curve. The tailwater depth is used to compute a reduced outflow based on submergence criteria for each outlet structure. This information is used to guide the iteration process until a final outflow is computed for each time interval. This second option is best used for reservoirs that completely span a stream, such as run-of-the-river reservoirs. The third option for computing tailwater depth is to consider the outflow of the reservoir, plus outflow at other locations, plus a rating curve. This option is typically used in so-called interior flood systems. In such systems the drainage from an urban area collects in a pond against a line of protection such as a levee or floodwall. When the stage in the main river is low, the water in the collection pond may move through a culvert and into the river solely under the affects of gravity. However, at high river stage, the ponded water must be pumped over the levee and into the river. This third option works well when the water discharged from the interior pond into the river may significantly affect the stage in the river. The fourth and final option for computing tailwater depth is a specified time-series of stage. This is again helpful for an interior pond situation where the discharge from the pond will not significantly affect stage in the river.

Existing and Expanded Capability Previous versions of the program allowed up to one low-level outlet. The outlet was modeled using orifice flow assumptions. Also, up to one spillway was allowed and the program user could choose from broad-crested or ogee options. Up to one uncontrolled overflow could be included. Options were provided for a single broad-crested weir, or a segmented weir defined by an eight-point cross section. Finally, there was an option to include an overtopping dam failure.

A new version now available expands the number of outlet structures and adds new modeling options. It is now possible to have up to 10 outlets. Each outlet is parameterized separately and may use either orifice assumptions, or culvert with inlet or outlet control. Up to 10 spillways may be included with the same broad-crested or ogee options. Also up to 10 uncontrolled overflows can be included with the same single or segmented representations. A new pump outlet structure has been added and up to 10 may be included. Finally, while there can still be only one dam failure; it may specify an overtopping or piping failure mode.

New Culvert Capability The new culvert capability greatly expands the usefulness of the low-level outlet. The sole previous option of orifice was limited to situations where the intake opening remained sufficiently submerged at all times. The new culvert outlet is not similarly limited. It fully accounts for inlet or outlet control conditions, automatically determining which prevails at each time interval or allowing the user to force it. It includes nine different cross section shapes with the corresponding FHWA chart and scale selections (FHWA, 1985). Further, it allows the possibility that the Manning's roughness coefficient is different for the bottom as opposed to the sides and top of the culvert barrel. Finally, it allows for the possibility that the culvert is partially buried and consequently has a reduced flow area.

New Pump Capability The new pump capability is implemented as a simple head-discharge pump. The principal parameters describing the installation of the pump are the intake elevation, discharge elevation, on elevation, and off elevation. The on elevation is the water surface elevation in the reservoir pool where the pump should turn on. The off elevation is likewise the elevation where then pump should turn off. The off elevation must be below the on elevation, thus the pump is being used to empty the reservoir. The description of the pump includes a static equipment loss and a head-discharge curve. For each time interval, the discharge of the pump depends on the current water surface elevation in the reservoir and the tailwater stage.

AUTOMATED DEPTH-AREA REDUCTION

One of the most common applications in practical hydrology is the use of frequency-based hypothetical storms. A storm is developed for a specific exceedance probability based on historical data. The storm is applied to a hydrology model and the computed peak outflow is assumed to have the same exceedance probability as the precipitation (Pilgrim and Cordery, 1975). Preparation of the storm usually includes consideration of the storm area and inclusion of a depth-area reduction relationship. The relationship is based on empirical data showing that average storm intensity decreases as storm area increases (Miller, et al., 1973).

Depth-Area Analysis Tool A new tool has been added to the program to assist with calculating peak flows as the result of frequency-based precipitation. Typical studies of large urban watersheds require evaluation of flow at multiple points within the watershed. These points may be damage centers or the location of proposed projects such as reservoirs or levees. Drainage area will be different at each on these selected locations. In order to correctly perform the frequency analysis, a separate storm with appropriate depth-area reduction must be developed for each analysis point. This can become tedious for many points and is subject to user error. The new tool allows the user to enter point-valued precipitation data, followed by the selection of analysis points. The analysis tool automatically develops appropriate storms for each point using the drainage area at the point, and computes the correct peak flow.

DISTRIBUTED INFILTRATION

The urban environment is typically very heterogeneous with respect to soil properties and surface land use. Soil properties naturally vary at the watershed scale, depending on the source of the parent material and spatial variations in weathering processes. These variations can result in substantial differences in key properties such as water holding capacity and hydraulic conductivity. Land use is also highly variable in the urban environment. A central business district may consist almost entirely of impervious area while residential areas contain yards and gardens. The urban fringe may contain significant open spaces permanently reserved or in transition to other uses.

Deficit Constant Loss Method The deficit constant loss method is designed as a simple, one-layer model for continuous soil moisture simulation. The soil is assumed to have a fixed water holding capacity, typically based on the active rooting depth of vegetation. It is also assumed to have a fixed infiltration rate, typically approximated by the saturated hydraulic conductivity. Simplifying assumptions are made regarding soil dynamics so that infiltration only occurs when the soil is saturated. Water is removed from the soil to simulate evapotranspiration. Potential evapotranspiration is computed by any of the methods available in the program. Again, by simplifying assumption, the full potential amount is removed from the soil without accounting for reductions due to increasing tension at low water contents. A percentage of directly-connected impervious area is included to assist in modeling urban watersheds.

Extension to Distributed Method A key parameter in many urban areas is the percentage of impervious area. The percentage is often highly correlated with surface land use. The heterogeneous nature of land use makes it highly desirable to vary the impervious area percentage and other parameters across the watershed. The gridded deficit constant loss method was developed and added to the program. It uses parameter grids instead of specifying several single-value parameters. The grids describe spatially how each of the parameters varies across the watershed. The parameters are the same as in the non-distributed case: water holding capacity, infiltration rate, and percentage impervious area. A grid is overlaid on the watershed to develop grid cells. The model parameters for each cell are obtained from the various parameter grids. Boundary conditions in the form of gridded precipitation and gridded potential evapotranspiration are applied to each grid cell. Each cell evolves a soil moisture state and computes excess surface runoff separate from its surrounding neighbor cells.

Parameter Grid Development GIS tools have been developed to quickly prepare parameter grids. The user may quickly specify a certain area as having a specified land use category. Using predefined information, the GIS develops parameter grids for the program to consume. The parameter grids are integrated into the simulation process to produce flow results for the hypothesized land use scenario. This process is expected to assist significantly in the urban planning process.

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