APPENDIX E: Hydrologic/Hydraulic Models

City of Minnetonka Water Resources Management Plan

Appendix E: Hydrologic/Hydraulic Models

This appendix describes the computer programs and methods of analysis used to model the rainfall runoff process and route runoff through the storm drainage system for determining flood elevations and rates of flow. This appendix focuses on the two hydrologic models used for the city-wide modeling completed during the development of the previous WRMP as well as the models used to evaluate the changes resulting from development and redevelopment. The Barr Watershed Model (BWM), a detailed hydrologic model and the volume routing method were used for the original city-wide modeling. The BWM along with other hydrologic models, such as XP-SWMM and HydroCAD, were used to evaluate proposed developments and redevelopments within the City of Minnetonka.

Hydraulic evaluations of pipes, drainage swales and other structures were performed using standard engineering procedures and are not discussed in this appendix. Previous hydraulic evaluations of major streams (e.g., Flood Insurance Study of Minnehaha Creek and flood profile information along Purgatory Creek) are adopted by this WRMP and were not restudied during its development.

The remainder of this appendix describes the BWM, the volume routing method, the XP-SWMM model and the HydroCAD model.

Barr Watershed Model (BWM)

In some situations where feasibility and design studies were performed, a detailed hydrologic computer model (Barr Watershed Model (BWM)) was used. The BWM was developed at Barr Engineering Co. It was first developed in the late 1950s as a hand method and was modified and computerized through its use in urban watershed management for several decades. Barr used the BWM through about 2000 for developing municipal stormwater management plans and for design projects.

The BWM works with each part of the rainfall-runoff process to arrive at a solution. The procedures focus on simulating the storage effects occurring throughout the runoff process. The model develops a hydrograph for each subwatershed in a drainage basin. When creating these hydrographs, the model uses four basic components:

1. The hyetograph (rainfall versus time relationship)
2. The abstractions from the hyetograph (interception, infiltration and depression losses)
3. Overland flow routing
4. Routing to account for flow through swales, ditches, street gutters and storm sewers to the watershed outlet

The BWM allows input of up to ten separate storms or snowmelt/runoff distributions for each run of the model. This feature allows for comparisons of results between each storm and is especially useful when determining the "critical" storm duration for individual ponds and subwatersheds. The following describes the BWM in detail.

Rainfall Distribution and Duration

The first step in the model is to determine the characteristics of the design storm. This requires determining both the amount of precipitation and the intensity distribution of the precipitation. Technical Paper Numbers 40 and 49 and Hydro-35 published by the National Weather Service were used to determine the amount of precipitation. Figure 3-2 (Chapter 3), the precipitation-frequency curve used in this study, combined information from these three sources.

A synthetic hyetograph is developed to represent the intensity of rainfall versus time. An actual rainfall or snowmelt distribution can also be input to the model. For short-duration storms (three hours or less), a synthetic hyetograph is developed from data in a paper entitled, "Relation of Hourly Mean Rainfall to Actual Intensities," published in Civil Engineering in May 1940. This hyetograph is shaped similar to the storm pattern shown by C.J. Keifer and H.H. Chu in a paper entitled, "Synthetic Storm Pattern for Drainage Design," published in the Proceedings of American Society of Civil Engineers, August 1957. The hyetograph is also very similar to the second quartile hyetograph discussed in a paper by F.A. Huff entitled, "Time Distribution of Rainfall in Heavy Storms," published in Water Resources Research, Fourth Quarter, 1967.

The rainfall intensity distribution developed for 6-, 12- and 24-hour storm durations were developed from Huff's third quartile, 50-percent probability hyetograph. The rainfall intensity distribution for the 2-day and 4-day storm durations was developed from Huff's fourth quartile, 50-percent probability hyetograph. These hyetographs are also discussed in Huff's paper.

The 10-day snowmelt intensity distribution was developed at Barr Engineering Co. assuming 40 percent of the runoff occurs on the peak day. The 30-day snowmelt event distribution used assumes that 40 percent of the runoff occurs during a 3-day period.

The storm duration that is critical for a watershed is dependent on the watershed size and slope, the volume of storage available in the system and the outlet capacity. The critical duration is determined by routing several different duration storms of a given frequency and determining which duration produces the greatest peak discharge or flood elevation. A small watershed with little available storage will have a critical storm of shorter duration than a large watershed with abundant storage.

Estimation of Losses

After the hyetograph is developed, the losses occurring after the rain reaches the ground are estimated. The three major losses are interception, infiltration and depression storage.

Interception is the portion of the rainfall captured and held on such items as leaves and blades of grass and the water needed to wet surfaces such as roofs, roads and parking lots. This water is returned to the atmosphere by evaporation. Information and data concerning interception losses can be found in the textbook, Hydrology for Engineers, by Linsley, Kohler and Paulhus, published in 1982.

The next loss considered is the infiltration of water into the soil. The method used to determine the infiltration is outlined in Technical Manual of Engineering Practice No. 28, published by the American Society of Civil Engineers in 1949. This procedure uses a standard infiltration curve which depends on soil types and ground cover. The standard infiltration curve is adjusted to account for low-intensity rainfall in the early parts of a storm.

Once interception and infiltration losses are removed from the hyetograph, the remaining water is runoff. However, part of this runoff collects in depressions along the drainage route and never reaches the primary collection system (e.g., gutters and swales). The amount of water held in depression storage is dependent on the slope and the grading of the area. After all three types of losses have been subtracted, the average point runoff is known.

Development of Unit Hydrograph

The next step in the rainfall-runoff process is the conversion of the remaining hyetograph to a unit hydrograph. This consists of routing runoff from the point on which it lands as rainfall to the primary collection system. The overland flow process has the effect of attenuating and lagging the point runoff due to detention of the water on the land surface. The overland flow distance and the slope of the land affect the rate that water from a given area reaches a collection system.

The method outlined by W.W. Homer and S.W. Jens in a paper entitled, "Surface Runoff Determination from Rainfall Without Using Coefficients," published in the Transactions of the American Society of Civil Engineers, Vol. 107, is used as a basis for the overland flow routing. Synthetic unit hydrographs are developed for impervious and pervious areas as well as water surfaces from the outflows of the overland flow routing.

The computations up to this point in the BWM generate five runoff hydrographs: one for impervious areas, one for water surfaces and three for pervious areas which account for three separate choices in the general range of slope and flow lengths in the overland flow process. These hydrographs are summed proportionately to give a composite runoff hydrograph.

Routing Through Primary Drainage System

The composite runoff hydrograph is routed through the watershed's conveyance system to develop the outflow runoff hydrograph for the downstream end of the watershed. This system is made up of swales, ditches, street gutters and storm sewers. The average velocity and the longest flow length of the primary conveyance system are used in a storage routing procedure to generate the hydrograph at the outlet of the watershed. The method used for channel routing is outlined in Technical Manual of Engineering Practice No. 28, published by the American Society of Civil Engineers. An option of not routing the water surface hydrograph through the conveyance system is provided in the BWM. This option is used if the water surface is at the outlet of the watershed, which is commonly the case in urban watershed analysis.

After the hydrographs are created for each subwatershed, they are routed through storage areas (wetlands, lakes, detention ponds, etc.) and conveyance systems (storm sewers and ditches) and combined with other hydrographs at junctions with other subwatersheds. Specific characteristics of the water body and its outlet are input into the elevation-flood storage-discharge relationship used in the routing through each water body.

Volume Routing Method

The storm drainage system for most areas in the city was originally evaluated using a simplified version of the detailed hydrologic model (BWM). This method, known as volume routing, was used to model the city's storm drainage system during the development of the 1982 management plan. This method is the same as the BWM with the exception that a time dependent runoff hydrograph is not generated and thus the peak rate of runoff is not estimated. Like the BWM, the volume routing method considered storms with durations between one-half hour and 4 days and snowmelt runoff events with durations of 10 days and 30 days to determine the critical flood event.

The evaluation of the rainfall runoff process is similar to the BWM except the evaluation is not time-dependent. Rainfall depths are the same and rainfall losses are considered for impervious, pervious and water areas similar to the BWM. The volume of runoff is determined for each storm duration. These volumes are shown in Tables 3-14a-d. The volume of runoff for each storm is routed through stormwater storage areas considering the storage available and the outlet capacity. The volume of runoff is divided into flood storage and discharge volume components based on the characteristics of the pond and its outlet. The routing assumes that the runoff volume occurs uniformly over the storm duration.

The outflow volumes for each storm duration are combined with other watersheds and routed through the storm drainage system. The rate of discharge is determined as the average rate of flow and is calculated as the volume of runoff divided by the storm duration. The volume routing method provides an accurate estimate of the flood storage required in the water body, but since it is not a time dependent model, it does not provide an estimate of the peak discharge rate.

To determine the critical flood level for water bodies during the city-wide modeling, runoff volumes from pervious and impervious areas were determined for storms with durations varying between one-half hour and 4 days and snowmelt runoff events with durations of 10 days and 30 days. These runoff volumes were routed to the water body with consideration for flow times and the critical volume was determined by subtracting outflow volume from inflow. Stage-volume curves were developed for each water body and were used to determine the critical flood elevation.

XP-SWMM Model

XP-SWMM is a dynamic rainfall-runoff simulation model that is based on the US Environmental Protection Agency's original Storm Water Management Model (SWMM), with a computerized graphical interface provided by XP Software. The model, which is used for single events or continuous simulation, generates local runoff hydrographs using rainfall data and watershed characteristics and routes the runoff through a system of pipes, ponds and channels. The model can account for detention in ponding areas, backflow in pipes, surcharging of manholes, as well as tailwater conditions that may exist and affect upstream storage or pipe flows.

Hydrologic Modeling

All hydrologic processes including snowmelt, evaporation, infiltration, surface ponding and ground-surface water exchanges can be modeled using XP-SWMM. Design storms for any duration and return period may be created from a variety of rainfall patterns including SCS Types I, IA, II, II Florida Modified, III, B, Huff Distributions, Chicago Storm, AR&R temporal patterns, as well as user- defined distributions. XPSWMM can also model snowmelt using the Degree-Day method developed by the US National Weather Service.

Within the model, there are numerous methods available for computing storm runoff hydrographs for events or continuous simulations, including (but not limited to) the non-linear runoff routing (US EPA Runoff Method), the SCS unit hydrographs using a curve number with curvilinear or triangular unit hydrographs, Kinematic Wave, the Snyder Unit Hydrograph, the Santa Barbara Urban Hydrograph, the Rational Method and the modified Rational Method.

Hydraulic Modeling

The XP-SWMM hydraulics module solves the complete St. Venant (Dynamic Flow) equations for gradually varied, one dimensional, unsteady flow throughout the drainage network. The calculation accurately models backwater effects, flow reversal, surcharging, pressure flow and tidal outfalls and interconnected ponds. The model allows for looped networks, multiple outfalls and accounts for storage in conduits. Flow can also be routed using the US EPA EXTRAN solutions and with kinematic or diffusive wave methods. To model the hydraulics of a system, XPSWMM includes more than 30 different pre-defined hydraulic as well as several user-defined open and closed conduits.

HydroCAD Model

HydroCAD computer model was developed in 1986 by Applied Microcomputer Systems (now called HydroCAD Software Solutions LLC). HydroCAD is a software package that combines the methods of TR-20, TR-55 and SBUH and includes a built-in hydraulics, graphics, automatic database and on-screen routing diagram.

HydroCAD generates complete runoff hydrographs using the SCS Unit Hydrograph procedure with a rainfall library including SCS Types I, IA, II and III, plus Florida, Illinois and many other storms.

Rainfall may be scaled to any duration or used as back-to-back storms and custom rainfalls can also be used. Long time spans can also be modeled. The SBUH method can also be used with any rainfall distribution. HydroCAD can also use the rational method or modified rational method to generate hydrographs.

HydroCAD can also do reach and pond routing. In HydroCAD, a reach is frequently modeled as a flow segment within a subcatchment, although separate reach routing may be performed for rectangular, vee, trapezoidal and circular channels as well as using a custom cross-section (with constant or variable Manning's value), or based on wetted perimeter or gauge data. Several reach routing procedures are available, including Muskingum-Cunge. HydroCAD performs basic pond routing by the storage-indication method (the Modified Puls method or Level Pool routing). For more complex situations involving tailwater dependencies, interconnected ponds, or even tidal tailwater effects, HydroCAD can do dynamic storage-indication routing or simultaneous routing procedures.

HydroCAD calculates pond stage-discharge curves for weirs (broad crested, sharp-crested, V-notch, trapezoidal and rectangular), culverts, orifices, orifice arrays, custom weir/orifice devices, overlapped (compound) weirs, vortex valves and user-defined devices. Outlet devices may operate with fixed, differential, or dynamic (automatic) tailwater. HydroCAD also calculates exfiltration based on surface area, wetted area, or constant flow.