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Tyler Mahoney
University of Kentucky, tyler.mahoney@uky.edu

Carmen T. Agouridis
University of Kentucky, carmen.agouridis@uky.edu

Richard C. Warner
University of Kentucky, richard.warner@uky.edu

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Hydrologic Models

Tyler Mahoney, Civil Engineering, and Carmen Agouridis and Richard Warner, Biosystems and Agricultural Engineering

Water is a vital part of our everyday lives. Water is necessary for domestic activities such as drinking, cooking and cleaning; agricultural practices such as growing crops and livestock; and industrial uses such as manufacturing and transporting products (Figure 1). Some of our water use is *seen*, such as when we take a shower. However, most of our water use is *hidden*, meaning that water was used to make a product although little to no water may be in the product itself. Because water is so important, a branch of science is devoted to its study.

Figure 1. Water is a vital part of our everyday lives such as for (a) domestic and (b) agricultural activities.

Source: Stephen Patton, Agricultural Communications

Source: Carmen Agouridis, Biosystems and Agricultural Engineering

What is Hydrology?

Hydrology is the study of the distribution and occurrence of water resources above, below, and on the Earth's surface. The hydrologic cycle, often called the water cycle, shows how water is distributed throughout the earth (Box 1). Anthropogenic activities such as urbanization, agriculture, silviculture, and mining can alter the hydrologic cycle which can in turn negatively impact aquatic and terrestrial ecosystems. For example, increased levels of urbanization result in reductions in the amount of rainfall that infiltrates and evapotranspires and increases the amount of rainfall that becomes runoff. These changes can result in flooding, streambank erosion, and water quality degradation.

What is a Hydrologic Model?

One method of better understanding and managing hydrologic changes, such as those resulting from human impacts, is through the use of models. A model is a simplified representation of a complex process. Hydrologic models simplify one or more parts of the hydrologic cycle. For example, some hydrologic models focus only on modeling rainfall and runoff while ignoring other parts of the hydrologic cycle such as evapotranspiration (refer to Hydrologic Modeling Programs for more details). Hydrologic models are useful in understanding watersheds and how changes in a watershed can affect hydrology. Hydrologic models can predict the amount of rainfall that becomes runoff under different scenarios.

Main Components of the Water Cycle 1

Precipitation: Water that comes from clouds. Most precipitation falls as rain, but it can also fall as frozen water such as snow.

Infiltration: Process whereby water soaks into the ground. Some water infiltrates only a short distance before it travels to a stream where it comes back to the surface.

Evaporation: Process that changes water from liquid to gas. Evaporation is the main way that water on the Earth moves back to the atmosphere. Water changes from a liquid to a gas or vapor. Heat is necessary for evaporation to occur, which is why water evaporates more quickly when the sun is out.

Transpiration: Evaporation of water from plants via respiration. Evaporation and transpiration are often grouped as one process and called evapotranspiration.

Condensation: Process that changes water vapor into a liquid. Clouds are an example of condensation. Air high in the atmosphere is cool. As hot air from the earth rises, it cools causing the water vapor to condense or join together to form larger droplets of water. When the droplets get large enough, they fall to the ground as precipitation.

Runoff: Water that does not infiltrate into the ground but instead flows over the land (overland flow) towards water bodies such as streams, rivers, lakes and oceans.

Storage: Water is stored above ground in rivers, lakes and oceans as well as below ground as groundwater.

Why are Hydrologic Models Important?

Hydrologic models can help us better understand how human activity can impact a watershed. For example, as urbanization increases in a watershed, the amount of impervious land (e.g. roads, sidewalks, parking lots and buildings) also increases (Figure 2). Lands that are impervious do not let water soak into the ground meaning less rainfall is infiltrated and more becomes runoff (Box 2). Hydrologic models help engineers and planners estimate the increase in runoff volumes and peak flows that will most likely occur with a change in land use. This type of information is important in designing methods (e.g. detention basins) to reduce the impacts of such hydrologic changes.

Common Hydrologic Model Inputs

Hydrologic models vary in complexity meaning the number of model inputs required also varies from a few to many. For hydrologic models focused solely on rainfall-runoff relationships, common model inputs include watershed area, curve number (CN), time of concentration (t_c), and dimensionless unit hydrograph shape.

Watershed Area

To create a hydrologic model, one of the fundamental inputs is watershed area. A watershed is an area of land where all of the rainfall that falls on it drains to a common outlet. Watersheds can range in size from less than 1 to over a million square miles. Streams are often the low points in watersheds meaning runoff flows to streams as a result of gravity. Topography or land elevation typically divides one watershed from another.

Curve Number

A commonly used method to estimate runoff is the Natural Resources Conservation Service (NRCS) Curve Number Method. CNs are a means of expressing how much rainfall becomes runoff. Higher CNs (up to 100) indicate that more rainfall becomes runoff. Lower CNs indicate that more rainfall is intercepted, infiltrated and stored. Table 1 contains typical CNs used in urban areas. These CNs were developed using the assumption that yards and landscapes in urban areas behave in a hydrologically similar manner as pastures. Assumptions were also made on the percentage of impervious area associated with each urban land use.

Figure 2. Flooding is an issue in urban watersheds as less rainfall can soak into the ground.

Source: Amanda Gumbert, Agricultural Programs

Hydrograph

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A hydrograph is a chart that shows the change in water discharge or stream flow over time. When rain falls on a watershed, some of the rain infiltrates into the ground and some undergoes evapotranspiration. The remainder becomes runoff.

Urbanization directly affects the amount and rate at which runoff reaches a stream. Prior to development, most of the rainfall soaked into the ground. Relatively little runoff reached the streams, and what did required a longer travel time or time of concentration. Smaller runoff volumes and longer times of concentration meant that the water level in streams rose slowly and did not get that deep. The pre-development hydrograph has a relatively small peak and volume (area under the curve).

Following development, more runoff is produced as impervious areas allow less rainfall to soak into the ground. Downspouts, curbs, gutters and pipes quickly transport stormwater to streams. The combination of more runoff and faster delivery of this runoff to streams results in what is called a peaked hydrograph. The post-development hydrograph as a relatively large peak and volume plus the hydrograph peak occurs more quickly.

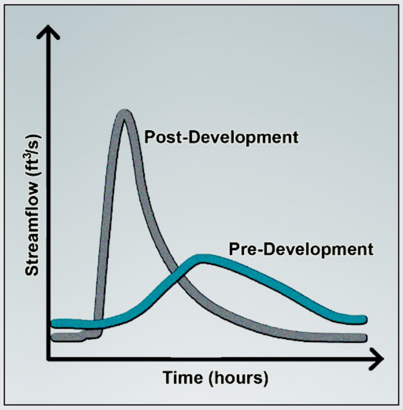

Table 1. Curve numbers[1] (CN) for urban lands.

Land Use	Hydrologic Condition[2]	HSG[3]			
		A	B	C	D
Open space[4]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Paved parking lots, roofs, driveways, etc.		98	98	98	98
Commercial and business districts (85% impervious area)		89	92	94	95
Industrial districts (72% impervious area)		81	88	91	93
Residential district (¼ acre lots, 38% impervious)		61	75	83	87

[1] Antecedent moisture condition II (average runoff condition) and $I_a=0.2S$. Current recommendations are to use an $I_a=0.05S$ which will result in lower CNs with runoff beginning at lower rainfall depths. To convert CNs developed with $I_a=0.2S$ to equivalent CNs with $I_a=0.05S$, use Equation 1.

[2] Hydrologic condition refers to factors that affect infiltration and runoff such as canopy cover, vegetation density, and surface roughness.

[3] Hydrologic soil group (HSG) is a grouping of soils based on their minimum infiltration rate after prolonged wetting.

[4] Poor: Grass cover <50%; Fair: grass cover 50-70%; Good: grass cover >75%.

Source: Natural Resources Conservation Service

Time of Concentration

Time of concentration is defined as the time it would take for a drop of water, at the most hydrologically distant or remote location in the watershed, to reach the watershed outlet. Land use changes such as urbanization can reduce the time of concentration meaning runoff will reach streams more quickly. This reduction in the time of concentration is due to the storm sewer system which conveys runoff quickly through a series of underground pipes to streams. A shorter time of concentration means that water levels in streams will rise quickly during rainfall events.

Both land use and soil type affect the CN of a watershed. The more impervious area in a watershed, the higher the CN. Soils are categorized into one of four hydrologic soil groups (HSG) based on their ability to infiltrate water after a prolonged wetting (Table 2). Since watersheds are heterogeneous, meaning land use and soil types are not the same throughout a watershed, a geographical information system program (GIS) such as ArcMap is useful to compute an area weighted CN for the entire watershed. An example for computing runoff volumes using the curve number method is provided (Box 3).

Table 2. Typical infiltration rates for soil types.

HSG[1]	Soil Texture	Infiltration Rate (in/hr)
A	Sand, loamy sand, sandy loam	>0.30
B	Silt loam, loam	0.15-0.30
C	Sandy clay loam	0.05-0.15
D	Clay loam, silty clay loam, sandy clay, silty clay, clay	<0.05

[1] Hydrologic soil group (HSG) is a grouping of soils based on their minimum infiltration rate after prolonged wetting.

Source: Natural Resources Conservation Service

Curve Number Example

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Jim wants to determine the amount of runoff produced from 1-year 24-hour rainfall event at a 5 ac residential district in Fayette County, Kentucky. Soils at the project site are Bluegrass-Maury silt loam. Using the Rainfall Frequency Values for Kentucky, Engineering Memorandum No. 2, Jim determines the 1-year 24-hour rainfall depth is 2.6 in. Assume an $I_a=0.05$.

Step 1: Determine the HSG
Using Table 2, the HSG for a silt loam is B.

Step 2: Convert CN
From Table 1, the CN for a residential lot with soils in HSG B is 75. However, Table 1 contains CN developed with $I_a=0.2S$. To convert the CNs in Table 1 to equivalent CNs ($I_a=0.05S$), use Equation 1.

$$CN_{0.05} = \frac{100}{\left\{1.879\left[\left(\frac{100}{CN_{0.2}}\right)-1\right]^{1.15}+1\right\}}$$

The equivalent CN, with an $I_a=0.05S$, is 65.

Step 3: Determine Runoff Depth
To determine the runoff depth (Q, in.), compute storage (S, in.) using Equation 2.

$$S = \frac{1000}{CN} - 10$$

For a CN of 65, S is 5.38 in. Using the rainfall depth (P, in.), compute runoff depth using Equation 3.

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$$

$$Q = 0 \text{ if } P \geq I_a$$

Q is 0.70 in.

Step 4: Determine Runoff Volume
Convert runoff depth to feet (recall 1 ft=12 in.). Multiply runoff depth by the area of the project site. Runoff volume is 0.29 ac-ft.

Dimensionless Unit Hydrograph Shape

A unit hydrograph is a representation of the amount of runoff or discharge that results from a 1 inch rain event falling uniformly over a watershed for a specific period of time. This method assumes that runoff rates are proportional to excess rainfall volumes. A dimensionless unit hydrograph is created by normalizing the unit hydrograph. Normalization is done by dividing discharge by the hydrograph's peak discharge and time by the hydrograph's time to peak (Figure 3). A dimensionless unit hydrograph represents the characteristic shape of many unit hydrographs.

The dimensionless unit hydrograph shape describes the hydrologic response of the watershed. As watersheds vary in land use and shape (e.g. length to width ratio) so do unit hydrographs and thus the resulting dimensionless unit hydrographs. In some watersheds, runoff may quickly reach the outlet thus producing a quick discharge peak while in others a longer amount of time is required for the hydrograph peak to occur.

Rainfall

Not all rain events are the same. Rain events vary in depth, duration, frequency, and in how the rainfall is distributed during the storm. Designers can choose to model a design storm (e.g. 2-year 24-hour) or an actual historic rain event.

Hydrologic Models

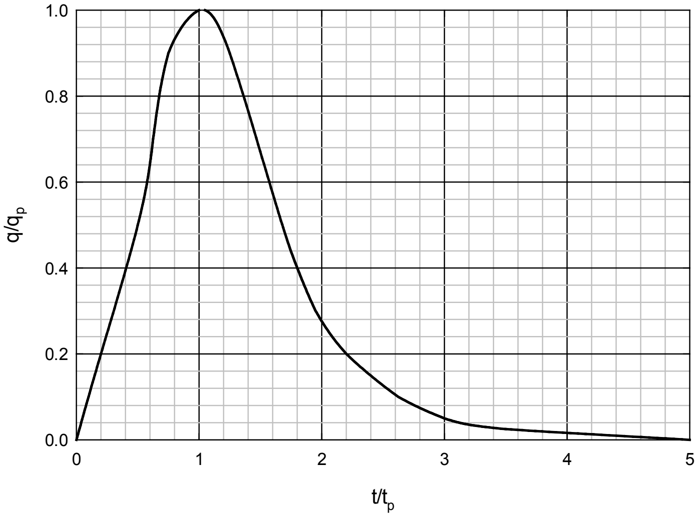
A number of models are available for modeling hydrology. Each model requires a different set of inputs and has different limitations (Table 3). Some models were designed for use primarily in urban watersheds while others were designed for agricultural ones. Many hydrologic models are also capable of modeling other components such as sediment and nutrients.

Table 3. Summary of common hydrologic models.

Model[1]	Description	Land Use	Source
AGNPS	Used to model the effect of watershed management decisions on hydrology, sediment and nutrients	Agricultural	U.S. Department of Agriculture, Natural Resources Conservation Service
CREAMS	Used to model nonpoint source pollution (hydrology, erosion/sedimentation and chemistry) and effects of best management practices	Agricultural	U.S. Department of Agriculture, Agricultural Research Service
HEC-HMS	Used to model hydrologic processes of dendritic watershed (i.e. one with many contributing streams, resembles branches on a tree in pattern)	Multiple types	U.S. Army Corps of Engineers
SEDCAD	Used to model alternative surface water, erosion and sediment control systems with a focus on earth-disturbing activities	Multiple types	Civil Software Design, LLC
SWMM	Used to model the effect of watershed management decisions on hydrology and pollutant loads	Urban	U.S. Environmental Protection Agency
TR-55	Used to model hydrology	Urban	U.S. Department of Agriculture, Natural Resources Conservation Service

[1] AGNPS represents AGricultural Non-Point Source Pollution Model; CREAMS represents Chemicals, Runoff, and Erosion from Agricultural Management Systems; HEC-HMS represents Hydrologic Engineering Center - Hydrologic Modeling System; SEDCAD represents Sediment, Erosion, Discharge by Computer Aided Design; SWMM represents Storm Water Management Model; and TR-55 represents Technical Release 55.

Figure 3. Dimensionless unit hydrograph.



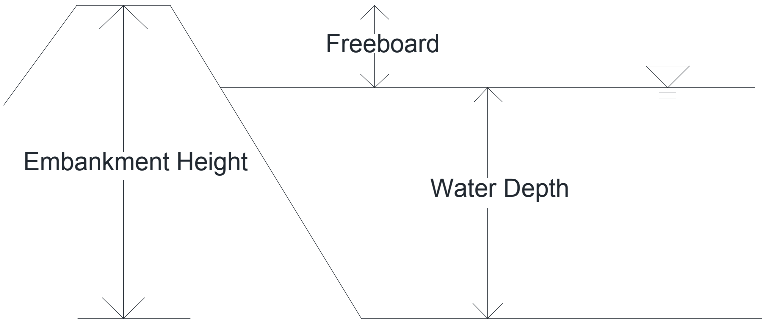
[1] q=discharge at time t (ft^3/s), q_p=peak discharge (ft^3/s), t=time (hr), t_p=time from start of hydrograph to peak discharge (hr).

Model Uncertainty (Errors)

Because models are simplified representations of real-world processes, model output contains a level of uncertainty or error. Oftentimes, model inputs are estimated or measured, and the error associated with these estimates and measurements is reflected in the model output. The use of models in decision making requires some amount of experience (i.e. professional judgement). For example, not all input variables are equally important in a model. While a model may be quite sensitive to changes in one input variable, variations in another may have little effect on the output. Thus a modeler must know which input variables need a greater level of accuracy to improve the quality of the model output.

One way to help account for uncertainty in models is to use a factor of safety. A factor of safety is a numerical adjustment to the output used to account for uncertainty. For example, engineers often use a factor of safety called a freeboard when designing detention basins. To account for model error, engineers may add 1 ft or more to the maximum water depth expected in a detention basin (Figure 4). The greater the level of uncertainty and consequences of failure (e.g. potential for loss of life), the larger the factor of safety one should use with hydrologic models.

Figure 4. A factor of safety, such as freeboard, is used to account for model uncertainty or error.



Source: Tyler Mahoney, Civil Engineering

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