Chapter 19
Modeling the Impact of Urban Trees on Hydrology

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19.1 Introduction

Urban trees provide numerous benefits to society, as well as costs. These benefits include moderating climate and cooling the urban heat island; reducing building energy use and atmospheric carbon dioxide (CO_2); improving air and water quality; mitigating rainfall runoff and flooding; enhancing aesthetics, human health, and social well-being; and lowering noise impacts (Dwyer et al. 1992, Nowak and Dwyer 2007, Dobbs et al. 2017). Urban forests have various costs associated with tree planting and maintenance, along with other possible indirect costs through pollen production and allergic reactions, winter shade increasing building energy use, lowered wind speed and dispersion increasing pollutant concentrations, and invasive plants altering local biodiversity (Lyytimaki 2017; Long et al. 2018). Annually, urban trees in the United States produce a total of \$18.3 billion in value related to air pollution removal (\$5.4 billion), reduced building energy use (\$5.4 billion), carbon sequestration (\$4.8 billion), and avoided pollutant emissions (\$2.7 billion) (Nowak and Greenfield 2018b). As urban land in the United States is projected to increase by 384,000 km^2 between 2010 and 2060 (increasing from 275,000 km^2 (3.0% of US land) to 660, 000 km^2 (8.6%)) (Nowak and Greenfield 2018b), the value and importance of the urban forest resources will continue to rise in the coming years. One of the more important benefits of urban trees relates to their impact on surface stormwater runoff, stream flow, and water quality.

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The removal of trees typically leads to increased stormwater runoff, potentially increasing localized and extensive flooding in urban areas. The economic impacts of flooding can be substantial (Nowak et al. 2007). The costs/impacts associated with urban flooding include wet structures with mold and potential increase in respiratory problems, increased insurance rates, lower property values, streambank erosion, degraded water quality, and reduced health of aquatic ecosystems. In Cook County, Illinois, total claims paid for urban flooding incidents over 5 years (2007–2011) were more than $773 million (CNT 2014). In addition to larger peak flows, increased stormwater can also lead to instability in drainage systems and reduced recharge of groundwater (Herricks 1995; Thorne 1998; FISRWG 1999). Instability in the drainage system can rapidly erode streambanks, damage streamside vegetation, and widen stream channels (Hammer 1972). Instability combined with reduced groundwater recharge results in lower water depths during non-storm periods, higher than normal water levels during wet weather periods, increased sediment loads, and higher water temperatures (Brookes 1988).

Trees can reduce stormwater runoff in many ways and help reduce the hydrologic impacts of urbanization (Kuehler et al. 2017). Trees affect stream flow rates primarily through three mechanisms: canopy rainfall interception, soil water infiltration, and evapotranspiration (US EPA 2016). These mechanisms result in the cumulative effect trees have on urban water volume. Trees also affect water quality, both by affecting water volume and thus pollutant transport and by affecting the concentration of pollutants in water.

According to US GAO (2001), when natural ground cover is present over the entire site, on average, 10% of precipitation runs off the land into nearby creeks, rivers, and lakes. In contrast, when a site is 75% impervious, and not all directly connected to receiving waters, on average, 55% of the precipitation runs off into receiving waters. Runoff from parking lots and other paved areas is estimated at 98% of storm event precipitation (USDA NRCS 1986). The impervious surfaces in a typical city block may generate nine times more runoff than a woodland area of the same size (US EPA 1996). Urban impervious cover in the conterminous United States averages 26.6% (Nowak and Greenfield 2018a). Runoff from urban land cover collects pollutants from the land surface and poses a threat to receiving waters (US GAO 2001).

Trees are capable of being dominant land cover elements in cities. In the conterminous United States, urban tree cover averages 39.3%, ranging from 10.1% in North Dakota to 61.6% in Connecticut (Nowak and Greenfield 2018b). To optimize land use planning and facilitate the inclusion of more tree canopy for their hydrologic ecosystem services, models can serve a useful role (Lin et al. 2007; Guswa et al. 2014). Due to the complexity of interactions among trees and the hydrologic and biogeochemical systems, models are often used to extend field observations and estimate the outcomes of these interactions in different scenarios. While models are simplifications of reality used to gain insight into select attributes of a particular system (US EPA 2009), hydrological models have proven useful tools in estimating the transport of water (Borah and Bera 2004), and biogeochemical models have proven useful in estimating the transformation of chemicals (Bouraoui and Grizzetti 2014). Chapters 17 (Carlyle-Moses et al. this volume) and 18 (Decina et al. this volume) describe urban impervious and urban tree impacts on hydrologic and biogeochemical processes, and this chapter summarizes and discusses various models used to quantify these urban tree hydrology impacts.

19.2 Modeling Urban Tree Effects on Water Volume and Quality

Computer models simulating how urban land cover impacts water quality and quantity are flexible, fast, and low-cost management options when compared with field or laboratory studies. Models can also be used to examine scientific hypotheses regarding the cause and effect feedback between land cover and water resources in urban systems. Given the importance of water quantity and quality in cities, and the range of components, systems, processes, and priorities involved, a wide variety of urban hydrology models have been developed. These models typically vary in their conceptual framework, input requirements, predictive goals, mathematical algorithms, applications, user support, and required user investment.

This chapter reviews a limited set of urban hydrology models, selected based on the following criteria that the model is (a) in the public domain and free to use; (b) considered useful to the broad range of urban hydrology management issues and not too specialized; and (c) capable of simulating tree or forest effects on hydrology. Readers interested in models that extend beyond these criteria can review a larger list of models compiled by the Minnesota Pollution Control Agency (MPCA 2018). A review of common modeling concepts is provided here to help compare and contrast between models, communicate with model developers, and appreciate how models are a simplified approximation of the actual system.

Spatial representation is a major model concept and can be explained using the following illustration. Consider a 1 km^2 area of an urban area, with pixelated maps for each watershed element, including soil types, land cover types, terrain elevation, precipitation, etc., with each pixel representing a 10 × 10 m sub-area. To continue with the illustration, consider a set of unique values for soil type (sandy loam, clay loam, silty clay) and land cover type (commercial, residential, forest), and ignore the variation in terrain elevation, precipitation, etc. Note that this illustration is using simple elements, and in most applications, there are more than three soil types or land cover types. Based on the 100 m^2 pixel size, there are 10,000 pixels in the 1 km^2 urban area, and map inventories determine the number of pixels, and hence percent of pixels, in each soil type (35% in sandy loam, 45% clay loam, 20% silty loam) and in each land cover type (15% in commercial, 60% in residential, 25% in forest).

In a spatially lumped model, the 1 km^2 area would be represented as a single area characterized by the percentages of soil type, land cover type, etc., and there would be no spatial relationship of adjacency within a map type (e.g., sandy loam adjacent to clay loam), nor spatial relationship of congruence between map types (e.g., forest congruent with sandy loam). Instead, the spatially lumped model could proceed with a water budget by treating each percent of cover independently and then averaging the response, or it could derive a set of effective parameters representing the composite land cover. In this illustration, if the spatially lumped model received a uniform 0.254 mm rainfall event, the area in forest might have 70% of this rain allocated to canopy interception and depression storage, and the area in commercial and residential might have 15% allocated to depression storage. This results in a lumped area average of 28.75% of the rain in storage and leaves 71.25% of rain available to proceed to infiltration in the three different soil types, each with a distinct infiltration rate. The spatially lumped model would likely ignore spatial variation in elevation and its influence on weather (e.g., cooler temperatures at higher elevations, stronger solar radiation on south-facing slopes).

In a spatially distributed model, the options include fully distributed, with each of the 10,000 pixels treated as a vertical stack with its unique precipitation, terrain elevation, land cover, soils, etc., and allow for lateral exchanges of water and constituents between pixels or, to partially simplify the system, often called semi-distributed or statistically distributed. One form of a semi-distributed model uses spatial congruence of watershed elements (e.g., forest above sandy loam, forest above silty loam, etc.) to identify systems that behave similarly in a water budget (e.g., same depth of interception and rate of infiltration for a given rainfall depth), which are referred to as hydrologic response units (HRUs). In the illustration of three soil types and three land cover types, the 1 km^2 urban area could have a maximum of 9 HRUs, which is computationally much faster than modeling 10,000 pixels and not much slower than modeling the lumped area. Another widely used form of the semi-distributed model uses the ratio of contributing area and slope for each pixel in the terrain elevation map to create a topographic index (TI) value, which represents wetness likelihood (Beven and Kirkby 1979), and then sorts the unique TI values for all pixel into a smaller set of bins, as in a histogram. In TI applications there are often 20–50 bins, and each bin might be assigned a lumped percent of land cover and soil types. The TI is then used in a function that laterally redistributes the precipitation that entered the soil as ground water at the end of each simulation time step, replacing a computationally expensive function to explicitly move water between 10,000 pixels.

Other ways to categorize models, along with the lumped vs. spatially distributed category above, include empirical vs. mechanistic modeling, stochastic vs. deterministic modeling, single-event vs. continuous modeling, event mean concentration (EMC) vs. buildup/washoff water quality routines, and object-oriented vs. function-based design. Empirical models represent the observed relationships in phenomena, such as rainfall partitioning to runoff, without representing the theory of cause and effect used in mechanistic models. As an example, if a field study measured the amount of runoff for several rainfall events in an area with residential land cover and silty loam soils, it could analyze the results and potentially derive a new parameter that estimated the amount of rainfall that becomes runoff for each event. Empirical models are limited to applications where the watershed conditions are similar to those of the study site, which is one constraint with regard to significant land or climate disturbance. With mechanistic models, there are varying levels of theoretical and mathematical sophistication, and first-order models tend to prefer greater simplicity over greater accuracy, parsimoniously keeping the governing terms in equations while removing higher-order terms.

Stochastic modeling can treat equation parameters as random variables with probability distributions to represent observed variability, while deterministic modeling assigns fixed values to parameters in a given model scenario. Single-event models simulate one precipitation event and typically ignore evapotranspiration, while continuous models simulate a period of time, at some time step, to represent precipitation and the evapotranspiration that follows. Length of time step is also an important defining factor in urban hydrology simulations, as there is a need for both shorter and longer time steps: sub-hourly time steps inform peak runoff rates green infrastructure may need to process and aid in proper sizing of drains, berms, and other flow conduits; and 24-hourly time steps inform total volumes that may need to be accommodated by the maximum capacity of green infrastructure. Shorter or longer time steps may be preferable depending on which type of resulting information is more pertinent and what kind of model inputs (temporal resolution of observed weather and/or discharge data) and computing resources (for data processing and storage) are available.

EMC-based estimates of pollutant loading, detailed in Sect. 19.2.1.1 of this chapter, are a parsimonious approach which can over- or underestimate pollutant concentration within a storm event, but this approach serves well to estimate total pollutant loading for an entire event. Buildup and washoff approaches to water quality estimates capture fluctuations in pollutant concentrations during an event and can more explicitly account for water quality BMPs (e.g., street sweeping), but these approaches tend to be difficult to parameterize and, in many cases, the important output is total pollutant loading, not a time series of pollutant washoff.

Object-oriented design organizes the model around watershed elements such as tree canopy and soil, which are called classes, and instances of the classes can handle data and functions acting on the data. Function-based design organizes the model around operations such as interception and infiltration, with algorithms linking these processes. The goal of object-oriented design is to make the model open for extension without modification, so that to the extent possible new ideas for the model only require new objects rather than modifying existing objects.

The models included in this chapter can be divided into three general categories of complexity, defined by number and availability of required inputs and parameters and the range of processes and systems simulated. The lower complexity models are (a) the Rational method approach and its application with the LMNO Rational Equation Calculator and the Minimal Impact Design Standards Calculator and (b) the Curve Number approach, and its application with WinTR-55 (NRCS 2018) and the Green Values National Stormwater Management Calculator. The moderate complexity models are i-Tree Hydro and the US EPA National Stormwater Calculator. The advanced complexity models are the (a) Storm Water Management Model (SWMM); (b) Hydrological Simulation Program-FORTRAN (HSPF); (c) Soil and Water Assessment Tool (SWAT); and (d) Regional Hydro-Ecological Simulation System (RHESSys). Models similar to the complexity of RHESSys used by research groups include the ecohydrologic (Ech2o) model (Maneta and Silverman 2013) and the Distributed Hydrology Soil Vegetation Model (DHSVM) (Wigmosta et al. 1994), while a fee-based decision support system by eWater of Australia is the Model for Urban Stormwater Improvement Conceptualization (MUSIC) (Wong et al. 2002). Models with a similar level of complexity can have substantially different methodologies in how they account for tree processes. Of these models, i-Tree Hydro (Wang et al. 2008) was explicitly designed to simulate tree effects in urban hydrological systems, and this model serves as a good starting point to introduce concepts and help the reader later compare and contrast simpler and more advanced approaches.

19.2.1 i-Tree Hydro

The i-Tree Hydro model, managed by the USDA Forest Service and Davey Tree Expert Company (Yang et al. 2011), is a spatially semi-distributed model that simulates runoff quantity and quality for watershed and non-watershed areas subjected to a single precipitation event or continuous weather. The i-Tree Hydro routines are divided into the hydrologic processes of the water balance, collectively with 100s of equations and descriptive parameters. The hydrologic processes include classifying precipitation as rain or snow based on air temperature, canopy interception, depression storage, impervious runoff, infiltration, soil moisture updating, pervious runoff, evaporation from surface water and canopy water, evapotranspiration from soils and leaves, subsurface runoff, lateral distribution of water, and estimates of water quality and quantity (Fig. 19.1).

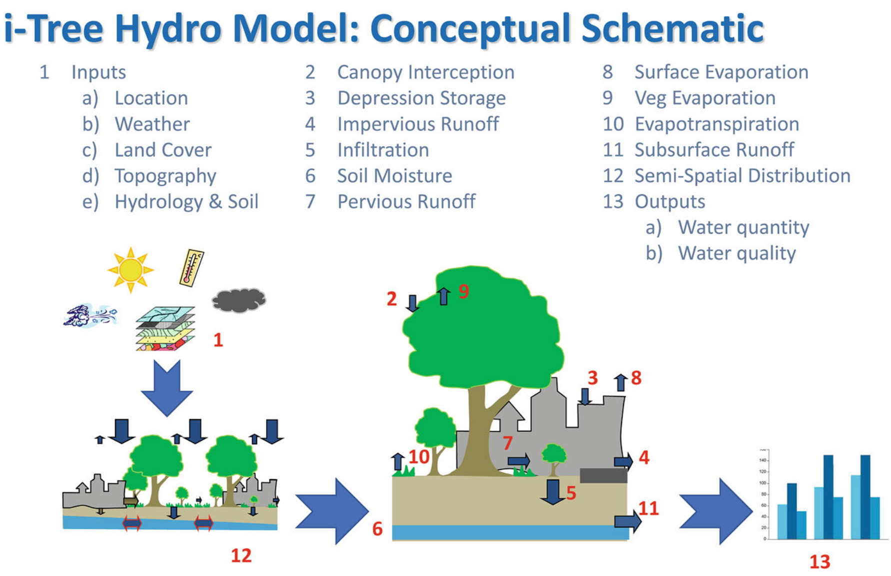

Fig. 19.1 Conceptual schematic of the i-Tree Hydro model

The model inputs require a time series of weather, terrain elevation data or a topographic index, and land cover with estimates of percent tree and impervious cover. The model maintains a water budget for snow and rain, implementing vertical redistribution of water between the vegetation canopy, depression storage, soil moisture, groundwater, and the atmosphere via evapotranspiration. A variable source area routine identifies saturation excess and infiltration excess surface runoff; the Green-Ampt model is used to determine infiltration, with a lateral redistribution of soil saturation implemented with the topographic index. Surface and subsurface runoff directed to the channel network is transformed to a hydrograph using a one- or two-parameter advection-diffusion routing model (Yang and Endreny 2013).

The user and input data define the time step (typically 1 h); land cover characteristics, including percent pervious or impervious cover beneath tree canopy and percent directly connected impervious area (DCIA); soil characteristics; and optionally other model parameters. Water quality constituents are represented with EMC values as described in the following section, and pollutant loads are determined by the volume of surface runoff. Storm sewer discharge is not simulated but approximated as the impervious runoff DCIA, which directly enters receiving waters. i-Tree Hydro is used to determine how changes in watershed management (e.g., percent tree cover, other land use, DCIA) or climate affect discharges based on preferred or regulated water quantity and water quality targets. A set of default soil parameters are provided based on prior model runs, and users can optionally use a custom implementation of the PEST tool (Doherty 2001a, b) for parameter calibration and evaluation when used in conjunction with a time series of observed discharge. This tool is based on the ObjTop and UFORE-Hydro models (Wang et al. 2005a, 2008), is actively updated, and is accessible on the www.itreetools.org website, with tutorials and technical support available. i-Tree Hydro is generally used as a scoping tool, estimating the effects of trees (Kirnbauer et al. 2013) and different land cover scenarios (Lefrançois 2015) on hydrology (Fig. 19.2).

19.2.1.1 Water Quality Modeling Using Event Mean Concentrations (EMCs)

The event mean concentration (EMC) method is considered a proven approach to quantify pollutant loading to receiving waters resulting from a runoff event (US EPA 2002). The EMC is not intended to predict the variation in concentration during an event, but rather to represent the total loading from an event. The EMC value itself (mg L^{-1}) is a statistical parameter representing the flow-proportional median concentration for a storm event and can be adjusted to represent other percentiles, such as the upper 90th or lower 10th (see Equations 4 and 5 in Stephan and Endreny 2016). Estimates of EMC are usually obtained from analysis of many flow-weighted composite samples taken during each storm, and not simply a time average of a single event. When an *EMC* from a look-up table is multiplied by the runoff volume,

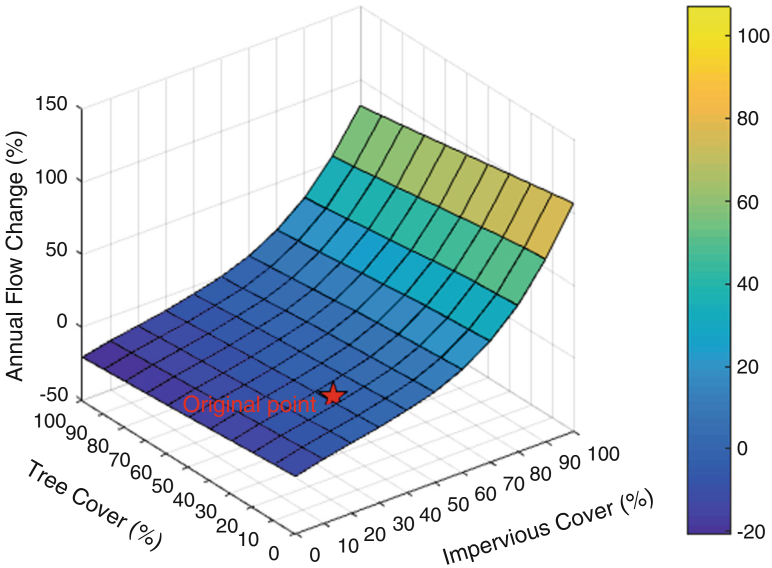

Fig. 19.2 i-Tree Hydro simulated effects of incremental changes to tree cover and impervious cover in 161 km^2 Rock Creek watershed near Washington, DC

V, for a new event, the resulting load, *L*, is the estimated total pollutant load for that event, with the equation given as:

$$L = EMC * V \tag{19.1}$$

To understand and control urban runoff pollution, the US Congress included the establishment of the Nationwide Urban Runoff Program (NURP) in the 1977 Amendments of the Clean Water Act (PL 95-217). In 1983, the US Environmental Protection Agency (US EPA 1983) published the results of the NURP, which nationally characterized urban runoff for 10 standard water quality pollutants in the United States, based on data from 2300 station-storms at 81 urban sites in 28 metropolitan areas. The USGS conducted a separate stormwater characterization from data measured through mid-1980s for more than 1100 stations at 97 urban sites located in 21 metropolitan areas (Driver et al. 1985). A third characterization of stormwater quality was compiled using data from stormwater discharge permits under the National Pollutant Discharge Elimination System (NPDES) for more than 30 cities, 800 station-storms, and 150 parameters (Smullen et al. 1999). The data from the three sources (NURP, USGS, and NPDES) were used to compute a pooled means with greater statistical confidence (Smullen et al. 1999), and the NURP and pooled mean EMCs for the ten constitutes are listed in Table 19.1. Pooled mean or NURP EMCs are based on field data collected from thousands of storm events and are representative of the United States nationwide rather than specific to any single site.

Table 19.1 National pooled EMCs and NURP EMCs

Constituent	Data Source[a]	EMCs (mg L^{-1})		No. of events
		Mean	Median	
Total suspended solids: TSS	Pooled	78.4	54.4	3047
	NURP	17.4	113	2000
Biochemical oxygen demand: BOD_5	Pooled[b]	14.1	11.5	1035
	NURP	10.4	8.39	474
Chemical oxygen demand: COD	Pooled	52.8	44.7	2639
	NURP	66.1	55	1538
Total phosphorus: TP	Pooled	0.315	0.259	3094
	NURP	0.337	0.266	1902
Soluble phosphorus: soluble P	Pooled[c]	0.129	0.103	1091
	NURP	0.1	0.078	767
Total Kjeldahl nitrogen: TKN	Pooled	1.73	1.47	2693
	NURP	1.67	1.41	1601
Nitrite and nitrate: NO_2 and NO_3	Pooled	0.658	0.533	2016
	NURP	0.837	0.666	1234
Copper: Cu	Pooled	0.0135	0.0111	1657
	NURP	0.0666	0.0548	849
Lead: Pb	Pooled	0.0675	0.0507	2713
	NURP	0.175	0.131	1579
Zinc: Zn	Pooled	0.162	0.129	2234
	NURP	0.176	0.140	1281

[a]Pooled data sources include NURP, USGS, and NPDES
[b]No BOD5 data available in the USGS dataset; pooled includes NURP+NPDES
[c]No TS data available in NPDES dataset; pooled includes NURP+USGS
Source: Smullen et al. (1999); reproduced with permission of IWA Publishing

19.2.1.2 Effect of Trees

There is explicit simulation of tree cover in i-Tree Hydro, as one of six land cover groups that also include shrub, herbaceous, water, impervious, and bare soil. Users identify land cover for a base case scenario and up to three alternative scenarios and give the percent of tree canopy over pervious cover and over impervious cover and the percent with evergreen canopy. The simulation includes a specific soil layer accessible to vegetation roots, using that soil water for transpiration, as well as a soil macropore fraction allowing precipitation falling on pervious soils to bypass the root zone layer (Aubertin et al. 1971). Canopy interception of liquid and snow precipitation are explicitly simulated at each time step. The model allows users to set the leaf on and off transition dates and transition duration, minimum and maximum leaf area index, bark area index, portion of canopy that is evergreen, and leaf storage depth available for water. Evaporation is explicitly modeled for canopy storage and surface (depression) storage and as evapotranspiration from soil pores and leaf stomata, which is used to reduce or reset the water storage in these layers. Additional details on these and related processes follow, to clarify how the model approximates a representation of the actual hydrologic cycle.

Interception is simulated in tree and short vegetation cover using methods based on the work of Rutter et al. (1971, 1975) rather than using empirical methods based on gross precipitation (Jackson 1975). Rutter interception theory was modified to account for throughfall in sparse vegetation (Gash et al. 1995; Valente et al. 1997) to represent the tree structure common in urban forests. Between-leaf throughfall is simulated as a function of canopy fraction, and when canopy storage is filled, canopy drip is simulated. Evaporation from the canopy reduces the storage. The interception depth is a function of weather dynamics of precipitation intensity and duration, wind, vapor pressure, and radiation values and tree characteristics of seasonally varying leaf area, storage capacity, and initial vegetation surface storage at each time step.

Depression storage is filled by precipitation reaching the ground; depressions include the water stored by leaf litter and other organic material as well as in potholes and impervious low spots. Impervious depression storage and pervious depression storage are modeled separately, and the maximum depth of storage is representative of a layer of water spread across the entire impervious or pervious area. Precipitation that exceeds the impervious depression storage depth is directly converted to surface runoff, with the DCIA fraction determining the amount going directly to the outlet as impervious runoff, while the remainder is passed to pervious areas. The amount of DCIA is determined by the user, with recommended values estimated based on work by Sutherland (2000).

Infiltration, ponding, and runoff are the partitions used to allocate precipitation over pervious areas and impervious runoff that exceeds pervious area storage. This partitioning uses the variable source area concept, where infiltration excess runoff occurs if precipitation rates are greater than the Green-Ampt infiltration rate and saturation excess runoff occurs if precipitation falls on saturated soils; otherwise precipitation will infiltrate or pond in queue for infiltration. Soil saturation can occur from a rising water table during the redistribution of subsurface water with the topographic index. The topographic index is modified for impervious surfaces, using the theory of TOPURBAN by Valeo and Moin (2000). Infiltration rates are a function of cumulative infiltration and soil properties, with hydraulic conductivity decaying with soil depth based on either an exponential function or power function (Wang et al. 2006).

Evaporation and evapotranspiration rates are calculated at each time step based on some fraction of the potential rate. The fraction is the ratio of actual water storage to maximum storage capacity based on work of Deardorff (1978) and Noilhan and Planton (1989), to represent the increasing resistance of a thinner layer of water. The maximum potential evaporation (*pE*) and evapotranspiration (*pET*) for various water storage zones are determined by preprocessing weather data (Hirabayashi and Endreny 2016). *pE* and *pET* are calculated in three distinct terms: *pE* from free water in the tree canopy; *pE* from free water in the short vegetation (shrub and herbaceous) and depression storages (pervious and impervious); and *pET* of soil water volumes through direct evaporation and vegetation transpiration. This distinction is used to allow for higher potential values above the turbulent tree canopy, lower values above the low-lying shrub and surface stores, and further constrained values in soils because of resistances. *pE* from vegetation is calculated using a modified Penman-Monteith equation (Shuttleworth 1993) with distinct values for canopy resistance. *pET* of soil water through vegetation is also based on Penman-Monteith formulations, where potential values are modified downward based on soil and leaf canopy moisture resistances. Direct evaporation from soil surfaces is based on the same soil moisture resistances. In allocating water to evaporation and evapotranspiration, an energy and water balance are maintained, guarding against taking more water than is physically possible.

Runoff in channels is the sum of precipitation falling directly on land cover types identified as water, subsurface flow, overland pervious runoff, and DCIA impervious area runoff. The water budget is a vertical balance in one dimension, recorded as depths, which can be integrated across the landscape area to generate volumes. The runoff hydrograph is presented as a volume per time, and the quantity of water in runoff can be reported with time step options of hourly, weekly, monthly, or yearly. The water quantity in runoff is reported in its component parts, showing the subsurface flow, the pervious runoff, and the impervious runoff. Pollutographs are also generated for any of the EMC constituents listed in Table 19.1. Both water quantity and quality for the base case and the alternative scenarios are plotted on a shared graph or table for quick comparison.

i-Tree Hydro's model architecture is designed for modularity and extendibility. This was originally achieved using object-oriented design (OOD), which is an approach to C++ software development which guides programmers to make programs, to the extent possible, open for extension and closed for modification. Using OOD, when simulation requirements change in the future, the model can be extended mostly by adding new code, not by changing old code that already works (Wang et al. 2005b). While i-Tree Hydro's model architecture has changed over time, adapting to changes in development constraints and goals, the principles of modularity and extendibility remain useful. This is true in the user-oriented side of model design as well: the program is designed to be flexible, allowing users to set up a simple project or extend it with additional parameterization and complexity as needed to meet a user's modeling goals.

19.2.2 Rational Method

The Rational method equation, used by engineers since the 1800s (Chin 2013), is a spatially lumped model that simulates peak runoff rates for the single outlet of a land parcel subjected to a single precipitation event. The Rational method water budget uses inputs of constant rainfall intensity for any duration equal to the time of concentration and represents the fraction of rainfall released as runoff. The model operates at one time step. The Rational peak runoff rate equation is:

$$Q_p = 0.00278\ C\ i\ A \tag{19.2}$$

where Q_p is peak runoff rate ($m^3\ s^{-1}$), C is runoff coefficient for a given frequency event (Table 19.2), i is rainfall intensity ($mm\ h^{-1}$), and A is drainage area (hectares),

Table 19.2 Simplified table of Rational method runoff coefficients

Ground cover type	Runoff coefficient, c
Lawns	0.05–0.35
Forest	0.05–0.25
Cultivated land	0.08–0.41
Meadow	0.1–0.5
Parks, cemeteries	0.1–0.25
Unimproved areas	0.1–0.3
Pasture	0.12–0.62
Residential areas	0.3–0.75
Business areas	0.5–0.95
Industrial areas	0.5–0.9
Asphalt streets	0.7–0.95
Brick streets	0.7–0.85
Roofs	0.75–0.95
Concrete streets	0.7–0.95

Source: LMNO 2018, reused with permission of LMNO Engineering, Research, and Software, Ltd.; https://www.LMNOeng.com/Hydrology/rational.php

and 0.00278 converts hectare millimeters per hour to $m^3\ s^{-1}$. The Rational method is often used to design flow capacity for a structure, getting rainfall from intensity-duration-frequency (IDF) curves for the region of interest, with duration equal to the time of concentration and frequency set by local authorities (e.g., a 10-year storm frequency). The Rational method is predominantly used to design stormwater infrastructure for the peak runoff rate, including for low-impact development and green infrastructure designs (Montalto et al. 2007; Soulis et al. 2017), with a history of fusion into other design software, including geographical information systems (Djokic and Maidment 1991).

19.2.2.1 Effect of Trees

The impact of trees on peak flow or runoff reduction and water quality is not explicitly represented in this approach. The Rational method is not designed for simulating changes in tree cover in a mixed land cover scenario. While users could create a composite runoff coefficient to represent a parcel with sub-areas in tree and non-tree cover, the Rational method does not implicitly represent the drainage flow paths of sub-areas. Instead, users should apply the Rational method for each sub-area within the mixed area and route runoff from each sub-area to the outlet. Using this approach, users can adjust the sub-area in tree cover, based on the forest runoff coefficient value. This process has the advantage of being relatively simple in terms of calculations but relies on coefficients that do not necessarily capture the local tree processes and conditions that impact local stream flow and water quality.

19.2.3 Curve Number Approaches

The Curve Number (CN) model, developed by the USDA Natural Resources Conservation Service (Chin 2013), is a spatially lumped model that simulates runoff depth for a land parcel subjected to a single precipitation event. It has been combined with hydrograph models to estimate peak discharge (TR-55) and has been inserted into continuous weather water budget models (e.g., SWMM and SWAT; see below). The CN model water budget uses input of a 24-hour duration rainfall depth and represents the initial abstractions of rainfall prior to runoff. The model typically operates at one time step of 1 day. The CN runoff depth equation is:

$$Q = (P - (I_a S))^2 / (P + ((1 - I_a) S)) \quad (19.3)$$

where Q is the runoff (cm), P rainfall (cm), S potential maximum storage (cm), and I_a initial abstraction (cm). The I_a is typically 0.2 and represents surface depression storage, canopy interception, and infiltration. The S is related to the CN value, with a maximum of 100 representing no storage:

$$S = (2540/\mathrm{CN}) - 25.4 \quad (19.4)$$

Factors that determine CN include the parcel land cover, soil hydrologic soil group, hydrologic condition, and antecedent moisture condition. The CN method is often used to determine how land use development changes CN values and affects runoff depths for design events taken from an IDF curve, with durations of 24 h and frequency set by local authorities (e.g., a 10-year storm frequency). The Curve Number model is predominantly used for estimating changes in stormwater runoff with changes to precipitation, land cover, and CN values by practitioners and academics (Chin 2017; Li et al., 2018), and the model is regularly being updated to increase flexibility and accuracy, including changes to antecedent moisture settings (Sahu et al. 2010) and initial abstractions (Jain et al., 2006).

Innovative uses of the Curve Number model for water quality analysis include the US-based National Green Values Calculator (CNT 2018) and the Center for Watershed Protection (CWP)'s Making Urban Trees Count tree crediting framework (CWP 2017). The Green Values Calculator compares the performance, costs, and benefits of BMPs to conventional stormwater practices. This calculator determines the runoff volume capture capacity of the BMPs and the total runoff volume produced by the pre-development, conventional development, and green development scenarios using CN values. The tool is meant for a single site or a campus of buildings contained on a single site. The CWP tree crediting framework uses a range of CN inputs to establish pollutant load reduction credits and stormwater performance-based credits for trees around the United States. This provides a standard method in the United States for trees to be accounted for in water quality regulation compliance and in site-based stormwater management requirements.

19.2.3.1 Effect of Trees

The impacts of trees on runoff reduction and water quality are not explicitly represented in the CN equations. It is common, however, to create a composite CN for mixed land cover when there is no internal drainage from one sub-area to another. An average tree cover is assumed with the urban type land cover (e.g., residential), but the amount of tree cover is unknown. As tree cover varies in urban areas across the United States, this average tree cover approach is a limitation in estimating the effect of urban trees on runoff across the United States. Trees are accounted for under land cover including woods-grass combination (orchard or tree farm) and woods classes under other agricultural land types.

The National Green Values Calculator also adds trees as a specific BMP. Trees only affect progress toward the runoff reduction goal by decreasing the site impervious area that is used to determine the volume of precipitation/runoff that must be captured on site. In addition, tree box filters can provide a volume capacity benefit when the user defines the area and depth of the filter box installed around the tree (CNT 2018).

The Making Urban Trees Count framework estimates stormwater credits for trees based on how trees influence precipitation, runoff generation, and soil water holding capacity over the course of a year in a range of locations, soil types, and tree types (small, medium, and large deciduous trees; and small and large coniferous trees). Precipitation is reduced as a function of leaf area index. Runoff generation is a function of CN values, with CN adjusted based on the temporal effects of stemflow, the improved physical structure of soils by tree roots, and the soil water holding capacity at a given time step. Soil water holding capacity is influenced by evapotranspiration, which in turn is a function of maximum potential evapotranspiration and soil water storage at a given time step (Hynicka and Caraco 2017). This framework extends the utility of the Curve Number approach, adding parsimonious accounting of tree effects to enable stormwater credits for trees in the United States.

19.2.4 EPA National Stormwater Calculator

The US Environmental Protection Agency (US EPA)'s National Stormwater Calculator (SWC), managed by the EPA (Rossman and Bernagros 2018), is a spatially semi-distributed model that simulates the amount of rainwater and frequency of runoff from a specific site, for either a continuous simulation period or event-based storm. Model parameters include local soil conditions, land cover, and historic rainfall records. The user interface accesses several US databases that provide soil, topography, rainfall, and evaporation information for a chosen site. The user supplies information about the site's land cover and selects low-impact development (LID) controls they would like to use. Land cover in the project area is described as percentages of forest, meadow, lawn, desert, and impervious cover. Different types of pervious cover capture different amounts of rainfall on vegetation or in natural depressions and have different surface roughness. Surface roughness affects the velocity of runoff and in turn the potential for infiltration. All non-pervious area is presumed to be DCIA, and there is an LID option for disconnecting some of the impervious area. The LID controls include seven green infrastructure practices: disconnection, rain harvesting, rain gardens, green roofs, street planters, infiltration basins, and permeable pavement. An LID cost estimation module is available to assist in LID project planning. Cost estimates are based on user-defined size configuration of the LID control along with other project and site-specific parameters. The SWC uses the EPA's Storm Water Management Model (SWMM; Rossman and Huber 2016) as its underlying computational engine, sending user inputs to SWMM and post-processing its outputs in the background without requiring user involvement. The SWC is intended to provide screening-level analysis of small footprint sites, offering an accessible tool for a broader audience than SWMM in most cases. The EPA National SWC is predominantly used by practitioners and developers to examine reduction in stormwater runoff with implementation of LID and other management measures, in locations supported by the preloaded data (Kertesz et al. 2014; Schifman and Shuster 2019).

19.2.4.1 Effect of Trees

There is no explicit simulation of tree cover in the SWC, but as in the SWMM model described below, there are features intended to represent the influence of trees on the water cycle. Forest land cover and certain LID controls can approximate tree canopy interception by adjusting depression storage and can approximate transpiration by adjusting evaporation.

19.2.5 SWMM

The Storm Water Management Model (SWMM), managed by the EPA (Rossman 2017; Rossman and Huber 2016), is a spatially semi-distributed model that simulates runoff quantity and quality for storm sewers and their contributing areas subjected to a single precipitation event or continuous weather. The SWMM routines are divided into hydrologic and hydraulic components, each using 100s of equations and descriptive parameters. The hydrologic component maintains a water budget (i.e., conservation of mass) for snow and rain for the area surrounding the storm sewer using weather inputs of precipitation, temperature, evaporation, and wind speed and then simulating surface runoff to storm sewer inlets, infiltration to soils, groundwater, snowmelt, and inflow and infiltration to sewers. The hydraulic component maintains conservation of energy, momentum, and mass equations within the storm sewer, using inputs of inflows from the hydrologic component, then simulating the storm sewer network conveyance of flow with dynamic wave or kinematic wave hydraulic methods, and considering the impact of pumps and flow regulators (e.g., orifices, weirs, outlets). The user and input data define the time step (typically

1 min to 1 h with the model able to interpolate evaporation from monthly data), storm sewer network characteristics, land use types, water quality constituents and sources, and buildup and washoff rates by land use type.

SWMM is often used to determine how changes in storm water management (e.g., installation of green infrastructure, street sweeping schedules, and sewer networks) affect discharges based on preferred or regulated water quantity and water quality targets. The analysis can use any duration or frequency design storms from an IDF curve or continuous weather from historical or predicted periods. SWMM is actively maintained and provides a user guide with a quick start tutorial and tables of common parameter values. SWMM is predominantly used by practitioners and academics to understand the hydraulics of runoff within the storm sewer, including the timing, frequency, and volume of discharges with changes in land cover or precipitation, with research into improved calibration (Barco et al. 2008), low-impact development (Palla and Gnecco 2015; Aad et al. 2010), and accounting for uncertainty (Muleta et al. 2013).

19.2.5.1 Effect of Trees

There is no explicit simulation of tree cover in SWMM, but there are features intended to represent the influence of trees on the water cycle. The SWMM low-impact development (LID) controls allow simulation of runoff capture and treatment prior to entry into the storm sewer, and these LID features include permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches, and vegetative swales. SWMM envisions trees and other vegetation would be in a certain LID, such as rain gardens and vegetative swales. For tree or other vegetation canopy interception, the SWMM manual recommends this depth of storage be included in the model depression storage property and that it will be reset when evaporation removes water from depression storage. For evapotranspiration by trees and other vegetation, SWMM allows for the user to define the soil depth to which evapotranspiration can occur and the fraction of total evaporation available to evapotranspiration. SWMM can also simulate the storage area within the LID that is occupied by vegetation, so water storage volumes can be adjusted. SWMM will simulate user-defined land uses, and their effect on water quality, including the removal efficiency of best management practices (BMPs) located with that land use. These BMPs are not specifically intended to represent the role of trees but could be parameterized to represent such effects.

19.2.6 HSPF

The Hydrological Simulation Program-FORTRAN (HSPF), managed by the EPA (Bicknell et al. 1993), is a spatially semi-distributed model that simulates runoff quantity and quality for watersheds, sub-watersheds, and interior land segment units with homogeneous hydrologic response, when subjected to continuous weather. The HSPF routines are divided into application and utility modules, most using 100s of equations and descriptive parameters. The application modules include pervious land, impervious land, reaches and reservoirs, and best management practices, while the utility modules include management and analysis of time series of weather input and water flux, storage, and quality output. The land segments maintain a water budget for snow and rain, considering elevation impacts on air temperature and implementing vertical redistribution of water between the vegetation canopy, depression storage, soil moisture, groundwater, and the atmosphere via evapotranspiration.

A lateral redistribution of surface and subsurface water is implemented to move excess water to the channel network, and the Green-Ampt model is used to determine infiltration and surface runoff. The reach and reservoir module simulates runoff hydrographs, transport and retention of pollutants from land segments, as well as water temperature, dissolved oxygen, carbon, and plankton. The user and input data define the time step (typically 1 min to 1 h, with a maximum of 1 day), reach and reservoir characteristics, depth to discharge relationships to determine hydrographs, land use types, water quality constituents and sources, and buildup and washoff rates by land use type. Water quality constituents can be in gaseous, soluble, or sediment-sorbed forms, and routines are available for sediment production and erosion and the fate of pesticides and nitrogen and phosphorus.

HSPF is used to determine how changes in watershed management (e.g., land use, reservoir operations, flow diversions, in-stream aeration, and best management practices including street sweeping) or climate affect discharges based on preferred or regulated water quantity and water quality targets. HSPF provides a database of parameters from prior model runs and supports use of the PEST tool for parameter calibration and evaluation. HSPF derives from the Stanford Watershed Model, is not actively updated, but is accessible in the actively maintained EPA BASINS, with tutorials. HSPF is predominantly used for analysis of changes to runoff quality and quantity to changes in weather, land cover, and configuration of routing or best management practices, often with regulatory applications such as total maximum daily load planning (Benham et al. 2006; Mohamoud and Zhang 2019; Lee et al. 2018)

19.2.6.1 Effect of Trees

There is no explicit simulation of tree cover in HSPF, but there are features intended to represent the influence of trees on the water cycle. The HSPF best management practice (BMP) module allows modification of the linkage between land and water segments through specification of generic functions, which could represent tree effects on runoff and pollutant reductions. HSPF expects trees and other vegetation would be in certain land uses, such as forest, agro-forestry, or urban green infrastructure, and simulates vegetation canopy interception, as well as the influence of vegetation on the nitrogen and phosphorus cycles. Evapotranspiration by trees and other vegetation will reset interception and reduce the water storage in both soil layers and subsurface discharge. The HSPF water temperature routines provide a parameter to reduce incoming radiation due to shading by trees and other structures.

19.2.7 SWAT

The Soil and Water Assessment Tool (SWAT) model, managed by the Texas Water Resources Institute (Neitsch et al. 2011), is a spatially semi-distributed model that simulates runoff quantity and quality for watersheds, sub-watersheds, and interior land segment units with homogeneous hydrologic response, when subjected to continuous weather. The SWAT routines can be divided into hydrologic and bio-geochemical, including soil, vegetation and atmospheric features, and water quality components, each using 100s of equations and descriptive parameters. The hydrologic response units maintain a water budget for snow and rain, requiring weather inputs and considering elevation impacts on air temperature and precipitation, implementing vertical redistribution of water between the vegetation canopy, depression storage, soil moisture, groundwater, and the atmosphere via evapotranspiration. SWAT is used for a variety of applications around the world including assessments of hydrology, pollutants, conservation agriculture (Ullrich and Volk 2009), and climate change impacts, as reviewed by Gassman et al. (2007).

SWAT simulates crop growth and scheduled management operations (e.g., fertilization, grazing, tillage) to estimate their impact on water quantity and quality. A lateral redistribution of surface and subsurface water is implemented to move excess water to the channel network, with the CN or the Green-Ampt model used to determine infiltration and surface runoff. SWAT uses a set of routing routines to transport water, its temperature, sediment, nutrients, and other constituents through its channels and reservoirs and a version of the Rational method combined with estimates of velocity, flow distance, and lag time to determine hydrograph timing and peak flow.

The user and input data define the time step (typically 1 h to 1 day, with the model able to interpolate from monthly data), reach and reservoir characteristics, land use types, water quality constituents and sources, and buildup and washoff rates by land use type. Water quality constituents can be in gaseous, soluble, or sediment-sorbed forms, and routines are available for sediment erosion and the fate of pesticides, nitrogen and phosphorus, carbon, and bacteria. SWAT is typically used to determine how long-term (> 1-year) changes in watershed management (e.g., land use, reservoir operations, flow diversions, in-stream aeration, and best management practices including street sweeping) or climate affect discharges based on preferred or regulated water quantity and water quality targets. SWAT provides several model input parameter databases, including plant growth, and a weather generator and example watershed configurations. SWAT derives from water quantity and quality models known as CREAMS, GLEAMS, EPIC, SWRRB, CFARM, ROTO, and QUAL2E and is actively updated (SWAT+ is in development) as of early 2019.

19.2.7.1 Effect of Trees

There is explicit simulation of tree cover in SWAT, as one of seven agricultural land cover groups that also include perennial and warm and cold season annual crops. SWAT simulates the rooting depth as the maximum allowed for the tree and soil, partitions new growth between leaves and woody growth, and converts a fraction of biomass to residue at the end of each growth season. SWAT uses minimum and maximum leaf area index with annual phenology to grow out the canopy area. SWAT explicitly simulates canopy interception of precipitation when the Green-Ampt infiltration method is used, but this is implicitly represented when the CN method is used to estimate initial abstractions. SWAT simulates the influence of vegetation on the nitrogen and phosphorus cycles. Evapotranspiration by trees and other vegetation will reset interception and reduce the water storage in both soil layers and subsurface discharge. The SWAT best management practice (BMP) modules allow specification of generic functions and include a specific vegetative filter strip module to represent tree effects on runoff and pollutant reductions.

19.2.8 RHESSys

The Regional Hydro-Ecological Simulation System (RHESSys) model (Tague and Band 2004) is a spatially semi-distributed model that simulates runoff quantity and quality for small- to mid-sized river basins, interior hillslopes, and smaller patches defined as hydrologic response units, when subjected to continuous weather. The RHESSys routines can be divided into hydrologic and biogeochemical, including soil, vegetation and atmospheric features, and carbon and nitrogen components, using 100s of equations and descriptive parameters. The patches, representing pervious land, roads, or channels, maintain a water budget for snow and rain, requiring weather inputs specific to microclimate zones. It implements vertical redistribution of water between the vegetation canopy, leaf litter, depression storage, soil moisture, groundwater, and the atmosphere via evapotranspiration.

RHESSys simulates plant and tree growth and can schedule management operations (e.g., fire, clear-cutting) to estimate their impact on water quantity and quality. A lateral redistribution of surface and subsurface water can be explicitly routed between patches or approximated with the topographic index, and hillslope water is sent directly to the basin outlet, with the Phillip and Green-Ampt models used to determine infiltration and surface runoff. RHESSys uses detailed carbon and nitrogen cycle routines. The user and input data define the time step (typically 1 day), parameters regulating carbon and nitrogen fluxes and storage, and a geographic information system is recommended to pre-process elevation, soil, and land cover data. RHESSys is typically used to determine how changes in watershed management (e.g., land use and road networks) or climate affect the storage and flux of water, carbon, and nitrogen based on water quantity and water quality targets.

RHESSys input pre-processing is supported with GRASS GIS routines and documentation. RHESSys derives from water quantity and quality models known as TOPMODEL (Beven et al. 1995), DHSVM, MTN-CLIM, BIOME-BGC, and $CENTURY_{NGAS}$ and is actively updated. The RHESSys model is predominantly used to analyze hydro-ecological processes and test hypothesis useful for guiding management, and uses have varied from analysis of snow-dominated areas (Christensen et al. 2008) to regions at risk of fires (Tague et al. 2004).

19.2.8.1 Effect of Trees

There is explicit simulation of tree cover in RHESSys. Trees are within a landscape patch that can contain a mixture of other land cover types. RHESSys simulates tree and other vegetation leaves, stems, and roots and the storage and flux of water, carbon, and nitrogen in these plant components when they are living and as dead organic residue. The model estimates the rooting zone temperature and moisture content, partitions new growth between leaves and woody growth, and converts a fraction of biomass to residue at the end of each growth season. RHESSys uses minimum and maximum leaf area index with annual phenology to grow out the canopy area and maintains an upper and lower canopy layer. RHESSys explicitly simulates canopy interception of precipitation and the extinction of solar radiation used in photosynthesis (and respiration) routines, considering shaded and sunlit leaves separately. RHESSys simulates the influence of feedback between vegetation growth and the carbon and nitrogen cycles and simulates the nitrogen cycle in the soil, as well as its flushing from patches to the receiving water. Evaporation resets canopy interception and reduces the water content in depression storage, and RHESSys simulates stomatal conductance to update carbon storage in the vegetation and soil moisture storage.

19.3 Summary of Modeling Urban Forest Hydrology

There are numerous models used to estimate tree effects on hydrology. These models have varying methods and levels of simplifying assumptions. Some models use simplified approaches to facilitate ease of estimation by managers. Other models use more detail and sophisticated estimation procedures but, in doing so, can limit the ease of use by managers. By understanding the differences in the models discussed in this chapter, users can choose the best models for their application and expertise. The models described in this chapter are summarized to aid in understanding their key attributes related to trees and hydrologic functions (Table 19.3). The models described in this chapter were selected to meet the following criteria:

Table 19.3 List of models described in this chapter and their key attributes

Model	Feature			
	Input complexity	Runoff (R), hydrology (F), or hydraulic (P)	Event-based (E) or continuous (C)	Water quality methods
i-Tree Hydro	Moderate	R, F	E and C	EMC
Rational method	Low	R	E	N/A
Curve Number	Low	R	E	N/A
EPA SWC	Low	R	E and C	N/A
EPA SWMM	Moderate	R, F, P	E and C	Buildup/washoff, urban BMPs
HSPF	High	R, F	E	Chemical applications, Buildup/washoff, sediment, pesticide, nutrient cycles, Ag and urban BMPs
SWAT	High	R, F	C	Chemical applications, Buildup/washoff, sediment, pesticide, carbon, bacteria, nutrient cycles, Ag and urban BMPs
RHESSys	High	F	C	Carbon and nitrogen biogeochemistry

R – runoff: This modeling approach partitions rainfall to runoff, without necessarily representing the theory and processes of cause and effect used in mechanistic models
F – flow, hydrology: This modeling approach maintains conservation of mass (i.e., a water budget) using weather inputs. Model processes can include surface runoff to storm sewer inlets, infiltration to soils, groundwater, snowmelt, and inflow and infiltration to sewers
P – pressure, hydraulic: This modeling approach maintains conservation of energy, momentum, and mass equations using inputs of inflows from the hydrologic component. Model processes including storm sewer network conveyance of flow with dynamic wave or kinematic wave hydraulic methods and considering the impact of pumps and flow regulators (e.g., orifices, weirs, outlets)
E – event-based: This modeling approach simulates one precipitation event to estimate runoff response, typically ignoring evapotranspiration
C – continuous: This modeling approach simulates a period of time to represent any number of precipitation events and the evapotranspiration that follows

– Public domain/free to use
– Useful to the broad stormwater management community/not too specialized
– Capable of simulating tree or forest effects on hydrology

This list may not be comprehensive, as some models may have been omitted that meet these criteria.

Each of these models has some form of a water balance to partition precipitation into runoff, and the moderate- to high-complexity models typically account for other water storage and fluxes, such as soil moisture and evapotranspiration.

Biogeochemical processes are typically regulated by these water storages and fluxes. In general, hydrological processes drive the transport of pollutants, as well as affect their chemical fate by regulating temperature, residence time, chemical interactions, and exposure to reactions, uptake, or assimilation. Some models have algorithms to simulate specific pollutant cycles, including those of sediment, pesticide, carbon, bacteria, nitrogen, and phosphorus. These cycles are generally more complex to model than hydrological cycles; thus many models use a simplified approach for estimating water quality or do not estimate water quality. All of the high-complexity models covered in this chapter allow the user to ignore complexity and simulation of pollutants and focus instead on parameterization and simulation of hydrologic processes. i-Tree Hydro, a moderate-complexity model, uses a fixed estimate of pollutant concentration (EMC) that is independent of hydrology and simply multiplies surface runoff by the EMC of a pollutant to estimate pollutant loading. The models which do explicitly account for pollutant cycles and biogeochemical processes (e.g., SWAT, RHESSys) are advanced tools that have more extensive and uncertain input requirements. The level of expertise required to use high-complexity pollutant cycle models often limits use to specialized audiences with advanced training. Given the increasing challenges in managing water quality in landscape scales, advances in accessibility of modeling biogeochemical processes related to vegetation will be an important next step for modeling the hydrologic effects of trees.

The degree to which the trees affect water quality is a function of many factors, including the hydrology, soils, and vegetation. Trees will have fewer beneficial impacts on water quality when the runoff is decoupled from natural processes related to physical filtering, chemical transformation, or biological uptake. This decoupling occurs when concentrated surface flow bypasses filtering, such as street runoff in a gutter, water transport through pipes, or pervious runoff in a rill. It also happens when deeper subsurface flows pass below tree root zones, which can occur in urban areas when flood control measures lower the water table. Actions to help minimize water pollution include (1) reducing surface runoff (e.g., reducing impervious area or increasing infiltration), (2) increasing water contact with soils and vegetation (e.g., increasing infiltration and water retention), and (3) reducing surface pollutants (e.g., increasing street sweeping or reducing deposition of pollutants). Urban trees and natural surfaces help break up the continuity of impervious cover, which can substantially reduce runoff. In addition, trees can provide numerous other benefits to society (Nowak 2018).

19.3.1 Future Directions

There are opportunities and a need for collaboration and cross-pollination among the diversity of hydrology models. Currently, some strengths of hydrology models are limited to only one tool or specialized tools, for example, explicit simulation of trees (i.e., i-Tree Hydro), whole-system biogeochemical modeling (i.e., RHESSys), and explicit documentation of a tool's modeling philosophy and architecture (i.e., HSPF). Technology can facilitate bridging gaps among models and users. Increased connectivity and transparency are exemplified in OpenSWMM, a free knowledge base for the user community of EPA's SWMM, hosted by CHI (OpenSWMM 2018). OpenSWMM includes an email-based forum for users to share ideas and ask questions; a web-based source code viewer with an interface for commenting or suggesting changes to SWMM code; and a platform for sharing SWMM-based research projects, enabling the project itself to receive expert attention and feedback from the community while also providing examples of model use for the community. Leveraging advances in the technology can empower the next generation of models to be more accessible and provide better support for their users.

The future of eco-hydrology modeling is likely to become more advanced in accuracy and accessibility as advances in computer science are applied to the field. Broader and richer data sources (from advances in remote sensing, instrumentation, and open data sharing) along with more powerful means of analysis (with advances in machine learning and hardware for data storage and computations) could revolutionize how hydrology models are developed, maintained, parameterized, and used. Distributed computing can enable basic devices to access robust, computationally intensive models. There are already examples of innovations in computer science diffusing into hydrology modeling, as is the case with Google's AI-enabled flood forecasting (Matias 2018).

The overarching needs that users have for models of urban tree effects on hydrology will continue to shape future model development. Those needs include crediting of trees to meet requirements of stormwater regulations, decision support for optimization of hydrologic benefits from urban forests, and valuation of tree effects on water resources. Crediting trees for their role in meeting stormwater management requirements has been the focus of recent investigations (Kuehler et al. 2017; CWP 2017; CWP 2018) and is being implemented in some US cities (MPCA 2017). Decision support is becoming a focus of more recent models, including i-Tree Landscape and the EPA's SWC. Valuation of runoff reduction and water quality improvement is complex, but approaches do exist (e.g., McPherson et al. 2007). Each of these modeling needs presents opportunities for significant improvement. As hydrology models and field studies advance in estimation of tree effects, the capacity to meet these modeling needs will increase. While more research is needed regarding urban tree effects on hydrology, models are currently being used to assess the hydrologic benefits that trees provide. Water resource managers can refer to these tools today to better account for the hydrologic effects of trees and hopefully improve urban water management and quality through better urban forest management and designs.

19.4 Disclaimer

The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such does not constitute an official endorsement or approval by the US Department of Agriculture Forest Service, Davey Tree, or the SUNY College of Environmental Science and Forestry of any product or service to the exclusion of others that may be suitable.

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