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15 Valuing Urban Tree Impacts on Precipitation Partitioning

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Abstract

Trees impact surface stormwater runoff, soil moisture, streamflow, water quality, and air temperatures by intercepting precipitation (rain and snow), enhancing soil water infiltration, shading surfaces, and evapotranspiring water. These impacts affect human health and well-being. Many of these tree impacts remain to be more accurately quantified and valued, particularly related to water quality aspects such as mass (e.g., sediments), chemical (e.g., nutrients, metals, pesticides), biological (e.g., pathogens, microbes), and thermal loads. Urban trees can help mitigate many of the negative hydrologic effects created by the relatively large amount of impervious surfaces in cities. Urban tree impacts are generally positive but can create negative outcomes if improperly managed (e.g., leaves or branches clogging drains or streams). Although more and better valuation of tree impacts is needed, studies to date value tree effects on reducing runoff into water bodies in the range of millions of dollars per year at the city or watershed scale.

Keywords

Rainfall interception • Throughfall • Stemflow • Stormwater • Hydrology • Urban forest • Urban forestry

15.1 Introduction

One of the more important benefits that trees provide in urban settings relates to their hydrological functions, which impact surface stormwater runoff, soil moisture, streamflow, water quality, and air temperatures. Trees affect hydrological processes primarily through three main precipitation partitioning mechanisms: canopy interception, soil water infiltration, and evapotranspiration, which includes evaporation from leaf and soil surfaces and transpiration of soil moisture through leaves. Trees also affect water quality by generally decreasing the concentration and amount of nutrients and pollutants reaching a water body. Air temperatures can be reduced by trees returning precipitation to the atmosphere via evapotranspiration (ET).

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With ET, some of the net radiation that would otherwise warm air temperature is directed to evaporating water when water is available (latent heat). Further, warm air passes its heat to the evaporating water, which also reduces the temperature of the air (sensible heat).

The impact of trees can vary within an urban environment depending upon the extent of impervious surfaces and variations in urban forest structure and management. Impervious surfaces limit the infiltration of water into soils, and due to their slopes and relative smoothness can accelerate runoff speed, increasing peak flows reaching streams through pipe or gutter networks. Urban forest structure affects rainwater storage, evaporation, and transpiration through variations in the number of trees, species composition, and leaf area. Likewise, urban forest management can affect local tree composition, density and leaf area through such actions as tree planting, removals, and pruning.

The purpose of this chapter is to discuss how urban trees and impervious surfaces combine to affect streamflow, soil moisture, and water quality, as well as air temperature; review economic impacts of changes in streamflow and water quality; and summarize how tree processes can affect these economic impacts and which impacts need to be valued. By understanding tree impacts on hydrology and their wide-ranging broader impacts, better management plans can devise uses for trees and forests to improve water quality, reduce negative economic impacts, and promote human health and well-being.

15.2 Tree Impacts on Hydrology (Evapotranspiration, Streamflow, and Soil Moisture)

Trees affect streamflow rates primarily through: (a) rain and snowfall interception, which captures precipitation in the tree canopy on leaf and stem surfaces and prevents, slows, and reduces precipitation reaching the ground; (b) enhancing soil water infiltration via tree root impacts, which reduces total and peak runoff and recharges unsaturated and saturated soils pores used to support plants and baseflow to rivers; and (c) evapotranspiration, which cools air temperatures and regenerates water storage space in the canopy and in soils for future precipitation. These processes are part of a natural hydrologic cycle. While these processes generally increase baseflow in streams and reduce peak streamflow events (e.g., flooding), unmanaged trees can also increase flooding if branches or leaves clog drains or dam streams.

15.2.1 Rainfall and Snow Interception, Throughfall and Stemflow

Tree canopies intercept precipitation in the form of snow and rain, on leaves and branch surfaces, thereby affecting runoff volumes and delaying the onset of peak stream flows. Trees have a specific leaf water holding capacity ranging from 0.07 to 0.6 mm, with an average of 0.25 mm, and an average branch water holding capacity of 0.15 mm (Wallace et al. 2013; van Dijk 2010). The snow storage capacity of leaves can be much greater, maximizing around 40 mm under favorable conditions, like high-density maritime snow on evergreen forests (Storck et al. 2002).

The leaf rain or snow water holding capacity is multiplied by the tree canopy leaf area index to get the total depth of canopy interception at any time. During a precipitation event, some of this water can evaporate, some can be blown off, and some can drip off and become throughfall or flow down the branches and trunk as stemflow. The effect of stemflow in concentrating rainfall from the relatively large canopy area to the relatively small trunk area is quantified as a funneling ratio; a funneling ratio of 10 implies 10 mm of rainfall depth arrives as stemflow for each 1 mm of rainfall measured above the canopy. Schooling and Carlyle-Moses (2015) report average funneling ratios of 17.7 for single leader trees, and 20.2 for multi-leader trees. Single leader trees have a dominant main stem trunk or leader, while a multi-leader tree has two or more leaders converging at the base of the tree, with each leader intersected by feeder branches (Schooling and Carlyle-Moses 2015).

The depth of the canopy water storage capacity often exceeds the depth of precipitation for many low intensity and short duration precipitation events. The water storage capacity of tree bark and the plants living on the canopy (i.e., epiphytes and parasites) can be substantial: 0.2–5.9 mm (Liu 1998; Pypker et al. 2011) and 0.4–16.6 mm (Jarvis 2000; Van Stan and Pypker 2015), respectively. Together, leaves, bark, and epiphytes can result in canopy water storage capacities up to 19 mm (Porada et al. 2018). For more information on water storage capacity of vegetation elements and their influencing factors during rainfall and snow, the reader is referred to Chap. 2.

Urban tree canopy interception may be different from that of natural forests because of differing microclimates and tree architecture (Fig. 15.1). Compared with rural forests, urban forests typically have fewer trees per unit area, larger average tree stem diameters, greater species diversity with different phenological patterns, and greater spatial variation in canopy

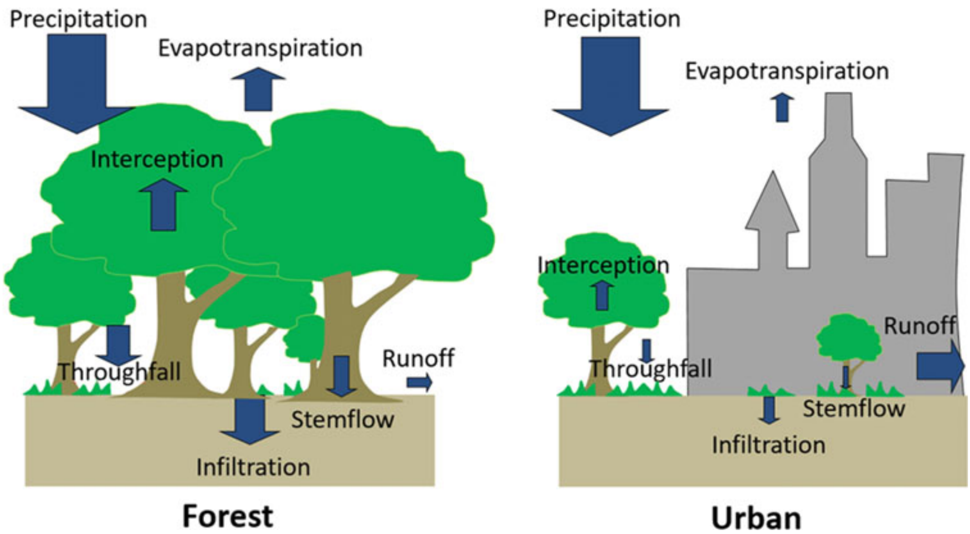

Fig. 15.1 Schematic of hydrologic process differences between a forest and urban area. Due to reduced tree cover and increased impervious surfaces, urban areas typically have reduced evapotranspiration, interception, throughfall, stemflow and infiltration, and increased runoff, relative to forested areas

cover (McPherson 1998). Urban forest structure is influenced by a mix of varying management actions (e.g., tree planting, pruning), natural regeneration and other natural (e.g., storms) and anthropogenic (e.g., development) forces that create forest change (Nowak 2012, 2017).

15.2.2 Soil Water Infiltration

Precipitation reaching the ground beneath canopies can enter soils in a natural hydrologic cycle. Terrain micro-topography and tree organic matter can pool and slow water movement on the soil, and tree root growth and decomposition in soils can increase water infiltration rates into soils and reduce surface runoff. Infiltration rates vary through time and are fastest when soils are dry due to suction of water into the pores via capillary action, and then progressively decrease to the slowest rate, which is typically limited by the soil saturated hydraulic conductivity. The soil saturated hydraulic conductivity varies with soil texture, structure, and compaction, with an estimated value of 2.99 cm hr^{-1} for loamy sands and 0.05 cm hr^{-1} for silty clays with standard compaction based on numerous observations from across the United States (Rawls et al. 1983). Tree roots also create soil macropores that can accelerate infiltration through soil pores, further reducing runoff and recharging deeper soil water (Aubertin 1971). Forests can be used as buffers around water bodies to naturally filter and infiltrate runoff. Thus, forest buffers can not only reduce the quantity of urban runoff but also reduce pollutants carried with urban runoff through physical, chemical, and biological processes in the soil. Greater detail on the relationship between soil moisture patterns and throughfall and stemflow can be found in Chap. 13.

15.2.3 Evapotranspiration

Land cover strongly affects evapotranspiration (ET). ET is a measure of the amount of water evaporated from surfaces or transpired (evaporation of liquid water in the plant) through leaf stomata. Globally, two-thirds of precipitation is evapotranspired, returned to the atmosphere through evaporation and transpiration (Hornberger et al. 1998). Evapotranspiration, on average, annually accounts for 484 mm, nearly 60% of the 800 mm that falls on average as precipitation over the global land area (Chin 2013). Over oceans, evaporation accounts for more than total precipitation, with additional water provided by river runoff to the ocean. The combined flux of evaporation and transpiration from trees is lower than the evaporation from an open water surface, due to resistances to vapor flux in tree stomata and the canopy air. Soil pores and the overlaying air typically have even greater resistances to vapor flux, and hence have lower rates of ET than trees. Given that ET from soils is at a lower rate than ET from trees, removal of forest cover can increase streamflow as a result of reduced ET, as well as lost attenuation through interception.

When water is not limited by storage, rates of ET are a function of tree leaf area index and stomatal conductance, as well as atmospheric variables such as vapor pressure gradient, wind speed, pressure, and radiation. Generally evergreen trees have the highest actual ET, due to year-round ET, followed by deciduous trees, shrubs, and grasses, with differences diminished in areas with low mean annual precipitation (Matheussen et al. 2000). Evapotranspiration changes the phase of water from liquid to gas and reduces local air temperatures (Akbari et al. 1992). A comparison of different evapotranspiration components in forest ecosystems and their dynamics/controls is provided in Chap. 3.

15.3 Tree Impacts on Stormwater Quality

Precipitation partitioning by plants not only affect water flows, but also water quality. Important tree-based processes that can improve stormwater quality include: (a) soil filtration of particles/sediments and adsorption of chemicals that can reduce the transport of substances such as plant and animal wastes, nutrients, pesticides, petroleum products, metals, and other compounds that can cause water quality problems (Clark 1985; Neary et al. 1988); (b) nutrient assimilation by plants which can reduce excess nutrients (e.g., nitrogen, phosphorous) reaching the stream and degrade water quality (e.g., eutrophication) (Dupont 1992; US EPA 1995); (c) slowing the movement of metals and other contaminants (e.g., pathogens, pesticides) to surface waters, thereby increasing the opportunity for the contaminants to become buried in sediments, adsorbed into clays or organic matter, or transformed by microbial and chemical processes (Johnston et al. 1984; Young et al. 1980; MacKay 1992); (d) degradation or volatilization of chemicals by microorganisms (Winogradoff 2002); and (e) shading surfaces and reducing air temperatures, which reduces thermal loads on shaded objects and can reduce the heating of river water, thereby mitigating biological activity that can degrade water quality (e.g., eutrophication) (Yang et al. 2008).

15.3.1 Sediments

Sediments are considered the largest pollutant by mass in surface waters and are primarily transported by surface runoff. Sediment refers to soil particles that enter receiving waters from eroding land, including plowed fields, logging sites, urban construction, and eroding stream banks (US EPA 1995). Trees can also increase sediments in surface runoff due to stemflow funneling water from the canopy to the base of the tree. The magnitude of this stemflow initiated erosion depends upon tree architecture, rainfall intensity, and soil cover/conditions (e.g., Herwitz 1986; Keen et al. 2010). To reduce the likelihood of stemflow initiated soil erosion in urban areas, Schooling et al. (2015) recommend maintaining high infiltration capacities at the base of trees, or maintaining micro-topography that retains soils rather than conveying them to receiving waters.

In addition to mineral soil particles, eroding sediments may transport other substances such as plant and animal wastes, nutrients, pesticides, petroleum products, metals, and other compounds that can cause water quality problems (Clark 1985; Neary et al. 1988). Sedimentation of receiving waters can have negative impacts on water quality and aquatic habitat. In a study of upper Chattahoochee River Basin, GA, the greatest suspended sediment yields were from urban areas, compared with forested and agricultural lands (Faye et al. 1980). In Virginia, forestry practices contributed little sediment; agriculture was an important source of sediment, and urban development contributed the most sediment (as well as other pollutants) (Jones and Holmes 1985).

Studies indicate that forest riparian buffers can effectively trap sediment when runoff is spread across the area and not concentrated in a rill or gully, ranging from removal of 60–90% of the sediment (Cooper et al. 1987; Daniels and Gilliam 1996). Along the Little River in Georgia, riparian forests have accumulated between 350 and 529 tonnes ha^{-1} of sediment annually over the last 100 years (Lowrance et al. 1986). Based on this finding, a hectare of riparian forest can protect between 39 and 112 ha, using national average erosion rates between 4.7 and 9 tonnes ha^{-1} of sediment annually. Many factors influence the ability of the buffer to remove sediments from land runoff, including the sediment size and loads, slope, type and density of riparian vegetation, presence or absence of a surface litter layer, soil structure, surface and subsurface drainage patterns, and frequency and intensity of storm events (Osborne and Kovacic 1993).

15.3.2 Nutrients

Nutrients are essential elements for aquatic ecosystems, but in excess amounts, they can lead to many changes in the aquatic environment and reduce the quality of water (Dupont 1992). Urban runoff can transport chemicals that lead to nutrient enrichment in rivers (Long and Dymond 2014; Allan and Castillo 2007). Lawn and crop fertilizers, sewage, and manure are major sources of nutrients in surface waters. Industrial sources and atmospheric deposition also contribute significant amounts of nutrients (Guldin 1989). One of the most significant impacts of nutrients on streams is accelerated eutrophication, the excessive growth of algae and other aquatic plants in response to high levels of nutrient enrichment (US EPA 1995). When this growth dies, its decomposition will lower the oxygen level in the water column and can lead to loss of target water species and uses. In addition, some forms of nutrients can be directly toxic to humans and other animals (Chen et al. 1994; Evanylo 1994). In general, the highest nitrogen and phosphorus yields typically occur in highly agricultural and urbanized watersheds, and lowest nutrient yields occur in streams of forested watersheds (e.g., Spruill et al. 1998; Hampson et al. 2000). Riparian forests have been found to be effective filters for nutrients, including nitrogen, phosphorus, calcium, potassium, sulfur, and magnesium (Lowrance et al. 1984a, b).

Riparian forests have been shown to reduce between 48 and 95% of nitrogen from stormwater runoff (Lowrance et al. 1984b; Peterjohn and Correll 1984; Jordan et al. 1993; Snyder et al. 1995). In urban areas, such forests and their soils can include vegetation bordering flow paths along drainage paths or other intermittent channels. The processes by which soils remove nitrates include denitrification, uptake by vegetation and soil microbes, and retention in riparian soils (Beare et al. 1994; Evanylo 1994). Trees can take up large quantities of nitrogen as they produce roots, leaves, and stems, with a fraction, returned to the soil as plant materials decay. For example, scientists in Maryland estimated that deciduous riparian forests took up 77.4 kg ha^{-1} of nitrogen annually, and returned 61.7 kg ha^{-1} (80%) each year in the litter (Peterjohn and Correll 1984). Nevertheless, Correll (1997) suggested that vegetative uptake is still a very important mechanism for removing nitrate from riparian systems, because vegetation (especially trees) removes nitrates from deep in the ground, converts the nitrate to organic nitrogen in plant material, then deposits the plant materials on the surface of the ground where the nitrogen can be mineralized and denitrified by soil microbes.

Riparian areas can be important sinks for phosphorus; however, they are generally less effective in removing phosphorus than either sediment or nitrogen (Parsons et al. 1994). Removal of phosphorus by riparian stands range from 30 to 80% (Cooper et al. 1987; Lowrance et al. 1984b; Peterjohn and Correll 1984). Some phosphorus may be taken up and used by vegetation and soil microbes, and like nitrogen, much of this phosphorus is eventually returned to the soil. For example, researchers estimated that less than 3% of the phosphate entering a floodplain forest in eastern North Carolina was taken up and converted to woody tissue, while scientists in Maryland reported a deciduous riparian forest buffer annually took up 9.9 kg ha^{-1} of phosphorus but returned 7.8 kg ha^{-1} (80%) as litter (Brinson et al. 1984; Peterjohn and Correll 1984). In some riparian areas, small amounts of phosphorus (0.06–2.4 kg ha^{-1}) may be stored as peat annually (Walbridge and Struthers 1993). Through leaf and branch drop into streams, trees add nutrients to streams and provide food and habitat for various aquatic organisms (Allan and Castillo 2007).

15.3.3 Metals

Riparian areas may slow the movement of metals and other contaminants to surface waters and increase the opportunity for the contaminants to become buried in the sediments, adsorbed into clays or organic matter, or transformed by microbial and chemical processes (Johnston et al. 1984). Urban runoff can increase the concentration of contaminants such as copper (Cu), zinc (Zn) (Strecker 1998), nitrogen (N), phosphorus (P), degradable carbon (Dong et al. 2013), and dissolved salts (Merikhpour and Jalali 2013). The fate of metals in riparian areas is not well understood. However, scientists in Virginia have found significant amounts of lead, chromium, copper, nickel, zinc, cadmium, and tin buried in the sediments of the floodplain along the Chickahominy River downstream of Richmond (Hupp et al. 1993). Analysis of the woody tissue of trees reveals that these compounds are also taken up by the trees. Therefore, sediment deposition and uptake by woody vegetation may help mitigate heavy metals in riparian areas.

15.3.4 Pathogens and Other Microbes

Pathogens such as waterborne bacteria, viruses, and protozoa are the source of many diseases that infect humans, livestock, and other animals (Chesters and Schierow 1985; Palmateer 1992). There is relatively little information on the role of riparian buffers on pathogens. In one study, strips of corn, oats, orchardgrass, and sorghum/sudangrass were all effective in reducing bacterial levels by nearly 70% (Young et al. 1980). They estimated a vegetation buffer 36 m wide would be required to reduce total coliform bacteria to levels acceptable for human recreational use. Other researchers have demonstrated the ability of grass sod filter strips to trap bacteria from dairy cow manure under laboratory conditions (Larsen et al. 1994). They found that even a narrow (0.61 m) strip successfully removed 83% of the fecal coliform bacteria, while a 2.1 m filter strip removed nearly 95%. Further information on the microbial communities hosted on habitats throughout the plant microbiome and how they may be connected and transported during storms can be found in Chap. 14.

15.3.5 Pesticides

Pesticides are a common issue in urban areas with a wide array of insecticides, repellents, herbicides, fungicides, disinfectants, and rodenticides used in urban pest management programs (Racke 1993). Pesticides were frequently present in streams and, to a lesser extent, groundwater, particularly in areas with substantial agricultural and/or urban land use. Pesticide concentrations exceeding human health benchmarks are more likely for streams with agricultural or urban watersheds, which account for ~12 and 1%, respectively, of public water supply intakes on streams (Gilliom 2007).

Few studies have been conducted that examine the fate of pesticides in riparian areas. However, where the proper conditions exist, riparian forest buffers have the potential to remove and detoxify pesticides in runoff. Probably the most important process is the breakdown of organic chemicals by soil microorganisms (MacKay 1992). Scientists have observed that soil microorganisms adapt to the presence of a pesticide and begin to metabolize it as an energy source (Fausey et al. 1995). As it is metabolized, the pesticide is broken down into various intermediate compounds, and ultimately carbon dioxide. In addition, most pesticides have a high affinity for clay and organic matter and may be removed from the soil water as they are bound to soil particles. Once bound, pesticides are often difficult to desorb from the soil (Clapp et al. 1995). Pesticides are often designed to degrade in soils in an effort to limit their adverse impacts when released in the environment (Kah et al. 2007).

15.3.6 Stream and Air Temperatures

Changes in both chemical and thermal properties of the water reaching rivers affect local water quality (Everard and Moggridge 2012; Herb et al. 2008; Somers et al. 2013). Trees have a substantial influence on incoming solar radiation and can reduce it by over 90% (Heisler 1986). Some of the radiation absorbed by tree canopies leads to the evaporation and transpiration of water from leaves. This evapotranspiration cools tree leaves and the surrounding air. Along with evapotranspirational cooling, tree shade can help cool the local environment by reducing the solar heating of some below-canopy surfaces (e.g., streams, buildings, parking lots). Together these evapotranspiration and shading effects can reduce air temperatures by as much as 5 °C (Akbari et al. 1992). Reduced air temperatures will contribute to reduced stream temperatures, given that air temperature leads to sensible heating of water (Mohseni et al. 1998). Shallower river water heats more rapidly due to lower thermal inertia and larger surface area to volume ratios. Infiltration will generally increase baseflow, and baseflow typically has a temperature equal to the average annual air temperature, which then cools the river during the warm season (Loheide and Gorelick 2006).

As runoff passes over impervious surfaces, the water is often warmed, creating thermal pollution within receiving water bodies. This thermal pollution changes aquatic ecology by directly and indirectly affecting living organisms (Gitay et al. 2002). The combination of nutrient enrichment and elevated water temperatures in rivers are precursors to harmful algal blooms (Erdner et al. 2008) and can lead to accelerated eutrophication (Rigosi et al. 2014; Lürling et al. 2017; Yang et al. 2008). After the algae bloom dies, its organic matter undergoes microbial decomposition, which can severely deplete the dissolved oxygen (DO) (Peperzak 2003) and lead to biomass-related hypoxia and anoxia, also known as dead zones (Chislock et al. 2013; Pang et al. 2017). In addition, the maximum or saturated DO is reduced by increased water temperature (Coutant 1985), which limits habitat zones for aquatic organisms.

15.4 Urban Impervious Cover Impacts on Water Volume and Quality

Conventional urban development dramatically increases the amount of stormwater runoff generated by the landscape (Chow and Yen 1976; Boyd et al. 1994; Beach 2002). The principal causes of this effect are impervious surfaces, primarily streets, parking lots, and buildings (Leopold 1968; Schueler 1994); and compaction of the soil due to construction activities (Hamilton and Waddington 1999; Pitt et al. 2003). Instead of infiltrating into the ground, precipitation, including rainfall and snowmelt, is converted quickly to surface runoff and is rapidly delivered to receiving waters via sewers and other man-made channels.

Impervious cover and compaction of soils in urban areas impede infiltration rates (Hamilton and Waddington 1999; Pitt and Lantrip 2000) and transform more precipitation into stormwater runoff. Increased stormwater runoff leads to reduced deeper percolation and consequently lower water table levels (Lerner 2002) and lowers stream baseflow regimes (Faulkner et al. 2000). Lower baseflow adversely impacts drinking water supplies, aquatic habitat, water temperature, navigation, and recreation. Increased stormwater runoff can increase surface flushing of pollutants to receiving waters, diminishing the chance for biogeochemical transformation. When stormwater is treated in engineered retention or detention basins, rather than infiltrated through forested areas, pollutants tend to experience less sorption with soils and are more likely to degrade subsurface water quality (Thomas 2000; Fischer et al. 2003).

According to US General Accounting Office (2001), when natural ground cover is present over the entire site, infiltration is higher and on average 10% of precipitation runs off the land into nearby creeks, rivers, and lakes. In contrast, when a site has 75% impervious cover that is 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 as 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 2018). Runoff from urban land cover collects pollutants from the land surface and poses a threat to receiving waters. Trees over impervious surfaces can help reduce these negative consequences by intercepting rainfall and reducing the amount of rainwater reaching impervious surfaces.

15.5 Cumulative Effects of Urban Trees on Stream Flows and Runoff

Relatively little research has been conducted on the effects of urban trees on stream flows and runoff compared to non-urban forest areas. In Tucson, Arizona, increasing tree canopy cover from 21% (existing) to 35 and 50% was projected to reduce mean annual runoff by 2 and 4%, respectively (Lormand 1988). In Austin, Texas, it was estimated that the existing trees reduce the potential runoff volume by 3.2 million m^3, or 7% of a 14 cm, 5-year storm (Walton 1997).

In Baltimore, Maryland, an increase in tree cover over pervious surfaces, from 12 to 24%, together with an increase in tree cover over impervious surfaces, from 5 to 20%, decreased peak flow by 12%, while increasing baseflow and only reducing annual streamflow by 3%. By contrast, reducing tree cover over pervious areas from 12 to 6% and replacing it with impervious surfaces connected to streams lead to a 30% increase in peak flow (Wang et al. 2008). The trend and relative magnitude of these tree effects on runoff is consistent with other model findings.

15.6 Economic Impacts of Hydrologic Changes

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. The costs/impacts associated with urban flooding include: wet structures with mold and potential increase in respiratory problems (Pind et al. 2017), potentially lower property values (Snyder 2013), stream bank erosion (e.g., Hammer 1972), degraded water quality, and reduced health of aquatic ecosystems (e.g., Brookes 1988). In Cook County, Illinois alone, total claims paid for urban flooding incidents over five 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 stream banks, 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). As described earlier, trees can reduce stormwater runoff in many ways and help reduce these impacts.

Over a third of our nation's streams, lakes, and estuaries are impaired by some form of water pollution (US EPA 1998). Pollutants can enter surface waters from point sources, such as single-source industrial discharges and wastewater treatment plants. However, most pollutants result from nonpoint source (NPS) pollution activities, including runoff from agricultural lands, urban areas, construction and industrial sites, and failed septic tanks. These activities can introduce harmful amounts of sediments, nutrients, bacteria, organic wastes, chemicals, and metals into surface waters (WEF/ASCE 1998). Damage to streams, lakes, and estuaries from nonpoint source pollution was estimated to be about $7 to $9 billion a year in the mid-1980s (Ribaudo 1986), with urban NPS runoff a leading cause of receiving water pollution (US General Accounting Office 2001). Nutrient pollution alone can lead to problems such as accelerated eutrophication or harmful algal blooms, creating millions of dollars in costs associated with impacts on tourism and recreation, property values, human health, drinking water treatment, and pollution mitigation (US EPA 2015).

Substantial economic value is derived from reducing river temperature (Seedang et al. 2008), increasing DO (Rabotyagov et al. 2014), avoiding harmful algal blooms (Anderson et al. 2000; Hoagland et al. 2002), and slowing eutrophication (Dodds et al. 2009; Pretty et al. 2003). The estimated annual damage costs of freshwater eutrophication are approximately $2.2 billion in the US (Dodds et al. 2009) and $105–160 million in England and Wales (Pretty et al. 2003). The loss in economic welfare from recreational fishing due to lowering DO levels in the Patuxent River, Maryland is between $100,000 and $300,000 per year (Lipton and Hicks 2003). The estimated economic impact of harmful algal bloom in the United States is approximately $0.5 billion (Anderson et al. 2000). About 45% of this value is from impacts on public health costs. To help

Table 15.1 Summary of general tree effects, hydrologic services provided and associated hydrologic impacts. Services and impacts of trees are denoted as generally increasing (+) or decreasing (−). The impacts could be assigned economic values based on their effects on human and aquatic health, recreation and tourism, groundwater supplies, sedimentation removal, property values, insurance rates, etc

Tree Effects	Services	Impacts
Evapotranspiration	Air temperature (–)	Aquatic life (+)
Interception	Aquatic food and habitat (+)	Base streamflow (+)
Litter deposition	Chemical[a]/biological[b] degradation (+)	Dissolved oxygen (+)
Root growth	Chemical[a] removal/uptake (+)	Erosion (–)
Shade	Chemical[a] transport (–)	Eutrophication (–)
	Infiltration (+)	Flooding (∓)
	Nutrients (uptake, litter) (∓)	Groundwater recharge (+)
	Runoff (–)	Treatment costs (–)
	Stream temperature (–)	Water pollution (–)
	Water uptake (+)	

[a]Metals, nutrients, pesticides, sediment
[b]Pathogens

Table 15.2 Estimated monetary values of urban tree effects on reducing runoff into streams

City	Value type	$/gallon avoided	Value/year	References
Austin, TX	Local[a]	0.27	$230 million	Walton (1997)
Plaster Creek subwatershed, Grand Rapids, MI	Local[b]	1.25	$52.7 million	Plan-It Geo (2015)
Core city subwatersheds, Grand Rapids, MI	Local[b]	1.25	$36.5 million	Plan-It Geo (2015)
Houston, TX	Average[c]	0.009	$11.6 million*	Nowak et al. (2017a)
Wakarusa River watershed, Lawrence, KS	Average[c]	0.009	$5.9 million	Nowak et al. (2014)
New York, NY	Average[c]	0.009	$4.6 million	Nowak et al. (2018)
Austin, TX	Average[c]	0.009	$4.3 million*	Nowak et al. (2016a)
Blue River watershed, Kansas City, KS/MO	Average[c]	0.009	$4.2 million*	Nowak et al. (2013a)
Cobbs Creek watershed, Philadelphia, PA	Average[c]	0.009	$3.0 million*	Nowak et al. (2016b)
Don Watershed, Toronto, ON	Average[c]	0.009	$2.2 million*	Nowak et al. (2013b)
First St. subwatershed, Grand Rapids, MI	Local[b]	1.25	$2.0 million	Plan-It Geo (2015)

[a]Stormwater retention pond costs
[b]Stormwater mitigation and environmental impact costs
[c]U.S. average stormwater control and treatment costs from several cities
*Value not given in publication, but reported here assuming $0.009 per gallon

mitigate damage from urban runoff, the US Clean Water Act (US EPA 2013) sets a total maximum daily load (TMDL) for rivers receiving urban runoff, which defines quantitative thresholds for the concentrations and fluxes of thermal and material pollutant sources (Seedang et al. 2008; US EPA 2007).

15.7 Valuing Tree Impacts on Hydrology

To value tree impacts on hydrology, the tree effects (e.g., interception, ET, and avoided runoff) first need to be quantified. Once the effects are quantified, these effects can be related to services and impacts (e.g., reduced pollution and improved human health) and then the impacts valued (Table 15.1). Various models exist to quantify tree impacts on hydrology and water quality (Coville et al. 2019), but the valuation of these impacts is limited. Once the flow or provision of the good or service (e.g., reduced pollution) is quantified, various market and non-market valuation methods can be applied to characterize their value. Methods of non-market valuation can be pecuniary or non-pecuniary (e.g., number of human lives saved). This valuation includes various procedures such as market prices, contingent valuation surveys, replacement or substitute costs, hedonic regression, and damage costs avoided (Nowak et al. 2017b). Some studies estimate the value of reduced runoff due to trees in cities is on the order of millions of dollars per year (Table 15.2).

For the most part, the economic valuation of tree effects on the myriad of hydrologic impacts remains to be evaluated as many of these impacts are not quantified. Once the impact of trees is more fully quantified, the total economic impact related to human and aquatic health, recreation and tourism, groundwater supplies, sedimentation removal, property values, and insurance rates, etc., can be evaluated. However, care must be exercised to avoid double-counting of benefits and costs. More research is needed to quantify the many tree and forest hydrologic impacts and values. This research can lead to better, more informed, and cost-effective management decisions to improve water quality, enhance groundwater recharge, and reduce flooding. These improvements can ultimately enhance human and aquatic health and well-being for current and future generations.

15.8 Valuing Total Tree Impacts and Costs

While this chapter is focused on urban tree impacts on hydrology, urban trees provide numerous other benefits and costs. To understand the true value and costs of vegetation, all the benefits and costs need to be understood and quantified. Other benefits provided by these trees include reducing building energy use and atmospheric carbon dioxide (CO_2), improving air quality, reducing ultraviolet radiation, creating wildlife habitats and esthetically pleasing environments, enhancing human health and social well-being, and lowering noise levels (Nowak and Dwyer 2007). Although national effects of urban trees on hydrology in the United States have not been analyzed, the national urban forest values from other benefits are estimated as $18.3 billion per year; $5.4 billion from air pollution removal, $5.4 billion from reduced building energy use, $4.8 billion from carbon sequestration, and $2.7 billion from avoided pollutant emissions (Nowak and Greenfield 2018). This estimate is conservative as it only addresses four benefits out of a myriad of potential benefits from trees.

Urban forests also have various costs associated with tree planting, maintenance and removal, and other indirect costs related issues such as allergies from tree pollen, chemical emissions from trees, and maintenance activities that contribute to air pollution, invasive plants altering local biodiversity, and increased tax rates due to increased property values (e.g., Roy et al. 2012; Lyytimaki 2017). Trees can also increase waste disposal, infrastructure repair, water consumption, and building energy use in the winter due to tree shade.

Studies suggest that benefits from urban street trees are on the order of 1.4–5.8 times greater than costs (McPherson et al. 2005, 2016). However, these estimates are likely conservative as many benefits remain to be quantified. While the direct management costs of street trees are generally known, these costs are often higher than other urban trees that require less direct individual tree management and maintenance (e.g., trees in natural forest stands). Thus, management costs can vary widely in urban areas. The benefits can also vary depending upon the number of healthy trees, species, sizes, and location. These changes in management costs and benefits will alter the cost-benefit ratios in urban areas. The overall urban forest likely has higher benefit-cost ratios than found for street trees due to often lower costs per tree and numerous benefits that remain to be quantified. More research is needed to better understand local variations in tree costs and benefits to help sustain optimal forest structures to enhance human health, well-being, and ecosystem sustainability.

15.9 Conclusions

Tree canopies can profoundly alter the amount, patterning, timing, and quality of precipitation reaching the ground and streams. Tree precipitation partitioning processes alter all subsequent hydrological processes, including many that hold market and non-market value, like stormwater runoff, soil moisture, peak streamflow, water quality, and air temperatures. The interception of precipitation by tree canopies, in particular, can help mitigate the hydrologic consequences of increased impervious cover in urban environments. This reduction of runoff to water bodies provides pecuniary benefits, being valued at $2–200 million US dollars per year at various scales, and, more importantly, non-pecuniary benefits like improved human health and well-being. Of course, urban trees have inherent costs (for installation and maintenance) to maintain these benefits and minimize negative hydrologic outcomes (e.g., clogging of stormwater management systems). As trees provide multiple benefits that go well beyond hydrologic benefits, net total benefits typically exceed total costs. Many theoretical and methodological unknowns remain that impact our ability to comprehensively quantify and value urban tree hydrologic benefits and costs, including the: (i) dynamics of suspended, dissolved, and thermal stormwater qualities; (ii) influence of stemflow and throughfall drip points on runoff versus infiltration in urban settings, and associated water quality; and (iii) relationship between variability in precipitation partitioning processes and societal processes beyond stormwater management, like recreation/tourism, property values, etc. Improved understanding of the costs and benefits of trees facilitates informed and cost-effective water resource management using nature-based solutions, that can enhance human well-being and ecosystem sustainability for current and future generations.

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