THE EFFECTS OF TREES ON STORMWATER RUNOFF

Prepared for

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Contents

Tables

Figures

Introduction

This report summarizes the results of a literature review of research conducted to quantify the effect of trees on stormwater runoff. The range of research reviewed for this report included field efforts that measured changes in the hydrologic cycle and modeling studies on the effects of tree cover on stormwater runoff. In most cases, the research was not focused solely on quantifying the stormwater-related benefits of trees. Most single studies generally lack the comprehensive environmental information that is useful in determining the direct stormwater benefits (e.g., measured precipitation, climate variations, and soil conditions). Nonetheless, this literature review provides a representation of the range of research conducted and the common conclusions of the various studies.

In addition, a number of municipalities across the country have established stormwater credit programs in which existing or newly planted trees receive credit toward meeting stormwater flow control requirements. These programs typically allow flow control credit for trees as a reduction of the effective impervious area included in drainage calculations. The impervious surface reduction credit is most often a function of the number of newly planted trees or the canopy cover of existing trees. This report summarizes tree credit programs from several other cities, and concludes with recommendations for developing a tree credit program for the City of Seattle.

Primary Effects of Trees on Stormwater Runoff

Trees affect stormwater runoff through three primary processes: interception, transpiration, and infiltration. *Interception* is the collection of precipitation on the structure of the tree and the subsequent evaporation of moisture, which would otherwise become runoff. *Transpiration* is the transfer of water from the soil through the tree and its eventual release in a gaseous form through microscopic pores in the leaves and stems. *Infiltration* is the movement of surface water through the soil. Tree roots, combined with organic material that typically builds on the soil at the base of trees, promote the infiltration of runoff through shallow subsurface zones, helping to reduce both the rate and volume of stormwater runoff.

Field Measurements of Interception

There is considerable research on the interception of precipitation by trees, all of which was generally conducted using similar methods. Rainfall was measured beneath the tree canopy (throughfall) and outside the drip line (precipitation). The water that runs down the trunk of the tree (stemflow) was added to throughfall, and this sum was subsequently subtracted from precipitation. The resulting value is the tree’s estimated interception. Research indicates that conifers generally intercept more water annually than deciduous trees, which can be explained by the greater foliage surface area of conifers and the presence of foliage on conifers during winter months. The studies reviewed for this report, the locations of each study, and where available, the percentage of precipitation intercepted by conifer and deciduous trees in each study are listed in Table 1.

Table 1. Measured interception from conifer and deciduous forested areas.

Study	Percentage of Precipitation Intercepted by Conifers	Percentage of Precipitation Intercepted by Deciduous Trees	Location
Pypker et al. (2005)	21.2	NA	Western Cascades, WA
Dunne and Leopold (1978)	28	13	NA
Reynolds et al. (1988)	19	8	NA
Crockford and Richardson (2000)	18	NA	Western Cascades, OR
Heal et al. (2004)	44	NA	Great Britain
Zimmerman et al. (1999)	51	NA	Europe
Link et al. (2004)	25	NA	Western Cascades, WA
Xiao et al. (1998)	NA	11	Sacramento, CA

NA = not available

Field Measurements of Transpiration

Three of the studies reviewed for this report describe the rate of transpiration associated with various tree types. These studies measured transpiration directly using micro-metrological stations positioned above the tree canopy, sap-flow monitors, and soil lysimeters. In general, these studies reported transpiration rates measured during the dry season. The studies, as well as the associated percentage of water loss due to transpiration in each study, are listed in Table 2.

Table 2. Measured transpiration from conifer and deciduous forested areas.

Study	Percentage of Precipitation Transpired by Conifers	Percentage of Precipitation Transpired by Deciduous Trees	Location
Heal et al.(2004)	12	NA	Great Britain
Unsworth et al. (2004)	10	NA	Pacific Northwest
Schlesinger (1997)	NA	25	New Hampshire

NA = not available

Field Measurement of Infiltration

A review of the literature found that there have been numerous studies that quantified the impact of trees on infiltration rates (Lal 1996; Mlambo et al. 2005; Wondzell 2003). Lal (1996) found that after the deforestation of a Nigerian forest, infiltration rates decreased by 20 to 30 percent. A more local study of infiltration before and after forest fires found similar results (Wondzell 2003). Though these results show that in natural settings trees can provide increased infiltration capacity in underlying soils, this may not hold true in an urbanized setting. In this setting, the removal of leaves and organic buildup by homeowners, businesses, and municipal grounds crews may degenerate the organic layer, and human and animal traffic may compact soils. Both of these factors may lead to decreased soil infiltration beneath trees. Consequently, the calculations presented in this report (see *Conclusions*) assume infiltration will be equivalent between grass-covered soils, and grass-covered soils with trees.

Field Measurements of Infiltration, Transpiration, and Interception Combined

The literature review for this report also included three studies that measured changes in stormwater runoff in streams that drain forested basins. The basins were then clear-cut and the subsequent runoff in the basins was compared to that in adjacent control basins to estimate the impact of deforestation on annual water yield. The studies reviewed and the associated results are listed in Table 3.

Table 3. Runoff before and after deforestation of conifer and deciduous forested areas.

Study	Percentage of Runoff Increase after Deforestation (Conifers)	Percentage of Runoff Increase after Deforestation (Deciduous Trees)	Location
Martin and Hornbeck (2000)	NA	23	New Hampshire
Jones (2000)	32	NA	Pacific Northwest
Hornbeck et al. (1997)	NA	32	New Hampshire

NA = not available

Two studies used a similar method to monitor the effect of trees on stormwater runoff, directly comparing precipitation to runoff within forested basins. The studies, and their associated results, are listed in Table 4.

Table 4. Measured stormwater runoff from conifer and deciduous forested areas.

Study	Runoff as a Percentage of Rainfall (Conifers)	Runoff as a Percentage of Rainfall (Deciduous Trees)	Location
Post and Jones (2001)	44	39	Oregon/New Hampshire
Waring et al. (1981)	45	NA	NA

NA = not available

The Effect of Seasonality

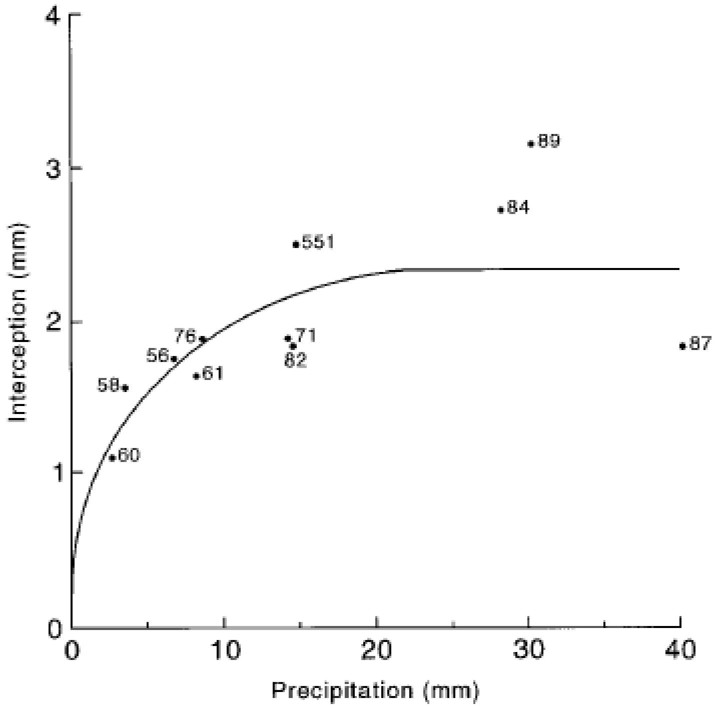
It is also important to consider meteorological conditions at the site when evaluating the benefits of trees in reducing stormwater runoff. For example, storm size and antecedent dry period, as well as rain intensity and wind strength, are all conditions that affect interception (Crockford and Richardson 2000). As meteorological conditions change with the seasons, interception will also change. Xiao et al. (1998) found that trees in urban Sacramento, California, intercepted approximately 18 percent of precipitation during a summer storm event, but only approximately 4 percent during a winter storm event. This difference in interception is due to the fact that evaporation and antecedent dry periods are greater in the summer than in the winter and, more importantly, because winter foliage tends to be less dense than summer foliage and winter storms are usually much larger than summer storms. Large storm events overwhelm the capacity of the tree canopy to retain water; therefore, the relative impact of interception on the water balance decreases with storm size. The reported relationship between storm size and interception is illustrated in Figures 1, 2, and 3.

It is apparent from these studies that as storm size increases, the relative percentage of intercepted precipitation decreases. However, this does not mean that interception during the winter is insignificant. Xiao et al. (2000) found that an oak tree in Davis, California intercepted approximately 27 percent of gross precipitation during 38 storms in the winter of 1997–1998. In the Pacific Northwest, large storms can typically occur in the months of October through June, although the intensity will vary considerably depending on the location and the characteristics of the storm. It is difficult to generalize the effect of season on interception in the Pacific Northwest. Likewise, few of the studies reviewed included results related to seasonal variations in transpiration.

Application of Field Study Results to Seattle

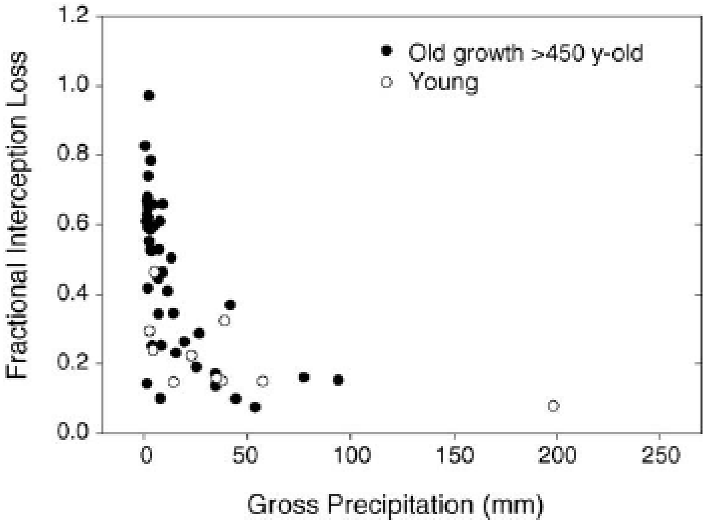
The available literature does not include data on the flow control benefits of trees in Seattle. While some of these studies were conducted in the Pacific Northwest, the conditions (meteorological, physical, etc.) at the study locations are not identical to those in Seattle. In addition, most of these studies were not specifically focused on urbanized basins. Furthermore, these field-based studies generally did not report the effects of season on the combined measured values for interception and transpiration. Ideally, these seasonal and environmental variations would be taken into account in any determination of tree stormwater credits. Despite the limitations of the available data, some reasonable inferences can be made regarding the general flow-control benefits of trees in the Pacific Northwest.

Based on the field studies presented in this report, the combined processes of infiltration, transpiration, and interception associated with trees can be expected to significantly reduce annual runoff. If the average values for interception and transpiration by conifers in the Pacific Northwest (Tables 1 and 2, respectively) are summed, it is reasonable to expect a 30 percent reduction in annual precipitation. Because the values in Tables 1 and 2 do not address the increased infiltration capacity that trees can provide, the 30 percent reduction may be underestimated. However, in a pre/post deforestation study that did include the effects of trees on infiltration, Jones et al. (2000) reported a 32 percent reduction in runoff due to coniferous forest cover in the Pacific Northwest (Table 3). Consequently, this 32 percent reduction in runoff can be used as a reasonable basis for establishing a maximum net benefit of individual coniferous trees or forested areas (based on canopy cover). It is also notable that the CITYgreen software, which has been used by a number of municipalities to calculate the effect of tree coverage on stormwater runoff reduction, has produced similar flow reduction values (MMSD 2007; Shreveport Green 2007; Soltis 1997).



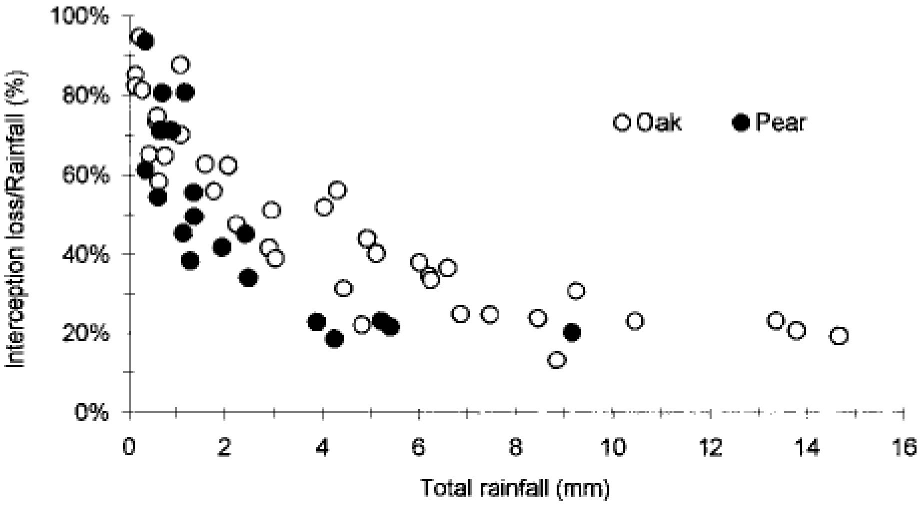
Source: Crockford and Richardson (2000).

Figure 1. Interception versus precipitation for continuous storm events in a pine plantation.



Source: Pypker et al. (2005).

Figure 2. Fractional interception loss versus gross precipitation for a Douglas-fir forest in the Pacific Northwest.



Source: Xiao et al. (2000).

Figure 3. Fractional interception loss versus total rainfall for an evergreen oak and deciduous pear tree in Davis, California.

Stormwater Modeling Studies

In addition to the field studies mentioned previously, several studies have also used hydrologic models to estimate the impact of trees on reducing stormwater runoff in urbanized settings (American Forests 2007). The bulk of the modeling efforts have been based on simple land use models with built-in curve numbers that predict runoff based on land use type. A modeling study of this type in Dayton, Ohio indicated that a 22 percent tree cover in an urbanized basin reduced small-event runoff by 7 percent (Sanders 1986). When the percentage of tree cover was increased to 50 percent, runoff reduction was increased to 12 percent. In a separate study modeling land use in Tucson, Arizona, increasing canopy cover from 21 percent to 35 and 50 percent decreased mean annual runoff by 2 and 4 percent, respectively (Lormand 1988).

A study by American Forests (using the CITYgreen software) estimated that a 20 percent loss of trees in metropolitan Atlanta, Georgia produced an increase in annual stormwater runoff of 1 billion cubic feet (Soltis 1997). Another CITYgreen study in Garland, Texas indicated that for a 3.9-acre residential basin, an 8 percent canopy cover provided a 3 percent reduction in runoff. When the site's canopy cover was modeled as 35 percent, runoff was reduced by 12.8 percent. Finally, when tree cover was modeled as 45 percent, runoff reduction reached 16.1 percent (Keating 2002). The CITYgreen model can be calibrated for local conditions by adjusting both curve numbers and soil. The CITYgreen model would be useful for looking at the basinwide impacts of retaining or increasing tree cover in Seattle watersheds. A detailed review of the CITYgreen model is available online (http://www.phytosphere.com/treeord/gis.htm).

More sophisticated modeling efforts (USDA Forest Service 2003) based on hydrodynamic canopy models, as opposed to land use hydrologic modeling, have been conducted by Xiao (2000) and McPherson (2002). These studies have shown that conifers in the Pacific Northwest can intercept 414 gallons per tree per year, and this value can range between 169 and 449 gallons per year, depending on tree size and type (McPherson et al. 2002). Unfortunately, these studies did not report total annual precipitation associated with the interception. Therefore, it is difficult to relate the gallons intercepted to the percentage of rainfall or runoff. Nonetheless, this per tree value, in conjunction with the data presented previously in this report, can be useful to supplement urban stormwater modeling and planning efforts.

Several municipalities themselves, as opposed to the private or academic research mentioned previously, have conducted similar research pertaining to the benefit of trees in reducing stormwater runoff. For example, Atlanta, Georgia (Soltis 1997), Milwaukee, Wisconsin (MMSD 2007), and Shreveport, Louisiana (Shreveport Green 2007), have all used the CITYgreen software to support tree-related stormwater management decisions.

Municipal Application of Stormwater Tree Credits

A number of municipalities across the country have established stormwater credit programs that grant flow control credits for existing or newly planted trees. The City of San Jose, California has a program that gives credits for trees planted within 30 feet of impervious surfaces and existing trees that are kept on a site if their canopies are within 20 feet of impervious surfaces. The impervious surface reduction credit for existing trees is the square footage equal to one-half the area of existing tree canopy (credit is equivalent to a reduction in the site's impervious area). The credit for each new deciduous tree is 100 square feet, and the credit for each new evergreen tree is 200 square feet. No more than 25 percent of a site's impervious surface can be credited through the use of trees (San Jose 2007).

Austin, Texas also has a program that provides stormwater credit for both new and existing trees. The program in Austin provides a much more modest tree credit than that of San Jose. For new trees to receive a credit, they must be planted within 25 feet of a ground-level impervious surface and have a minimum diameter of 2 inches at the time of planting. The impervious surface reduction credit for each newly planted tree is 20 square feet. Each existing tree within 25 feet of ground-level impervious surface and with a diameter of 4 inches is credited with an area equal to one quarter the area of the tree canopy (Austin 2007).

Portland, Oregon has a tree credit program equivalent to that of San Jose. The impervious surface reduction credit for new deciduous trees within 25 feet of ground-level impervious surfaces is 100 square feet, and the credit for new evergreen trees is 200 square feet. For existing trees with a diameter of at least 4 inches, the credit is one half of the area of the canopy (BES 2007).

Other municipalities with active stormwater tree credit programs include Tampa, Florida and Sandy, Oregon. These programs are becoming more commonplace, and the list of participating municipalities is growing rapidly. Unfortunately, most of the municipal tree credit programs that were included in the literature review provide no details on how the specific credit values were determined. Therefore, it is difficult to determine what, if any, studies or performance expectations were used to justify or substantiate the credits.

By comparing the research results presented in this literature review to the stormwater credits given by the aforementioned municipalities, it appears that the percentage of equivalent impervious area that several of the municipalities accredited to trees may be too generous. That is, the credits generally exceed the roughly 30-percent reduction in surface runoff that was reported in the research.

Conclusions

As stated previously, the research referenced in this report is limited and not directly applicable to Seattle’s urbanized setting, or its meteorological and seasonal conditions. Nonetheless, inferences regarding the flow control benefit of trees in Seattle can be made and are presented below.

Available data indicates that interception by evergreen trees in the Pacific Northwest can range from 18 to 25 percent of annual rainfall (Table 1). Depending on the intensity of the storm, the average annual interception value of approximately 20 percent will vary (Figures 1 through 3), with small storms characterized by high relative interception and large storms characterized by low relative interception. Because most of the rainfall in the Pacific Northwest occurs during the winter, the values reported from studies in the Pacific Northwest are representative of winter interception values. Interception in areas that receive rainfall during the warm summer months is expected to be higher.

Although data are limited (Table 2), the percentage of precipitation transpired by conifer trees in the Pacific Northwest may be close to 10 percent. Based on this assumption, it can be estimated that a conifer in the Pacific Northwest intercepts and transpires approximately 30 percent of the precipitation falling upon it. This reduction in precipitation can be related to a reduction in stormwater runoff. Runoff reduction is dependent upon characteristics of the underlying surface type including degree of perviousness and other precipitation loss mechanisms (e.g., evapotranspiration). For the purpose of this analysis, the reduction of runoff attributed to a conifer is evaluated for two scenarios:

- Conifer with underlying impervious surface versus impervious surface with no conifer, and
- Conifer with underlying grass on till surface versus grass on till surface with no conifer.

The first scenario involves a conifer over an impervious surface (Figure 4). Approximately 20 percent of the precipitation falling on the tree canopy would be intercepted, allowing 80 percent of the rainfall to reach the surface. Of this 80 percent throughfall, approximately 5 percent would be lost to evaporation (assuming a runoff coefficient of 0.95).

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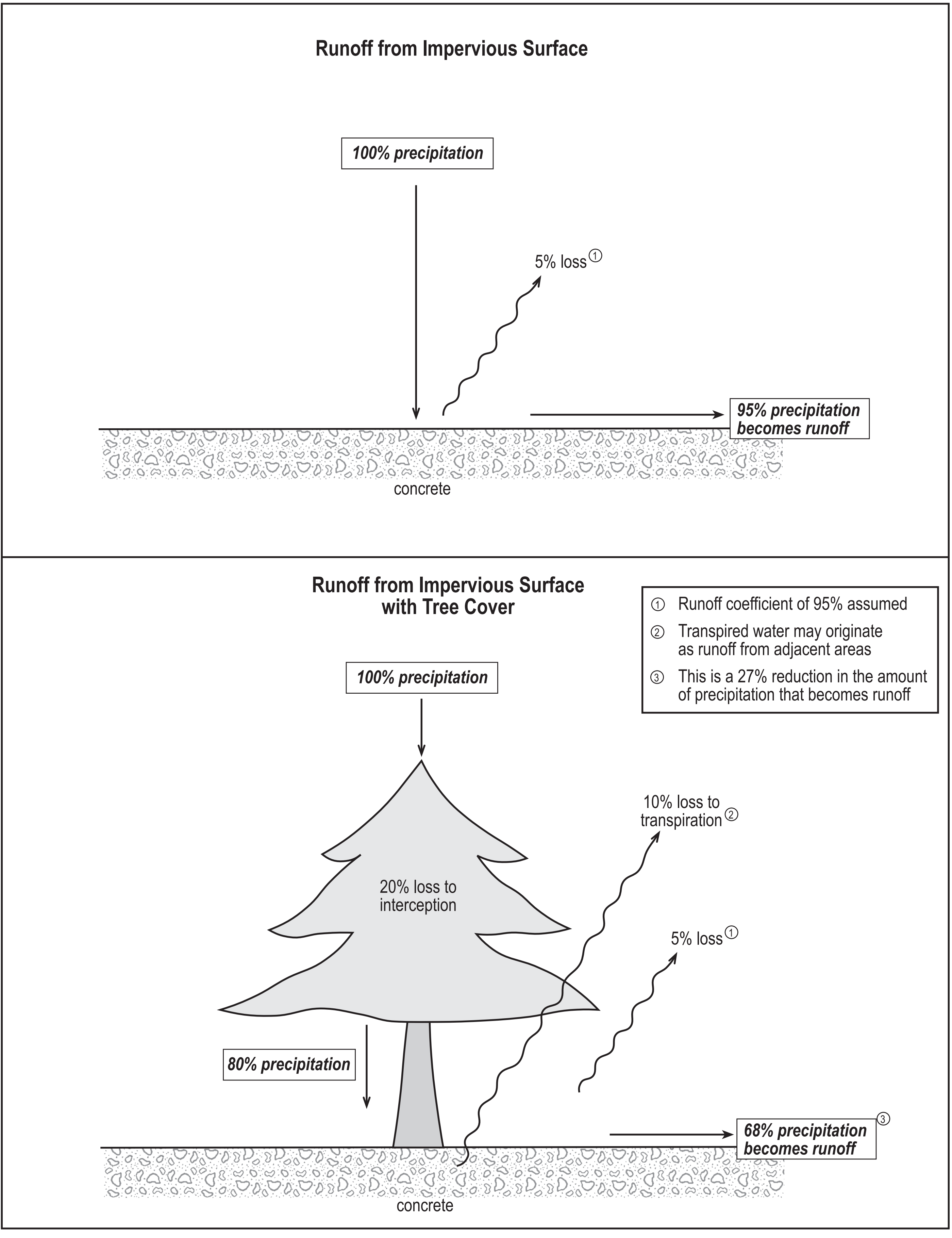

Runoff from Impervious Surface

Runoff from Impervious Surface with Tree Cover

① Runoff coefficient of 95% assumed

② Transpired water may originate as runoff from adjacent areas

③ This is a 27% reduction in the amount of precipitation that becomes runoff

Figure 4. **Conifer over an impervious surface.**

Another 10 percent could potentially be lost to increased transpiration due to the tree (assuming that the runoff from the impervious surface is routed via surface or subsurface flow to the pervious area at the tree base). In this scenario, the runoff produced from a conifer over impervious surface would be 27 percent less than the runoff produced from an impervious surface with no conifer.

The second scenario involves a conifer over a grass surface (Figure 5). Approximately 20 percent of the precipitation falling on the tree canopy would be intercepted, allowing 80 percent of the rainfall to reach the surface. Of this 80 percent throughfall, approximately 80 percent would be lost to evaporation and infiltration assuming moderately sloped grassy land cover on till soil (runoff coefficient of 0.20). Another 10 percent would be lost to increased transpiration due to the tree. In this scenario, the runoff produced from the conifer over grass/till surface would be 12 percent less than the runoff produced from a grass/till surface with no conifer.

The reduction in stormwater runoff estimated for a conifer tree over an impervious surface approaches the 30 percent suggested by the literature. It should be noted that the scenario described above assumes a 10 percent loss due to transpiration. The water that is transpired may be the same water falling through the canopy (if the impervious surface runoff flows to the base of the tree), or it may originate from adjacent areas. In either scenario, it is a reduction specifically associated with the presence of the tree.

As is apparent from Figures 4 and 5, the reduction in stormwater runoff estimated for a conifer tree over a grass surface is lower than for a conifer tree over an impervious surface. What this suggests is that trees overhanging impervious areas will have a greater impact on total runoff volumes than trees that cover only pervious surfaces. Consequently, trees that are planted or remain near impervious surfaces are more likely to achieve the full 30% reduction, while trees planted further away from impervious surfaces will be less effective in reducing runoff volumes. This is reflected in the recommendations presented below.

This same exercise can be repeated for deciduous trees by replacing the interception value of 20 percent with 10 percent (Table 1), and estimating a transpiration value of 5 percent (Xiao, unpublished). Because there was no available transpiration data for deciduous trees in the Pacific Northwest (Table 2), this 5 percent value was estimated from unpublished data provided by Professor Qingfu Xiao (Xiao, unpublished). By using the 10 percent interception and 5 percent transpiration values, it is apparent that coniferous trees are twice as effective as deciduous trees at reducing stormwater runoff. This relationship is reflected in the recommendations presented below.

Recommendations

The literature and analysis presented above indicates that the three most important factors that control the ability of a tree to reduce urban runoff are the tree type, size of canopy cover, and proximity to impervious surfaces.

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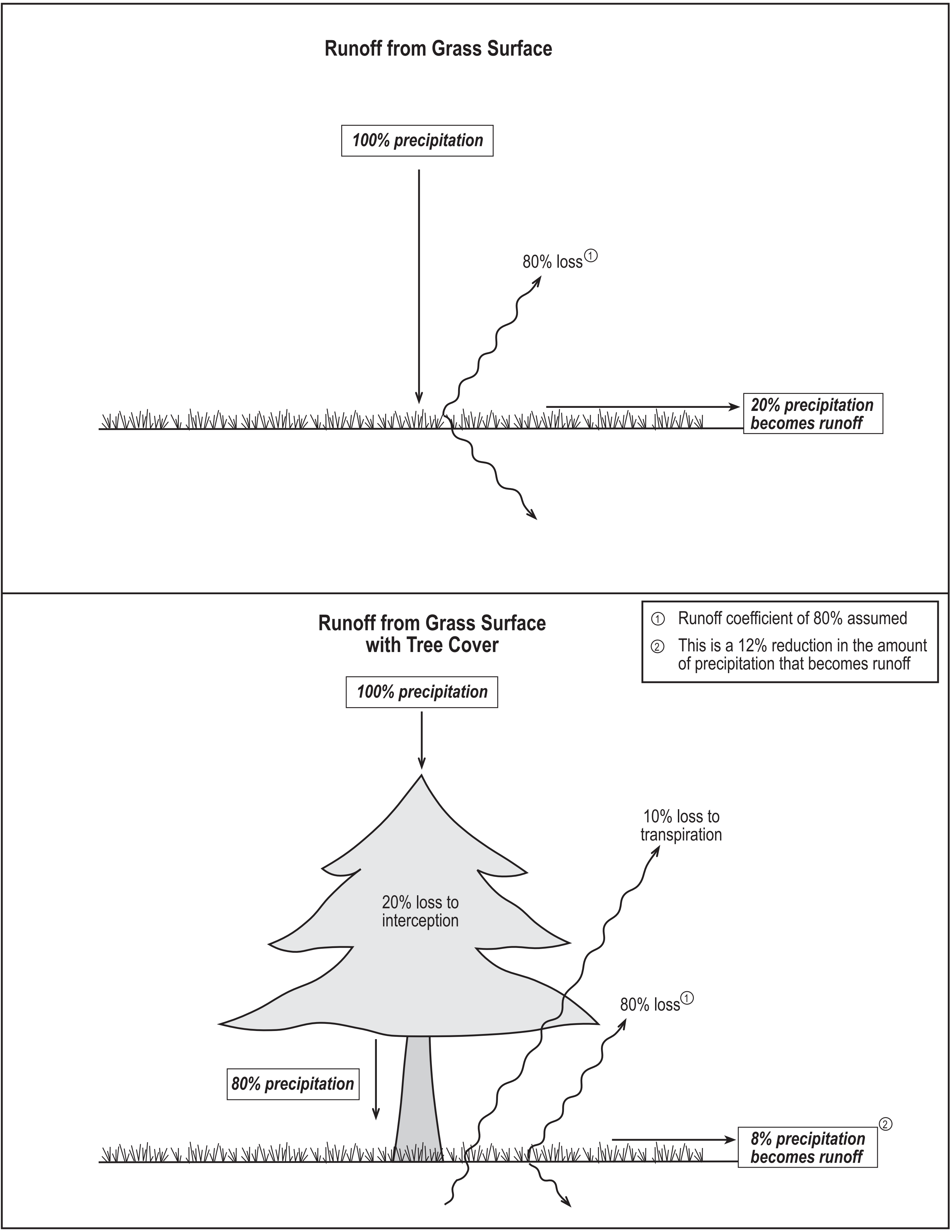

Figure 5. **Conifer over a grass surface.**

Given this information, the ideal scenario for maximizing runoff reduction in an urbanized area would be to plant a mature, wide-crowned conifer as close as possible to ground-level impervious surfaces. This is not to suggest that other trees and other configurations should not receive a stormwater credit, but that the credit system should encourage planting or retaining coniferous trees near impervious surfaces (near enough that they overhang the surface but do not compromise the infrastructure). The recommended tree credit presented in Table 5 is organized with a credit hierarchy that accounts for tree type, tree age, and the proximity of the tree to impervious surfaces.

Table 5. Recommended impervious surface credit for trees in the City of Seattle

Tree Type	Newly Planted/ Existing	Center of Truck Within 10 Feet of Ground-Level Impervious Surface	Center of Trunk More Than 10 Feet from Ground-Level Impervious Surface
Deciduous	Newly planted	50 square feet	25 square feet
	Existing	15% of canopy area	7.5% of canopy area
Coniferous	Newly planted	100 square feet	50 square feet
	Existing	30% of canopy area	15% of canopy area

The recommended 10-foot threshold for distance of the trunk center from a ground-level impervious surfaces is more restrictive than the thresholds set by other municipalities, but for effective runoff reduction it is important for trees to overhang impervious surfaces. Even with this more restrictive setback, the credits are likely generous given that the entire canopy is unlikely to completely overhang impervious surfaces at this distance.

In addition, although the municipalities referenced in this report generally give greater credits than those outlined in Table 5, these municipalities do not give credit for trees that are outside the specified distance to impervious surfaces. This seems to discount the fact that even when trees are placed over pervious areas, every inch of precipitation intercepted by a tree in turn reduces surface runoff and/or allows for additional infiltration to occur in the dry soils beneath the tree canopy. Whether via throughfall or through lateral inflow from upslope areas, the interception the trees provide allows for additional water storage and potential infiltration capacity in the soils beneath trees. Therefore, the recommendations presented in this report call for a credit to be given for all trees. This acknowledges the basin-wide benefit of trees, and will encourage tree retention and/or planting across the whole site, not just near impervious surfaces.

For existing coniferous trees with trunk center within 10 feet of a ground-level impervious surface, a credit of 30 percent of the canopy footprint is recommended (as outlined in Table 5). For deciduous trees, the recommended credit is one-half as much (15 percent) because, as explained above, deciduous trees in the Pacific Northwest will, on average, reduce runoff by approximately one-half as much as coniferous trees. Likewise, the credit for newly planted deciduous trees is one-half that of coniferous trees (50 square feet versus 100 square feet). The credit for newly planted trees was derived assuming an average lifetime canopy diameter of 20 feet. The canopy area of a tree with a 20-foot canopy diameter is approximately

300 square feet. Therefore, the 100-square-foot credit is approximately 30 percent of the tree area (which is equivalent to the area credited for existing coniferous trees).

When the trunk center of a tree is farther than 10 feet from a ground-level impervious surface, the likelihood that a portion of the tree will overhang the impervious surface is greatly reduced. Consequently, there will be a decline in the reduction in stormwater runoff attributed to the tree. The stormwater flow control benefits for a tree canopy above a pervious grass surface are estimated as half of those for canopies over impervious surfaces (Table 5).

There are a number of additional requirements which must be established if the stormwater tree credit system is to function properly. For example, some jurisdictions limit the percent of a site's impervious area which can be controlled by tree planting (typically a 25 percent maximum). Because the flow control credits recommended for the City of Seattle are more conservative than those offered by other jurisdictions, a maximum credit may not be necessary. However, a minimum tree spacing requirement is recommended for newly planted trees. This will help to ensure tree survival, establish the intended canopy coverage, and prevent a land owner from taking advantage of the credit by planting numerous trees in one corner of a lot to offset the creation of extensive impervious areas.

In addition, requirements for tree size must be set to assure that trees that receive a credit are in fact intercepting a water volume equivalent to the credit. The newly established Seattle Green Factor program requires new development in neighborhood business districts to meet a landscaping target using a menu of landscaping strategies. For consistency with the Seattle Green Factor requirements, it is recommended that newly planted deciduous trees be at least 1.5 inches in diameter measured 6 inches in height above the ground, and coniferous trees be at least 4 feet tall. To receive credit, the mature height of a tree must be at least 15 feet. Other jurisdictions (i.e., City of Austin and the City of Portland) also use size requirements for existing trees (e.g., 4 inches in diameter measured 6 inches in height above the ground). The city arborist should be consulted when determining which tree species are recommended for planting via this stormwater credit program, but from a stormwater volume reduction perspective, wide-crowned conifers should be given preference.

For the tree credit program to be most effective, additional considerations will need to be addressed relating to tree survivability, retention, and protection; public and infrastructure safety; coordination with other tree-related Seattle standards (e.g., requirements associated with green factor, landscaping, exceptional tree retention, and street trees); and other related factors beyond the scope of this report.

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