What we know and don't know about the surface runoff reduction potential of urban trees

M. A. Rahman and A.R. Ennos

Landscape Planning and Management, Technical University of Munich
Emil-Ramann-Str. 6, D-85354 Freising, Germany

School of Biological, Biomedical and Environmental Sciences, University of Hull,
Cottingham Road, Kingston-upon-Hull, HU6 7RX, UK

Tel 01482 466274
R.Ennos@hull.ac.uk

Abstract

Urban trees potentially reduce surface runoff of rainfall, so reducing the chances of surface flooding by intercepting rain in their canopy and allowing throughfall to infiltrate into the soil. The process has been investigated using both empirical and mechanistic models derived from rural catchment studies, but both types of model show that trees only have a limited effectiveness, reducing runoff by 0.5-0.8% for every 1% of tree cover added. However, such models ignore the potential of trees to increase soil infiltration and to enable rainfall from outside their canopy to infiltrate into the soil. Quite extensive experimental studies have been conducted of canopy interception of rain, but very little on the effect of trees on infiltration, and even less on the overall effects of urban trees. However, the limited research has shown that trees can greatly increase soil permeability, while large amounts of rainwater from outside tree canopies can be diverted into their planting pits; both suggest that urban trees could reduce flooding by more than the conventional models predict. A great deal of research needs to be conducted on the best ways to plant trees, both in conventional streets and SUDS schemes, to allow optimal growth and mazimise their flood prevention.

Introduction

Like the carbon balance and microclimate, the hydrology of cities is severely affected by the process of urbanisation. In rural areas, some rainfall is intercepted by vegetation and may eventually evaporate from the canopy, greatly reducing the amount of water that hits the soil, especially at the start of a rainfall event. Of the water that does reach the soil, either by falling through the canopy (throughfall) or running down the stems or trunk (stemflow) much is either stored in puddles or leaf litter in the rough ground or infiltrates into the soil. This leaves only a small percentage to runoff into rivers or streams, especially from forests, which have deeper, taller canopies, and whose thicker, less superficial roots grow dry out the soil more, and increase the soil permeability. In consequence the runoff coefficients of rural areas, especially forests, tend to be low, and there is often a long delay before peak runoff is reached.

In urban areas, in contrast, the removal of vegetation, the compaction of soil and its covering with impermeable buildings and roads, and the construction of drainage systems greatly reduces the amounts of rainwater intercepted, evaporated or stored. This greatly increases the runoff, which peaks rapidly after a storm.

Considering this, it is easy to see the hydrological benefits that including vegetation, especially trees, could confer to an urban area, since they will to some extent reverse the processes caused by urbanisation. However, there are two quite different ways in which trees and other vegetation may be managed in cities. The great majority of vegetation in urban areas grows in patches of soil that are essentially disconnected from the urban drainage network, and can be considered to act hydrologically in parallel with it. Parks, gardens, sports pitches and small areas of urban woodland therefore act like separate small patches of countryside; they should produce less runoff than the built component of the environment, but they cannot affect the runoff from the buildings and roads themselves. In contrast, modern SUDS schemes may contain areas of soil and vegetation to which water running off from the built environment is diverted (EPA, 2013). They can thus be considered to act in series with the built component and can reduce runoff from buildings and roads by temporarily storing water, delaying its passage to the drains, and diverting it away from them; they could potentially totally eliminate urban runoff. Most urban trees, whether growing within soil or within paving, belong to the first set of vegetation types, and it is these that will be mostly discussed here, though recently trees have also been incorporated into SUDS schemes and we will look at these towards the end of the review.

Our understanding of hydrology comes from extensive studies of large catchments with differing surface cover (NRCS, 2004). In particular the hydrology of rural areas has been extensively studied and is now well characterised and understood. In particular much work has gone into experimentally investigating and modelling the contrasting runoff behaviour of forests, arable and grassland. Empirical studies on large areas of land show that woodland typically has far lower runoff coefficients (the ratio of runoff to total rainfall) around 0.2 compared to 0.5 to 0.6 for arable and grassland (NRCS, 2004). Mechanistic models have shown that this is due to two main factors: more of the rainfall is intercepted by tree canopies and subsequently evaporates, without ever reaching the ground; and more of the rainfall that reaches the ground is either stored in the leaf litter or infiltrates into the soil, which tends to be drier, less compacted, and penetrated by thicker, deeper roots (Wang et al, 2008).

With the benefit of the results of the rural research and the techniques developed there, it might be thought that quantifying the effect of trees on urban runoff would be simple; all one would need to do would be to perform similar experimental investigations in cities, or incorporate the results from the rural models to the urban situation. Unfortunately, however, large scale experiments to investigate the role of vegetation, especially trees, are hard to perform in cities since it is impossible to find large urban areas which are identical apart from the presence or absence of trees. Modelling the effect of the trees using the results from rural areas is also problematic, since patches of urban forest are far smaller, and indeed often consist of single trees, growing within hard landscaping. Their growth and hydraulic behaviour are likely to be different from forest trees. Finally, urban soils are often more compacted and urban drainage systems more extensive than their rural equivalents. Therefore models developed for rural hydrology have had to be used with care, while new small scale experiments have had to be devised.

Empirical Modelling

Researchers have used modelling approaches to examine management of urban stormwater since the 1960s (James, 1965; Wang et al., 2008). Perhaps the simplest method to investigate the effect of urban trees on runoff is to use empirical models devised from extensive catchment level measurements, such as that of the US Soil Conservation Service (USDA, 1986). Their curve number approach estimates the percentage runoff from storms of different sizes (but not intensity), depending on the surface cover (for instance, artificial cover, bare soil, arable or tree canopy), soil type, and antecedent moisture conditions. Percentage runoff is higher in large storms (as proportionally less intercepted by vegetation or stored by soil), on artificial cover, and in less permeable and wetter soil. Runoff from forests can fall to as low as 20% for a forest on well-drained soil in a 12 mm rain event (Whitford et a. 2001), but can be up to 98% from artificial cover.

Sanders (1986) estimated runoff from 77 of Dayton, Ohio's 79 neighborhoods for three scenarios: one for the existing surface cover; one in which trees were hypothetically removed; and a third that replaced exposed soil with vegetation, half of which was trees. He showed that for an intensive 46 mm storm the existing tree canopy (around 22%) alone worked to lower potential runoff by about 7% and this reduction could be increased to nearly 12% by increasing canopy coverage of the land surface to 37%.

The curve number approach was also used by Whitford et al. (2001) and Pauleit et al. (2005) to investigate the effect of vegetation in residential areas of Merseyside, UK. Whitford et al, (2001) showed that runoff coefficient for a 12 mm storm, at 0.82, was 60% higher for an area with around 20% vegetation cover than for one with 50% vegetation, which had a runoff coefficient of only 0.51. Pauleit et al, (2005) meanwhile investigated changes in runoff due to development in 11 residential areas in Merseyside, UK, over the period 1975 to 2000, and estimated a mean increase of 4% in runoff coefficient for 12 mm storms due to a mean increase in built up area of 6%. Gill et al. (2007) more specifically modelled the potential runoff reduction capabilities of trees in Manchester, UK. The authors showed that in a 28mm storm, a once in a year event by the 2080's, an increase of 10% tree cover in high density residential areas could reduce surface runoff by 5.7%.

The models are rather generalized and do not account for differences between summer and winter, when deciduous trees lose their leaves. Nevertheless, the results from all these studies are consistent, and suggest that for the sorts of large rainfall events that could cause flooding, increasing tree cover only has a relatively small effect upon surface runoff, and even large tree planting efforts would not be able to climate proof cities against the increasing size and intensity of storms predicted due to climate change. For instance one in a year storm size is predicted to increase in Manchester UK by 60% by 2080 (Gill et al, 2007).

Mechanistic Modelling

A major problem with the empirical models described above is that they require numerous input parameters yet do not investigate the processes over the time course of a rain event. Nor do they provide an adequate simulation taking time of year, plant type and soil characteristics into consideration. For instance Longcore et al. (2004) set out to investigate the applicability of the GIS-based tool CITYgreen which was based on the work of the Soil Conservation Service (USDA, 1986) for assessing benefits of trees in reducing stormwater runoff in a densely populated Los Angeles neighbourhood. The authors reported that the CITYgreen module did not work properly with overlapping coverages. In the real world trees, shrubs, grass, and buildings have overlapping footprints on the horizontal plane while they are separated in the vertical plane (Longcore et al., 2004). Therefore, a simple summation of model according to their respective area can only be a first approximation. Advanced hydrological simulations of mixed species stands with spatial and temporal variability and various soil characteristics are therefore needed and should be used with relevant hydrological data. One such complex mechanistic model has recently been developed: the i-Tree-Hydro model Wang et al. (2008). The model calculates instantaneous values of surface runoff using an iterative procedure. First it calculates the instantaneous throughflow of rainwater to the soil by calculating the amount intercepted and stored in the canopy, while simultaneously calculating the evaporation rate from the canopy using the Penman-Monteith equation. Of the throughflow it calculates the infiltration rate depending on the hydraulic conductivity at different soil depths and the wetting front suction force. Any remaining throughflow once the soil is saturated is converted to surface runoff known as saturation excess overland flow. The model therefore closely mimics natural processes and takes into account variations in leaf area index, though the effect of tree roots on infiltration depth through increasing hydraulic conductivity (reducing compaction and increasing infiltration depth) is not directly considered.

Using the i-Tree-Hydro model in Baltimore, Maryland Wang et al. (2008) simulated two different scenarios: The first scenario reduced pervious tree cover from 12.0 to 6.0% and replaced it with connected impervious area with no trees. The second scenario doubled pervious tree cover from 12.0 to 24.0% in bare soil and short vegetation areas, and increased impervious area covered by trees from 5 to 20%. The authors showed a 10% (500,000 m^3 yr^{-1}) annual runoff increase in the first scenario with reduced tree cover, while in the second scenario, with increased tree cover, annual runoff decreased by 3% (140,000 m^3 yr^{-1}). In addition to the total volumetric changes, i-Tree-Hydro simulated peak discharge rates for storms, giving a 12% lower peak discharge rate for 24% tree cover than 6%. As for the empirical models, the percentage differences in runoff were small relative to the large differences in tree cover simulated, suggesting that urban trees are fairly ineffective at preventing surface flooding.

Experimental Studies

Considering the large potential differences between the hydraulic behaviour of urban and rural trees, one might expect that modelling studies would be backed up by extensive experimental studies on urban trees. Unfortunately, however, very little research has actually measured the runoff of urban areas with or without trees. This is largely due to the difficulty in identifying even small urban areas that are identical apart from tree cover, and in measuring runoff in urban areas.

Studies on Runoff

To overcome these difficulties, Armson et al. (2013) designed and built nine experimental plots at five sites in Manchester, UK, to investigate the effect of surface type and tree cover. Each plot was composed of three individual 3m × 3m areas, one surfaced with asphalt, one with grass, and one with asphalt with a 1m×1m tree pit in the centre, planted with a 7-9 year old *Acer campestre* tree. Each plot was constructed with a 1:40 gradient sloping towards surface drains located in one corner so that runoff could be measured by a tipping bucket flow gauge. Armson et al. (2013) showed that trees and their associated tree pits, reduced runoff from asphalt by as much as 62% and by much the same in winter as in the summer. The reduction was more than interception alone could have produced, and was not affected by whether the tree was in leaf or not, so the reduction must largely have been due to infiltration into the tree pit. Interestingly, relative to the canopy area the trees actually reduced runoff by 170% in summer and 145% in winter, suggesting that with the correct landscaping, urban trees could have a greater effect than simply eliminating runoff from their canopy area, and emphasising the potential of incorporating trees into SUDS schemes.

There were problems with this experiment, however. For instance grass almost totally eliminated surface runoff, which would be unusual in urban areas; the reason was probably the experiment was carried out in areas with newly laid permeable soils with no footfall. Areas with more compacted soil would probably have given much more runoff. Another problem was that even the tarmac had a low runoff coefficient of around 0.6, far less than predicted by hydrological models. The slope of the ground, permeability of the paving and arrangement of drains is clearly extremely important in determining the runoff in urban areas This, too, has been little investigated, though Ramier et al.'s (2011) experimental and modelling study suggests that runoff coefficients of as low as 0.6-0.7 might be quite common for urban roads, particularly in the summer when rainwater can evaporate or infiltrate into the tarmac before reaching the drains. Much more research clearly needs to be done to investigate the effectiveness of different tree species and trees of different sizes. In particular different growing arrangements, and contours of planting sites should be investigated, to identify the optimal methods of planting street trees to reduce runoff, while avoiding waterlogging of their roots. Experimental work also needs to be performed on the runoff of urban forests and parkland. Once again, however, there are difficulties with performing such experiments, not least due to the high cost of building experimental sites or instrumenting existing sites with flow gauges in the drains.

In the absence of information on the actual runoff from drains around urban trees and the difficulty in conducting research on it, the interest of urban forest researchers has concentrated on some of the factors that affect runoff: interception by tree canopies; and infiltration into the soil.

Studies on Interception

Trees play an important role in urban hydrology through canopy interception of rainfall, so reducing throughfall and therefore peak catchment flows (Livesley et al., 2014). Most studies of canopy interception, however, have been made in natural or managed forest systems; urban trees might be expected to differ in their response because their canopy cover is discontinuous, tree canopies are often isolated, and there is high species variability which makes the interception measurements difficult (Livesley et al., 2014). Area-based interception percentages are smaller than those reported by natural forests (Guevara-Escobar et al., 2000, 2007; Jackson, 2000; Xiao et al., 2000; and David et al., 2006). However, their spatial dimensions and the edge effect due to the discontinuity of the canopy might be expected to increase evaporation from wet canopies (Veen et al., 1996; Klaassen et al., 1996) and differences in interception storage capacity and the rate of evaporation might cancel each other out.

Most studies have used similar techniques to calculate the interception of urban canopies, using the Rutter (Rutter et al., 1971; Rutter and Morton, 1977) and Gash models (Gash, 1979). Gross precipitation and throughfall are both measured with tipping bucket rain gauges, one outside, and one below the canopy, while stemflow can be measured with gauges attached to the tree trunk (Guevara-Escobar et al. 2007; Asadian and Weiler, 2009). The evaporation from the canopy, meanwhile can be estimated from meteorological measurements using the Penman equation (Xiao et al., 2000).

However, though this would seem to be adequate to determine the effect of wind on interception and evaporation, there is a problem with scattered trees (Kainkwa and Stigter, 1994). In high winds, isolated trees can produce a rain shadow downwind (David et al., 2006). Therefore, David et al. (2006) measured rainfall at ground level using a set of rain-gauges located in a radial layout centred on the trunk of an isolated *Quercus ilex* tree and extending beyond the crown. They computed interception loss as the difference between the volume of rainwater that would reach the ground in the absence of the tree and the volume of water that actually fell on the ground sampling area.

The results of the studies are extremely variable. In all cases throughflow was much great than stemflow, but interception varied from 15-60%, depending on the size of the tree, weather conditions, and size of the rainfall event. In general larger trees with denser canopies intercepted a greater percentage and the relative effects were greater in small rainfall events. Unfortunately, though, the conditions varied so much between the studies that they do not give reliable information about how effective urban trees canopies generally are, or which species would perform best. In conclusion, therefore, they cannot be used to validate or modify the assumptions of hydrological models such as i-Tree Hydro (Wang et al. 2008).

Studies on Infiltration

Many studies have shown that infiltration in rural forests is higher than in arable or grasslands (USDA, 1986, Wang et al. 2008). Tree roots are often proposed as biological drills or tillers that can strongly influence water movement through soils (Johnson and Lehmann, 2006), and it has indeed be shown that tree roots can increase macroporosity, hydraulic conductivity, and preferential flow (Yunusa et al. 2002). Consequently Bramley et al. (2003) found infiltration through flooded impoundments containing trees was 2 to 17 times faster than in impoundments without trees. The process of forestation can increase conductivity and hence infiltration very rapidly. For instance, in a study at PontBren, Wales (Bird et al. 2003), planting of trees on a formerly heavily grazed pasture increased infiltration of the soil by a factor of 10-100 within a matter of 6 years, probably due to a reduction in soil compaction and the development of the trees' roots.

However, much less is known about the conductivity and infiltration rates into urban soils; it might be expected to be lower than in rural areas, especially in street and park trees, because of the compaction caused by footfall and traffic, though the effect should be less in dense plantations. The few studies that have been carried out (Bartens et al. 2008; Millward et al. 2011 and Yang and Zhang, 2011) have used double ring infiltrometers or similar equipment to measure the downward movement of water. Initially, water moves rapidly down into soil, filling up the air holes and driven by capillary forces, but the ratio of air-filled pores to water-filled pores decreases as soil becomes proportionately wetter (Burden and Randerson 1972) and reduces cohesion between particles (Millward et al., 2011). In such situations water only moves by gravity, and the infiltration rate stabilizes over time (Yang and Zhang, 2011). The studies also investigated the soil texture and bulk density to determine compaction, along with soil organic matter content, which might be expected to improve soil texture and increase infiltration.

Bartens et al, (2008) did indeed show that roots of young developing trees increased infiltration rates 2.5 to 27 times over a two year period, but the trees were growing in specially prepared soil cores, so these experiments cannot be extrapolated to the urban fabric. Working in Kew Gardens Park, Toronto, Canada, Millward et al. (2011) investigated the effect of removing people from parkland by using “naturalisation” enclosures. They found that removing footfall in this way increased infiltration rates from a mean of 60 mm hr^{-1} to 470 mm hr^{-1} due to a reduction in compaction. The most relevant study, though, was that of Yang and Zhang (2011) who studied the hydrology of land under ten typical land use patterns, including various vegetation categories in Nanjing city, China. The final infiltration rates of urban soils varied widely and ranged from very slow (≤1 mm h^{-1}) to very fast (>254 mm h^{-1}), but the highest mean infiltration rates were in lawns with trees (220 mm h^{-1}), ten times higher than for lawns, and a hundred times faster than non-vegetated areas. Further research is clearly needed to determine whether this is a universal effect. It will be particularly important to investigate the infiltration properties of the sorts of structural soils used by Bartens et al. (2008, 2009) in their experiments, and nowadays commonly used to grow urban trees in areas which are subjected to heavy traffic or high footfall. Rahman et al. (2011) have indeed shown that the use of structural soils can greatly increase the growth of *Pyrus calleryana* trees growing in suburban streets in Manchester, U.K., largely because the soil is weaker and less compacted, though they did not measure infiltration rate.

It will be even more important to investigate how differences in infiltration rates of soil in urban areas actually affects their runoff characteristics and the amount of water that is diverted to the drains; this will involve extensive experimental investigation.

Trees in SUDS Schemes

In SUDS schemes water is diverted from buildings and hard landscaping into areas of permeable materials, often sand or light soils in which plants are growing (EPA, 2013).

Water is therefore filtered and some may be stored before being running off into the drainage network. Such schemes are therefore by no means natural, representing an expensive engineered component; they require sensitive design of the planting to ensure that any vegetation incorporated into the schemes actually survives; in permeable sands plants might die of drought, whereas in heavier soils to which too much water is diverted they might die of waterlogging. In recent years there has nevertheless been a trend to use trees within sustainable urban drainage schemes (SUDS). Extensive use of trees in SUDS schemes have been pioneered in the USA and Australia and have proven to have hydrological advantages (Mitchell, 2006; Bartens et al, 2009; Denman et al., 2011; EPA, 2013). The first is that they are excellent at improving water quality, common urban pollutants such as nitrates being typically reduced by around 80% in the filtered water (Denman et al., 2011; Read et al., 2008, Xiao and McPherson, 2008). There is less information on the reduction in runoff because of trees, much less than that from studies involving green roofs or permeable paving. Indeed the effectiveness of such schemes depends greatly on the area and depth of the installation and on the location and depth of the exiting drain. All schemes will therefore behave very differently. In the UK and the rest of Europe SUDS schemes are less common and there is very little information on their effectiveness at reducing runoff or indeed on the design characteristics that will lead to effective vegetation establishment.

Discussion

The current state of knowledge about the effectiveness of trees at reducing runoff and hence urban flooding is relatively poor. Empirical and mechanistic models both suggest that tree planting only has a modest effect. In general every increase of 1% in tree cover would be predicted to decrease runoff from large storms by only 0.5 – 0.7%, so tree planting would be unable to climate proof cities against the 50-100% increases in storm size and intensity that have been predicted over the next century (Hulme et al. 2002; Watts et al, 2004). However, both empirical and mechanistic models assume two things: first that trees do not alter soil properties; and second that rainfall from outside the canopy is not diverted and drained into their planting holes. Neither is likely to be correct as the results of Armson et al. (2103) show. Much more experimental research is clearly needed on the effect of trees on runoff in urban areas. In particular we barely now anything about the local diversion of rainwater in vegetated areas, and how much is directed own the drains or into planting holes. Trees' ability to increase soil permeability might increase the effectiveness of urban trees to almost abolish runoff from beneath them, while diversion of rainfall from outside the canopy, (particularly in SUDS schemes) might also effectively reduce the runoff from areas of hard landscaping. Much more research is therefore needed on the effect of trees on soil permeability and on the effect of planting methods and urban soils on water infiltration and runoff.

A great deal of research also needs to be carried out on the effect of tree species and size, and conversely on the effect of different planting methods and urban soil choice on the establishment and growth of urban trees. The challenge must be to work out methods in which trees can be incorporated into the urban landscape in such a way as to maximise their hydrological effectiveness, while maintaining their health. Ideally this would be done in ways that are simple enough to reduce the complexity and costs of planting below that of conventional SUDS schemes. A great deal of experimental research combining arboriculture and hydrology needs to be undertaken.

What We Know

1. Trees reduce runoff in urban areas by reducing throughfall and increasing infiltration of rain.
2. Modelling suggests that the effect of trees are relatively small because of their inability to affect runoff from adjacent built areas.

What We Don't Know

1. We don't have experimental measurement of the actual size of the runoff reduction due to trees.
2. We don't know the effect of trees on urban soils.
3. We don't know how much runoff is affected by planting methods, soil type or tree species.
4. We don't know how effective trees can be in diverting runoff from areas outside their canopy.

What We Need to Do

1. We need to carry out street level studies of the runoff from areas with and without trees.
2. We need to investigate optimal methods of growing trees and the soil media in which to plant them within SUDS schemes.

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